Innovative Construction in Canada's Extreme Environments: Combining Computational Design and Digital Fabrication with Modern Timber Techniques

by

Yakine ZERRAD

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Construction innovante dans les environnements extrêmes du Canada : intégration de l’impression 3D et du bois lamellé croisé à travers la conception computationnelle et la fabrication numérique

Yakine ZERRAD

RÉSUMÉ

Afin de contribuer à résoudre la crise du logement dans les régions de pergélisol du Canada Nord. Cette thèse par articles explore la combinaison de la conception computationnelle (*Computational Design* - CD) et des techniques de construction modernes. L’analyse aborde de comment le bois lamellé-croisé (*Cross-Laminated Timber* - CLT) et l'impression 3D peuvent être utilisés pour développer des solutions de logement adaptables, durables et culturellement appropriées qui répondent aux défis logistiques, culturels et environnementaux des climats extrêmes. La recherche met en avant l'utilisation d'Ameba et de Karamba 3D pour l'optimisation des configurations structurelles et des ressources sur des chantiers de construction éloignés, où les coûts de transport sont élevés et l'accès est souvent difficile, voire impossible. La recherche s’articule autour de deux axes principaux. La nécessité d'incorporer les valeurs culturelles autochtones dans la conception architecturale et le potentiel technologique d'utiliser le CLT et l'impression 3D dans des environnements extrêmes. Des études de cas provenant du Canada et de projets internationaux sont utilisées comme références pour évaluer comment les technologies de construction sont appliquées dans des contextes réels. Les résultats suggèrent que l'impression 3D offre une opportunité majeure en matière de réduction des déchets, de personnalisation, de standardisation et de facilité d'assemblage.

Un aspect important de cette recherche a été ma participation à une mission analogique de deux semaines à la station de recherche LunAres en Pologne. La mission a simulé un environnement d'isolement et à fournir des informations précieuses sur les défis psychologiques auxquels l'être humain peut être confronté dans la vie quotidienne. Enfin, la recherche révèle la nécessité d'une innovation continue et d'une collaboration entre l'industrie, les chercheurs et les communautés autochtones pour aborder efficacement la crise du logement distincte du Nord canadien et promouvoir la durabilité environnementale et le respect du patrimoine culturel.

Mots-clés : Conception computationnelle, impression 3D, bois lamellé-croisé, environnements extrêmes, pergélisol, architecture autochtone, construction durable, mission analogique, crise du logement

Innovative Construction in Canada's Extreme Environments: Combining Computational Design and Digital Fabrication with Modern Timber Techniques

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ABSTRACT

To help solve the housing crisis in Northern Canada's permafrost zones, this article-based thesis explores the combination of Computational Design (CD) and modern construction techniques. The study discusses how Cross-Laminated Timber (CLT) and 3D printing can be used to develop adaptable, sustainable, and culturally suitable housing solutions that address the logistical, cultural, and environmental challenges of extreme climates. The research highlights the use of CD for the optimization of structural configurations and resources in remote construction sites, where transportation costs are expensive, and access is often challenging or even impossible. The research is organized around two main themes: the need to incorporate Indigenous culture values into architectural design and the technological potential of employing CLT and 3D printing in extreme environment. The case studies from Canada and international projects are used as references to evaluate how these construction technologies are applied in real-world contexts. Findings suggest that 3D printing presents a great opportunity in terms of waste reduction, customization, standardization, and ease of assembly. On the other hand, CLT offers a great alternative for conventional building materials, accelerating construction and reducing the carbon footprint.

An important aspect of this research involved a participation in a two-week analog mission at LunAres Research Station in Poland. The mission simulated an isolated environment and brought relevant information of psychological challenges that a human can face in daily life during space missions. The mission underlined the need to design spaces that support psychological well-being, reduce stress, and offer privacy and human interaction. The mission presents essential results on resource management, health monitoring, waste reduction, and self-sustained habitat. Finally, the research reveals the need of continued innovation and collaboration between, industry, researchers, and indigenous communities to effectively address the distinct housing crisis of Northern Canada and promote environmental sustainability and respect of cultural heritage.

Keywords: Computational design, 3D printing, Cross-Laminated Timber, extreme environments, permafrost, Indigenous architecture, sustainable construction, analog mission, housing crisis

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LIST OF ABREVIATIONS

3D	Three-Dimensional
3DCP	3D Concrete Printing
AI	Artificial Intelligence
ATCS	Active Thermal Control System
BEAM	Bigelow Expandable Activity Module
BIM	Building Information Modeling
BMI	Body Mass Index
CAD	Computer-Aided Design
CD	Computational Design
CHAPEA	Crew Health and Performance Exploration Analog
CHARS	Canadian High Arctic Research Station
C	Celsius
CMAR	Construction Management at Risk
CNC	Computer Numerical Control
CLBT	Cross-Laminated Bamboo and Timber
CLT	Cross-Laminated Timber
CLTCC	Cross-Laminated Timber Concrete Composite
CLTVC	Cross-Laminated Timber Volumetric Construction
ECLSS	Environmental Control and Life Support System
DB	Design-Build
EVA	Extravehicular Activities
F	Fahrenheit

FTA	Fault Tree Analysis
GIS	Geographic Information Systems
GLT	Glulam Laminated Timber
GSC	Geological Survey of Canada
GWP	Global Warming Potential
HDPE	High-Density Polyethylene
HERA	Human Exploration Research Analog
HF	Human Factors
HRA	Human Reliability Analysis
HVAC	Heating, Ventilation, and Air Conditioning
IATPS	Integrally Attached Timber Plate Structures
IPD	Integrated Project Delivery
ISRU	In-Situ Resource Utilization
ISS	International Space Station
LAN	Local Area Network
LEED	Leadership in Energy and Environmental
MLI	Design Multi-Layer Insulation
MDRS	Mars Desert Research Station
NEEMO	NASA Extreme Environment Mission Operations
NRC	National Research Council of Canada
OSC	Offsite Construction
pH	Power of Hydrogen

PLA	Polylactic Acid
PSL	Parallel Strand Lumber
RACC	Reinforced Additively Constructed Concrete
RAMS	Robust Advanced Modeling and Scheduling
SFS	Scroll Filter System
TCC	Timber-Concrete Composite
UV	Ultraviolet
WRB	Weather-Resistant Barrier
XPS	Extruded Polystyrene

INTRODUCTION

The construction of houses in the permafrost regions of Northern Canada presents challenging problems that surpass the technical problems caused by extreme environments. These regions are recognized by harsh weather conditions, including freezing temperatures, shifting permafrost, limited resources availability, as well as the unique cultural context of indigenous communities. Therefore, effective housing solutions need to combine modern technology and respect for cultures. Facing these challenges involves more than conventional construction methods, which are unsustainable, unsuitable and impractical for remote areas marked by permafrost. Building on permafrost is a serious issue due to ground instability, thermal sensitivity, and causing the foundations to shift, crack and collapse. Moreover, logistics in Northern Canada are expensive and the environments often lack developed infrastructure like roads, ports and airports, making the transportation of materials, equipment more difficult and less cost effective.

This thesis explores innovative approaches for sustainable construction by integrating computational design (CD), 3D printing, and Cross-Laminated Timber (CLT). Computational design helps for optimization of architectural shapes and materials, leading to structures that are energy-efficient and resilient to severe weather. 3D printing technology, which supports onsite construction components, reduces transportation cost and material waste, creating a great alternative for remote construction. Using CLT, a highly durable material, can help to reduce the carbon footprint and provide high thermal insulation, important to ensure that the indoors is comfortable when the outdoor is extremely cold. Additionally, this research incorporates the author’s participation in a two-week analog mission at the LunAres Research Station, which simulated isolation in extreme environments. The findings from this mission highlight the human and environmental problems caused by living in extreme environment, bringing a crucial knowledge of how construction can improve psychology, well-being and sustainability in Northern Canada.

Moreover, this thesis aims to illustrate how the integration of these technologies, alongside data from analog mission may promote the creation of adaptive, sustainable, and culturally responsive homes for Northern Canada. This thesis seeks to contribute to the academic disciplines of architecture and the use of housing solutions in permafrost regions. ChatGPT was used to refine the language and correct grammatical errors.

Research questions

In response to the challenges stated in this thesis, the following research questions have been formulated to focus not only on the integration of new technologies, including CD, 3D printing, and CLT, but also on finding from the analog mission at LunAres research station to address the human and environmental factors of living in permafrost regions of Northern Canada:

- Q1: How can CD and 3D printing theoretically be integrated with CLT to create adaptable and sustainable housing solutions for Northern Canada's permafrost region?
- Q2: What role can CD play in optimizing these materials and construction techniques for extreme weather conditions?
- Q3: How can housing designs integrate indigenous cultural values and traditions while simultaneously solving the technical and logistical challenges forced by permafrost regions?
- Q4: How can results from analog missions guide the design of homes to improve psychological well-being, resource efficiency and adaptability in extreme and isolated environments?

Research papers

This article-based thesis consists of three papers: one journal article (submitted for review) and two conference papers (already published). The journal article is presented as a chapter, and the two conference papers are included as appendices. These publications together enhance the research on construction in extreme environments. The article provided are

- Chapter 5: Human and Environmental Challenges in Analog Missions: The LunAres Case Study (*journal article - under review for publication in the proceedings of Space: Science & Technology Journal, September 2024*).
- Appendix I: Constructing in Extreme Climates: An In-Depth Examination Across Varied Environmental Conditions with a Focus on Canada (*First conference paper -*

published in the *proceedings of The Canadian Society for Civil Engineering Annual Conference, June 2024*).

- Appendix II: Designing for the Extreme: Computational Strategies for Adaptable and Sustainable Housing in Northern Canada Permafrost Regions (*Second conference paper - published in* the *proceedings of The BuildingSMART International Summit Conference, October 2024*).

Organization of the Thesis

Chapter 1 provides a literature-based case study analysis of construction techniques in different extreme climate zones, covering polar regions, tundra, deserts, and outer space. It analyzes how different projects responded to these environments, addressing both geographically and physical characteristics of construction in Canada. The case studies present a comparative analysis of how each climate zone can influence the choice of construction systems and materials and involve the development of innovative technologies and sustainable practices.

Chapter 2 examines the housing situation in Nunavut and Inuit Nunangat by defining the historical, cultural and environmental impacts faced in these areas. This section discusses 3D printing and CLT as a creative construction method, outlining the potential to adopt them in Canada.

Chapter 3 explores the integration of 3D printing in Northern Canada. It examines the logistics of construction shipping, reviews several 3D printing configurations, and discusses and compares the design characteristics of different scenarios, bringing out the importance of offsite and onsite construction.

Chapter 4 presents the conceptual design of the proposed housing solution for Northern Canada's permafrost regions. It explains the application of CD tools including Grasshopper, Ameba, and Karamba 3D for structural and material optimization, to propose a new design that combines 3D printing and CLT. The chapter presents detailed drawings, plans and sections, and renders of different perspectives.

Chapter 5 focuses on human and living factors during the analog mission, and presents both qualitative and quantitative data to learn more about how isolation and design habitat can affect the psychology and well-being of the analog astronauts.

In conclusion, the final chapter discusses and summarizes the findings from the chapters and introduces the field of space architecture and how it can contribute not only to solve the housing crisis in Canada and worldwide, but also face climate change and prepare for potential natural disasters that could strike the Earth. A multidisciplinary approach in architecture and construction which defines space architecture can help to develop and to use new technologies, material composition, and robots to design buildings that withstand extreme environments. Finally, the conclusion summarizes the main ideas of the thesis and provides recommendations for future research and real-world applications. The appendices provide additional quantitative data, the questionnaire used during the survey, and images from the analog mission.

Figure 0.1 on the following page visually clarifies the structure of the thesis, showing the organization and interconnection of the different chapters, research papers, and appendices within the entire research framework.

Building on the structure shown in Figure 0.1, Figure 0.2 illustrates the interconnected progression of the research objectives presented in this thesis. Objective 1, which investigates construction techniques in harsh climates, serves as a fundamental notion connecting Conference Paper 1 and Conference Paper 2. This objective includes three primary domains: sustainable materials, automation, and cultural considerations, each enhancing the comprehension of how modern technologies and culturally pertinent design techniques might address the challenges presented by extreme environments. The results from Conference Paper 2 feed Objective 5, which is based on experiential findings from the LunAres analogue mission. This objective connects the concepts of the analogue mission to architectural solutions for Northern communities, as described in the Journal Paper. The mission findings informed the creation of dome-shaped home designs, incorporating detailed drawings, 3D models, and sections to build a thorough proposal addressing the specific issues of Northern climates.

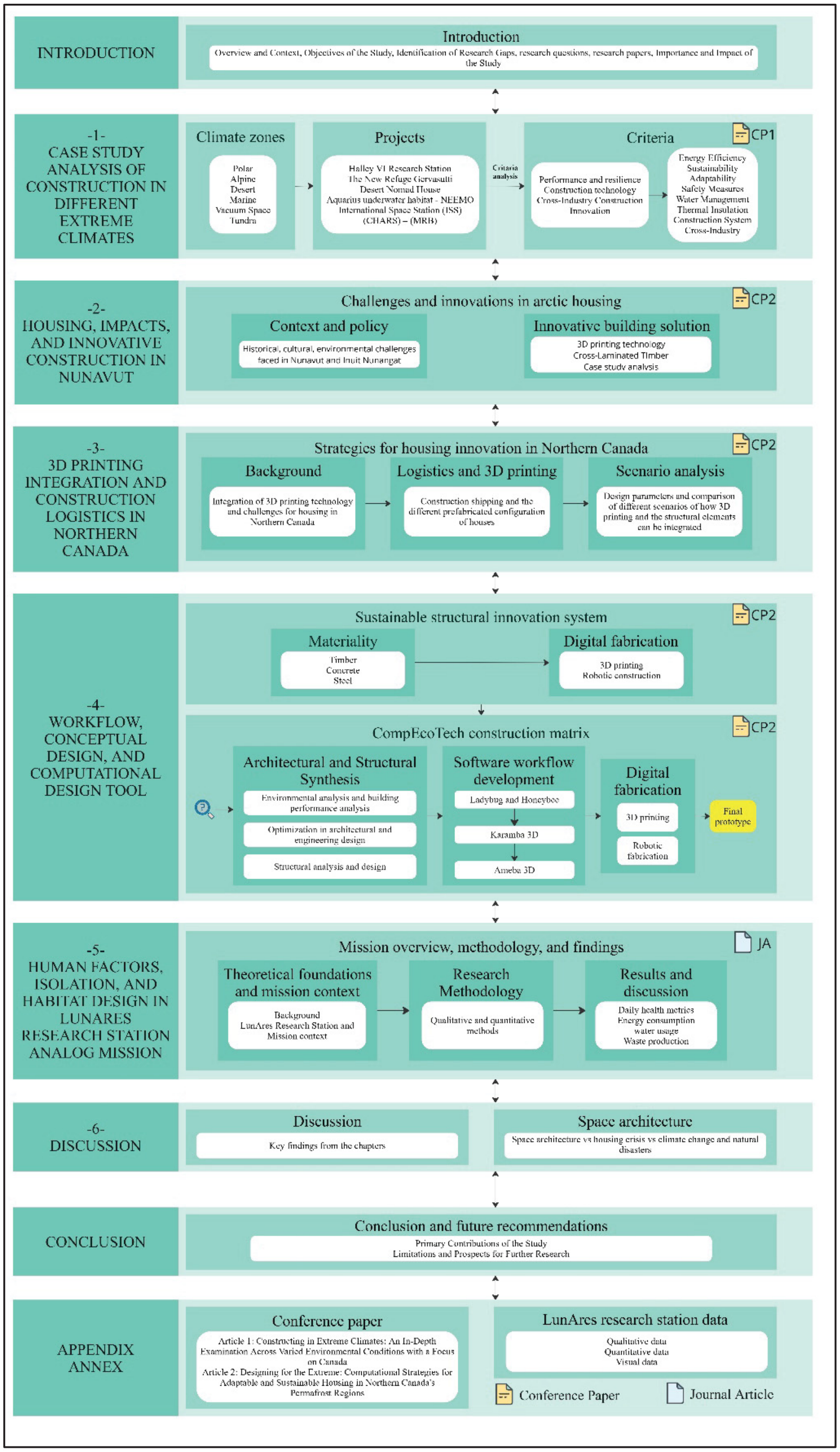


Figure 0.1 An overview of thesis structure

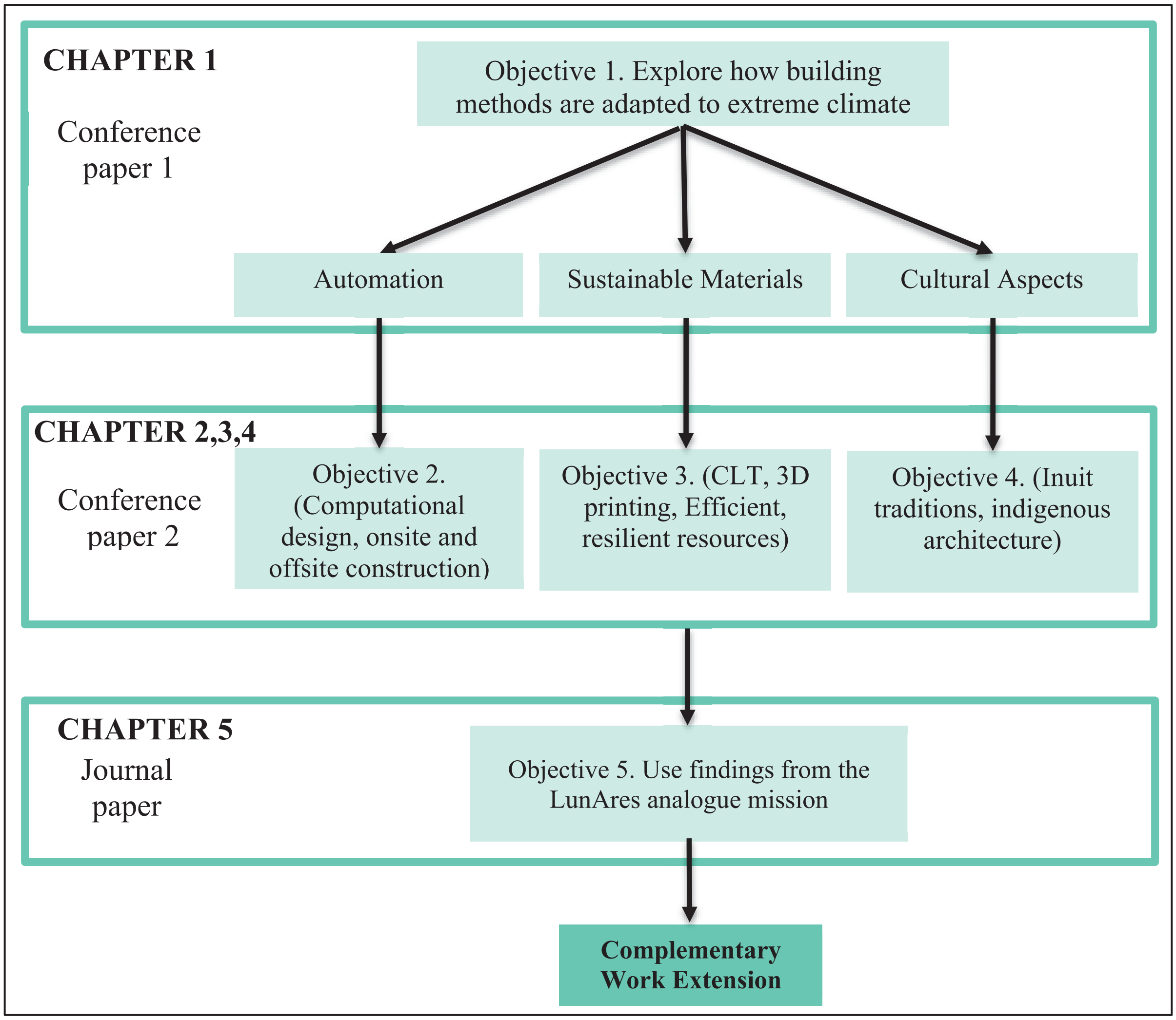


Figure 0.2 Alignment of research objectives and interconnections across publications

CHAPTER 1

CONSTRUCTION IN EXTREME CLIMATES: AN IN-DEPTH EXAMINATION ACROSS VARIED ENVIRONMENTAL CONDITIONS WITH A FOCUS ON CANADA

1.1 Introduction

Constructing in extreme climates can significantly affect the building structure and pose a variety of challenges, requiring the development of inventive solutions. Various climate conditions, including the cold of polar regions, the aridity of deserts, underwater habitats, and the vacuum of outer space, each present a unique challenge. This study examines six distinct projects, each located in a different type of challenging climate, to investigate solutions used to adapt to environmental difficulties, promote sustainability, and incorporate technology for enhanced efficiency and safety. A prominent aspect of this research relates to the Canadian context, where extreme cold temperatures and permafrost conditions offering a big construction challenge. Examining construction practices in Canada's extreme environments, alongside diverse global climate conditions, offers a valuable comparative approach. The strategies implemented in the Canadian High Arctic Research Station (CHARS) initiative, located in the tundra climate of Cambridge Bay, Nunavut, illustrate the integration of inventive design and operational approaches to overcome extreme climatic challenges. The objective is to collect enough acknowledgement of construction techniques prevalent in challenging environments and how these techniques contribute to increase operational efficiency, safety, and environmental stewardship. The investigation extends to the field of space architecture, exploring how extraterrestrial construction technology can improve terrestrial techniques.

The objective of the first section is to determine a framework for an in-depth examination of each project. This foundation will support a comprehensive analysis aimed at uncovering practical understandings that can significantly contribute to the existing body of knowledge in construction practices within extreme environments. Subsequent sections will provide a more detailed analysis of the methodology, projects, and findings, constructing a narrative that highlights potential avenues for achieving a construction industry that is resilient, sustainable, and technologically advanced.

1.2 Definition of extreme environments

An extreme environment is a geographical region characterized by extreme and difficult physical conditions, substantially diverging from the usual or moderate environmental parameters. These environments are often characterized by extreme temperatures, higher or lower pressures, intense radiation, corrosive substances, or other elements that significantly affect human life or structural adaptability. Consequently, multidisciplinary solutions and security are typically essential to address these challenges. For example, individuals may face conditions marked by extreme pH levels (either highly acidic or alkaline), wide temperature ranges, high salt concentrations, high radiation, and high pressures, among other harsh conditions. In most instances, these circumstances are considered unfavorable for maintaining the quality of life. However, there's a notable exception in the form of extremophiles. These organisms have the remarkable ability to thrive in environments with extreme conditions, characterizing a unique domain of adaptability within their classification. The concept of extreme environments extends to outer space, including celestial bodies like the Moon and Mars, as well as Earth's orbit. The engineering approaches required for these locations are distinct due to their challenging environment, which includes extreme temperatures, lack of breathable atmosphere, and high levels of cosmic radiation. (Vachon, J., Gallant, V., Siu, W.Gómez, 2011)

Conditions that are challenging and demanding but may not always reach the absolute limits are referred to as harsh environments. These can encompass a variety of difficult situations, such as extreme cold or hot weather, rugged terrain, scarce resources, and other factors that make living and conducting human activities more strenuous (Takacs, 2019).

1.2.1 Types of extreme environments

The Earth and beyond exhibit a wide spectrum of climatic conditions, each of them presenting its own conditions and opportunities. Extreme environments, such as the polar regions, hot deserts, tundra, high altitude mountains, as well as more unconventional locations like Earth's orbit, other planets like Mars, and underwater environments, demonstrate the remarkable diversity and adaptability of nature (Mumilaaq Qaqqaq, 2021).

However, Table 1.1 provides the global distribution of these extreme climate types, including Polar, Tundra, Hot Desert, and High-Altitude Mountain climates, along with extraterrestrial environments such as Earth's orbit and Mars, and aquatic environments like underwater habitats. The table presents prominent examples from each category, highlighting their distinct meteorological, environmental, and spatial characteristics.

Table 1.1 Zones with extreme environment

zone	Location	Climate	Characteristics
Polar	Arctic & Antarctic regions	Permanent ice caps cover landscape, long cold winters, windy with little precipitation	The soil is covered by ice during the year, Polar biome is home to a diverse array of moss, algae, and lichen species, polar bears are known to inhabit the Arctic region, while penguins are typically found in the Antarctic.
Tundra	High-latitude landmasses found in Alaska, Canada, Russia, Greenland, Iceland, and Scandinavia that are located above the Arctic Circle. They can also be discovered in extremely southern places like Antarctica.	Referred to as deserts since they typically receive less precipitation than 25 centimeters (10 inches) each year.	Permafrost soil, which is a layer of soil that stays frozen during the year, and it can be found where the annual average temperature is below 23°F (- 5°C).
Desert	Can be found between latitudes of 15 and 30 degrees. The Sahara Desert in North Africa, the Australian Desert, the Arabian Desert, and the Syrian Desert in Western Asia, the Kalahari Desert in Southern Africa, the Sonoran Desert in the United States and Mexico, the Thar Desert in India and Pakistan, the Dasht-e Margo and Registan Deserts in Afghanistan, etc.	In a low-elevation inland desert, the daytime temperature can reach 40°C to 50°C and the nighttime temperature may fall to about 5°C.	Covered in sand and rocks, making it too flat and devoid of vegetation to serve as a windbreak.

Table 1.1 Zones with extreme environment (cont'd)

zone	Location	Climate	Characteristics
High altitude mountains	The Everest: between Nepal and Tibet. Mount Kilimanjaro: Tanzania. Denali: south-central Alaska. Aconcagua: western province of Mendoza, in center west of Argentina	In Everest, the death zone, over 8000 meters in altitude and the climate causes brain swelling. Mount Kilimanjaro, wind speeds reach 50 km/h and temperature drop roughly -20 degrees. Denali, wind speeds reach 240 km/h and temperature.	The air pressure at the peak of Everest is about one third of that at sea level. Mount Kilimanjaro is a volcano Kilimanjaro is a very huge volcano comprised of stone, lava, and volcanic ash. Kibo, Mawenzi, and Shira are its three cones. The highest of the three volcanic structures, Kibo is the mountain's summit.
Low Earth Orbit	The altitude above the Earth's surface ranges from 250 kilometers to 2,000 kilometers (1,200 miles), with an orbital period ranging from around 84 to 127 minutes.	-170°C to 120°C (-274°F to 248°F)	High cosmic radiation. Microgravity. Frequent changes from day to night are caused by a fast-orbital period. Exposure to micrometeoroids.
Mars	Fourth planet from the sun.	Temperatures average around -63°C (-81°F) and range between -125°C and 20°C (-193°F and 68°F	Dust storms. Mars has a gravitational pull that is about 38% of Earth's gravity. Presence pf water ice in underground
Underwater	All bodies of water	According to the depth and location, underwater temperatures range from close to freezing to very warm, transparency is affected by light, surface conditions are impacted by weather conditions, and currents are influenced by temperature and salinity variations.	High cosmic radiation. Microgravity. Frequent changes from day to night are caused by a fast-orbital period. Exposure to micrometeoroids.

Understanding each climate zones will help to develop adaptive architectural strategies. These zones ranging from extreme heat of desert to freezing temperature of the polar, and to vacuum space, are illustrated in Figure 1.1. However, the polar climate is characterized by consistently low temperatures, with average monthly temperatures remaining below 10°C (50°F). These regions are typically located at significant distances from the Earth's equator, near the polar areas. Winters in these zones are marked by prolonged periods of darkness, while summers experience continuous daylight (Robinson, 2022). In contrast, the tundra climate features at least one month with temperatures above the freezing point (0°C or 32°F). In contrast, the ice cap climate is distinguished by having no months in which temperatures reach or surpass these freezing levels. (Britannica, 2023) The hot desert climate experienced a high temperature and aridity, resulting from persistent high atmospheric pressure, limited precipitation, and intense solar radiation (Eckardt, Maggs-Kölling, Marais, & de Jager, 2022).

Beyond Earth surface, we discover another type of extreme environment. The Moon, Mars, and Low Earth Orbit represent distinct categories of extreme environments. The temperature excesses and near-vacuum conditions of the Moon, the thin atmosphere and freezing temperatures of Mars, and the challenges presented by microgravity in Earth's orbit, all require specialized engineering, where solutions can be brought from different disciplines for construction and habitation. Utilizing extraterrestrial and near-Earth environments offers valuable opportunities for developing inventive technologies. These places provide a platform for exploring unconventional construction techniques, such as in-Situ resource utilization (ISRU), and addressing unique challenges, like managing space rubbish (debris) in Earth's orbit. Space architecture is pivotal for designing and building structures in both terrestrial and extraterrestrial environments. Those structures are not only limited in habitats, but also, other facilities and vehicles capable of withstand extreme weather conditions. It assists in creating designs capable of withstanding harsh conditions, including extreme temperatures, radiation, and oxygen scarcity. While not the primary focus of our study, space architecture is mentioned to highlight its contributions to the development of innovative construction techniques and technology, essential for addressing extreme environments on Earth (S. Hauplik-Meusburger & O. Bannova, 2016).

Figure 1.1 Different climate zones
Taken and adapted from National Park Service (2015); Coolman (2022); NASA (2013)

1.2.2 Analog missions and Extreme environment research

Table 1.2 lists different analog missions, their locations, and objectives. First, analog missions play a crucial role in this context. They serve as onsite testing facilities for construction technologies and methods, ensuring their reliability and effectiveness under challenging conditions. By simulating the environmental challenges construction crews may face, these missions provide insights into the performance of materials and equipment. Analog missions support sustainable practices, evaluate human adaptation to extreme environments, and optimize habitat design. The data gathered during these missions enhance our ability to build and survive in the most challenging environments on Earth and beyond (John Olson, 2011).

It is important to study real analog habitats that demonstrate the relevance of analog missions in extreme conditions. The table below compiles various missions conducted in different analog habitats. These initiatives serve as concrete examples of the effectiveness and adaptability of analog missions in simulating and addressing the challenges of harsh environments. For example, HERA (Human Exploration Research Analog) simulates conditions that astronauts might experience during extended space missions, allowing researchers to study the psychological and physical impacts of long-term isolation and confinement. HERA provide crucial information for designing and constructing habitats for future space exploration, as well as for challenging terrestrial environments. This research also explains how humans adapt to and perform in extreme conditions (Nasrini et al., 2020).

Table 1.2 Analog mission projects

projects	Location	Mission	Reference
CHAPEA	The Johnson Space Centre, Houston, USA	Study the impact of Mars-like conditions on human health and performance such as resource limitations in confinement and isolation.	(NASA, 2023)
HERA	The Johnson Space Centre, Houston, USA	Understand how confinement and isolation affect people. the risks associated with human spaceflight	(Nasrini et al., 2020)
Desert RATS	Black Point Lava Flow, Arizona	examining and improving technology, robotic systems, and spacewalk equipment for future space missions	(NASA, 2022)
ICEE Space, Iceland (CHILL-ICE)	Lava tube, Iceland	Geological research on the creation and mapping of lava tubes. Construction of infrastructure for harsh areas and the best place for habitation. Technological advancements including environmental sensors and changes to astronaut suits. Studies of human performance in challenging, solitary, and confined environments.	(CHILL-ICE, 2021)
NEEMO	Undersea research station, Aquarium Reef Base, Key Largo, FL, USA	2-week undersea mission. Plan, evaluate, and build technology that will steer future human solar system exploration.	(Sarah A., 2015)

1.2.3 Extreme environment construction in Canada

The present chapter explores a variety of global climates and gives useful understanding on construction practices in extreme environments, with a particular focus on Canada. Known for its unique challenges, including permafrost and temperature fluctuations, Canada provides an important context to learn inventive solutions in various climates, and developing a significant standard for comparable challenging environments worldwide. Permafrost, as illustrated in figure 1.2, refers to any ground that consistently remains at or below the freezing point for at least two consecutive years. Roughly half of Canada, predominantly within the Arctic Archipelago, Yukon, Northwest Territories, and Nunavut, is situated above this layer of permafrost. In engineering, permafrost requires considerable attention and often necessitates unique approaches during design and construction phases. This includes planning and implementing appropriate strategies, building and operational stages for diverse engineering structures and facilities. Such structures range from building foundations to dams, dykes, pipelines, roads, railways, airfields, and even utilities for communities in northern regions (N. R. C. Canada, 1981).

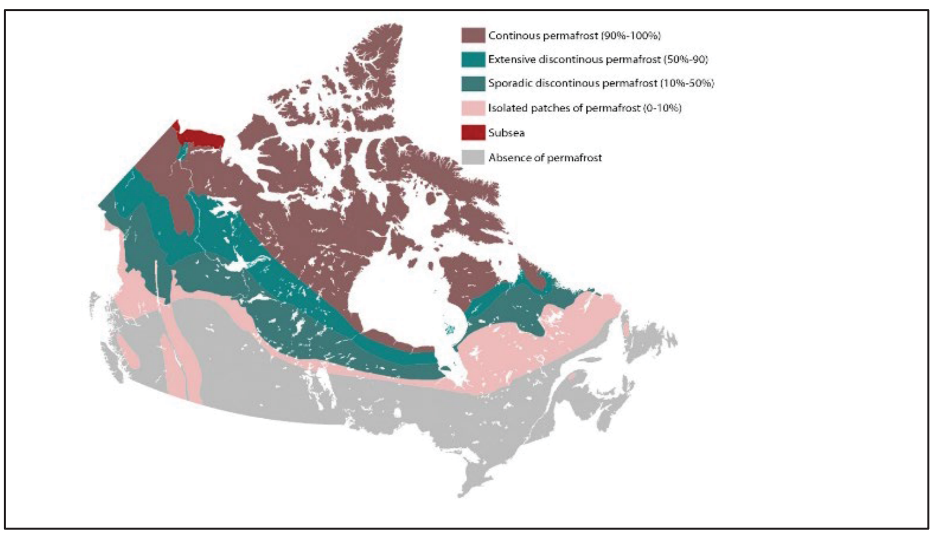


Figure 1.2 Cartography of B. O’Neill
Taken and adapted from Heginbottom et al. (1995)

In Canada, the substantial temperature fluctuations throughout both winter and summer force the adoption of construction techniques and materials to guarantee the well-being, safety, and thermal comfort of occupants (CCOHS, 2023). Indeed, an important number of building projects in Canada take place on or near Indigenous communities' lands. Given this proximity, it is mandatory to show respect for their traditions and rights and requires their involvement in the planning and construction phases.

The Climate-Resilient Buildings and Core Public Infrastructure Initiative, a five-year project funded by Infrastructure Canada and led by the National Research Council of Canada (NRC) from 2016 to 2021, illustrates these efforts. The objective was to integrate climate resilience into the design, guides, and the building code. Using its expertise in infrastructure and building science, the NRC developed the capacity within Canada's construction industries to adapt to the increasing demands required by climate change on built infrastructure. The program is applicable to both existing and new projects. Existing projects may be retrofitted as needed, with some improvements, such as reinforcing structures and enhancing drainage systems. For new projects, climate resilience is integrated from the design and construction phases to mitigate any climate change impacts that could put the population in danger. One notable NRC plan is the funding of traditional and natural infrastructure solutions, including renovations and upgrades. These investments intend to improve community resilience, reduce vulnerability to disasters, and yield long-term financial savings. Additionally, the initiative encompassed testing and monitoring various infrastructure systems, such as wastewater systems, the resilience of building façades and roofs, and bridge design, and in our context, resilience means the capacity of a system or structure to adapt and sustain functionality when faced with environmental, operational, and unexpected challenges. The National Research Council of Canada also expanded its research scope to include fires, rivers, oceans, and engineering disciplines (Lounis et al., 2019).

1.2.4 Geological and physiological aspects of Canada and construction

In the Canadian context, the choice of construction techniques and materials is influenced by several elements, including physiographic, geographic, and geological information. Physiographic information in construction involves analyzing the physical landscape characteristics. This involves aspects such as soil type, water bodies, land slope, and rock composition. Each of these elements plays a critical role in determining the most suitable construction methods and materials for a given location, guaranteeing safety, durability, and environmental compatibility (Slaymaker, 2015).

Design considerations like insulation in cold climates and wind resistance in hurricane-prone areas are influenced by geographic information. This includes broader factors like climate, vegetation, resource availability, and local regulations. Engaging with local construction experts or civil engineers who are knowledgeable about these aspects is crucial to ensure that construction is appropriate for its environment and complies with regulations (Goodchild & Longley, 2021).

Geological data significantly affects construction in Canada's challenging environments, where the impacts of various loads and the soil's response are critical considerations. CSA PLUS 4011.1 offers a comprehensive guide for building foundations in permafrost, a factor that requires special attention due to its significant implications on infrastructure. This guide emphasizes the complexity of permafrost's geographic and geological aspects, its responsiveness to climate change, and the necessity of adaptive design. It details how permafrost influences land characteristics, soil stability, and water drainage, all vital for the integrity of construction projects. Furthermore, CSA PLUS 4011.1 discusses the specificities of foundation types suitable for permafrost, such as steel pile foundations. It highlights that these foundations should be selected based on the variable strength of permafrost against different loads. CSA PLUS 4011.1 is an essential reference for understanding these dynamics and for the successful planning and execution of construction projects in northern, remote areas. It assists developers and designers in making informed decisions to mitigate the risks associated with the freezing and thawing cycles characteristic of permafrost regions. This guideline provides current knowledge and best practices for the design and construction of foundations in permafrost regions, making sure that structures can withstand the unique challenges faced in these environments. For detailed technical information on permafrost foundations, CSA PLUS 4011.1 stands as the definitive resource for engineers and construction professionals working in Canada's permafrost regions (Canadian Standards Association, 2019).

In addition to CSA PLUS 4011.1, the CSA S500:21 standard is crucial in Canada's Northern regions, particularly in permafrost areas. It ensures the stability of new buildings with thermosyphon-supported foundations. Thermosyphons, utilizing an enclosed refrigerant to transfer heat from the ground, are integral in this context. They effectively prevent the thawing of the ground, thus maintaining it in a frozen state. This method is a key adaptation in addressing the challenges posed by permafrost, complementing the guidelines set out in CSA PLUS 4011.1. Together, these standards offer a comprehensive framework for construction in these extreme conditions, merging the technical specifics of foundation design with innovative solutions like thermosyphons to maintain structural integrity in the face of challenging environmental factors (Canadian Standards Association, 2021).

The Geological Survey of Canada (GSC) serves as the national authority for geoscientific data and research. Its geological surveys play a pivotal role in informing policy, land management, and ethical resource development. These surveys are particularly critical in supporting the selection of appropriate foundations for resilient building construction in Canada's diverse landscapes. By highlighting the need for extensive soil studies and expert advice, the GSC ensures the structural integrity and longevity of construction projects nationwide (Geological Survey of Canada, 2023).

Understanding the challenges posed by permafrost is a key aspect of this process. The thawing of permafrost under structures, accelerated by increasing temperatures and persistent summer sunlight, presents unique challenges. Water's role in facilitating heat transfer from the surface to the ground is crucial in this context, as it accelerates thawing. Conversely, snow acts as a thermal insulator, helping to maintain the permafrost by preventing the replenishment of cold winter air. Additionally, wind can influence permafrost conditions by either facilitating moisture evaporation and snow removal or contributing to thawing by redistributing snow to areas like low-lying zones or against structures. To effectively mitigate the thawing of permafrost, strategies recommended by the GSC and other authorities include maintaining natural vegetation, establishing effective drainage systems to divert water away from buildings, and efficiently managing snow by removing it from surrounding areas. Enhancing airflow under buildings during winter using mesh material instead of solid skirting can also be effective in reducing heat accumulation. It is advisable to avoid storing materials under or near structures to ensure optimal airflow and minimize the risk of thawing. For more detailed guidance, resources such as the Standards Council of Canada's NISI-101 provide valuable insights into managing construction challenges in permafrost regions (Standards Council of Canada, 2020).

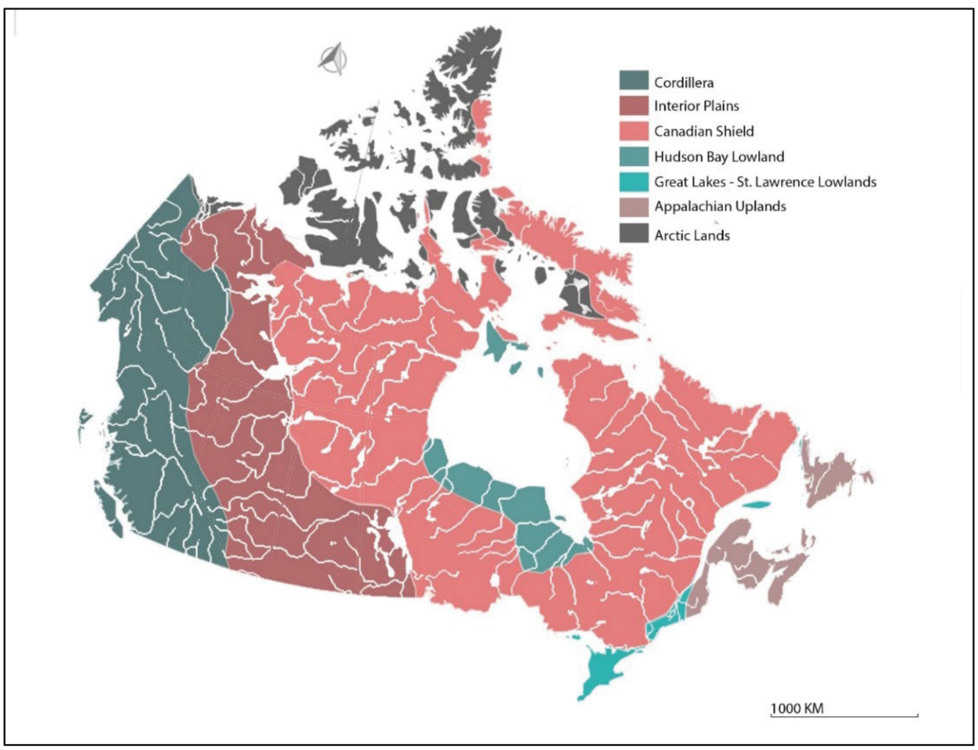


Figure 1.3 The physiographic regions of Canada
Taken and adapted from The Canadian Encyclopedia (2024)

1.3 Methodology

The research methodology is based on a comprehensive strategy of analyzing case studies, which is carried out through a series of well-structured procedures. We initiated the process by carefully choosing a wide variety of projects based on their innovative use of materials and the availability of detailed information for analysis, each located in a distinct temperature zone and posing its own set of environmental obstacles. To improve the level of clarity, a visual aid in the form of Table 1.4 was devised. This table incorporates checkboxes and is further supported by Figure 4, which includes line connections. These features assist to concisely outline the essential characteristics of each project, offering a clear visual overview that helps in comprehending the specific context of each study.

It is crucial to clarify that although this format may suggest a comparative framework, the purpose of this study is not to directly compare these initiatives with one other. Instead, the emphasis is placed on doing a thorough examination of each project within its unique environmental context. This methodology enables a detailed examination of how each project addresses and adapts to its own climatic obstacles, without making explicit comparisons between them.

Our systematic methodology facilitated a thorough analysis of these varied climate areas, capturing the distinct character of each individual case study. The projects chosen, as outlined in Table 1.3, cover a diverse range of environments, spanning from the frigid widens of Antarctica to the tundra conditions of Cambridge Bay, Nunavut. This diverse variety provides valuable perspectives on the distinct interaction between the climatic obstacles faced by each project and the innovative methods employed in its development.

Each project's response to its climatic conditions, as illustrated in Table 1.5, weaves a narrative of sustainability, adaptability, and technological innovation. This narrative underscores how each project's design and operational strategies are shaped by its environment, showcasing the ingenuity required to overcome extreme conditions.

The significance of the concept is most evident when used to construction in challenging locations. For instance, the Canadian High Arctic Research Station (CHARS) in Cambridge Bay, Nunavut, exemplifies creative design and operating solutions that are specifically adapted to address extreme environmental constraints. This case study, similar to other studies in the research, offers valuable insights into construction processes in challenging environments. It specifically emphasizes the importance of considering specific environmental factors rather than doing a comparative analysis across other locations.

Although the case study approach provides in-depth insights, it is crucial to recognize its limitations. An essential challenge arises from the potential variability and intricacy inherent in every project, caused by their distinct environmental circumstances. The unpredictability inherent in extreme environments poses challenges when attempting to extrapolate findings across multiple contexts. Furthermore, the diversity of case studies, although varied, is not comprehensive and so may not represent all potential situations found in the construction of extreme conditions. However, as this study specifically examines individual analyses without making direct comparisons, there is a possibility of overlooking opportunities to get cross-project knowledge and valuable insights that a comparative method could offer. It is essential to acknowledge these constraints to have a well-rounded comprehension of the study's results and to direct future investigations in this field of study.

1.3.1 Case studies analysis framework

This research aims to advance construction practices within extreme environments, analyzing diverse projects tailored to unique climatic challenges. It uncovers adaptive through sustainable and innovative strategies, thereby enriching the construction industry's knowledge. The comparative analysis across different climate zones enhances understanding of the varied challenges and solutions in such environments. These insights could guide future construction practices towards greater sustainability and adaptability, contributing significantly to the sector's evolution.

Table 1.3 Case studies analysis – presentation of the projects

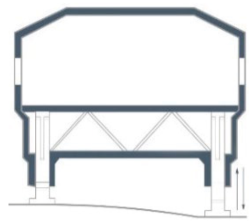
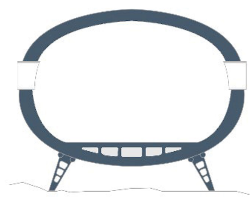
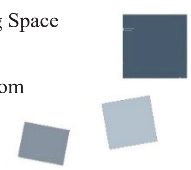
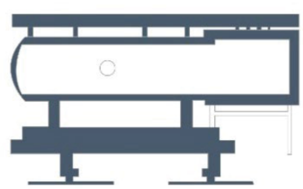
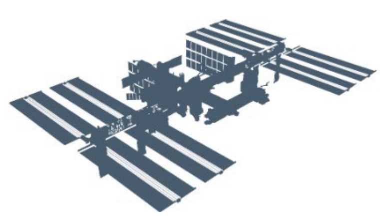
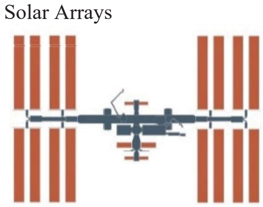
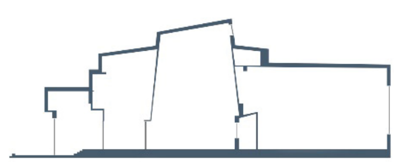
Project	**Typology**		
Halley VI Research Station		Sleeping Module Command Module Living Module Generator & Plant Module Science Module 	(Building, 2007) (Hughet, 2017)
The New Refuge Gervasutti by LEAPfactory		Sleeping space, bathroom Living space 	(LeapFactory, 2023)
Desert Nomad House		Living Space Office Bedroom 	(Naser Nader, 2020)
The Aquarius Underwater Habitat - NEEMO		Main Lock with Bunks and Counter Entry Lock with Science Area Wet Porch and Entry-Exit Hatch 	(Sarah A., 2015) (oneworldoneocean, 2012)
International Space Station (ISS)		Habitable Modules Solar Arrays 	(Kitmacher G., 2010)
(CHARS) – (MRB)		Public Space Offices Rough Labs Field and Maintenance Services Circulation Technological Labs 	(AANDC Arctic Science Policy Integration et al., 2012)

Table 1.4 Case studies analysis – category and subcategory

Category/Sub-Category		Halley VI Research Station	The New Refuge Gervasutti by LEAPfactory	Desert Nomad House
Geographical Context	**Location**	Polar - Antarctica	Courmayeur, Italy, on Freboudze glacier, Mont Blanc Range. Elevated at an altitude of 9,843 feet (3,000 meters) above sea level	in Tucson, Arizona, USA
	Climate Zone	Polar, Common sunny days -10°C, winters below -20°C, extreme lows -55°C	Alpine, cold temperatures	Arid desert
Architectural Specifications	**Structure Type**	Movable	Movable	Permanent
	Size	Has transportable pods of varying sizes, around 8m x 16m x 8m, adapted for different functions and configurations. The station has eight modules on hydraulic legs: a red central one for communal use and blue ones for various purposes, including accommodation, labs, offices, and more.	Thirty-square meters of usable space including kitchen, dining, living area and twelve bunks for sleeping. It has a gear storage and a weather monitoring station.	Three volumes. Seventy-three square meters for living space, 40 sq. meters for the bedroom, 20 sq. meters for office and guest area. All the volumes have bathrooms.
Function and Challenges	**Function**	Facilitating Antarctic scientific research, data collection, international collaboration, and logistics for research expeditions.	Provides a refuge for alpinists, mountain climbers, hikers, and skiers.	Dwelling
	Challenge Addressed	Snow Accumulation: Above 1.5m Annual Snowfall. Mobility: Floating Ice Shelf, Requires Full Relocatability. Logistics: Inaccessible for 9 Months, Limited Resupply. Budget: Financial Constraints. Construction Time: 9-12 Weeks.	Harsh High-Altitude Temperatures: Addressing Extreme Conditions. Innovative Construction: Aeronautical/Nautical Engineering Techniques. Transportation: Solving Logistical Challenges for Isolated Alpine Location.	Landscape conservation Climate control

Table 1.4 Case studies analysis – category and subcategory (cont'd)

Category/Sub-Category		Halley VI Research Station	The New Refuge Gervasutti by LEAPfactory	Desert Nomad House
Performance and sustainability	Energy efficiency	"Renewable Energy: Solar, Wind, Jet Turbines. Efficiency: Nanoaerogel Insulation, CHP System, Heat Recovery, Waste Heat Use, Fuel-Saving Practices."	Photovoltaic panels built into the exterior of the shelter can provide 2.5 kWh of solar power.	Ventilated façade, the choice of material and the orientation.
	Sustainability	Environmental Footprint: Minimized Impact, Carbon-Free Approach. Sewage Treatment: Bioreactor Utilization for Waste Disposal and Resource Recovery.	The structure was prefabricated offsite, and helicopters were used to airlift it. Sustainability is increased using recyclable glass-fiber reinforced plastic (GFRP).	Designing the house to seamlessly integrate with the surrounding desert environment and protect the ecosystem.
	Adaptability	Fully relocatable research station. Resting on ski-based foundations and equipped with hydraulic legs to climb out of the ice.	Prefabricated components enable adjustments and customization based on location and demands while reducing onsite construction work	Environmental adaptability by minimizing disruption and preserving the untouched landscape.
	Safety Measures	Line perpendicular to prevailing wind. Snow drifts on the leeward side. Windward side remains clear. Base split in two for life safety.	Environmental Impact: Limited Negativity on Surroundings. Weather Integration: Data Utilized in Design/Construction. Safety: Two-Way Escape Routes Due to Interior Design and Entrance Locations. Maintenance: Replaceable Damaged Pod Sections.	Elevated structure of the three volumes allows natural water flow when it's raining and preserve the landscape while allowing water and wildlife to move underneath, ensuring safety and environmental preservation.
	Water Management	1) A booster pump is used to pressurize the water.2) Micron filter: to removes microparticles from water using. 3) UV disinfection: Microorganisms are destroyed. 4) Water is used cleanly throughout the entire station. 5) Waste Collection: Gathers wastewater from the station. 6) Sewage treatment: prepares wastewater for release while being clean.	Biological system of lavatory and toilet are made to break down waste without polluting the environment. Melting and boiling snow to obtain drinking water.	

Table 1.4 Case studies analysis – category and subcategory (cont'd)

Category/Sub-Category		Halley VI Research Station	The New Refuge Gervasutti by LEAPfactory	Desert Nomad House
Performance and sustainability	**Thermal Insulation**	Panels highly insulated glass fiber system and Glass Reinforced Plastic (GRP) fixed to the steel superstructure. Polyisocyanurate foam Insulation (PIR.) The models are linked together	excellent insulation, keeping the interior at a constant temperature. Using ventilation systems to control air exchange and retain heat inside. Comfortable interior micro-climate	Ventilated façade with an air gap between the perimeter wall and exterior cladding. Use of teak wood, steel and maple wood. Orienting spaces for comfort and to reduce sunlight exposure,
Technology	**Construction System**	Prefabricated timber floor cassettes. Prefabricated service, elements of plants, rooms, offices and laboratory spaces. All are shipped out from the UK to Antarctica to speed up the construction process.	The manufacturing of functional units, complete with interior equipment and accessories. Unit is transported by common helicopters (B3) to its destination. Assembling with simple and quick procedures to join modules and securely attach them to a metal base.	The structural system consists of reinforced concrete piers and steel beams providing support, while wood framing is used for both the walls and roof. The house's exterior is enveloped in steel plates.
Cross-Industry Construction Innovation	**Aerospace Technology Integration**	Aerospace Technology Integration	Aeronautical and Nautical fabrication techniques	Environmental & Material Science
	Construction Method/ Technology	Double-glazed system filled with aerogels. Aerogels are used in a double-glazed system in this technology, which was first developed by NASA to insulate the space shuttle during re-entry into the atmosphere. By allowing for efficient daylight transmission while maintaining a high level of thermal resistance, this construction technique helps keep the research station's interior warm in the cold climate of Antarctica.	Used Methyl Methacrylate-Based Adhesives to join its main components, which were made of Glass Fiber Reinforced Plastic (GFRP). Antibacterial materials used to build the bunks. Aeronautical fabrication techniques were considered regarding aerodynamics and the specific challenges associated with high altitudes. Nautical fabrication techniques were employed, incorporating principles of lightweight construction, durability, and resistance to harsh conditions.	It uses distinctive materials like steel, wood, and maple veneer, a creative structural system, and a ventilated facade for effective heat dissipation.
References		(Building, 2007); (Hughet, 2017)	(LeapFactory, 2023)	(Naser Nader, 2020)

Table 1.4 Case studies analysis – category and subcategory (cont'd)

Category/Sub-Category		The Aquarius underwater habitat - NEEMO	International Space Station (ISS)	(CHARS)- (MRB)
Geographical Context	Location	About 5.6 kilometers (3.5 miles) off Key Largo, Aquarius is in the Florida Keys National Marine Sanctuary at a depth of 62 feet (19 meters).	Low Earth Orbit (LEO), which is located 408 km (about 253 miles) above the Earth.	Cambridge Bay, Nunavut.
	Climate Zone	Marine	Space vacuum, radiation exposure, and microgravity environment	Tundra climate
Architectural Specifications	Structure Type	Permanent	Movable & temporary	Permanent
	Size	37 sq. meters	Modular Length: 51 meters. Truss Length: 109 meters. Solar Array Length: 73 meters. Habitable Volume 388 cubic meters. Pressurized Volume 916 cubic meters	5500 sq. meters.
Function and Challenges	Function	Serves as a platform for research in coastal and ocean resource science and management and serves as an analog for space exploration, enabling simulations of spacecraft living and spacewalking techniques.	Home where astronauts live and conduct research in a variety of fields. The duration is between 6 months to 12 months.	It is a state-of-the-art research facility devoted to advancing Arctic science and technology and fostering cooperation between Arctic communities and the larger scientific community.
	Challenge addressed	Effects of working and living in an isolated, extreme environment on both physiological and mental well-being.	To support life in space, a habitable environment must be maintained by controlling waste, oxygen, carbon dioxide, and temperature. Protection from solar and cosmic radiation. Effects of microgravity on astronauts, including fluid shifts, bone density loss, and muscle atrophy. Psychological challenges for astronauts, including confinement, isolation, and distance from home.	Design emphasizes blending with the Arctic environment, showcasing Canadian Arctic research, and fostering community interaction and sustainability. Mechanical challenges include cost optimization, HVAC efficiency, equipment heat management, and adaptation to Arctic storage conditions. Consideration of onsite power generation and integration of alternative energy sources.

Table 1.4 Case studies analysis – category and subcategory (cont'd)

Category/Sub-Category		The Aquarius underwater habitat - NEEMO	International Space Station (ISS)	(CHARS)- (MRB)
Performance and sustainability	Energy efficiency	The Aquarius life support system allows for operations at depths of up to 120 feet and consists of a buoy and a 9x43-foot steel pressure vessel that houses and accommodates six crew members.	Power is generated by solar panels and stored in nickel-hydrogen batteries that may be recharged.	Using high-efficiency equipment and exhaust air energy recovery. The facility implemented occupancy-based controls for lighting and ventilation, and optimized equipment placement, clustering heat-generating devices for efficient heat recovery and minimizing fume hoods.
	Sustainability	Minimizing environmental disruption. Using mooring system to reduce the footprint, for example anchors to prevent substantial damage to the seafloor.	The Environmental Control and Life Support System (ECLSS) on the ISS recycles about 90% of the station's water by reclaiming wastewater, including urine, and purifies the cabin air by removing contaminants and excess carbon dioxide. Additionally, it generates oxygen for the crew to breathe.	Silver-Level LEED certification. The laboratory's design is prioritizing environmental sustainability by adhering to the LABS21. Environmental Performance Criteria (EPC), which is based on the LEED-NC Version Rating System.
	Adaptability	Flexibility in terms of how it performs as a research platform. Various studies and missions can be carried out. Internal spaces can be modified to accommodate different research tools and living setups depending on the mission's needs.	Modular Design: As requirements change, the ISS's structure makes it simple to add, replace and reconfigure modules. Standardized Interfaces: The ISS can be connected by a variety of spacecraft from various suppliers thanks to uniform docking ports and interfaces.	The shelter is designed to be adaptable and flexible to accommodate evolving research goals.
	Safety Measures	Life support buoys that supply air, and power throughout cables and hoses. The habitat is connected to the surface by communication cables. Intensive training before living in the habitat. Emergency evacuation. Watertight door lock.	Astronauts prepare for emergencies like fires, depressurization, and toxic gas leaks through training, and the ISS has lifeboats (Soyuz or Crew Dragon) for potential evacuations.	Worker/Community Safety: WHMIS Compliance, Lab Containment, Safety Gear, Protective Gear, Safety Protocols

Table 1.4 Case studies analysis – category and subcategory (cont'd)

Category/Sub-Category		The Aquarius underwater habitat - NEEMO	International Space Station (ISS)	(CHARS)- (MRB)
Performance and sustainability	Water Management	Freshwater sink located in life support buoys and connected to the habitat and waste is suitably treated and removed.	The Environmental Control and Life Support System (ECLSS) of the International Space Station (ISS) recycles about 90% of the station's water by reclaiming and purifying wastewater, including crew urine, using multifiltration beds and a catalytic oxidizer.	CHARS employ a closed-loop water system, uses water-efficient equipment, and follows strict waste disposal protocols. Its location also suggests potential future access to a potable water pipeline.
	Thermal Insulation	The thick metal shell of Aquarius has been designed to withstand both the corrosive effects of the saltwater environment and the pressures of the ocean at its operating depth, ensuring its structural integrity throughout missions.	Multi-Layer Insulation (MLI) blankets are used as insulation on the International Space Station (ISS), reflecting solar radiation and preserving internal heat. By capturing heat through exchangers, moving it through water and ammonia-filled pipes, and then rejecting extra heat into space using radiators, the Active Thermal Control System (ATCS) keeps internal temperatures stable. To prevent cold spots and maintain a comfortable environment for astronauts, the ISS also needs consistent air circulation.	Thermal comfort at CHARS adheres to ASHRAE 55. Separate HVAC zones for each unique thermal area and laboratory suite. Central HVAC systems designed for Arctic climates with redundancy in heat sources. HVAC units use 100% outdoor air and meet ASHRAE 52.2 standards (MERV 6 pre-filtration and MERV 13 final filtration). Building features include UV-protected exteriors, R20 insulation, thermally efficient doors, Low-E windows, consistent heating, designated water and power provisions. A month-long sewage system is in place to support up to six people.

Table 1.4 Case studies analysis – category and subcategory (cont'd)

Category/Sub-Category		The Aquarius underwater habitat - NEEMO	International Space Station (ISS)	(CHARS)- (MRB)
Technology	**Construction System**	The habitat and foundation were constructed on land before being positioned underwater. The elements were transported to the deploying site and assembled underwater.	Individual modules for the International Space Station (ISS) were designed on Earth, launched into space, and assembled there using a modular construction system. Robotic systems like the Canadarm2 and spacewalking astronauts were essential to its construction. The ISS has tested experimental inflatable technology like the Bigelow Expandable Activity Module (BEAM) in addition to its modular main structure.	CHARS features a steel frame structure with wood and concrete accents in key areas. Foundations are adapted for the Arctic, using elevated pilings and thermosyphons for slabs. Certain labs have enhanced stiffness for equipment stability, and some foundations are built directly on bedrock for added vibration resistance.
Cross-Industry Construction Innovation	**Aerospace Technology Integration**	Marine Engineering, communication technology	Aerospace & Aviation, Software & IT, Materials Science & Engineering, Chemical Industry, Communications & Electronics:	
	Construction Method/ Technology	Underwater communication technology. The habitat is assembled and maintained by experienced workers and divers using underwater welding and fabrication methods that guarantee structural integrity and watertight seals.	Aerospace & Aviation: Using robotic arms like Canadarm2 and astronaut spacewalks for manual labor. Chemical industry: Advanced chemical processes recycled water and air to support life on the ISS, and chemicals like ammonia were used to regulate the temperature. Communications & Electronics: electronic systems were integrated into the ISS for power and control, enabling continuous satellite communication with Earth. Software & IT: ISS is operated by software.	
References		(Sarah A., 2015); (oneworldoneocean, 2012)	(Kitmacher G., 2010)	(AANDC Arctic Science Policy Integration et al., 2012)

Table 1.5 Evaluations of the projects based on architectural and structural considerations.

Location

Projects	Climate Zone: Polar	Tundra	Alpine	Marine	Desert	Vacuum Space
Halley VI Research Station	✓					
The New Refuge Gervasutti			✓			
Desert Nomad House					✓	
Aquarius underwater habitat - NEEMO				✓		
International Space Station (ISS)						✓
(CHARS) – (MRB)		✓				

Performance and Resilience (Energy Efficiency, Sustainability, Adaptability)

Projects	Energy Efficiency: Materials/Orientation	Photovoltaic Integration	Renewable Energy Tech.	Sustainability: Environmental Protection	Resource Recycling	Sustainable Building Practices	Sustainable Materials	Adaptability: Environmental preservation	Location-specific adaptation	Relocation Capability	Mission Flexibility	Modular Adaptability
Halley VI Research Station	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
The New Refuge Gervasutti	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓
Desert Nomad House	✓			✓		✓	✓	✓	✓			
Aquarius underwater habitat - NEEMO	✓			✓				✓	✓		✓	
International Space Station (ISS)	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓
(CHARS) – (MRB)	✓			✓		✓	✓	✓	✓		✓	

Performance and Resilience (Safety Measures, Water mngt, Thermal Insulation)

Projects	Safety Measures: Life Support measures	Safety Emphasis	Communication Measures	Training Measures	Emergency Measures	Structural Safety Measures	Water mngt: Wastewater Treatment	Water Recycling	Biological Waste Treatment	Thermal Insulation: Insulation Materials	Temperature Control	Building Design	HVAC Systems
Halley VI Research Station	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
The New Refuge Gervasutti	✓	✓	✓			✓	✓		✓			✓	
Desert Nomad House											✓	✓	
Aquarius underwater habitat - NEEMO	✓	✓	✓	✓	✓	✓						✓	
International Space Station (ISS)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(CHARS) – (MRB)		✓	✓	✓	✓	✓				✓	✓	✓	✓

Technology and **Cross-Industry Construction Innovation**

Projects	Construction Systems: Modular Construction System	Robotic Assembly	Inflatable Technology	3D print	Wood Framing	Steel Framing	Reinforced Concrete and Steel Support	Prefabricated Construction	Cross-Industry Construction: Aerospace Technology	Aeronautical / Nautical Fabrication	Environmental & Material Science	Software & IT	Communications & Electronics	Chemical Industry
Halley VI Research Station	✓					✓	✓	✓			✓	✓	✓	
The New Refuge Gervasutti								✓	✓	✓	✓			
Desert Nomad House						✓					✓			
Aquarius underwater habitat - NEEMO						✓			✓	✓	✓	✓	✓	
International Space Station (ISS)	✓	✓	✓			✓		✓	✓		✓	✓	✓	✓
(CHARS) – (MRB)	✓				✓	✓					✓	✓	✓	

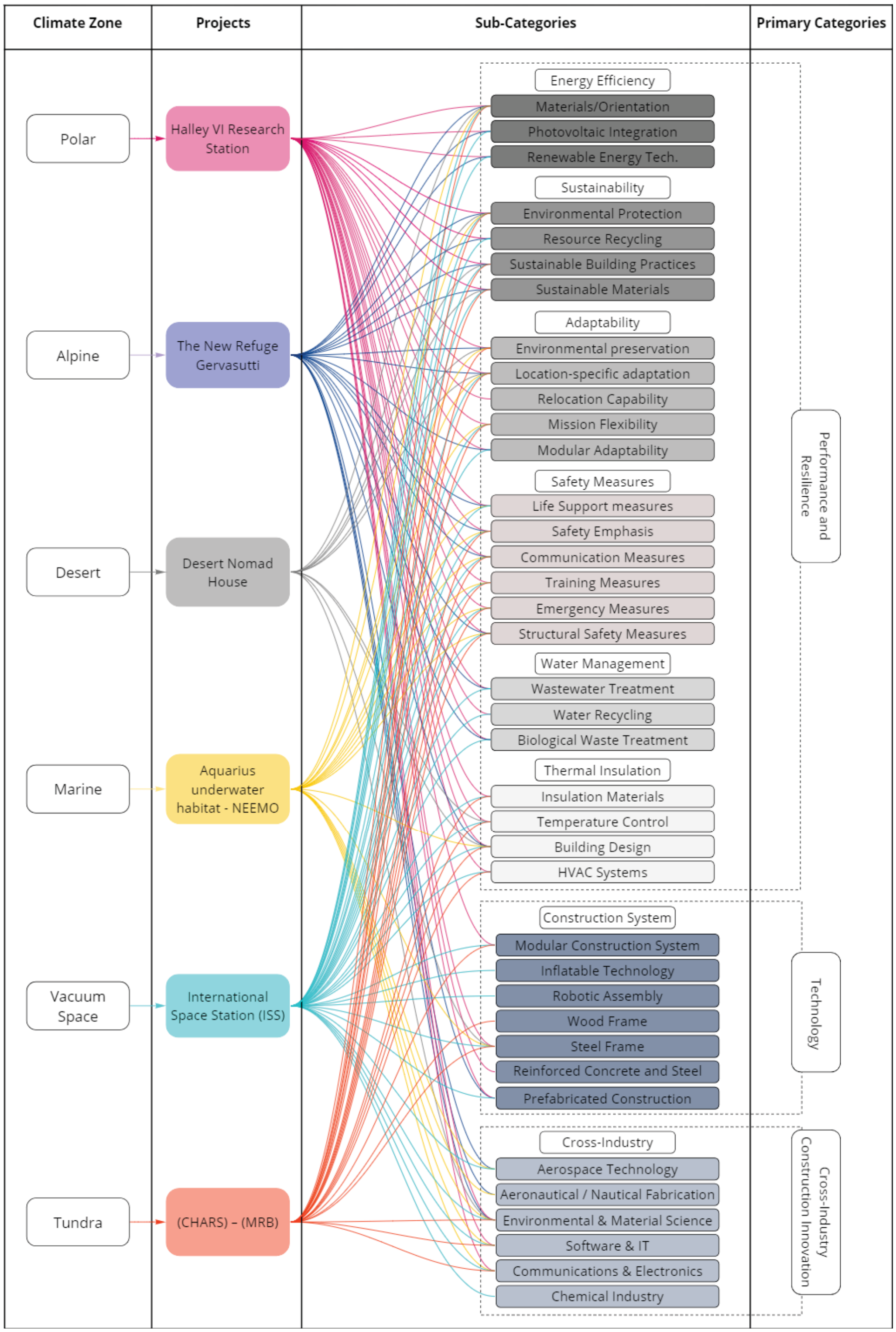


Figure 1.4 Presentation of similarities across climate zones

1.3.2 Results and discussion

The analysis conducted a comprehensive examination of various climate zones, each presenting distinct challenges. The projects implemented within these zones were purposefully designed to effectively address these challenges. The Categorical Comparison Chart and the Similarities Across Climate Zones table have been carefully constructed to present the findings of this analysis. These tools assist in illustrating the unique strategies and innovative solutions employed by each project, making it more convenient to observe how these projects address the challenging circumstances within their respective environments.

1.3.2.1 Presentation of categorical comparison chart

The "Categorical Comparison Chart" proposed in this chapter is an instrument created to effectively summarize and display the detailed characteristics of each chosen project, based on their corresponding climate zones. This chart serves as a valuable tool for identifying the adaptive strategies, sustainability measures, and technological innovations employed in each project. It provides a comprehensive perspective on the unique approaches taken to address the climate-related challenges specific to their environments.

Structure and purpose: The chart is organized to present each project according to its corresponding climate zone. This deliberate structure allows for a coherent and systematic depiction of how diverse environmental challenges require unique adaptive strategies and inventive solutions. The main objective of the chart is to provide a visual and categorical comparison, assisting in the identification of patterns, distinct strategies, and noteworthy innovations that highlight the projects' endeavors to attain sustainability, adaptability, and operational efficiency in challenging climatic circumstances.

Discussion of projects: Halley VI Research Station, Antarctic: Notable for its use of renewable energy, a fully relocatable design, and aerospace technology for insulation. Features like translucent nanoaerogel panels effectively mitigate energy dissipation, showcasing remarkable technological ingenuity.

New Refuge Gervasutti, Alps: Exhibits prefabricated construction methods, renewable energy generation through photovoltaic panels, and fabrication techniques from the aeronautical and nautical industries. A distinctive approach is the airlifting of prefabricated components, addressing the logistical challenges of the isolated alpine region.

Desert Nomad House, Desert Region: Highlights architectural features for environmental integration, including a ventilated façade for climate regulation and the use of unique construction materials. The ventilated façade system effectively addresses the challenges of extreme desert temperatures.

Aquarius Underwater Habitat - NEEMO: Demonstrates adaptability in operational configuration, a mooring system designed to minimize ecological impact, and underwater communication technology. Key advancements include underwater welding and fabrication techniques, ensuring structural integrity and operational effectiveness.

International Space Station (ISS): Exemplifies modular design, adaptability in outer space, an advanced life support system for recycling water and air, and the integration of robotics and spacewalks for construction and maintenance. Uses experimental inflatable technology, like the Bigelow Expandable Activity Module (BEAM), for expanding operational space.

Canadian High Arctic Research Station (CHARS), Tundra: Awarded Silver-Level LEED certification, reflecting its commitment to sustainability. Equipped with advanced HVAC systems for Arctic climates and promotes community engagement. Notable advancements include the use of raised pilings and thermosyphons in foundation construction, catering to the unique Arctic environment.

1.3.2.2 Presentation of similarities across climate zones

The purpose of the "Similarities Across Climate Zones" presented in table 1.6 provides a systematic means of visually representing and contrasting the shared characteristics and approaches found in diverse projects located in different climate zones. The table presents a categorization of six projects, namely the Halley VI Research Station located in Antarctica, The New Refuge Gervasutti situated in the Alps, the Desert Nomad House situated in a desert environment, the Aquarius Underwater Habitat - NEEMO located in an underwater climate, the International Space Station (ISS) is situated in outer space, and the Canadian High Arctic Research Station is situated in the Tundra. Every project is classified according to its corresponding climate zone, providing a clear depiction of how diverse environmental challenges have influenced comparable strategies or solutions across various geographical regions.

Structure and purpose: The table has been methodically organized to highlight the fundamental similarities among the projects, regardless of their different climates. The main objective of this table is to clarify the recurring patterns and inventive approaches used in various climate zones, thus providing valuable perspectives on the overarching strategies that effectively address the distinctive challenges present in extreme environments. The primary objective of this initiative is to offer an easily understood and visually representative portrayal of common characteristics, including but not limited to energy efficiency, adaptability, and technological innovation, observed among the various projects.

Discussion on common features: One prominent shared characteristic observed among the projects is the prioritization of energy efficiency and the integration of renewable energy sources. Both the Halley VI Research Station and The New Refuge Gervasutti utilize renewable energy sources, specifically solar panels, to reduce their environmental footprint. The International Space Station (ISS) and the Canadian High Arctic Research Station both exemplify sophisticated sustainable resource management systems, thereby emphasizing a collective emphasis on sustainability within diverse climatic regions.

The adoption of prefabricated and modular construction is a notable commonality observed in both The New Refuge Gervasutti in the Alps and the Canadian High Arctic Research Station in the Tundra. The construction methodologies demonstrate a collective shift towards more efficient, regulated, and environmentally conscious building practices, which are crucial in extreme environments characterized by limited resources and difficult working conditions.
The utilization of advanced technologies to address the unique challenges presented by various extreme environments is a recurring motif observed in all the projects. As an example, the Desert Nomad House incorporates a ventilated façade system to regulate the indoor climate, whereas the Aquarius Underwater Habitat - NEEMO employs advanced underwater communication technology to enhance operational efficiency.

The implications for construction in extreme environments within Canada, as illustrated by the case of the Canadian High Arctic Research Station (CHARS), are significantly based on the findings of various climate zone projects. The Canadian Arctic presents distinctive environmental challenges that require specialized solutions. In this regard, CHARS serve as a notable example of an effective response, demonstrating the implementation of advanced HVAC systems and construction techniques such as raised pilings and thermosyphons in foundation slabs. These adaptations are specifically designed to address the unique characteristics of the region. The comparative analysis provides additional insights into potential strategies that could be utilized in various extreme environments across Canada. The adaptability demonstrated by modular and prefabricated construction techniques in the International Space Station (ISS) and The New Refuge Gervasutti in the Alps holds significant potential for addressing logistical and operational obstacles in remote or extreme Canadian climates. Furthermore, the emphasis on energy efficiency and the incorporation of renewable energy sources, as defined by the Halley VI Research Station and The New Refuge Gervasutti, aligns with the sustainability objectives inherent in projects such as CHARS, highlighting a common focus on environmental stewardship across diverse climatic conditions.

Table 1.6 Categorical comparison chart

Category	Antarctica	Alpin	Desert	Underwater	Outer Space	Tundra
Climate-Specific Challenges	Snowfall, moving ice, severe cold, logistics, and inaccessibility	Harsh temperatures at high altitudes, Transport logistics	Climate control and landscape conservation	Isolation and a harsh environment	Microgravity, Radiation, Isolation, Extreme environment	Blending with Arctic environment, HVAC efficiency, Equipment heat management, Adaptation to Arctic storage conditions
Solutions for Energy Efficiency	Renewable energy (solar, wind), Insulation (nanoaerogel panels, PIR), Heat recovery	Photovoltaic panels, Excellent insulation	Ventilated façade, material selection, and orientation	Life support system	Solar panels, Battery storage	High-efficiency equipment, Exhaust air energy recovery, Occupancy-based controls
Sustainability Measures	Waste heat repurposing, Bioreactor for sewage treatment, Renewable energy	Prefabrication offsite, recyclable materials (GFRP)	Integration with the surrounding	Mooring system, Environmental disruption minimization	Water and air recycling (ECLSS)	Silver-Level LEED certification, LABS21 Environmental Performance Criteria adherence
Adaptability	Hydraulic legs, ski-based foundations, and fully relocatable legs	Prefabricated components, location-based adaptation	Minimal disturbance, preservation of untouched landscape	Internal space modification, adaptable research platform	Modular design, Standardized interfaces	Adaptable design to accommodate evolving research goals
Safety Measures	Snow drift management, Base split for life safety	Weather data integration and two-way escape paths	Elevated structure for water flow, Landscape preservation	Life support buoys, Emergency evacuation	Emergency training, Lifeboats (Soyuz or Crew Dragon)	WHMIS regulations, Specific lab containment levels, Safety equipment and protocols
Innovative Construction Methods	Aerospace technology (aerogels), prefabricated elements	Aeronautical and nautical engineering, Methyl Methacrylate-Based Adhesives	Reinforced concrete piers, ventilated façade, steel beams	Underwater assembly, Welding and fabrication underwater	Modular construction, In-space assembly, Robotic systems	Steel frame structure, Elevated pilings, Thermosyphons for slabs

Table 1.6 Categorical comparison chart (Cont'd)

Category	Antarctica	Alpin	Desert	Underwater	Outer Space	Tundra
Water Management	Water management system that includes UV disinfection and sewage treatment	Melting and boiling snow for drinking water, biological lavatory system	(Information not provided)	Waste treatment, freshwater sink	Water recycling (ECLSS)	Closed-loop water system, Water-efficient equipment, Strict waste disposal protocols
Thermal Insulation Techniques	Polyisocyanurate foam Insulation (PIR) and a highly insulated glass fiber system	Controlled ventilation and constant interior temperature maintenance	Air gap between perimeter wall and exterior cladding	Thick metal shell	Multi-Layer Insulation (MLI), Active Thermal Control System (ATCS)	ASHRAE 55 adherence, Separate HVAC zones, UV-protected exteriors, R20 insulation, Low-E windows

Table 1.7 Similarities across climate zones

Similarity Categories	Antarctica	Alpin	Desert	Underwater	Outer Space	Tundra
Use of Renewable Energy	✓	✓	✓		✓	
High Efficiency Systems	✓					✓
Prefabrication	✓	✓			✓	
Innovative Insulation	✓	✓	✓		✓	✓
Modular/Adaptable Design		✓		✓	✓	✓
Safety Protocols	✓	✓		✓	✓	✓
Water Management	✓	✓		✓	✓	✓
Sustainability Measures	✓	✓	✓	✓	✓	✓
Unique Construction technique	✓	✓	✓	✓	✓	✓
Construction Materials			✓			✓
Technology Integration	✓	✓		✓	✓	

Table 1.7 Similarities across climate zones (Cont'd)

Similarity Categories	Antarctica	Alpin	Desert	Underwater	Outer Space	Tundra
Certifications/Standards						✓
Community Interaction						
Environmental Blending			✓	✓		
Logistical Challenges	✓	✓				
Equipment Management	✓					✓
Operational Duration					✓	
Cost Management	✓					
Research and Development	✓			✓	✓	
Waste Disposal	✓	✓		✓	✓	✓
Emergency Preparedness	✓	✓		✓	✓	✓
External Collaboration	✓			✓	✓	
Occupancy Control						✓

1.4 Conclusion

This study has made significant strides in identifying and analyzing creative adaptation techniques, sustainable practices, and technological advancements crucial for construction in extreme climates, with a particular emphasis on the Canadian context. Through detailed case study analysis, we have broadened our understanding of construction methods suited to challenging conditions, underscoring the importance of adaptability, sustainability, and technological integration. These components are vital for enhancing operational efficiency, safety, and environmental responsibility in extreme climates, especially relevant to the diverse and demanding environments found across Canada.

The exploration of in-Situ resource utilization, autonomous robotics, and 3D printing has opened new avenues for construction techniques, which are particularly pertinent to Canadian extreme environments. These findings, while directly applicable to Canada's unique climatic challenges, also provide a global perspective on building in harsh conditions. However, it is important to acknowledge the limitations of our focused case study approach. The absence of direct comparisons between the projects and the specific concentration on individual environmental contexts might restrict the broader application of our findings, especially when considering the diverse and vast nature of Canada's extreme climates.

Looking forward, future research should delve into the application of advanced technologies like autonomous robotics, 3D printing, and in-Situ resource utilization, specifically in the context of Canada's varied extreme climates. Investigating how these technologies can be adapted to the unique challenges posed by Canadian environments will be crucial. Additionally, there is a significant opportunity for cross-disciplinary approaches, merging insights from global extreme environment construction practices with Canadian-specific scenarios. The examination of policy and regulatory frameworks within Canada, governing construction in extreme environments, is also an essential area for future research. This could provide insights into how these frameworks can evolve to better support innovation, safety, and environmental sustainability. Finally, comparative studies within Canada's different extreme environments could offer invaluable insights, identifying best practices and innovative solutions that could enhance construction across the country's varied landscapes.

In essence, this study contributes to a deeper understanding of construction practices suitable for extreme climates, with a focus on Canada's unique challenges. It lays the groundwork for future research and practical applications, aiming to advance the field of construction in extreme environments both within Canada and globally.

CHAPTER 2

INNOVATIVE SOLUTIONS FOR ARCTIC HOUSING: ADDRESSING THE CRISIS IN NUNAVUT AND INUIT NUNANGAT

2.1 Introduction

The current housing crisis in Nunavut and the Inuit Nunangat regions of Canada has experienced challenges that extend the absence of physical structures. It is marked by a significant gap in living conditions compared to other parts of Canada, with extreme overcrowding and deteriorating housing quality. This crisis is not just a matter of housing but reflects severe socio-economic inequalities, health problems, and educational consequences, all strongly related to the unique environmental conditions and historical context of these regions. This chapter explores different research findings and reports, providing a detailed understanding of the various dimensions of this crisis.

The living conditions in these arctic and subarctic regions clearly show the consequences of historical policies and socio-economic inequality. Overcrowding, a term that represents the extent of the crisis, has become popular in many Inuit communities. However, some reports, such as Sultan's 2023 study, has shown that overcrowding rates were 72%. This leads to "hidden homelessness," where families, lacking adequate housing opportunities, are forced to go between homes of friends and families.

The extreme Arctic conditions involve housing solutions that are not only strong to withstanding severe weather but also sustainable and culturally appropriate. Traditional construction methods and materials are often not a good choice in these harsh climates, leading to deterioration of buildings and contributing to the housing crisis (Sultan, 2023).

Furthermore, the housing crisis in these regions has a negative impact on the health and education of the indigenous communities. Overcrowded and poorly constructed homes become sources for the spread of diseases and lead to deterioration of mental health due to lack of space and privacy. For children, these conditions are unfavorable to educational success, impacting their academic performance and future opportunities.

This chapter explores potential solutions to these complex challenges. Among the promising paths are innovative building techniques such as 3D printing and timber wood such as Cross-Laminated Timber (CLT). These technologies offer potential for efficiency, personalization, and sustainability in construction, which are critical for meeting the specific needs of housing in Nunavut and Inuit Nunangat. By synthesizing existing research and identifying the gaps, this review aims to contribute to the current debate on eco-friendly, culturally sensitive housing for these remote and challenging environments.

2.2 Housing crisis in Nunavut and Inuit Nunangat

2.2.1 Historical and cultural context

The housing crisis in Nunavut and Inuit Nunangat was involved in a historical and cultural context that has radically affected the current living conditions within these communities. This crisis resulted from a complex relationship of historical policies and cultural dislocation, resulting to a housing landscape that fails to align with the needs and traditions of the Inuit people. The impact of colonization in Canada's far north, as detailed by Sultan (2023) and the Canadian Human Rights Commission (2022), has left a serious impact on the housing conditions in Inuit communities. Historically, federal policies, often formulated without consulting the Inuit communities, resulted in housing solutions that were undesirable and incomplete. These policies disregard the unique environmental conditions and cultural practices of the Inuit, resulting in homes that were structurally incompatible for the arctic climate and to Inuit culture.

Figure 2.1 Improvised shack in Igloolik, Nunavut
Taken from The Senate of Canada (2017, p. 15)

Furthermore, the impact of residential schools has deeply affected Inuit society, breaking traditional family structures and limiting the transmission of cultural knowledge and practices, including those related to housing and peaceful living in the Arctic environment. This has resulted in lasting effects on community cohesion and the ability to maintain appropriate living conditions. Traditional Inuit lifestyles, characterized by semi-nomadic routines closely associated to hunting and fishing cycles, were significantly disrupted by the imposition of permanent, southern-style houses. This change modified not only the physical landscape but also impacted social norms and community dynamics resulting in challenges such as overcrowding and a lack of housing that reflects traditional Inuit values and needs. These policies have often led to overcrowding, a significant issue in many Inuit communities. Figure 2.1 illustrates the reality of this overcrowding in Igloolik, Nunavut, where some residents have resorted to living in temporary dwellings due to the lack of space in their primary residences. This image illustrates the pressing need for housing solutions that are not only structurally and environmentally appropriate but also culturally aligned with Inuit lifestyles (The Senate of Canada, 2017).

Furthermore, the housing crisis represents more than just a physical issue; it is also a problem of cultural identity. The Canadian Human Rights Commission (2022) states that the lack of housing that respects and integrate Inuit cultural values has led to a sense of displacement and identity loss among Inuit people. Housing solutions that abandon to recognize and integrate these essential cultural aspects may contribute feelings of isolation and detachment from conventional lifestyle.

2.2.2 Environmental challenges and overcrowding

Figure 2.2 Nunavut's capital city, Iqaluit
Taken from Kilpatrick (2017, p. 1)

Figure 2.2 illustrates the small residential for met against the arctic environment, highlighting the challenging conditions associated with house growth. In the harsh and difficult landscape of Nunavut and Inuit Nunangat, the environmental challenges significantly exacerbate the region's housing crisis. As mentioned in Sultan's 2023 report, the extreme climate, with its sub-zero temperatures and permafrost, requires construction techniques and materials to ensure homes are warm, durable, and able to withstand the variable ground conditions. However, the region's isolation presents considerable logistical challenges, making the transportation of construction materials both difficult and expensive. This not only inflates the cost of building new homes but also restricts quick repairs and maintenance of existing structures, contributing to their degradation.

Environmental issues are becoming worse by overcrowding in the communities, with some areas experiencing rates of 72%, according to the same report. This overcrowding, a direct result of the sufficient and adequate homes, forces families to live in terrible conditions or engage in "hidden homelessness," where they frequently move between the homes of friends and relatives. The Senate Committee on Aboriginal Peoples (2016) and the Canadian Human Rights Commission (2022) both encourage an urgent need for housing solutions that are not only structurally durable for the northern climate but also sufficient in number to reduce the overcrowding problem. The current situation results in a cycle when limited housing options led to overcrowding, which in turn accelerates the deterioration of the existing limited housing infrastructure.

2.2.3 Health, safety, and educational impacts

The complex housing crisis in Nunavut and Inuit Nunangat has a significant impact for the health, safety, and education of its residents, Increasing the socio-economic barriers faced by these communities.

Health Implications: Overcrowding and poor housing conditions, common in these regions, dramatically contribute to public health crises. The rates of respiratory diseases, especially tuberculosis, are very high among Inuit populations. Studies by Sultan (2023) and the Canadian Human Rights Commission (2022) reveal that tuberculosis rates in Inuit communities are over 250 times higher than among the non-Indigenous Canadian population.

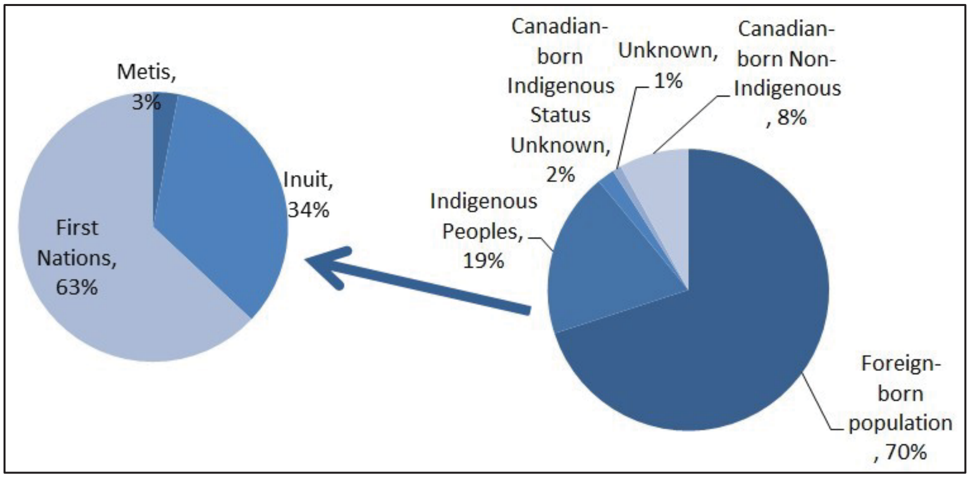


Figure 2.3 Distributions of active tuberculosis cases by
population group, Canada, 2016
Taken from Vachon (2018, p. 6)

Figure 2.3 illustrates the demographic distribution of Indigenous populations in Canada, including First Nations, Inuit, and Métis, as well as the non-Indigenous Canadian-born and foreign-born populations. The left pie chart indicates the representation of Inuit, who constitute 34% of the Indigenous peoples, a significant statistic considering the disproportionate impact of housing-related health issues such as tuberculosis within these communities. The right pie chart provides another perspective on the ethnic composition of Canada, indicating the relative size of the Indigenous population, including the Inuit, in the national context. This demographic observation, drawn from the work of Vachon, Gallant, and Siu (2018), set the stage for understanding the large-scale nature of health implications resulting from the housing crisis in Nunavut and Inuit Nunangat, especially as they relate to the increase of communicable diseases in crowded environments.

These concerning statistics are directly correlated to the living conditions, with poor ventilation and small spaces enabling the rapid spread of communicable diseases. Additionally, the lack of adequate housing infrastructure affects the basic hygiene and sanitation which help to increase health risks.

Mental health and safety concerns: The housing crisis also has severe implications for mental health. The Canadian Human Rights Commission (2022) reports a rise in depression, anxiety, and other mental health issues, exacerbated by overcrowded living conditions.

Figure 2.4 Interior of an Overcrowded Dwelling in Kugaaruk
Taken from Mumilaaq Qaqqaq (2021, p. 7)

Figure 2.4 shows the interior of a home in Nunavut, proving the impact of overcrowding and the consequent pressure on living conditions. The visible deterioration and damage to the walls reflect the broader housing challenges faced by many residents, as discussed in the Qaqqaq Housing Report (2021). Following the report's approach, the image has been edited to remove any identifying traits to respect the privacy of the residents. This image illustrates the real impact of the housing crisis on the daily lives and mental well-being of community members while protecting individual privacy.

These conditions, along with a lack of privacy and personal space, contribute to a higher stress levels and social conflicts, leading to a higher incidence of domestic violence and substance abuse. The Senate Committee on Aboriginal Peoples (2016) focuses on the relationship between inadequate housing and the high suicide rate among Inuit youth, drawing attention to the urgent need for interventions.

Impact on education: The overcrowded housing conditions impact educational results. Sultans (2023) study reveals that children living in overcrowded homes often struggle with insomnia due to noise and limited space, leading to difficulties in concentration and poor academic performance. Moreover, the absence of a supportive atmosphere for studying and doing homework contributes to higher dropout rates and limited educational achievement among Inuit children. This educational inequality promotes the cycle of poverty and limits career opportunities.

Broader socio-economic consequences: The effect of these health and educational challenges has broader socio-economic consequences. The Canadian Human Rights Commission (2022) comments that poor health and limited education reduce the ability of community members to participate fully in the work, hold back the economic development. The resultant socio-economic instability further forces community resources and exacerbates the housing crisis, creating a vicious cycle that is challenging to break.

2.2.4 Policy failures and the need for federal involvement

The housing situation in Nunavut and Inuit Nunangat has been influenced by policy failures and a need of more federal involvement. As detailed in the report by Dyck & Patterson (2017), the crisis comes from inadequate federal housing policies that failed to plan and understand the Inuit needs, since the policies were developed without the participants or collaboration with Inuit communities, resulting in the creation of a dwelling that was inappropriate for the northern climate and separated from the cultural practices of the Inuit. This divergence caused in homes that were not only structurally inappropriate to withstand the harsh arctic conditions but also culturally inappropriate, contributing to a sense of dislocation among Inuit residents.

Moreover, the report indicates the need of federal involvement and strategic funding to address the poor housing quality and accessibility, this includes a call for direct funding to Indigenous organizations, helping them to develop housing solutions that integrate the culture and durable to face the extreme environment. However, the decision making of the federal government to fund and support housing initiatives in Inuit Nunangat was catastrophic and resulted in a severe housing crisis and sheds light to a social and health issues inside these communities. Also, the report mentions that without significant and immediate federal action, the housing crisis in Nunavut and Inuit Nunangat could rise into a public health and refugee disaster.

2.2.5 Nunavut 3000 strategic plan and federal funding

The "Nunavut 3000" strategic plan is a crucial project to address the housing crisis in Nunavut, it is developed by the Nunavut Housing Corporation (NHC) to build 3000 new housing units over the next decade to face to the actual need of dwellings in the region.

Scope and strategy: The plan covers a wide range of housing needs, starting from emergency shelters to a property ownership with the goal of eliminating or at least reduce the gaps in the housing crisis in the region. The objective is to provide a smooth transition across various housing categories for individuals as their situations change which was not address in the past.

Challenges and implementation: The "Nunavut 3000" strategy involves dealing with different difficulties, including the isolation of some regions, the climate condition, qualification of workers, and construction materials. Modern and creative construction methods, including modular housing and standardization are key elements of this strategy. Furthermore, the plan also includes variability and aging in place to make sure that housing solutions are adaptable to the diverse needs of the community.

Federal funding and support: The "Nunavut 3000" strategy depends on federal support and funding and the current federal funding as mentioned in the report are inadequate to meet the high housing needs in Nunavut. Yet, there is a strong call for new and updated strategy to provide adequate, predictable, and stable funding to support long-term housing solutions. This includes the construction of new units and retrofitting the existing ones.

Community involvement and capacity building: The strategic plan highlights the importance of engaging local communities in housing projects which concerns Inuit organizations and residents in the design and implementation of housing solutions to guarantee that the developments are culturally appropriate and resonate with the local population.

Maintenance and remediation challenges: An important element of the plan is retrofitting where houses will start process of changes to the system inside the dwelling and sometimes the structure itself. The objective is to reduce the consumption of energy and increase the building performance, such as mold, structural issues, and the need to upgrade the mechanical system. Systematic reviews and full strategies, including mold remediation programs and training for local housing organizations are essential components of the plan.

However, while retrofitting can help some dwelling to be more sustainable and durable, it is limited to the existing structures and to face the housing crisis in Northern Canada we need new projects. Moreover, adoption of new construction technologies, like 3D printing can offer a new alternative to explore the potential of the use of local materials and combine them with other construction systems. The next sections explore the 3D printing technology and the CLT that can be used as a solution by combining offsite and onsite construction.

2.3 Shaping the future of building: the rise of 3D printing in construction

The construction industry has experienced an important transformation due to the emergence of new technologies that improve the safety, the quality, and reduce waste and optimize resources. One of the examples today is 3D printing technology, a revolutionary system in architectural innovation. However, Figure 2.5 illustrates the process of transforming a digital CAD into a physical 3D structure. Starting with CAD software, where the initial concept model is created, the design is processed by a telepath generator that converts it into precise printing instructions. These instructions guide the hardware components: the control unit coordinates the printing instruction, the motion system operates the nozzle in 3D space, and the material system with its mixer, feeder, and nozzle unit manages the flow and mixture of concrete. The materials, including cement, water, aggregates, admixtures, and reinforcements, are combined to form the printing medium. This medium is then extruded layer by layer to fabricate the object and resulting in a 3D printed element with high precision. This flowchart below summarizes the synergy between software, hardware, and material components that drive the 3D printing technology in construction.

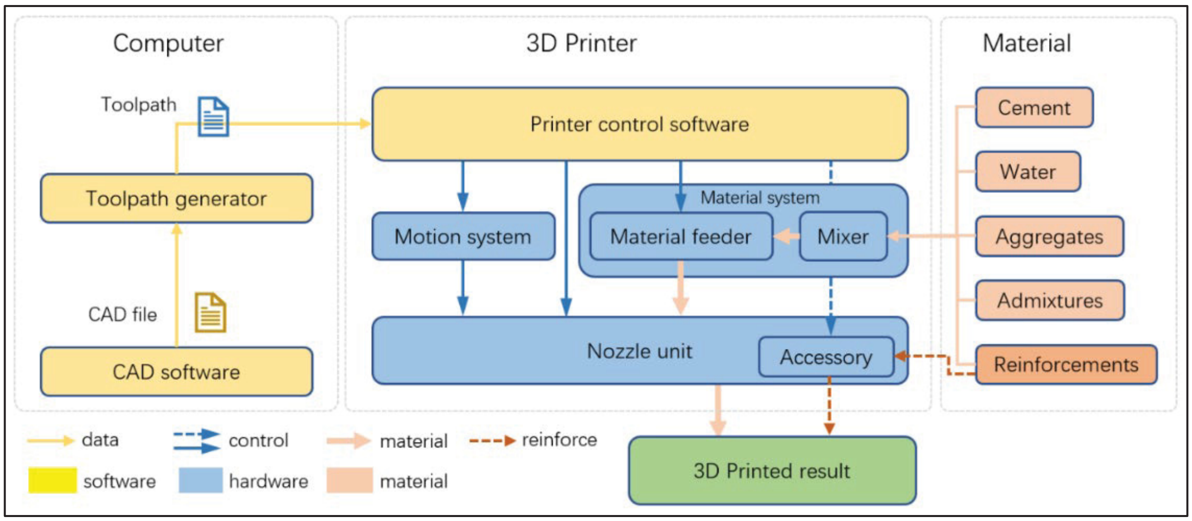
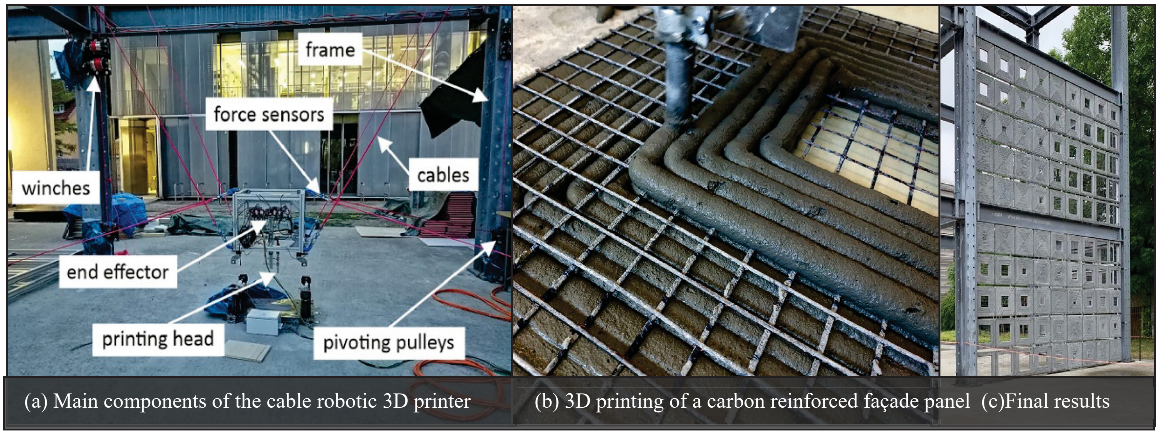


Figure 2.5 The concrete printing system
Taken from Cao, Yu, Cui, et Li (2022, p. 2)

The latest research in this field has further expanded the possibilities of 3D concrete printing. The study presented in 'Cable Robotic 3D printing: Additive Manufacturing on the Construction Site' introduces a new approach by using a cable-driven parallel robot for extruding of concrete in three-dimensional space. Figure 2.6a, shows the main components of the cable robotic 3D printer. This method enables us to print larger scale construction and integrates the computational design and robotic fabrication, increasing both design flexibility and construction efficiency. As seen in Figure 2.6b, the 3D printing of a carbon-reinforced façade panel, this process allows for complex geometries and protect material properties. The full-scale demonstration of this technology, represented in Figure 2.6c, reveals the potential to revolutionize traditional construction methods, promising greater adaptability and precision in architectural applications (Hahlbrock et al., 2022).



(a) Main components of the cable robotic 3D printer (b) 3D printing of a carbon reinforced façade panel (c)Final results

Figure 2.6 Cable robotic 3D printing process and outcomes
Taken from Hahlbrock et al. (2022, pp. 306, 308, 310)

Moreover, another study with the use of a complex wall of polymer foam and concrete developed by Benoit Furet, Philippe Poullain, and Sébastien Garnier. This technique, known as Batiprint3D™ engages the creation of a complex wall structure with two polymer-foam printed walls around a concrete wall. Figure 2.7a shows the robotic system during the initial printing phase. Figure 2.7b illustrates the use of polymer foam in 3D printing to improve thermal insulation and efficiency for onsite construction. Finally, Figure 2.7c reveals the completed 95 m² Yhnova™ social dwelling, demonstrating the potential this technique can offer in terms of sustainability and flexibility (Furet, Poullain, & Garnier, 2019).


(a)Robots at work (AGV+PAA) (b)Picture of YhnovaTM without coating (c)The finished social housing

Figure 2.7 The Batiprint3D™ process from Start to finish
Taken from Furet et al. (2019, p. 63)

The integration of computational design and robotics, 3D printed concrete enables the precise and efficient creation of complex structures directly from digital models. A transition from traditional construction methods into more creative techniques can speed up the construction process, reduce material waste, and promote the architectural creativity. Furthermore, many companies put more efforts to develop materials that not only complement this technology but also improve the quality compared to traditional concrete. Often, these materials combine conventional concrete with innovative additives like biopolymers, reinforce the structural integrity and sustainability. For instance, the work by AI Space Factory, in collaboration with Techmer PM, has led to the development of an innovative composite made from Martian rock basalt fiber and bioplastic (polylactic acid, or PLA). According to their 2022 report, this composite surpasses traditional concrete in both strength and durability. This breakthrough in material science is important, addressing the longstanding challenge of creating a material that is both strong and effective. The evolution of these materials projects the bright future of new construction materials towards more sustainable and efficient building practices.

Still, a study conducted by Li & Tsavdaridis (2023) develops an innovative interlocking system for Cross-Laminated Timber Volumetric Construction (CLTVC), suitable for taller structures. However, this system integrates the 3D printing and simplifies the assembly by eliminating traditional onsite screwing methods. The possibility of refining these connections through 3D printing could offer unparalleled precision and adaptability. The design of the system highlights structural integrity with connections capable of transmitting forces while minimizing damage, a crucial factor for safety and sustainability. This research demonstrates the versatility of 3D printing, extending its application beyond concrete construction to improve connection systems in CLTVC, thereby covering the way for more efficient construction methodologies.

In a similar vein, Youn et al. (2023) have explored the use of 3D printing with polylactic acid (PLA) to transform mold production in construction. Their methodology merges CAD with 3D printing, which leads to the development of highly accurate and reusable free-form molds for concrete construction, as shown in Figure 2.8.

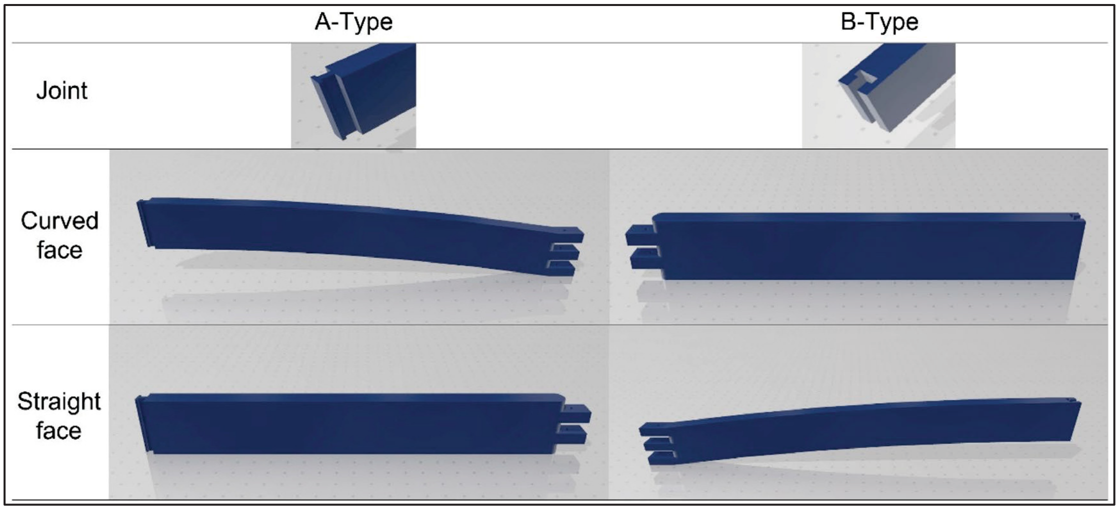


Figure 2.8 Innovative mold design using 3D printing
Taken from Youn et al. (2023, p. 5)

Nevertheless, Figure 2.8 illustrates the advanced design and assembly of 3D-printed mold and focus on the precision and adaptability in creating complex concrete structures. This approach can significantly improve the precision and efficiency over traditional methods. The key findings reveal that these molds can minimize errors and guarantee a degree of sustainability, marking a transition towards sustainable and standardized construction practices.

Spreading the exploration of 3D printing in construction, the study by Kruger (2020) presents a groundbreaking approach to explore3D Concrete Printing. This study focuses on the development of a constructability design model that optimizes the printing parameters like speed and filament layer height. The goal is to maximize the building rate and maintain the structural integrity. In addition, Kruger justifies this model using a 3D-printed structural wall element with the need to address variability in material properties. By proposing a probabilistic design model, the study effectively reduces inaccuracies caused by material variations, a key factor in ensuring reliable and efficient results in 3DCP. However, this research contributes to improving the mechanical efficiency of 3D printing in construction and underline the importance of parameter optimization in achieving both speed and structural stability in the field of digital construction.

Furthermore, another study provides a comprehensive analysis of the potential impacts of 3D printing in construction. It focuses on the technical challenges such as the need for materials with specific rheological properties, the integration of reinforcement, the economic implications including productivity and changes in cost structure, and the environmental benefits through reduced material use and efficient designs. Figure 2.9 illustrates the environmental impact, particularly the Global Warming Potential of walls constructed via digital fabrication compared to conventional methods. It highlights the potential environmental benefits of 3D printing, especially in terms of reducing GWP in more complex construction designs. The results indicate the transformative potential of 3D printing in concrete construction, considering its technical feasibility, economic viability, and environmental implications (De Schutter et al., 2018).

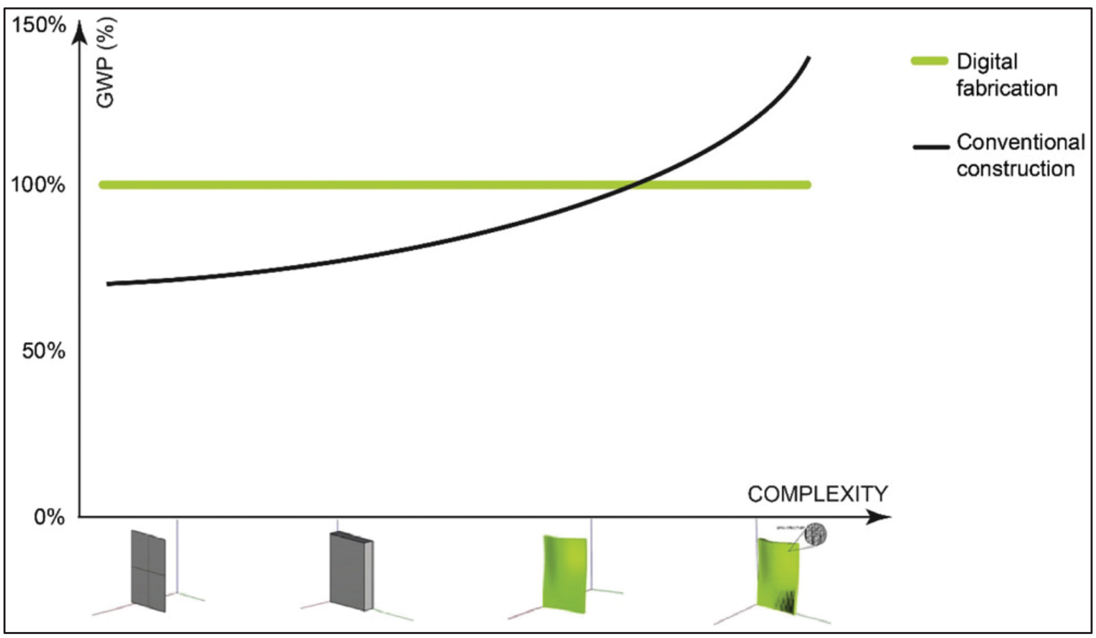
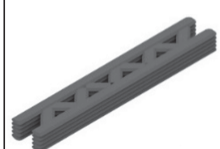
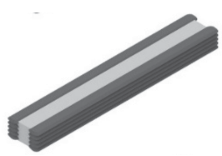
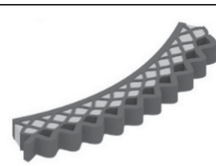


Figure 2.9 Comparison of digital and conventional construction
Taken from De Schutter et al. (2018)

In addition, Kreger et al. (2019) explore the use of 3D printing for reinforced concrete construction. Their research highlights the cost and efficiency benefits of reinforced additively constructed concrete (RACC), offering a more sustainable and economically viable approach to building. They demonstrate the potential of RACC in reducing construction time and labor costs, making it a competitive method in modern construction. This study marks a significant step in integrating traditional reinforcement methods, like standard reinforcing bars (rebar) and grouting techniques, with innovative 3D printing technology, increasing structural integrity and durability.

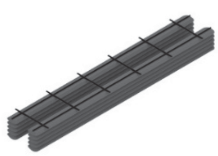
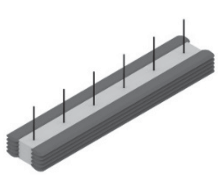
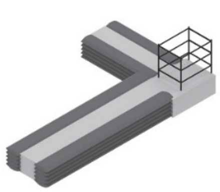
Table 2.1 defines different wall designs of 3D printing and categorized them into four main types: simple, hollow, grid, and filled with natural ventilation. However, the simple wall arrangement provides a rapid printability and material efficiency but not a good choice in sound insulation and structural strength. The second type is empty parallel arrangement allow for natural ventilation, require less material compared to a solid wall, and reduces the cost production, therefore this type offers less sound insulation and limited structural strength. The third one is parallel arrangement with grid, this one shows a balance by increasing structural strength and possibly improving insulation, while it consumes more time and material. Finally, the last categories are a combination of filled parallel arrangement and natural ventilation. It offers potential load-bearing walls, improved insulation, and a synergy of ventilation and strength. Despite these advantages, the design's complexity causes printing times to be longer and material costs to be higher. This categorization highlights the importance of considering the costs and benefits of various wall designs for 3D-printed buildings in relation to factors like speed, material efficiency, structural integrity, and insulation performance.

Table 2.1 3DCP wall types

Printed wall types	**Illustration**	**Pros**	**Cons**	**References**
Simple arrangement		- Fastest to print due to its simplicity. - Fewer materials. - Uses less material.	- Offers less sound insulation. - Limited structural strength.	(Garcia Alvarado, Moroni, & Banda, 2021)
Empty parallel arrangement		- Provides natural ventilation. - Requires less material compared to a solid wall. - More economical.	- Offers less sound insulation. - Limited structural strength.	
Parallel arrangement with grid		- Strong compared to simple and empty parallel arrangements. - Gives opportunity to improve insulation. -Aesthetic design.	- Slowest to print due to its complexity. - uses more material	
Filled parallel arrangement		- Strong because of the filled design. - Offers better insulation. - May serve as load-bearing walls.	- Complex design - Longer time for printing. - Higher material cost	
Filled grid wall with natural ventilation		- Offers a combination of strength and ventilation.	- Complex design - Longer time for printing. - Higher material cost	

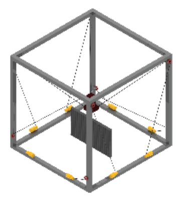
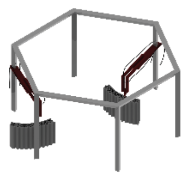
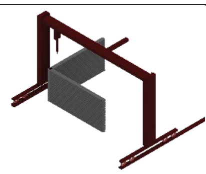
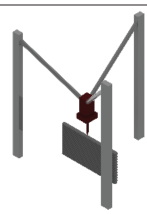
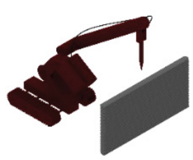
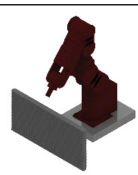
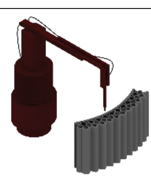
Advancement in 3D printing goes beyond wall designs and requires some reinforcement strategies to meet the structural requirements. Table 2.2 explores different options of reinforcement alternatives focusing on the cost and benefits of material use, construction speed, structural capacity, and overall cost. However, reinforcement options range from the absence of reinforcement, suitable for load-bearing walls and offers a cost-effective solution with faster construction for non-load-bearing applications, to horizontal structure bars that increase wall stability and horizontal strength, improving the speed of printing compared to fully filled walls. In contrast, filled vertical structure bars in one hand are ideal for high stress applications and increase vertical load-bearing capacity, in other hands require more material consumption and weight. Finally, concentrated reinforcement is commonly used because of the material and weight optimization while maintaining structural integrity, while it has some complexities in design and precise engineering, potentially leading to an increase of construction cost. Each of these reinforcement strategies presents pros and cons between material use, construction speed, structural capacity, and cost, indicating the need for careful consideration based on the specific demands of a construction project.

Table 2.2 3DCP wall types of reinforcement

Type of reinforcement	**Illustration**	**Pros**	**Cons**	**References**
Absence of reinforcement		For non-load-bearing applications, lower material and manufacturing costs, faster construction.	Not strong enough for load-bearing walls may need support.	(Garcia Alvarado et al., 2021)
Horizontal structure bars		Increases horizontal strength, wall stability, and print speed compared to fully filled walls.	Limited vertical support, less effective against bending or buckling.	
Filled vertical structure bars		Ideal for high-stress applications, significantly improves vertical load-bearing capacity and structural integrity.	Heavy material uses increases in weight, cost, production time, and overengineering for some applications.	
Concentrated reinforcement		Utilizes materials efficiently, strengthens crucial places, and may minimize weight while retaining structural integrity.	Design complexity, precise engineering, and cost may increase.	

While wall designs and reinforcement strategies are key elements in 3D printed construction, the choice of the type of 3DCP is crucial and should be carefully selected due to different factors such as the project size, the precision and accuracy, speed and efficiency, material computability, and mobility and adaptability. Table 2.3 presents various types of 3D construction printers, each with unique characteristics and limitations. The Cable robot is characterized by its large build volume and flexibility, with the ability to operate over long distances and can be used for expandable designs, yet it falls short on precision and requires a complex setup. The Crane printer robot, similar in modularity and build volume, also faces challenges in precision and complex setup. The two-column gantry robot excels in speed and precision but is not easily scalable and is better suited for smaller projects. In contrast, the Delta robot integrates mobility with a robotic arm for greater flexibility but demands intricate programming and maintenance. The Mobile robotic arm stands out for its precision and multifunctional capabilities, though it is limited by a smaller operational reach and necessitates complex programming. Finally, the spherical robotic arm offers a wide range of motion in its work envelope and is designed to be expandable, yet it is not ideal for linear or planar tasks and requires detailed programming and maintenance. Each of these printers is supported by academic references, indicating the depth of research and development in the domain of automated construction.

Table 2.3 Types of 3DCP

Types of 3DCP	Illustration	Pros	Cons	References
Cable robot		Large build volume, maneuverability, long-distance capability, expandable design.	Less precise, complicated setup and calibration, bigger operational area.	(Hahlbrock et al., 2022)
Crane printer robot, modular system				(WASP, 2021)
Two column gantry robots				(Icon)
Delta robot		Very fast and precise,	Hard to be scalable, used for small construction. High level of complexity and sensitivity	(Cheng Tiao, 2017)
Mobile robotic arm		Combining a robotic arm with mobility. Better flexibility	complex programming and maintenance.	(Zhang et al., 2018) (CyBe Construction)
Robotic Arm		Highly precise, flexible, flexible, capable of complex movements, multifunctional.	Smaller reach, slower in large tasks, complex programming and maintenance.	(Gosselin et al., 2016)
Spherical robotic arm		Wide range of motion in its spherical work envelope, expandable design.	Inadequate for linear or planar performance, complex programming and maintenance.	(Apis-Cor)

The incorporation of 3D printing in construction brings notable benefits, including faster construction processes, significant cost reductions, and increased design flexibility allowing for more complex geometries. It also promises enhanced sustainability through efficient use of materials and improved safety on construction sites. (Davtalab, Kazemian, & Khoshnevis, 2018; El-Sayegh, Romdhane, & Manjikian, 2020; Ghaffar, Corker, & Fan, 2018; Hager, Golonka, & Putanowicz, 2016; Kothman & Faber, 2016; Lim et al., 2012) However, this innovative technology is not without challenges. Material-related issues such as printability and buildability, scalability and cybersecurity concerns related to printers, and design and construction challenges, including the integration of building services and ensuring structural integrity, are significant hurdles. (Ali, Issayev, Shehab, & Sarfraz, 2022; Ghaffar et al., 2018; Jipa & Dillenburger, 2022; Labonnote, Rønnquist, Manum, & Rüther, 2016; Lim et al., 2012; Romdhane, 2020; Sandeep & Rao, 2017). These challenges underscore the importance of continued research and development in the field. As the construction industry evolves with these technological advancements, addressing these obstacles becomes crucial to fully harness the potential of 3D printing in sustainable and efficient building practices.

2.4 The evolution of Cross-Laminated Timber technology

2.4.1 Canadian context

In Canada, the Cross-Laminated Timber (CLT) and timber industry are growing, especially in mass timber, which includes CLT and Glulam structures. This growth is due to the environmental benefits of these materials. The Canadian market is still developing, but there is increasing interest and support from the public sector, government, and research. By 2021, there were more than 550 mass timber projects in Canada, mainly in public buildings and homes, especially in southern British Columbia. The country has about 20 factories making mass timber, with British Columbia and Quebec leading in this area.

However, the time it takes for Canadian manufacturers to supply mass timber is about 6-8 months which shows the challenge of meeting demand and competing with European products.

Nevertheless, Canadian constructors often choose to use local timber to support the Canadian timber industry. Also, the National Building Code of Canada (NBCC) is allowed to build up to 12 stories high with mass timber by 2020. This change, along with standard guidelines for making mass timber is expected to help the industry to grow and will likely increase the number and size of timber buildings in Canada. British Columbia has the most mass timber projects in Canada and it is because of government support and collaboration between the industry and government. Currently, most mass timber projects in Canada are fewer than 4 stories high but things might change with new building code rules that support taller timber buildings. While there are challenges, CLT and timber industry has a significant growth potential and it is motivated by environmental considerations that prioritizes sustainable building practices and evolve building regulations for more materials with less carbon footprint.

2.4.2 Cross-Laminated Timber (CLT)

Cross-Laminated Timber is a modern timber product that was developed during the last twenty-five years and is made by cross-laminating different layers of softwoods to create boards with high and predictable strength. CLT panels are composed with layers oriented perpendicularly and glued together under high pressure, typically with three to nine layers of boards.

Figure 2.10 Cross-Laminated Timber
Taken from Enso (2024)

Figure 2.10 illustrates the composition and structure of Cross-Laminated Timber panels, demonstrating how layers of lumber are cross-laminated to improve strength and stability. This technique minimizes the fluctuation of the size of the panel for better rigidity and structural capacity. The engineered composite formed through this lamination process enables the construction of taller, stronger, more stable, and safer timber structures suitable for high-density building. The origin of CLT can be traced back to the traditional timber technologies of Central Europe and Scandinavia. However, modern CLT emerged from joint research between industry and academia in Austria in the mid-1990s, and its development has been continuously supported by ongoing research. The material's high strength-to-weight ratio, comparable to steel and concrete, ensures resilience against shear forces and bending, while its fire resistance and ability to withstand seismic and blast forces add to its resilience. The speed of CLT construction is 20% faster than traditional methods, and its prefabricated nature reduce waste and increase project efficiency. Moreover, the use of CLT increases health and safety on construction sites and its design flexibility allows for multiple architectural design (Waugh Thistleton Architects, 2018)

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The study by Shahnewaz, Jackson, et Tannert (2022) examines Timber-Concrete Composite (TCC) floor systems that combine CLT with concrete, improving tension and vibration performance compared to traditional floors. The findings include a 167% increase in shear capacity for composite CLT-concrete connections and effective performance under short-term loads. Long-term benefits were observed in half-reinforced CLT panels, where diagonal screws improved weak-axis shear failure. The study also found that steel kerf plates are the most economical and effective connectors, transitioning failure modes from shear to bending in reinforced panel.

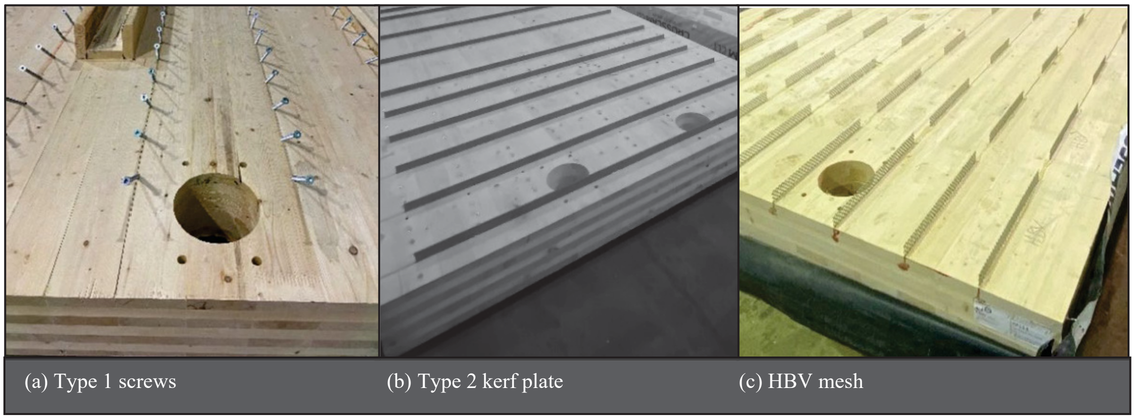


Figure 2.11 Types of shear connectors in TCC systems
Taken from Shahnewaz et al. (2022, p. 2)

Figure 2.11 Presented here are the various shear connectors used in TCC systems: (a) Type 1 screws, (b) Type 2 kerf plates, and (c) HBV mesh, each contributes to the overall shear capacity and structural integrity of the composite floor system. Research conducted by Shan, Chen, Wen, et Xiao (2023) explores sustainable building materials, specifically focusing on the thermal performance of CLT and Cross-Laminated Bamboo and Timber (CLBT) panels. The study evaluates their performance in various climates and indicates that CLBT panels are slightly less insulated than CLT but still satisfy the required insulation standards.

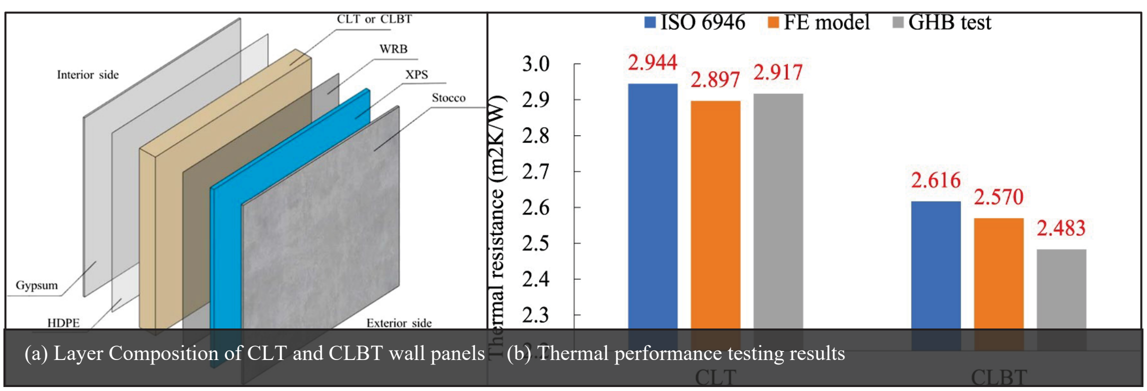


Figure 2.12 Wall panel composition and thermal efficiency
Taken from Shan et al. (2023, p. 526)

Figure 2.12a illustrates the layered composition of CLT and CLBT panels. The assembly includes High-Density Polyethylene (HDPE) for a vapor barrier, Extruded Polystyrene (XPS) for insulation, and a Weather-Resistant Barrier (WRB) to protect from moisture. These components are essential for the panel's thermal performance and durability. Moreover, Figure 2.12b shows the results of hot box testing, which assesses the actual thermal efficiency of the panels. The testing confirmed that while both types of panels maintain suitable insulation levels, CLT panels provide a high thermal resistance which indicates a better performance in terms of energy efficiency. However, the findings from these tests are crucial for regions with extreme temperature variations, as they validate the panels' effectiveness in insulation and saving energy, making CLT and CLBT suitable materials for modern construction.

Rogeau's 2023 thesis contributes to sustainable architecture by digitizing timber construction with Integrally Attached Timber Plate Structures (IATPS) with the use of CNC machining and CAD/CAM technologies. This approach improves the use of wood as a construction material. A key innovation is 'Manis' an open-source software that automates the design and assembly process of timber joints, promoting a new fully automated approach to timber construction (Rogeau, 2023).

Canetti et al. (2023) introduce an innovative concrete beam foundation system in their studies to increase the durability of timber construction. This prefabricated system can significantly prevent moisture-related issues that are crucial for timber durability. Also, this system can be used with various timber types such as Light Frame Timber and Cross-Laminated Timber simplify the building process. The results show the system’s durability with an excellent moisture barrier performance and an easy installation to reduce construction complexities. The system was tested under diverse mechanical loads, which highlights its potential for multiple applications in timber construction. Yet, Figure 2.13 illustrates the innovative concrete beam foundation system developed by Canetti et al. It shows the prefabricated design, detailing how it integrates with various timber styles and its moisture barrier elements contribute to the durability and sustainability of timber construction.

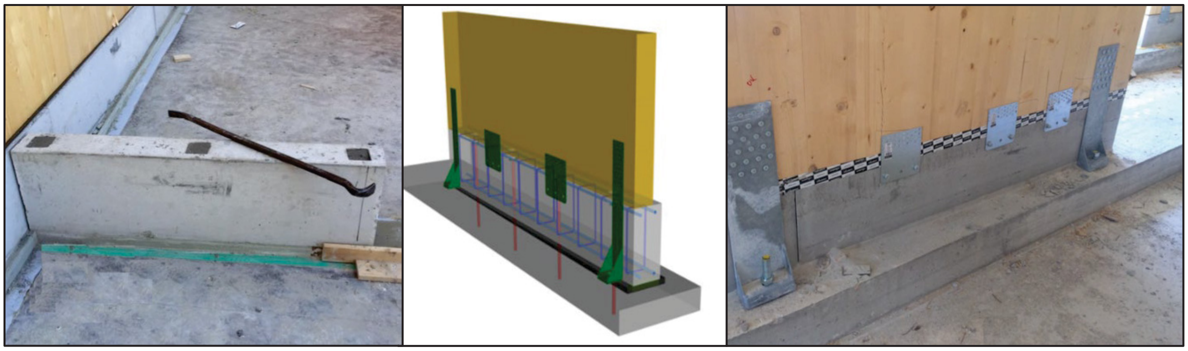


Figure 2.13 Concrete beam foundation system
Taken from Canetti et al. (2023, p. 1418)

An article from ArchDaily sheds light on the successful strength testing of SOM's Timber Tower System This research project was initiated in 2013 and dedicated to developing a structural system for skyscrapers using timber as the primary material. The proposed system, known as the Concrete Jointed Timber Frame, ingeniously involves mass timber with reinforced concrete at critical connection points. The study was done in collaborating with Oregon State University to test strength and demonstrated its capability to meet and in some cases exceed, existing code requirements and to propose a new alternative to traditional construction methods. A remarkable aspect of the test was a full-scale mock-up that impressively withstood loads well above the standard code requirements. Significantly, the adoption of this timber-based system in building construction has the potential to reduce the carbon footprint of structures by an estimated 60 to 75 percent compared to conventional concrete buildings, marking a substantial step forward in sustainable architectural practices (Lynch, 2016).

As the research for sustainability in building methods continues further studies explore other possibilities for timber structure. However, another study investigates the load-bearing capabilities of two-way spanning cross-laminated timber (CLT) with concrete composite slabs (CLTCC). Using experimental tests, FEM simulations, and static spring models, the research focuses on CLT for its biaxial load-bearing capacity and examines two types of shear connectors: angled screws and rectangular notches. A key result is the influence of connector alignment on load-bearing capacity and shear stiffness. The study also introduces a practical joint connection using glued-in reinforcement bars suitable for concrete and CLT junctions. The findings include the high load-bearing capacity and consistent deformation behavior of the two-way spanning system, with similar tensile levels to one-way-spanning systems up to 55% of ultimate strength. The research concludes that the two-way spanning TCC method is more effective offering material use and practical solutions for shear connector arrangement, highlights a step forward in sustainable construction methods (Loebus, Dietsch, & Winter, 2017).

2.5 Case study analysis

In this research section, we initially focus on Canada's first 3D printed affordable house to demonstrate the innovative use of 3D printing technology. This study highlights its potential for reducing construction costs and time for remote regions like Nunavut, where traditional building logistics are challenging. However, the analysis then transitions to a project using CLT highlighting its environmental sustainability and architectural flexibility. This case study will not only consider the construction benefits of CLT but also delve into the transportation logistics of prefabricated CLT panels, a critical aspect for remote area constructions. Both case studies collectively offer insights into the challenges and opportunities of transporting construction materials and equipment to isolated locations in Canada’s extreme environment.

2.5.1 Habitat for humanity Windsor Essex

The house was built with a collaboration between the University of Windsor's Faculty of Engineering, Habitat for Humanity, Windsor-Essex, and Nidus3D and the goal was to construct the first 3D-printed homes for residential use in Canada as shown in Figure 2.14a, which provides fourplex housing. The project involved engineering researchers, graduate students, and laboratory technicians who used a large-scale industrial printer, provided by Nidus3D, within the university's Structural Engineering Testing Lab, as illustrated in Figure 2.14b.

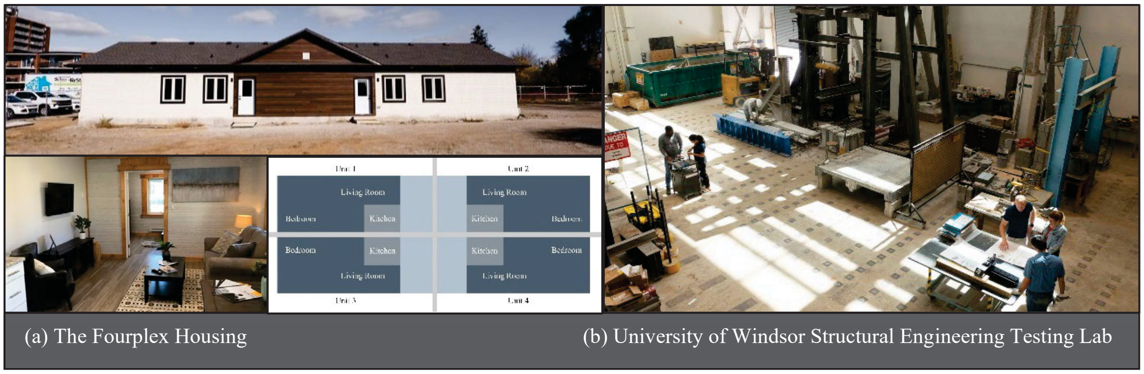


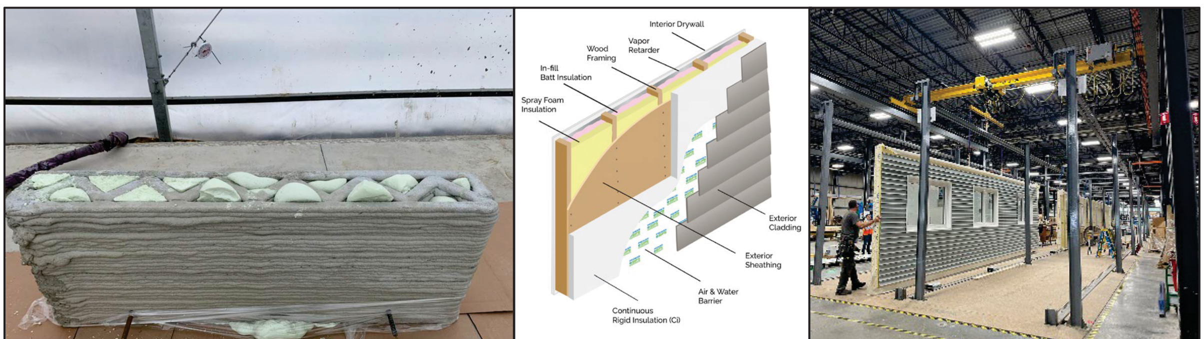
Figure 2.14 Habitat for humanity Windsor Essex
Taken from Nidus3D (2024)

2.5.1.1 Construction process

The 3D construction process, as explained by Nidus3D, starts with site preparation, including surveying and clearing. The onsite installation of a large-scale 3D printer follows, crucial for accurate printing. Moreover, the foundation is printed first using a layer-by-layer concrete extrusion method marking a deviation from traditional building techniques. Next, the ground floor walls are printed, incorporating spaces for insulation and utilities. For taller structures, this process repeats for additional floors. The building is then completed with a roof, windows, doors, and, if needed, twin-masonry veneers. Interior finishing, including painting and installing electrical and HVAC systems, finalizes the house. This approach markedly reduces construction time, labor, and material waste (Nidus3D, 2024).

2.5.1.2 Structural Integrity of 3D Printed Wall

Within the scope of examining the fourplex house by Nidus3D, Figure 2.16 serves as a vital comparative tool, highlighting the forward-thinking role of 3DPC in crafting affordable and efficient housing solutions. This figure is pivotal to understand the innovative strides taken in the Nidus3D project, where 3DPC's benefits are brought to the forefront. Figure 2.16a reveals a segment of a wall from the Nidus3D fourplex house, showcasing the streamlined process of 3DPC that integrates essential features like insulation directly into the build, thereby enhancing energy efficiency and reducing overall construction costs. This is particularly impactful for affordable housing projects such as the fourplex, highlighting the potential of technology to make homes more accessible and sustainable. In opposition, Figure 2.16b shows a traditional wall construction method, emphasizing the comparative lack of efficiency and higher costs typically associated with conventional building techniques. Figure 2.16c presents a prefabricated wall system inside a factory, where precision and fast onsite assembly are the characteristics of prefabrication. However, the logistical constraints of transporting these prefabricated units is important compared to Nidus3D's 3DPC approach in remote regions.



(a) 3D printed wall (b) Conventional wall (c) Prefabricated wall

Figure 2.15 Comparative Analysis of Wall Construction Techniques
Taken from Nidus3D (2024)

2.5.1.3 Installation of 3D printing machine

Figure 2.17 presents the BOD2 3D printer by Nidus3D illustrating the various stages of the construction process and its modular and scalable construction during building a multi-unit dwelling. The BOD2's adaptability is highlighted by its ability to be customized onsite to match the scale and specifications of the project, As well as the efficiency in fast concrete layering supported by an advanced construction management software, ensuring that operations are optimized for the Canadian context.

Figure 2.16 Progressive stages of 3D printing construction
Taken from Nidus3D (2024)

Table 2.4 presents the technical details of the BOD2 3D construction printer by Nidus3D, it underlines features that enhance its functionality in large-scale builds. The BOD2 3D is weighing 5390 kg and is operating with a voltage range of 380-480V. In addition, it offers a high printing speed on all axes and powered by precise servo motors. Moreover, the printer's connectivity options include Wi-Fi or LAN enables the use of advanced management software for efficient operation, which is accessible through standard web browsers. The recommended operating temperature range from 5 to 35 degrees Celsius ensures the BOD2's adaptability to various Canadian climates.

Table 2.4 BOD2 machine information

Description	**Unit**	**Value**
Product	-	3D construction printer
Model	-	BOD2
Wight	[kg]	5390
Current	[A]	32
Voltage	[V]	380-480 3 phases, + N + PE (WYE)
Max. speed (X-axis)	[mm/s]	250
Max. speed (Y-axis)	[mm/s]	250
Max. speed (Z-axis)	[mm/s]	50

Table 2.4 BOD2 machine information (Cont'd)

Description	**Unit**	**Value**
Movement system	-	Servo
Connection	-	Wifi or LAN
Software	-	Soft-NA and COBOD Web Control Interface
Interface	-	browsers
Recommended operation system	[°C]	5-35

2.5.2 Brock Commons Tallwood House (UBC)

Mass timber may be used to create tall buildings, as demonstrated by the Brock Commons Tallwood House project at the University of British Columbia (UBC), a remarkable achievement in sustainable architecture. When it was completed in May 2017, this eighteen-story skyscraper was the highest wood structure ever built, highlighting advancements in engineered wood products and construction techniques. The hybrid structure which combines mass timber for the higher stories with a concrete foundation and lower floors, demonstrates a dedication to sustainability, effective building techniques, and the creative use of virtual design and construction modeling for the project's design and construction. (naturally:wood, 2017, p. 3)

Figure 2.17 Brock Commons Tallwood House-UBC
Taken from Acton Ostry Architects Inc. & Forestry Innovation Investment (2017)

2.5.2.1 Construction process

The construction of Brock Commons Tallwood House was done in three main steps: the concrete work, the assembly of large timber elements, and finalizing both the interior and exterior of the building. The project planning is used to ensure that the project is a success, and to simplify it started with a reconstruction meeting where the client and the team address questions or clarifications to learn about the project's expectations and goals such as reviewing the contract terms, construction site and logistics, action and terms, and the approval from the authorities. Nonetheless, construction drawings are the backbone to deliver a successful project, these drawings can be categorized into 5 types, architectural drawings, structural drawings, electrical drawings, plumbing and sanitary drawings, and finishing drawings. These drawings are the main part of the construction documentation that will be submitted for review to get the permits from local authorities. One they receive the approval; the construction process begins with the site preparation were cleaning the site and excavation are very important before the preparation of the foundation and building the concrete structure. The next step is using Glued-Laminated Timber (GLT), CLT, and prefabricated walls for structural frame and floor installation. Next was the installation of plumbing, electrical systems, HVAC was done with the interior finishing. Final inspection was conducted for safety and compliance to receive the occupancy permits (naturally:wood, 2017, p. 9).

2.5.2.2 Structural integrity

The construction system of the Brock Commons building is supported with a concrete foundation and connected to entire structure. Figure 2.20a shows the first phase of the construction process, where the solid concrete foundation is placed, crucial to support the weight of the building and provide a stability and structural integrity. In Figure 2.20b, we see CLT panels installed. Thie concrete structure serve as the core of the building and provides resistance to wind and seismic forces. In addition, Figure 2.20c illustrates the second floor, which acts as a transitional layer distributing the loads from the wooden elements above to the concrete structure below, we can see a complex collection of floor panels composed of CLT panels with some openings for services like pipes. The vertical supports are made up of GLT and Parallel Strand Lumber (PSL) columns, each reinforced with steel connectors at both ends for strong structural connection. The envelope panels consist of a steel frame rainscreen system, equipped with perforated windows that contribute to the building's thermal performance and visual aspect. However, the decision to use concrete for the foundation and core is a testament to its strength and cost effectiveness. It simplifies the authorization procedure with city regulators and keeps construction within budget. Moreover, it provides the building with the enough strength to withstand environmental stressors. The careful planning and execution of these concrete components are instrumental in the building's overall safety and durability (naturally:wood, 2017, p. 12).


(a) Concrete Foundation
(b) Core Structural Formation for Staircases and Elevators
(c) Integration of Second-Floor Support with Timber Structure

Figure 2.18 Structural foundation and core construction of Brock Commons
Taken from Acton Ostry Architects Inc. & Forestry Innovation Investment (2017)

2.5.2.3 Installation

The project uses advanced architectural techniques to guarantee the design beauty and structural integrity of the upper floors. Figure 2.21a illustrates the CLT panels integral to the building's structure. These panels are not only significant for their strength but also for their contribution to the building's overall sustainability profile. However, In Figure 2.21b we can see the precision involved in the installation of columns that support the building to maintain the integrity of the structure to withstand various stresses. Moreover, Figure 2.21c demonstrates the innovative prefabricated building envelope system developed specifically for this project. This system was designed to reduce the time of the construction process, allowing for a more efficient and precise assembly. Lastly, in Figure 2.21d, a worker is finalizing the envelope installation, highlighting the process of sealing each joint to protect the building from damage caused by water and other environmental factors. The lifecycle of the project Brock Commons building reveals the precision from the design of the steel frames, the integration of insulation and windows, to the precise to assemble every element carefully. The use of special machines and tools in the factory indicates the precise assembly and installation of different components, while sealing of joints with blinking and glue guarantees the building's longevity and durability. While the panels were assembled with precision offsite, final touches, including the addition of insulation and drywall, were carried done onsite to show how it is possible to integrate the prefabrication with traditional construction techniques (naturally:wood, 2017, pp. 16-19).

Figure 2.19 Stages in the construction of the Brock Commons building envelope
Taken from Acton Ostry Architects Inc. & Forestry Innovation Investment (2017)

2.6 Conclusion

The construction technology such as 3D printing and CLT, present an opportunity to address the housing crisis in Nunavut and Inuit Nunangat. These technologies offer a solution to overcome the unique challenges of Arctic construction by integrating modern engineering with traditional knowledge to meet the environmental, cultural, and logistical requirements of the North.

3D printing offers a flexible structure to withstand the extreme environment while respecting the indigenous culture. Its ability to generate complex geometry introduces a new idea in construction and has the potential to make the process more adaptable, faster, and efficient. The case studies, such as the Habitat for Humanity Windsor Essex by Nidus3D project show that 3D printing house can deliver an affordable, efficient, and sustainable housing solutions, proving its applicability in remote regions. CLT knew for its strength, environmental sustainability, adaptability, and reduce of transportation to make it a viable option for Northern climates, offering a large reduction in carbon footprint and aligning with sustainable development goals. However, the Brock Commons Tallwood House project demonstrates how CLT can revolutionize tall buildings, combining speed, efficiency, and minimize the environmental impact compared to traditional building methods.

The integration of these two technologies has the potential to reduce the logistical and environmental challenges of building in remote areas while also honoring the cultural heritage and preferences of Indigenous communities. By leveraging computational design and digital fabrication, these solutions offer a framework to address the housing crisis in a way that is environmentally sustainable and culturally respectful.

The exploration of case studies clearly illustrates the practical application of these technologies, demonstrating their viability and efficiency in real-world application. These examples bring out the critical importance of collaborative efforts, including partnerships between academic institutions, industry, and communities in encouraging the adoption of innovative construction methods.

In conclusion, 3D printing and CLT have potential to transform construction practices while supporting a sustainable development that respects and integrates Indigenous culture. As we move forward, it is important to keep investing in research and development, and collaborative efforts to fully realize the potential of these building solutions in creating sustainable, efficient, and culturally appropriate housing for the arctic regions.

CHAPTER 3

INDUSTRIALIZED STRATEGIES: THE INTEGRATION OF 3D PRINTING IN CANADA'S NORTHERN HOUSING DEVELOPMENT

3.1 Introduction

Given Northern Canada is facing a serious housing crisis, the introduction of 3D printing technology offers an opportunity to build high-quality and sustainable homes. This chapter explores scenarios where 3D printing can be used for construction in this climate zone aiming at pinpointing the best strategies for implementation. The primary goal is to explore and compare 3D printing methods to identify the practical, economical, and culturally appropriate applications for local communities. This chapter seeks to gather a range of viewpoints, on the feasibility, barriers and potential advantages of using 3D printing technology in the construction sector.

Through the analysis of different scenarios, from entirely onsite printed structures to hybrid approaches that involve offsite manufactured components, this chapter evaluates each technique based on criteria related to Northern conditions, these criteria include material suitability, thermal efficiency, affordability, construction speed and resilience to extreme environments. Furthermore, there are logistical considerations for transporting printing equipment and materials to distant areas. It also explores the possibilities of 3D printing to adapt to the unique needs and preferences of indigenous communities while overcoming infrastructural challenges.

3.2 Background

This chapter explores current modular and offsite construction practices, including planning, materials, and delivery systems. Additionally, it will examine barriers to modular construction's growth in Canada, focusing on negative perception and absence of successful case studies.

The research reveals that modular construction, predominantly using steel and the design-build delivery system, plays a crucial role in offsite construction, highlighting the importance of stakeholder roles, contracts, and Building Information Modeling (BIM). However, it experiences barriers such as poor credibility, a lack of documented results, restrictive standards and regulations, procurement strategy issues, and contradiction in financing models. The previous challenges indicate the necessity to improve marketing, strategic partnerships, regulatory reform, and standardization to improve perceptions and adapt processes. Addressing these barriers could substantially increase modular construction's market share and adoption in Canada.

Quantitative data obtained from a survey on Canada's modular construction industry, focuses on material preferences, project types, and delivery methods. It highlights that 79.6% of respondents use steel as the primary material, compared to 63.0% for wood and 27.8% for concrete. Modular construction is the leading offsite construction method, with 77.8% of respondents producing modular components. The Design-Build (DB) delivery system is most common, used by 44.9% of participants; medical buildings (22%) and residential projects (40%) were found to regularly adopt DB and Construction Management at Risk (CMAR), respectively. Annual sales volumes have shown a consistent increase from 2012 to 2016, while exact figures weren't provided. Key responsibilities for modular companies include manufacturing, design, and transportation. About 47% have reported a maximum transport distance of less than 50 km, while 27% have indicated distance from 200 km to 500 km. For minimum transportation distances, 57% of respondents faced costs of less than $2 per square foot. Over half of the respondents admitted a poor perception of modular construction, a significant lack of promotional success examples, and 83.6% noted that transportation regulations significantly impact costs, timelines, and design. This data provides a comprehensive overview of the industry's characteristics, practices, and challenges, highlighting the need for addressing barriers to increase modular construction's market share in Canada (Salama, Moselhi, & Al-Hussein, 2021).

Another study by Verderber, Wolf, et Skouris (2020) about Indigenous Ecohumanist Architecture for Health in the Far North Canada reveals similar themes and findings to those explored in the research by Salama, Moselhi, & Al-Hussein. Both studies underscore the prevalent use of steel and the design-build method as an important element in the development of modular construction projects. Additionally, they highlight a common set of shared challenges facing the modular construction industry, such as the negative reputation associated with modular methods, a noticeable lack of documented successful projects, and the restrictive nature of current standards and regulations. These barriers are recognized as critical obstacles to the broader adoption and growth of modular construction in Canada. Furthermore, both studies acknowledge the potential benefits of modular construction, particularly its predictability in terms of costs and schedules, and suggest that overcoming the identified challenges through strategic marketing, partnerships, regulatory reforms, and standardization could substantially improve the modular construction industry's market share. Moreover, the importance of stakeholder roles, contracts, and Building Information Modeling (BIM) is emphasized, highlighting the complexity and the need for collaborative efforts in modular construction projects. In essence, Verderber's study complements and reinforces the findings of Salama, Moselhi, & Al-Hussein, with a specific focus on improving healthcare infrastructure in indigenous communities in Canada's Far North, demonstrating a consensus on the key factors influencing the growth of modular construction and its application in healthcare and other sectors.

Including the results from the case study "Information Management in Offsite Construction: Case Study of Mid-Rise Building Construction in Québec" by Messa, Iordanova, and Carbone, the literature review can be expanded to illustrate a nuanced exploration of Offsite Construction (OSC) practices within the context of mid-rise buildings in Québec, Canada. This study examines the challenges of cost overrun, communication issues, the necessity for multiple innovations including modular OSC systems, increased responsibilities for the manufacturer, and the crucial role of insufficient information management. It highlights the complex balance required between innovative construction techniques and practical project management to overcome these obstacles. Moreover, it underscores the potential of Building

Information Modeling (BIM) to enhance communication efficiency among stakeholders, suggesting that adopting collaborative approaches like Integrated Project Delivery (IPD) could mitigate many of the identified challenges. The findings from Messa et al. resonate with the broader themes identified in the literature by Salama, Moselhi, & Al-Hussein (2021) and Verderber, Wolf, & Skouris (2020), further highlighting the critical need for industry-wide transition towards standardized, well documented, and efficient health and safety at the workplace. This addition not only provides a framework for specific challenges faced in the Québec construction sector but also aligns with the identified national trends, reinforcing the argument for strategic marketing, partnerships, regulatory reforms, and the adoption of advanced technologies to push the Canadian modular construction industry forward (Messa, Iordanova, & Carbone, 2023).

3.3 Construction Shipping to Northern Canada

Shipping construction materials, to Northern Canada involves negotiating a complex transportation route, which includes highways and Arctic shipping lanes. This task is significantly challenging by obstacles and limited infrastructure in the region. The vast distances, weather conditions and lack of road connectivity require planning to ensure the timely delivery of materials for construction projects. The highways outlined on the Figure 3.1 serve as main routes for transporting goods across Canada, connecting parts of the country to Northern and remote communities. Strategic centers like Yellowknife, Whitehorse and various Nunavut communities serve as points in the distribution network enabling transportation into isolated regions. However, the limited road network in these areas, along with ice roads and reliance on air transport at times of the year pose significant logistical challenges.

Arctic shipping routes provide an alternative for transporting goods, especially when ice conditions allow during months. These maritime paths are essential for supplying communities and supporting construction projects where road access is limited or unavailable. Utilizing these shipping routes can help reduce transit times and logistical expenses by enabling delivery of large quantities of construction materials.

Efficient shipping to Northern Canada requires a serious review of different aspects. The changing seasons impact how Arctic shipping routes can be used and the ability to reach areas through ice roads, making it important to plan to manage any disruptions that may occur. Moreover, the lack of infrastructure, in towns can make unloading and storing materials more challenging, requiring cooperation with groups to ensure access to necessary equipment and facilities. Additionally, the environmental effects of shipping activities in Arctic ecosystems necessitate the implementation of regulations to reduce negative impacts on the environment.

To successfully deliver construction supplies to these regions, a mixed transportation approach including roads, sea and air freight is needed based on destination accessibility and seasonal constraints. Planning and working closely with communities and businesses are crucial for navigating the logistics of Northern Canada. By recognizing the obstacles and utilizing logistics planning, it is possible to achieve efficient delivery of construction materials for development projects, in the North.

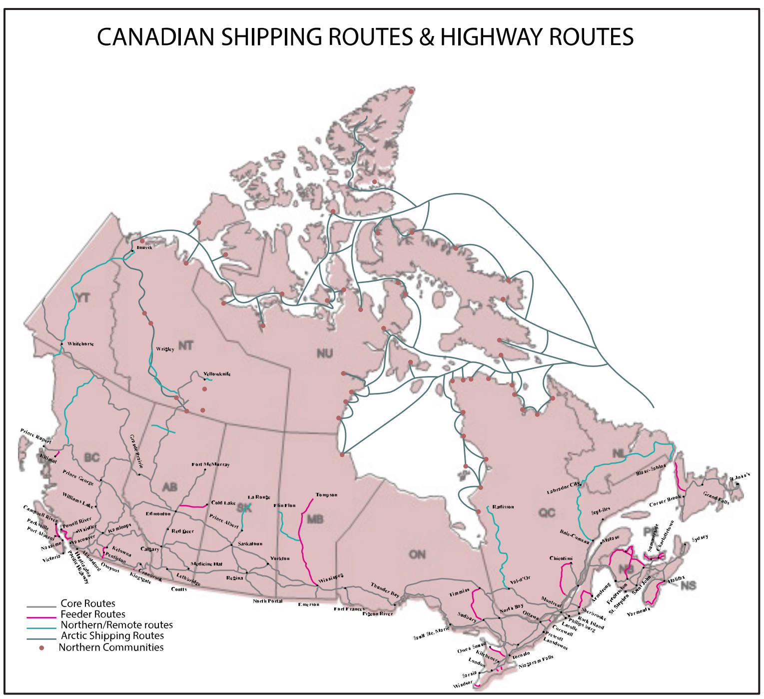


Figure 3.1 Canadian shipping routes & highway routes
Taken and adapted from Office of the Auditor General of Canada (2014); Office of the Auditor General of Canada (2014)

3.4 3D printing technology

While the background analysis sheds light on the transformative potential of modular and offsite construction methods in meeting Canada's housing crisis and infrastructure requirements, it also reveals significant barriers that limit their widespread adoption and efficacy, particularly in the unique and demanding context of Northern Canada. Among these challenges are the logistical complexities of transporting materials and modules to remote areas, the environmental impact of traditional construction materials, and the difficulties in customizing solutions to fit the cultural and climatic specifics of indigenous communities.

3D printing technology presents a flexible solution to the challenges of building houses in Northern Canada, with potential benefits including reducing waste, the ability to use local materials, and the adaptability to environmental and cultural contexts. This technology offers thermally efficient, cost-effective housing that meets the requirements of Northern communities, while also tackling the logistical challenges associated with conventional construction. This chapter explores the potential of 3D printing as a key tool in overcoming construction barriers, improving material efficiency, reducing transportation costs, and encouraging culturally sensitive design in Northern Canada.

3.4.1 3D printing and prefabrication configurations for housing

In modern construction, the integration of 3D printing technology with offsite construction techniques represents an innovation in housing development. Figure 3.2 illustrates how these techniques can be applied to create several home structures and offers unique benefits in terms of adaptability, sustainability and efficiency. Three main configurations can be used: fully 3D printed houses, combinations of 3D printing with offsite prefabricated modules, and hybrid methods that reconcile 3D printing with prefabricated elements. Every configuration has a different advantage based on design goals, material availability, logistical requirements.

The first, involves the use of 3D printing to build the entire structure, including, roof, envelope, and foundation, directly onsite without prefabricated elements, only windows and doors are used. The second method integrates prefabricated modules that can be part of the house, like room, kitchen, and bathroom, these models are customized based on project needs and customers. In the last configuration, instead of using offsite models, we can use prefabricated elements like walls and floors where the electricity, plumbing and windows are already installed.

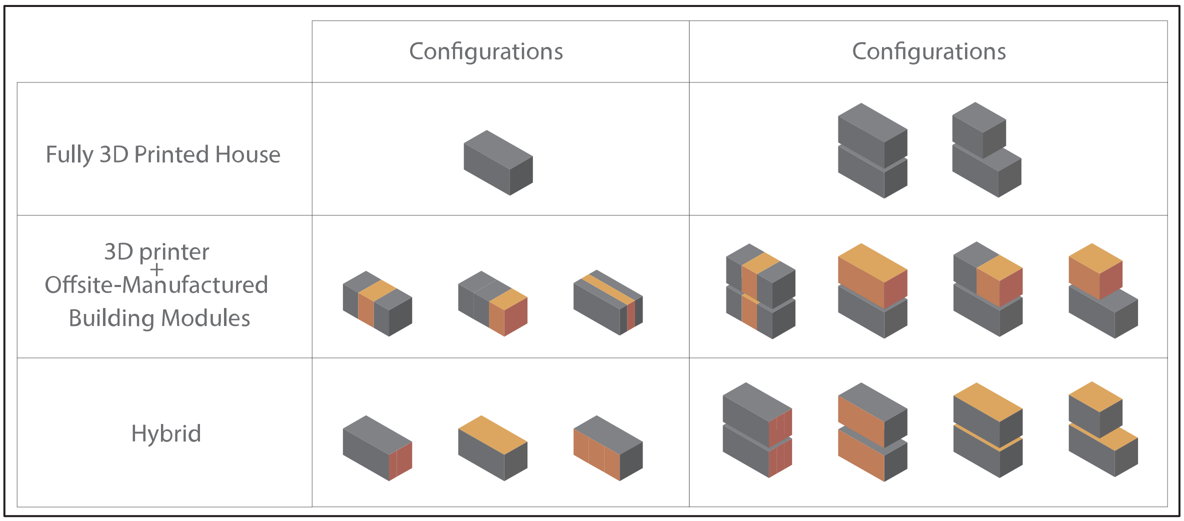


Figure 3.2 Configurations of 3D printing in grey color and prefabrication techniques in orange color for housing construction

3.4.2 Design parameters

Figure 3.3 illustrates a comparison between conventional construction methods and those using 3D printing technology, focusing on the entire process of building a house. The construction workflow begins with finding materials, which are subsequently to factories for processing. These materials are turned into building components or prefabricated parts, designed for assembling the structure of a house. After fabrication, these components are delivered to the construction site. A group of workers along with construction equipment handle the assembly of these parts on site. The equipment facilitates tasks like lifting and placing objects, as well as ensuring that all structural elements are properly connected for construction. A completed house is the outcome of the construction process. However, demolishing such a building lead to generating demolition waste that needs management or disposal, often done in landfills.

Indeed, 3D printing technology greatly streamlines the construction process. It begins with a selection of materials and then uses a 3D printer construction system called 3DPC to directly print house components on the construction site. This approach reduces the number of phases and may eliminate the necessity of transporting materials and reducing the required manual labor. Additionally, this technology provides a chance, In contrast to traditional concrete construction, which frequently generates demolition waste, 3D Concrete Printing (3DCP) promotes recycling by allowing reuse of printed elements or crushed concrete as aggregates in new builds.

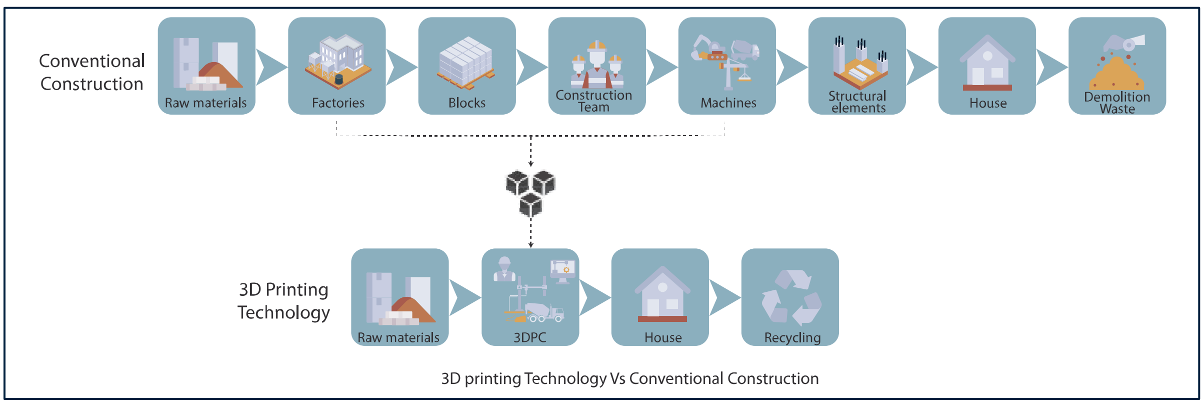


Figure 3.3 Comparisons of conventional construction and 3D printing technology in housing construction

The following table classifies essential design parameters in construction projects and identifies Canadian suppliers' companies of related materials and components. The parameters including 3D printing methods, the envelope, the structural elements, partitions, core services, raw materials, modular components, and HVAC systems. For instance, Nidus3D provides 3D printing technologies, while Due North Housing and Modular Connections focus on manufacturing building envelope components. Suppliers such as Butler Concrete & Aggregate Ltd specialize in selling basic materials, and Unilux VFC and LG Electronics provide HVAC equipment. This systematic approach facilities the connection between material needs for construction and industry leaders, promoting a better understanding of the supply chain dynamics in modern construction.

Table 3.1 Design parameters and material suppliers in construction projects

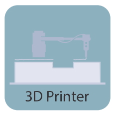
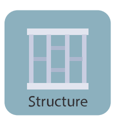
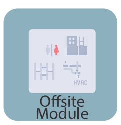
Design parameters	Explanation	Role	Example of material suppliers
	Machines for additive manufacturing in construction, capable of printing building components.	Expedite construction process, reduce material waste.	Nidua3D
	Components like walls, windows, roofs, insulation that separate interiors from exteriors.	Protects against elements, energy efficiency.	Due North Housing Modular Connections STO Canada Viewmax Cascadia Windows & Doors Luxal Canada
	elements like beams and columns.	Provides stability and support.	Structural Truss Systems Hans Steel Canada Canam Nordic Structures Element5 Structurlam
	Non-load-bearing walls that subdivide spaces within a building.	Space organization, design flexibility.	
	Essential services like plumbing, bathroom, kitchen	Functional operation of building services.	BathPods Eurocomponents Bathsystem

Table 3.1 Design parameters and material suppliers in construction projects (Cont'd)

Design parameters	Explanation	Role	Material Suppliers
	Basic construction materials like concrete, steel, timber.	Form basic structure and aesthetic.	Butler Concrete & Aggregate Ltd Lafarge Heidelberg Materials Sarjeants CO. LTD. CBM Rainbow Concrete
	Prefabricated building sections made offsite.	Reduces onsite time, improves quality control.	720 Modular ATCO Triple M Housing Fort Modular Arctic Modular Homes NRB Modular Solutions
	Systems for heating, ventilation, air conditioning.	Climate control, indoor comfort.	Unilux VFC EffectiV HVAC Inc. Cozy Comfort Plus Gree Canada LG Electronics Inc. Nortek Air Solutions LLC

3.4.3 Design parameters and construction scenarios

This section introduces six construction scenarios designed to tackle the housing crisis in Northern Canada. These scenarios explore combination of 3D printed and offset prefabrication, focusing on efficiency, environmental sustainability, and cultural adaptability. The following figures provide relevant design parameters and different components required for each situation. The six scenarios represent only a subset of potential circumstances, and extra variations may apply depending on the specific project needs and local constraints.

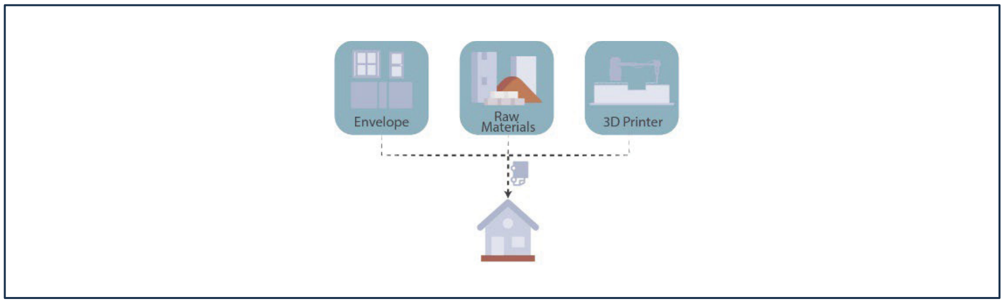


Figure 3.4 Scenario 1 combining onsite 3D printing and offsite prefabrication for housing construction

The first scenario illustrates a construction method that combines modern techniques by using 3D printing technology. Initially, construction begins with transporting materials to the site, where different onsite 3D printers are used. One printer will create structural and the others will have the capability to 3D print complex elements like the kitchen, bathroom and plumbing systems directly at the construction site, to guarantee accurate integration and functionality within the home's design. Simultaneously, a large part of the building known as the 'Envelope' will be prefabricated offsite. However, the envelope typically includes elements like the exterior cladding, interior finishes, openings for doors and windows, vapor barrier and waterproofing, soundproofing materials, electrical and plumbing components, structural frame, and insulation. Once the prefabricated components are delivered to the construction site, these prefabricated components are assembled to create the outside structure of the house. The integration of onsite 3D printing and offsite prefabrication creates a construction approach that combines precision and efficiency from 3D printing with speed and consistency of the elements.

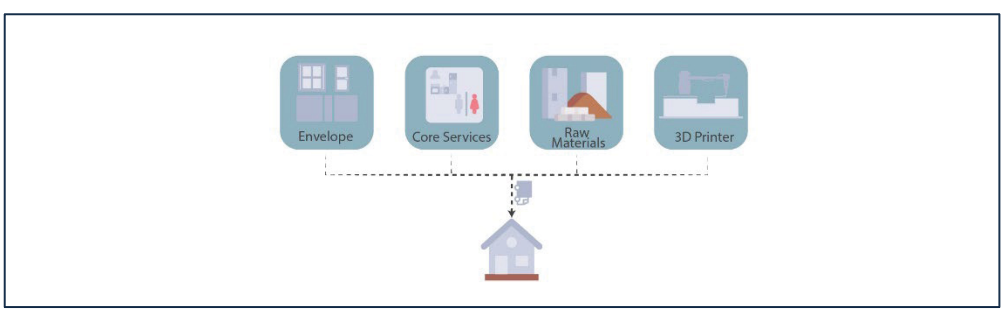


Figure 3.5 Scenario 2 integration of core services in 3D printing and prefabrication construction

The second scenario (Figure3.5) differs from the previous one by integrating core services into the building's framework. In this scenario, raw materials are transported to the construction site for use in the printing process. However, unlike before, core services like plumbing, electrical systems and potentially HVAC are not built onsite. Instead, these components are prefabricated in a controlled factory environment to guarantee quality control, reduce costs and waste, improve safety, and ensure compliance with standards and regulations before being delivered to the site. When the prefabricated services arrive at the construction site, they are incorporated into the structure as the 3D printer builds it. This method has the potential to simplify on site work by making it more efficient and less labor-intensive than assembling these systems in place. Furthermore, building envelope is also prefabricated in a factory, and then transported to be assembled with the pre-installed core services at the construction site.

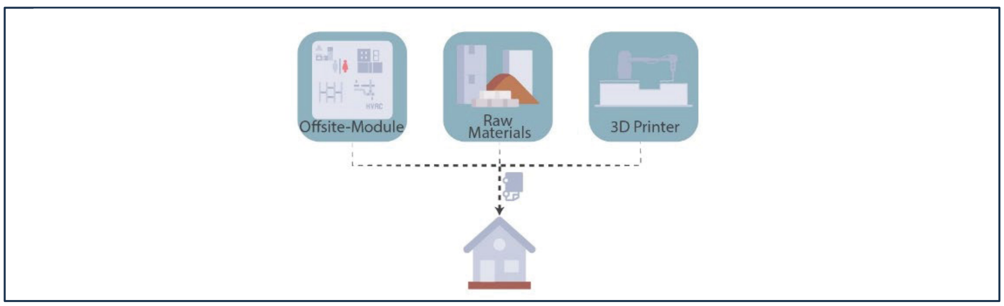


Figure 3.6 Scenario 3 hybrid construction method with onsite 3D printing and offsite modular systems

Scenario 3 introduces a technique that combines onsite and offsite construction. Where certain elements are made both onsite and, offsite to create a structure. Raw materials, 3D printer, and offsite models are transported to the construction site. The offsite models are prefabricated parts of the house like rooms, kitchen, bathroom, HVAC, plumbing and structural elements. The integration of these systems within the module occurs in a controlled factory, enabling quality control and simplifying the assembly process. Once the offsite module arrives at the site, it is mandatory to make sure that the different elements are connected and assembled correctly. Combining onsite and offsite construction methods can provide the strength of both technologies. By integrating systems such as HVAC and plumbing, offsite manufacturing guarantees a high-quality production and speeding the construction process. Using 3D printing allows adaptability and flexibility of the different site conditions.

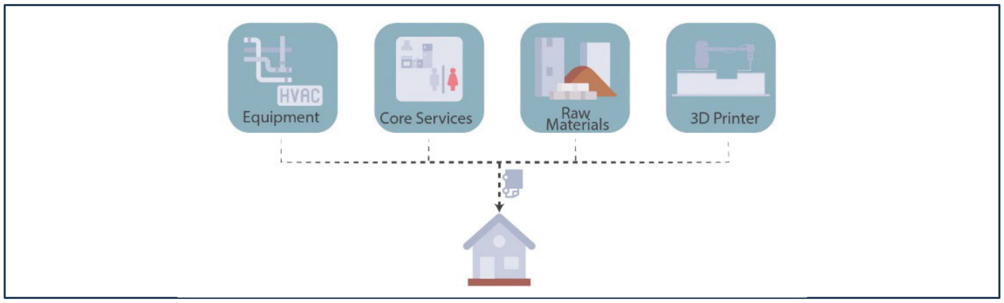


Figure 3.7 Scenario 4 onsite 3D printing with integrated HVAC and core services

The scenario 4 illustrated in Figure 3.7 expands upon the earlier scenarios by particularly concentrating on the integration of essential services and HVAC equipment as separate preassembled units, highlighting their significant role as integral elements of the construction process. In the contrast to scenario 3, where these systems are integrated into the offsite modules, scenario 4 treats the HVAC system as a separate, prefabricated kits that are brought and installed after the completion of the 3D printed construction. Moreover, the core services are included in the structure once the 3D printing process is finished, instead of being prefabricated as part of a bigger offsite module. This approach allows a high degree of customization while maintaining an efficient and streamlined construction process.

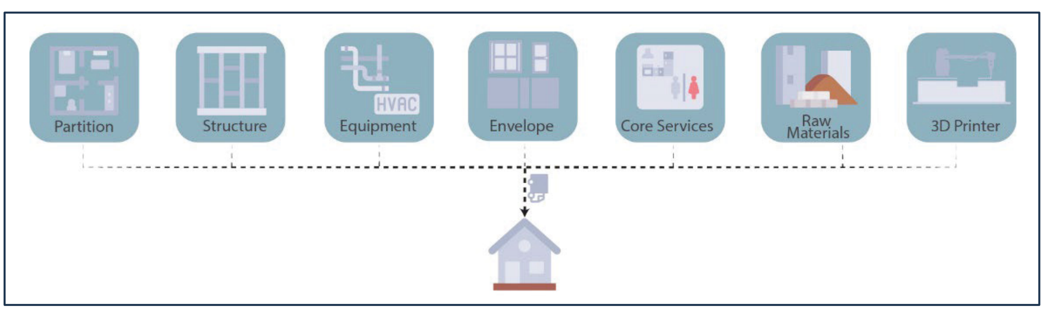


Figure 3.8 Scenario 5 precision and customization in hybrid construction with 3D printing and offsite prefabrication

Scenario 5 prioritizes precision and customization, this system uses prefabrication partitions that can be interchangeable, fabricated under a specific standard, and installed later. Following this, bringing more structural elements will ensure stability and provide protection against extreme climate conditions. Giving that the remaining components, including envelope, HVAC equipment, core services, raw materials, and 3D printing process, have previously been described, the same method is applicable in this case, ensuring the easy integration of these elements to complete the structure.

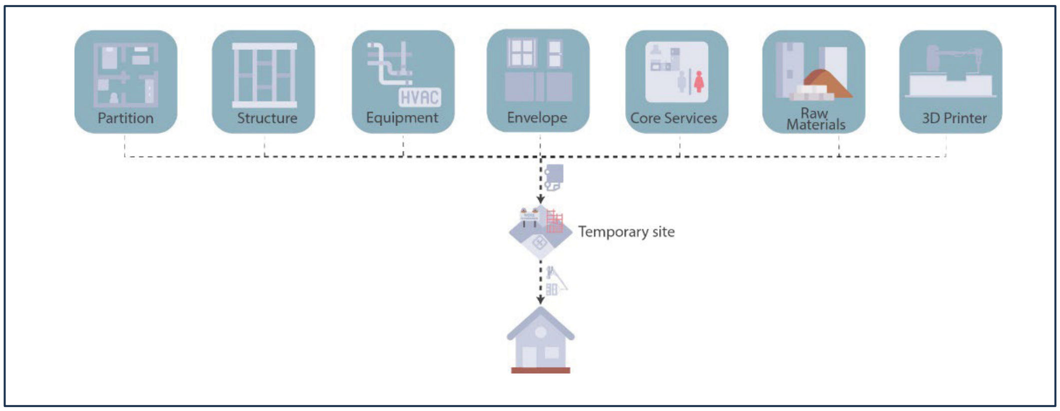


Figure 3.9 Scenario 6 temporary site construction with 3D printing before relocation to permanent location

A new construction technique is presented in Figure 3.9, where the house is first built and assembled in a temporary location, then transported to its permanent site. To minimize any issues related to the transportation and save expenses, the structure, the envelope, equipment, and utilities are assembled close to the raw materials and 3D printer. Once the house is fully constructed and relocated to its destination, some minor work and adjustments for connections are needed.

3.4.4 Analysis of scenarios

Table 3.2 presents a comparative study of the six scenarios introduced earlier, and focuses on different factors of construction, including transportation and logistics, environmental impact, material supply chains, regulatory and safety standards, cost-benefit analysis, and infrastructure requirements. These factors highlight the advantages and challenges associated with different hybrid construction techniques that combine 3D printing and offsite prefabrication.

In scenario 1, the objective is to reduce transportation challenges by using 3D printing materials and minimize waste by highly accurate printing. Scenario 2 introduces effective prefabrication services with increased complexity in storage and logistics for modular components. Scenario 3 points out a balance between onsite 3D printing and large offsite modules, assuring the advantages of modular construction and cost benefits for labor saving. In scenario 4, logistics becomes more complex, with separate envelope, HVAC, and core services, requiring detailed preparation for system integration. However, scenario 5 introduced more complexity and details in construction logistics and additional layers of coordination due to the use of partitions and structures. The last scenario presents unique challenges related to building at a temporary site near to the source of materials, reducing transportation cost, but needing certain safety and logistical considerations during the relocation process.

Overall, this comparative table highlights how each scenario manages the balance between accuracy, cost, precision, and environmental impact in modern construction methods. Each case offers a perspective on the integration of 3D printing and prefabrication to achieve construction objectives, depending on site conditions, material availability, and logistical constraints.

Table 3.2 Comparative analysis of construction scenarios

Analysis Areas	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Transportation and logistics	Reduced large structure transport. Compact 3D printing materials. Seasonal transport considerations for the envelope.	Onsite material and prefab. service transport. Logistics coordination for modular parts.	Mix of raw materials and large module transport. Planning for module delivery to match onsite printing.	onsite 3D printing; separate HVAC delivery. Requires logistics for assembled units.	Prefabricated partitions and sequential delivery streamline construction logistics	Construction near materials reduces transport; moving the entire house presents unique challenges.
Environmental Impact	Waste reduction via precise printing. Assess energy for 3D printing and prefab fabrication. Reduced emissions from transport.	Efficient prefab services, less onsite waste. Assess the environmental impact of transport for complex components.	Onsite printing waste minimized. Controlled offsite module impact. Evaluate transport emissions for larger modules.	Potential waste reduction with 3D printing; environmental footprint of HVAC transport and installation assessed.	Offsite fabrication and onsite 3D printing minimize waste; efficient energy use.	Reduced transportation impact: overall construction footprint lowered by building near material sources.
Material Supply Chain	onsite storage for printing materials. Weather-robust supply for the envelope.	Increased complexity for prefab components. Critical storage for prefab parts.	Balancing onsite printing with offsite module needs. Just-in-time delivery strategies.	onsite 3D printing and HVAC/core services procurement; timing is critical for the assembly.	Prefabricated and onsite materials management; just-in-time delivery for efficiency.	Simplified supply chain due to material proximity; coordination crucial for temporary site construction.
Regulatory and Safety Standards	Adapt building codes for hybrid methods. New integration standards for printed and prefab parts.	Controlled compliance in prefab factory. 3D printed structures must fit prefab components.	Quality control in module construction. Compatibility regulations for onsite and offsite work.	Compliance for 3D structures and reassembled units; integration standards important.	Quality control in offsite fabrication; regulatory adherence for 3D printing integration.	Temporary and final site regulations; safety for house relocation and installation.
Cost-Benefit Analysis	Higher initial costs, operational savings. Long-term material efficiency and customization benefits.	Prefab efficiency may offset higher upfront costs. Assess long-term integration costs and benefits.	Cost balance between onsite printing and offsite modules. Labor/time savings vs. transport costs.	onsite 3D printing cost efficiency; additional costs for HVAC/services.	Cost savings from prefabrication and 3D printing flexibility; multistage approach assessment.	Construction near materials cuts costs; evaluation of house moving versus traditional construction needed.
Infrastructure Requirements	Sufficient power for printing and assembly. Less heavy machinery needed.	Support for prefab assembly. Increased power and logistical complexity.	Infrastructure for printing and module assembly. Site prep and layout for dual construction mode.	Supports 3D printing and HVAC/core service integration; specialized equipment for assembly.	Assembly of partitions and 3D printing support; storage and handling facilities.	Infrastructure for temporary construction site and relocation preparedness; challenges in dual-site setup.

As we evaluate the different construction scenarios, it is important to consider the types of residential buildings that may benefit from these approaches. Figure 3.10 illustrates the three main forms of residential buildings, vertical multifamily, horizontal multifamily and single family. Each building types need a different construction strategy that is aligned with the scenarios discussed in the previous sections.

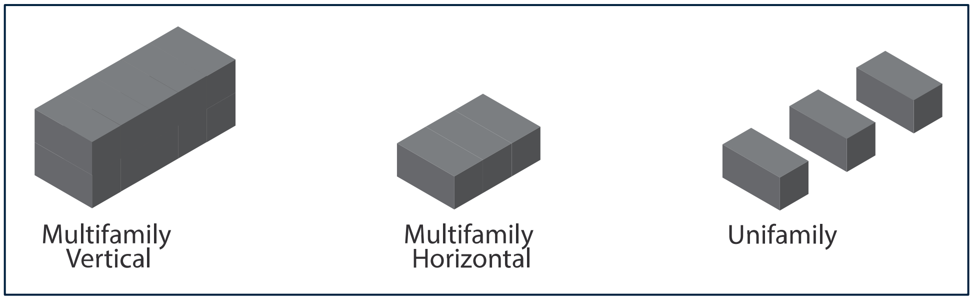


Figure 3.10 Types of Residential Buildings Based on Structure and Space Arrangement

3.5 Conclusion

This chapter has examined six separate construction scenarios involving hybrid techniques of 3D printing and offsite construction. Since these examples provide a valuable knowledge into the potential advantages of modern construction techniques, the research has some limitations. The data used was primarily collected from academic articles and internet sources, and has not been verified by a third party, which may contradict the precision of some findings. Considering these constraints, future studies should include empirical data, gathered via surveys and interviews with industry experts to support and improve the results provided in this chapter. Furthermore, a case studies analysis where these scenarios were applied could expand the results. By considering these guidelines, future research can provide a more complete and detailed analysis of combining 3D printing technology and offsite construction.

CHAPTER 4

SIMULATIONS

4.1 Introduction

This chapter is a result of a computational design methodology for constructing adaptable homes in the permafrost landscapes of Northern Canada, particularly in regions like Nunavut. By using tools like generative design software and energy simulation software, the study aims to optimizing structural configurations and material usage, integrating innovative approaches such as CLT and in situ 3D printing. This strategy addresses the logistical and environmental challenges characteristic of offsite construction, where transportation costs are significant, and conditions are critical. Additionally, the research highlights the necessity of incorporating Indigenous cultural considerations into the architectural design, ensuring that the final design respect and align with local traditions and values. This section 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.

4.2 Design workflow and optimization

In this chapter, we focused on developing optimized architectural solutions for Arctic environments, using Grasshopper and its plugins Ameba, Karamba 3D, and Ladybug. Figure 4.1 shows 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.

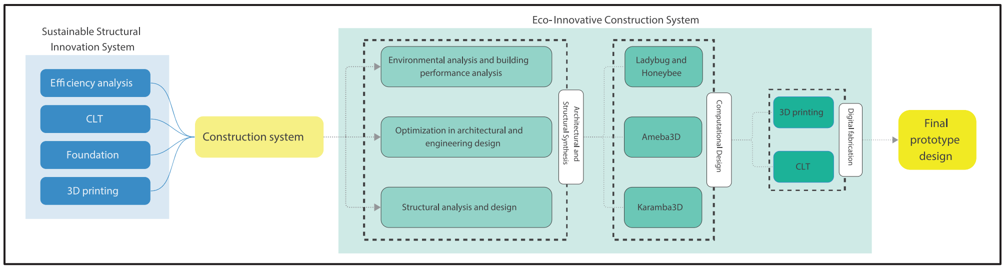


Figure 4.1 Schematic overview of the computational design workflow

The workflow starts by defining a flexible design by using parametric tools, where changing inputs parameters will generate different architectural forms based on the specificity of the project in the Arctic environment. However, Figure 4.2 illustrates the Grasshopper script partially automates the exploration of design alternatives. This way the architects can explore different solutions related to the geometry performance and structure optimization. Geometry performance refers to the ability of a structure to meet design requirements like minimizing material usage and optimizing structural ability while maintaining functional goals.

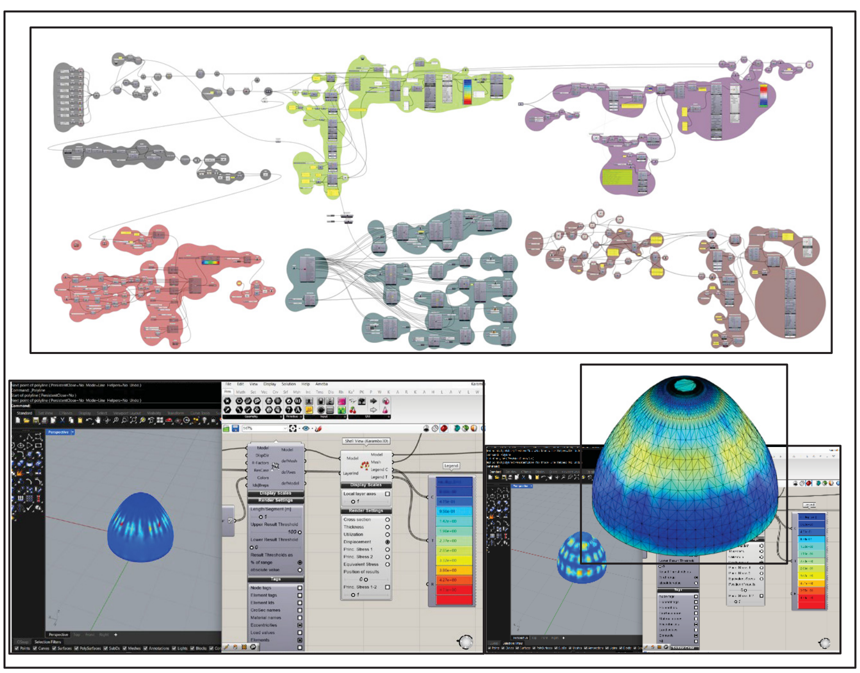


Figure 4.2 Parametric design workflow for adaptable housing in Arctic environments.

4.3 Material and environmental optimization

The optimization of the envelope process uses stress and displacement analyses to help for material selection, as shown in Figure 4.3a. This analysis provides information about the integration of 3DCP and CLT panels, chosen for their rapid fabrication capabilities and excellent thermal insulation properties. Additionally, the construction steel subframe provides a stable foundation for modular buildings on permafrost, depicted in Figure 4.3b. Following the subframe construction, the steel structure designed to support mass timber panels is optimized for strength and durability, detailed in Figure 4.3c.

Material optimization of the flooring through Ameba results in an organic form by combining both aesthetic and functional aspects of the building, as detailed in Figure 4.3d. Simultaneously, environmental optimization by Ladybug, shown in Figure 4.3e, measures the climate impact and improves solar efficiency to guarantee that the building's design is both energy-efficient and suitable for its environmental context. Durability is measured by material longevity under severe temperatures and cyclic stress in Figure 4.3. Embodied carbon, freeze-thaw degradation, and energy performance are used to evaluate the climate impact using computational techniques specific to Northern Canada.

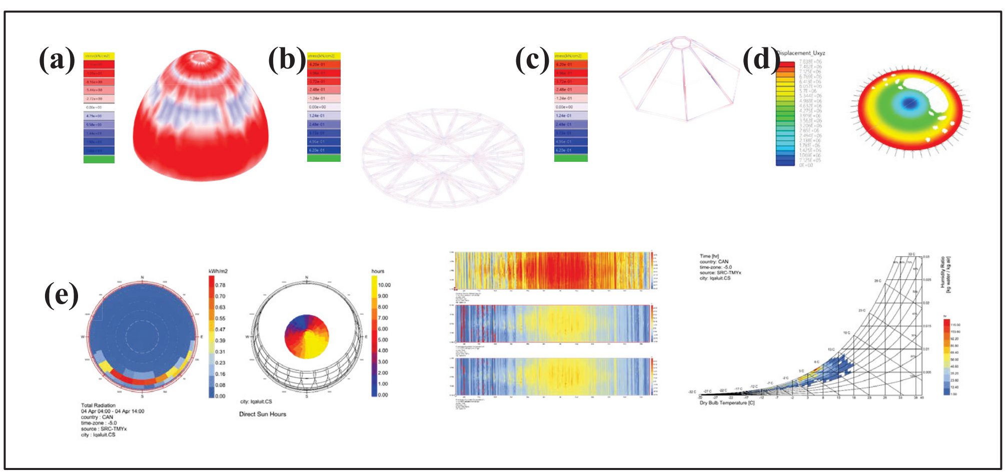


Figure 4.3 Computational analysis of building design (a), envelope. (b), steel subframe. (c), structure. (d), material. (e), energy

4.4 Construction process

In response to the harsh climatic challenges of Northern Canada, our design integrates advanced construction techniques suitable for extreme environments, as illustrated in Figure-4.4. 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.

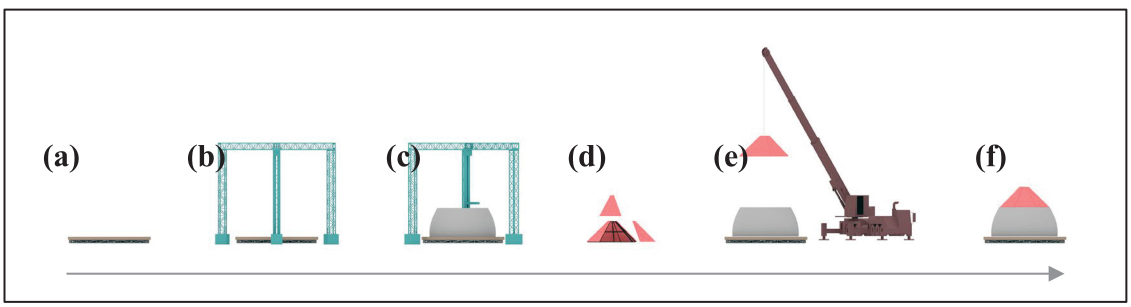


Figure 4.4 Sequential construction process. (a), base setup. (b), frame assembly. (c), 3D printing the structure. (d), assembling the prefabricated components. (e), installing the assembled structure. (f), final house

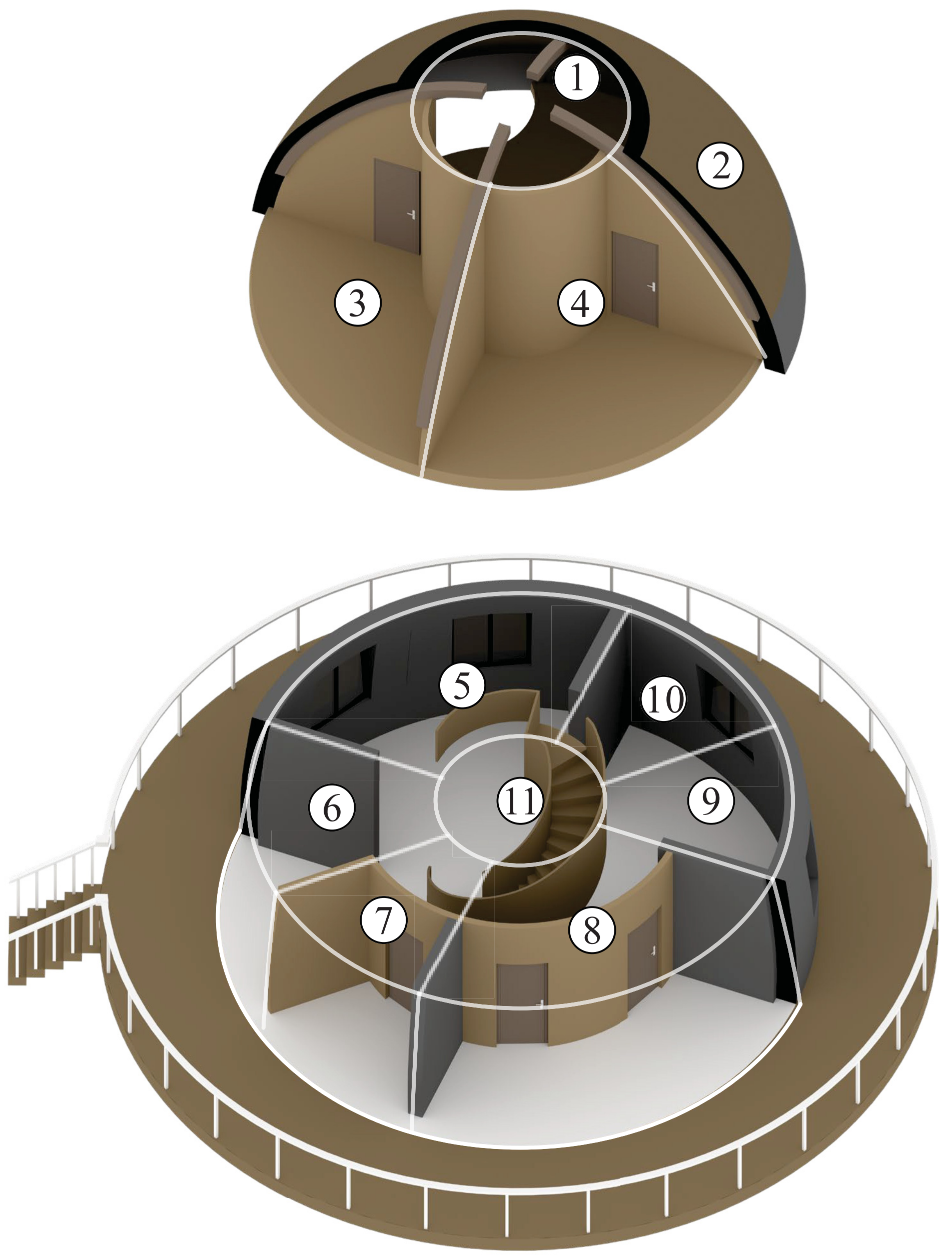
4.5 Functional program and design

Figure 4.5 presents the 3D 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 modular kitchen, a dining space, and an adjustable space that can be used as a workspace for remote work or study, a storage in the entrance to maximize available space. Additionally, there is a perimeter walkway in the outside that provides protection from weather conditions.

On the first level, there are two bedrooms designed for privacy and comfort, a bathroom, an open to below spaces that gives the feeling of openness and connectivity between the floors, and finally an adaptable space that can be transformed when needed. The design highlights modularity and adaptability by incorporating construction methods such as 3D printing for components and prefabricated CLT panels for walls. This combination ensures assembly, excellent thermal insulation, and the structural strength necessary for the Arctic climate.

Moreover, one significant element of the house's design is zenithal window, this window helps sunlight to reach the house. 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 Figure 4.5 presents a 3D plan of the house that combines modern technology with traditional Inuit architectural principles to create a practical living space that respects cultural values.

Finally, the 3D plan in Figure 4.5 incorporates design principles that are in line with the requirements of Northern Canada, but additional discussions with local stakeholders including indigenous communities and regional construction experts are necessary. Prioritizing the use of indigenous resources and labour would improve logistical feasibility and economic sustainability.



1. Adaptable space
2. Bathroom
3. Bedroom 1
4. Bedroom 2
5. Living space
6. Entrance
7. Bathroom
8. Adaptable Space
9. Kitchen
10. Dinning space
11. Stairs

Figure 4.5 3D plan

4.6 Structure and spatial composition

The axonometry illustrates the composition of the proposed house and focus on the integration of CLT and 3DCP. The building contains four prefabricated 5-ply CLT panels for the upper structure with a thickness of 175 mm and an insulation layer of 66 mm to guarantee a thermal efficiency for the Northern Canada. Moreover, the house is equipped with triple-glazed windows and a zenithal window to have enough natural light during the day and reduce the energy consumption. In addition, the structural columns made from GLT are load-bearing systems to transform the structural loads from the roof and upper floor to the foundation.

The 3DCP envelope, a filled grid wall composed with 100 mm of concrete layer, has a thickness of 500 mm for durability and strength, while the interior 3DCP walls have a thickness of 400 mm and may host the plumbing and electrical systems. Also, the ground floor and the upper floor provide CLT walls designed to be adaptable and movable for easy configuration of the interior spaces to accommodate future change in the family. Additionally, the structure is reinforced by a steel frame elevated foundation of 300 mm to prevent potential issues caused by permafrost. (see Figure 4.6)

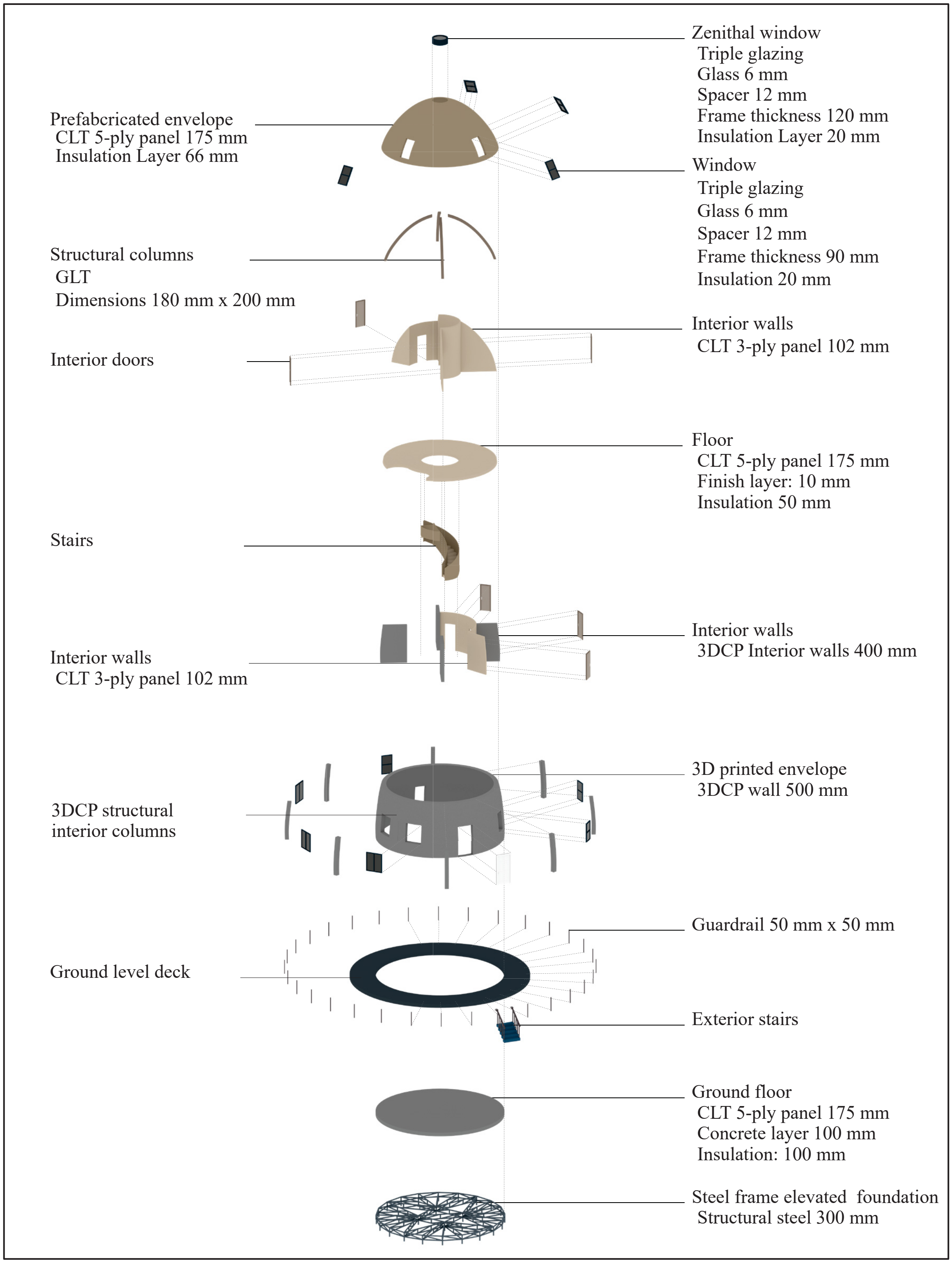


Figure 4.6 Exploded axonometric view

4.7 Detailed sections

Figure 4.7 illustrates the CLT wall detail section and floor designed to meet the challenges of Northern Canada's harsh climate, and each element increases the thermal efficiency and the structural integrity. However, figure a present the vertical section of the CLT wall assembly with the different layers such as the thermal insulation, membrane, the barres omega for air gap rain screen for adequate drainage and moisture management, vapor barrier, window frames, and triple glazing for more energy efficiency. Furthermore, Figure b shows the horizontal cross-section of the CLT floor system, it has a 15 mm interior finish and followed by 100 mm of impact sound insulation to prevent noise transmission between levels. Besides, the floor consists of a 5-ply panel (175 mm) and a 70 mm design for plumbing and electrical services, easy for installation and maintenance, followed by a 35 mm modular slat system for a beautiful design.

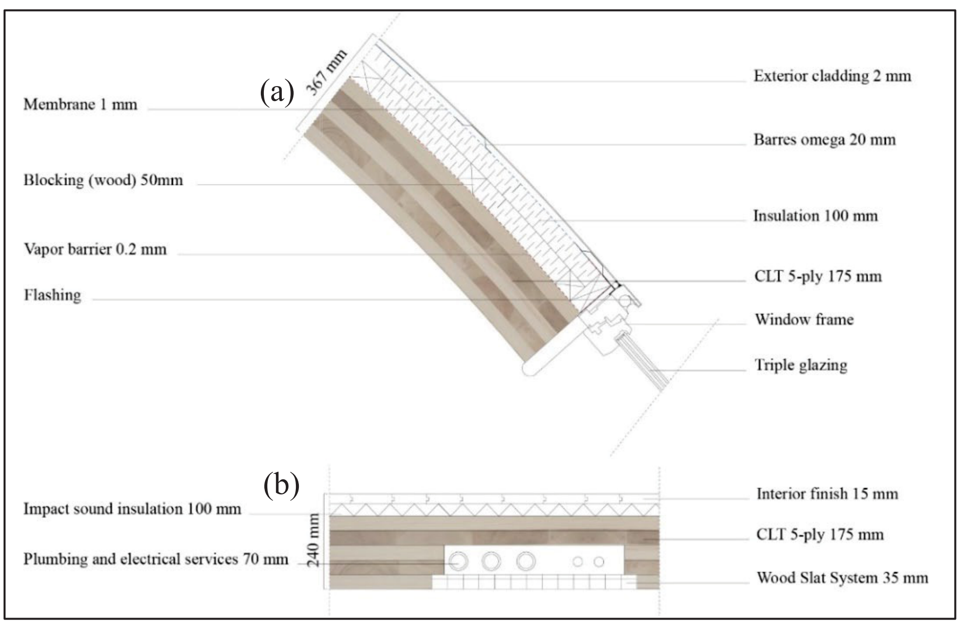


Figure 4.7 Cross-section of CLT structure

The horizontal cross-section of the 3DCP wall on the ground floor shows an exterior cladding of 2 mm metal layer and 20 mm Barre Omega for air gap to control moisture, followed by a 15 mm layer of Fiber-Reinforced Polymer (FRP) for more structural integrity suitable for

Arctic environments. Also, the wall integrates SureCrete DK 700 1 mm which is a waterproof breathable membrane to maintain moisture regulation and acts as a vapor barrier.

Moreover, to reinforce the structure, 20 mm rebar is inserted into the 400 mm by 500 mm of eight 3DCP columns, while the wall layer is 100 mm in the thickness. In addition, the occupants can choose between having an interior finish or exposed the wall material for good appearance of living areas. (see Figure 4.8)

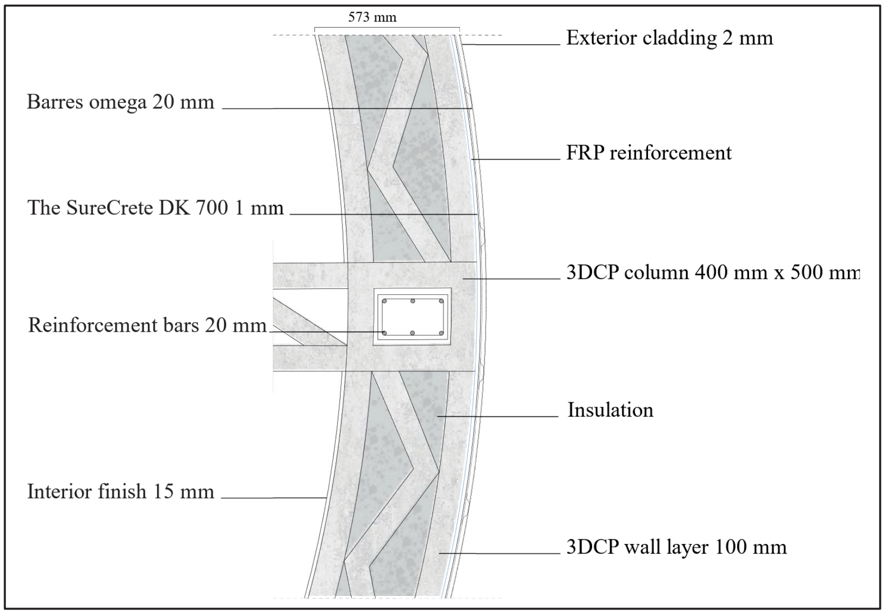


Figure 4.8 Cross-section of 3DCP structure

The figure 4.9 illustrates the assembly of the structure's main components with detailed connections between each element, the male and female connectors are strong load-bearing connector developed by Li and Tsavdaridis (2023) to interlock securely between the CLT panels and the glulam beam. Also, a self-tapping screw are used in the fix the glulam columns with the CLT panels, while steel brackets add more vertical load support where columns and beam are connected. In addition, an anchor bolts connect the 3DCP to the beam which is sealed with a moisture-resistant substance to protect the wood and avoid moisture.

To stop moisture, we can first place a rubber membrane between the glulam beam and the 3DCP wall, between male and female connectors, and between beam and columns joints.

Finally, areas where CLT panel joints are exposed need a waterproof flashing to avoid moisture and improve the resistance and durability of the assembly.

The following figures present different aspects of dome-shaped housing design including top, elevation, and section views (Figure 4.10), an exterior render (Figure 4.11) and the integration of the houses in a northern community landscape (4.12).

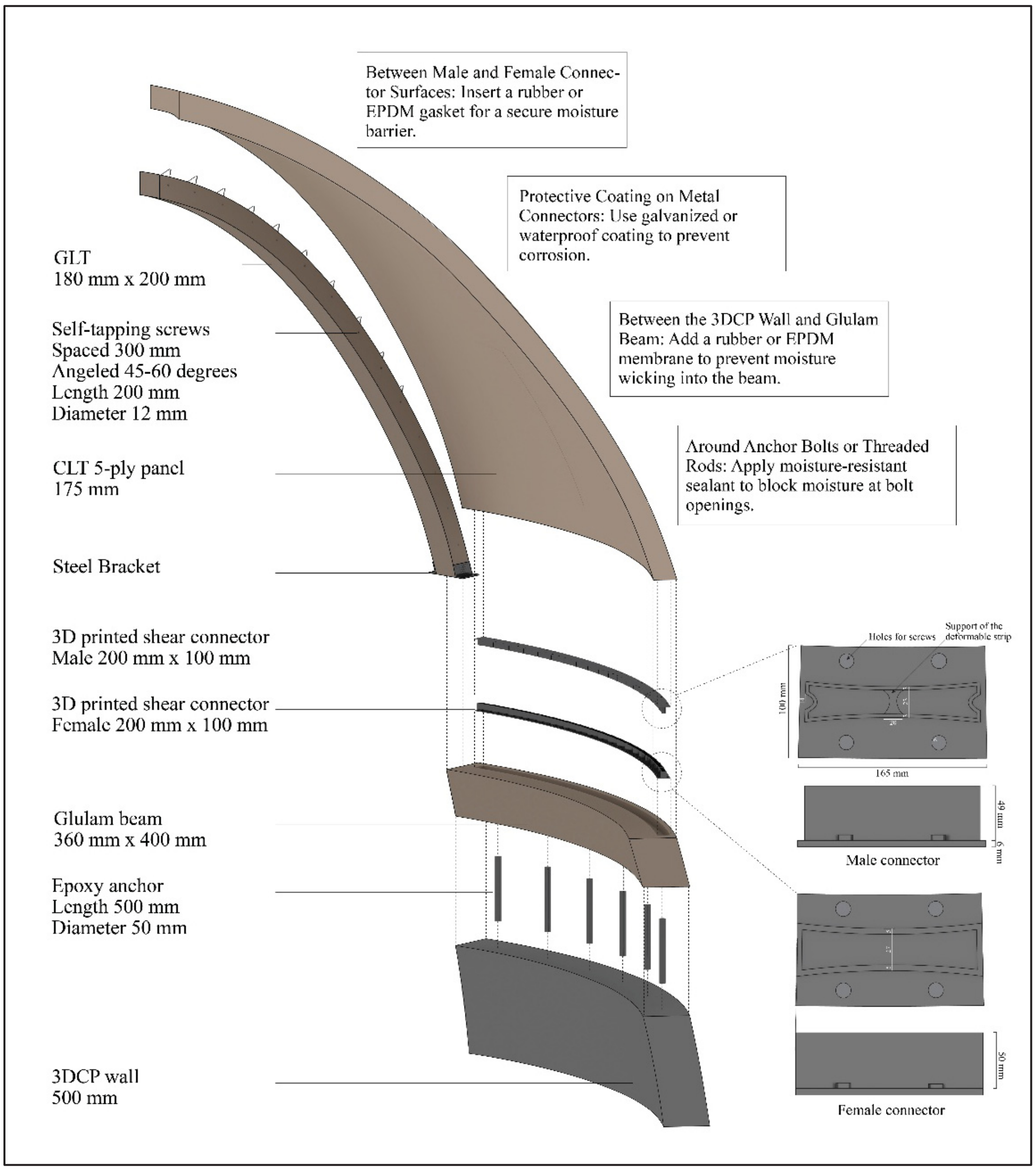


Figure 4.9 Detailed assembly of CLT and 3DCP wall connection

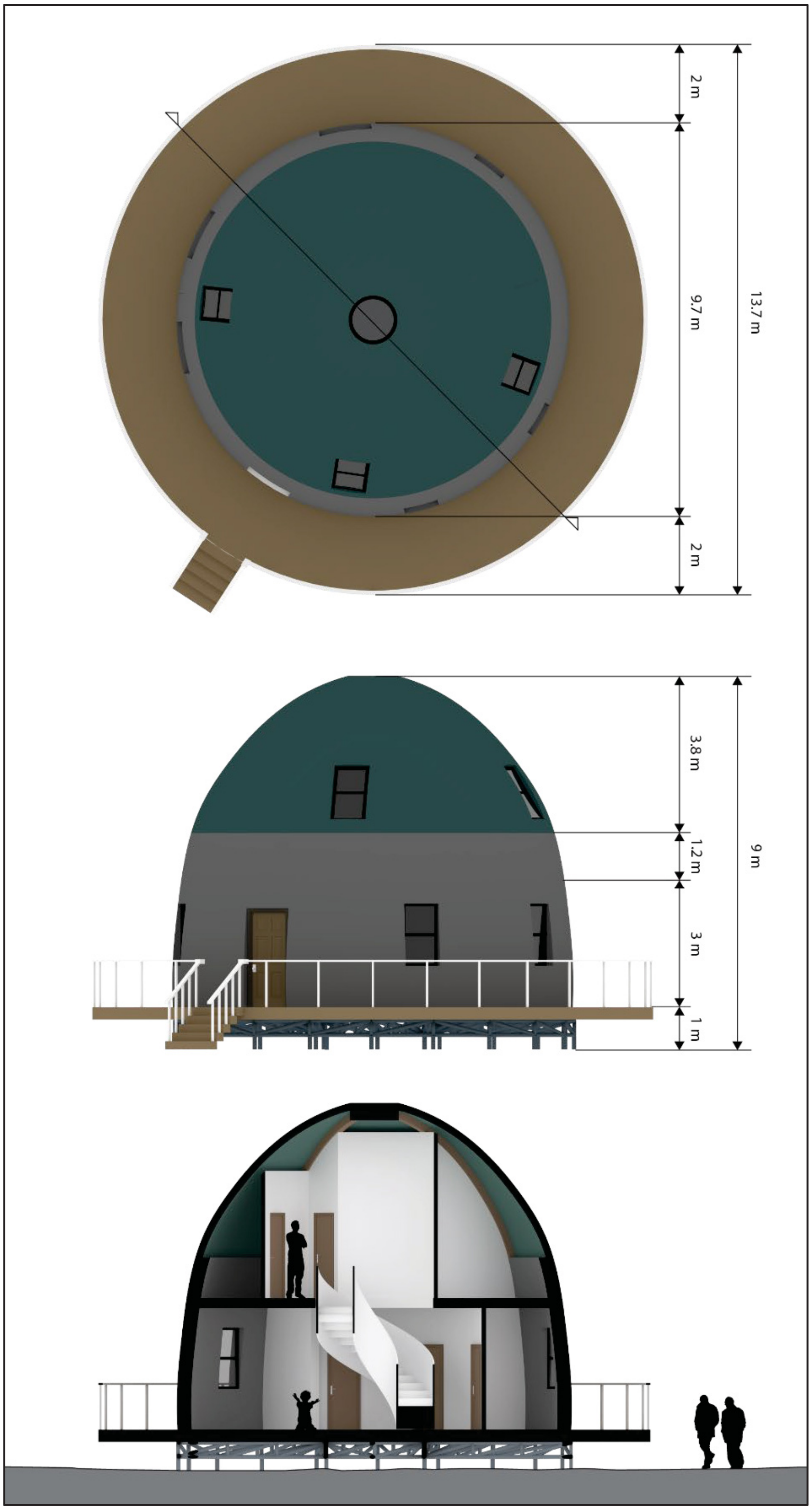


Figure 4.10 Top and elevation and section view of dome-shaped housing design

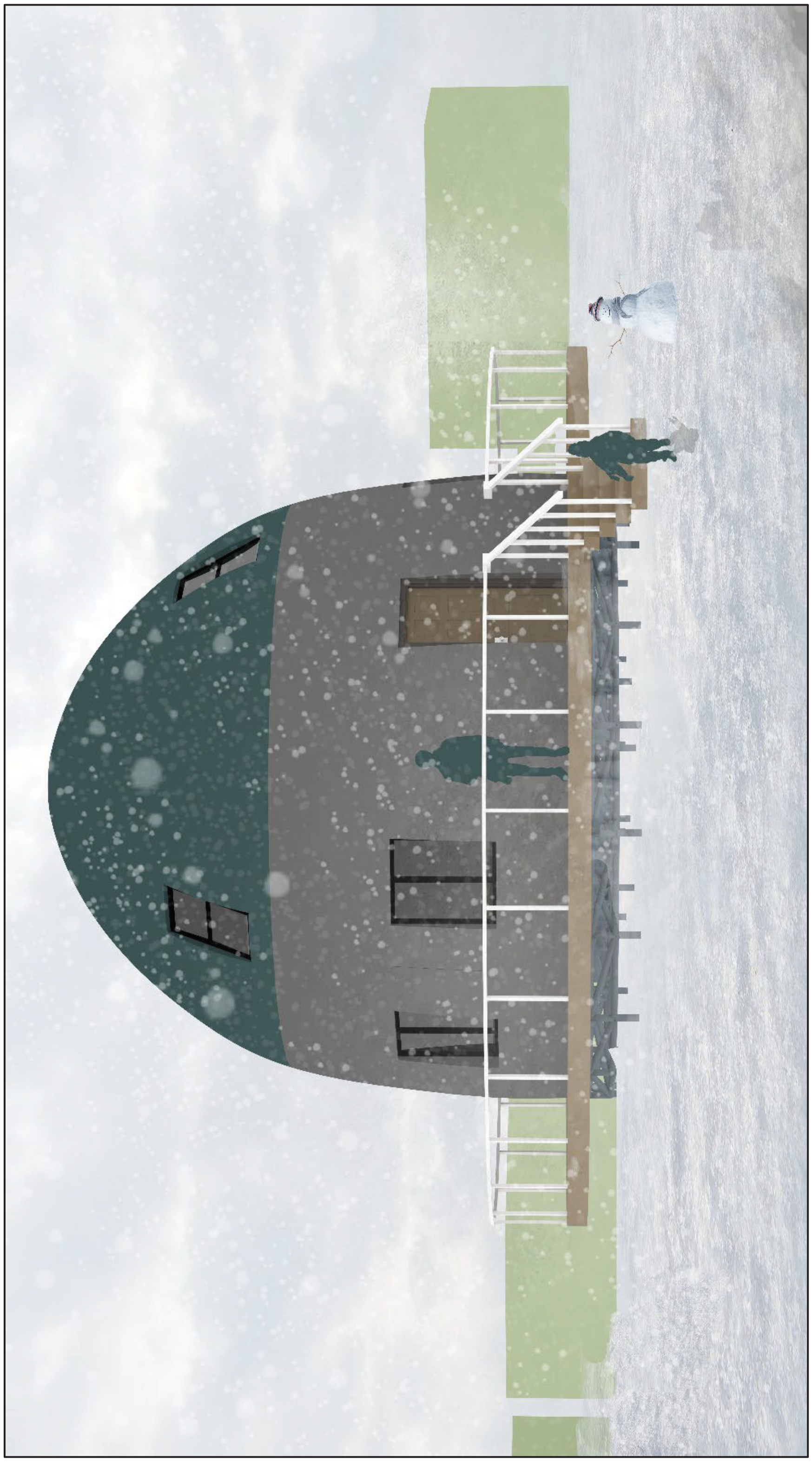


Figure 4.11 Exterior render view

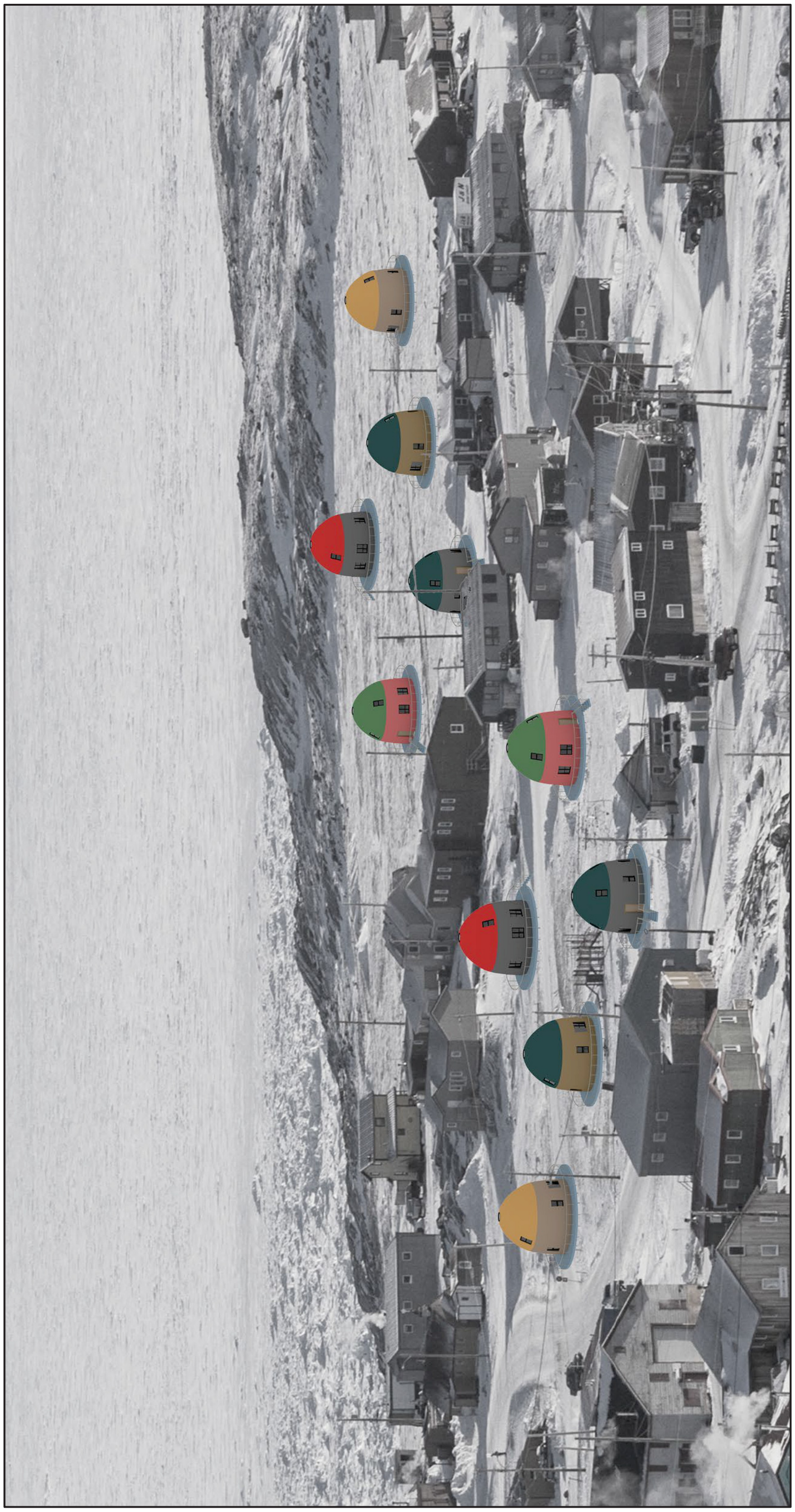


Figure 4.12 Dome-shaped housing in a northern community

4.8 Conclusion

This chapter explores the integration of computational design tools, design process, and building techniques by using CLT and 3DCP structure, we offer a solution that combines the offsite and onsite construction to minimize the transportation costs, reduce the carbon footprint and speed up the construction process.

Moreover, the suggested design approach not only aims 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.

Outstanding 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. Moreover, the chapter highlighted the importance of modular adaptability in design to face any changes can occur to the family, making it easy for the configuration spaces. Also, the drawings provided help to understand the proposed house via detail sections, plans, axonometry and the construction process.

Finally, the computational design tools used in this chapter such as Ameba which is specialized in topology optimization that focusing on material distribution structural efficiency, and Karamba 3D designed for interactive structural analysis and optimization are used in the Grasshopper interface and are just examples of tools that we can find in construction industry. Some traditional FEM-based packages, like ANSYS or ABAQUS, are designed for general applications, providing advanced capabilities for simulating many physical phenomena, however requiring higher computational efforts and more specialized expertise.

CHAPTER 5

HUMAN AND ENVIRONMENTAL CHALLENGES IN ANALOG MISSIONS: THE LUNARES CASE STUDY

Yakine Zerrad[1] ; Ivanka Iordanova[1]

[1] Department of Construction Engineering, École de Technologie Supérieure
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
yakineer@gmail.com

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5.1 Abstract

This research paper analyzes findings obtained from a two-week analog mission at LunAres Research Station located in the city of Pila, Poland, designed to study, test, and solve problems that can occur in the locations that mimic the physical conditions of extreme space environments. The mission titled Space Bears took place from May 18 to June 1, 2024, involved five analog astronauts, including one of the authors. The study aimed to examine the practical implications of resource consumption like energy and water, the monitoring of health, and managing waste in an isolated habitat. Moreover, the participant survey provided qualitative information, offering a comprehensive perspective on the mission's impact on operational and human aspects. The survey covered various aspects such as emotional stability, mental health support, living conditions, social interactions, privacy, and mission experience. The results underline various important factors to consider developing a sustainable building practice in the context of extreme and isolated environments. The key findings include optimizing resource management, maintaining crew well-being via continuous monitoring, and implementing waste reduction techniques. These findings are relevant not only for design and operation of analog missions, but also have a wider implication for construction in extreme environments, such as Northern Canada, and interplanetary construction on Moon and Mars.

Keywords: Analog mission, Lunares Research Station, extreme environments, resource consumption, health monitoring, waste management, sustainable construction

5.2 Introduction

Analog missions are crucial for planning and preparing for future space exploration. New technologies, equipment, operations, and human factors can be tested in environments that mimic the physical condition of space. However, analog habitats are required to these missions for many reasons, they allow researchers and astronauts to collect a valuable data by simulating the working and living conditions that astronauts would face during space missions. In 2017, the LunAres Research Station was founded in Pila, Poland, to mimic the physical environment on the Moon and Mars. This research station promotes a multidisciplinary environment where studies can cover different aspects such as engineering, biotechnology, extreme medicine, psychology, sustainability, and architecture. However, five analog astronauts, including one of the authors, of "Space Bears" mission, ran from May 18 to June 1, 2024. The objective was to study the implications of resource consumption, health monitoring, waste management, isolated environment, and social and psychological dynamics inside the habitat. The background and literature review lead to multiple challenges and creative solutions to keep the habitat functional and sustainable in extreme and isolated environments. The principal elements include communication, air quality and dust mitigation, team synergy, documentation and decision-making, training and task design, safety and risk management, sustainability, health monitoring and well-being, modular design, and innovative technologies. This literature review offers a solid foundation for understanding the crucial elements of analog missions and their implications for building in extreme environments such as Northern Canada, characterized by permafrost, severe cold, and remote locations, as well as environments beyond Earth, such as Moon and Mars characterized by low gravity, radiation, and extreme temperatures.

5.3 Background and literature review

Analog mission is a simulated space mission operated in an environment on Earth that has physical similarities in space environments like Mars and the Moon. The objective is to test and study new technologies, equipment, new procedures, and understand human factors. Moreover, analog missions provide a great data for researchers and astronauts to help them to prepare for future space missions. On the other hand, analog habitats are necessary to the success of these missions. They are designed to mimic the working and living conditions that astronaut car has during space missions. These habitats are designed and equipped to withstand extreme environments (Agaptseva, Kussmaul, Belakovskiy, & Orlov, 2024; Reagan, Janoiko, Johnson, Chappell, & Abercromby, 2012).

Considering this, comprehensive literature review revealed that there is various challenges and solutions to build and maintain habitats in extreme environments. The main concepts include air quality and dust mitigation, communication and team synergy, documentation and decision-making, training and task design, safety and risk management, health monitoring and well-being, modular design and sustainability, advanced technologies, and autonomous systems.

5.3.1 Air quality and human factors

In extreme environment, keeping the equipment working and preserving air quality are mandatory. The Mars Desert Research Station (MDRS) is a space analog facility in Utah and where they conduct different types of research, one of them was dust transport during extravehicular activities (EVAs) that required physical task. The solution provided was the use of Scroll Filter System (SFS) to reduce airborne particle counts in the work area. However, this strategy is less efficient in airlocks during EVAs that called for a new filtration solution to the stop the contamination causes by dust and to maintain crew health.(Kobrick & Agui, 2019) Moreover, Human Factors (HF) and environmental habitability were also point out during a study at the Flashline Mars Arctic Research Station (FMARS), the results show that physical training and telecommunication support can be a great choice to reduce stress during the isolation. Moreover, cohesion and group dynamics will reduce conflict and increase trust and maintain an agreeable living environment. Also, self-prepared meals can improve crew morale and nutrition for better mental and physical health (Binsted, Kobrick, Griofa, Bishop, & Lapierre, 2010).

5.3.2 Documentation and decision-making

A well-documented process can make decision-making easier during the analog mission, this is important to reduce stress during isolation in extreme environments. A study conducted by Bednar et al. (2019) underline the necessity of a standardized template and thorough documentation of sub-team discussions. Positioning documentarians with mission control is crucial to help the planning and the execution of projects in extreme environments.

Advanced technology such as Geographic Information Systems (GIS) and immersive Virtual Reality (VR) are great tools in operational decision-making and data interpretation in extreme environments. The GIS tools can provide a detailed geomorphological map to understand the environmental conditions and terrain, and guide mission planning and execution between the team based on comprehensive spatial data. Furthermore, the immersive VR can be used in the context of the rover to provide a good perspective of the environment where the rover is operating, helping the team members to visualize and interact with the environment in a realistic while feeling physically present. These technologies increase the spatial awareness and improve planning and execution. GIS maps can be used to identify optimal construction sites, assess potential hazards, and plan infrastructure layouts while VR simulations can provide a realistic understanding of the site conditions (Morse et al., 2019).

5.3.3 Training, task design and crew autonomy

Realistic task design, training and performance evaluation are important during a long-duration analog mission to maintain engagement and motivation, preventing the psychological fatigue occur from repetitive and pointless tasks, involving regular feedback, adaptive learning strategies, and performance metric to development of problem-solving abilities to unexpected situations.(Shiro et al., 2022) Moreover, the importance of crew autonomy to manage their schedules will help crew members to elaborate a self-organization routine, and structured group-living habits to adapt to dynamic demands of mission environment.(Heinicke, Poulet, Dunn, & Meier, 2021) To support crew autonomy to scheduling and managing their activities, a Robust Advanced Modeling and Scheduling (RAMS) called Romie system was tested during analog missions at the Mars Desert Research Station (MDRS), the study shows that Romie system is a user-friendly interface, which can help crew members to adapt their schedules in real time if any expected changes can occur like health problems or malfunctions (Saint-Guillain, Gibaszek, Vaquero, & Chien, 2022; Saint-Guillain et al., 2023).

5.3.4 Safety and risk management

Ensuring safety and successful risk management is crucial during the design of habitats in extreme environments. Some risk analysis techniques like Human Reliability Analysis (HRA) and Fault Tree Analysis (FTA) are essential for detecting and managing risks in extreme environments. The FTA is a systematic, deductive approach used to decompose the causes of system failures. In our context, FTA can help to identify any vulnerability in the life support system, structural components, and any risk can put human life in danger. The second risk analysis methodology is HRA that focuses on the interaction between system and human to identify potential errors that lead to system failures (Mastro, Salotti, & Garofalo, 2022).

Another study during the AMADEE-20 analog mission highlight the need of medical screening before the mission to detect any potential health risk and make sure that crew members can successfully finish the mission. Also, emergency response capabilities were also integrated into the mission simulation such as fire outbreaks, equipment failures and medical emergency training. Finally, the study recommends the continuous improvement of safety procedures based on feedback from the previous analog mission (Klicker, Zoller, & Rehnberg, 2023).

5.3.5 Health monitoring and well-being

Health monitoring and nutrition balance are critical aspects of maintaining performance of crew members in extreme environments. Freeze-dried diet has shown a significant improvement in oral hygiene and reduce inflammation. Poor oral health can affect the crew's ability to perform their tasks successfully. This study by Gronwald et al. (2022) complements the importance of implementing of regular health monitoring routines, like dental check-ups to preserve minor health problems that can lead to more serious conditions that could affect the mission. During ARES-III and LEARN missions at LunAres habitat, Bouriat, Poliacek, et Smith (2021) were also mentioned the importance of retaining a balance between diet and adequate nutrient intake for sustaining health and performance for long-duration missions in extreme environments. The study integrates the necessity of regular health monitoring systems to track some physiological parameters like blood pressure, heart rate, body temperature and weight. The study highlighted the critical aspect of water management and how crew members can find the best strategy to preserve water, by installing systems to monitor water usage for urine, drinking and practical purposes.

5.3.6 Modular design, sustainability and self-sufficient

Modular design has been used for construction in extreme environments for decades. Standardization, speed of construction, quality control, transportability, adaptability, and reduction of environmental impact are the main advantages of using this design approach. A study conducted by Heinicke et Arnhof (2021) by reviewing different analog habitats and concluded that modularity can be easily expanded and reconfigured to host different missions' requirements. Moreover, modular design can be maintained and repair easily because of the standardization components that can be upgraded or replaced without demolition. Furthermore, human factors should be considered in the design of modular habitats by providing space that respect the privacy of the occupants and public space to support group cohesion. The adaptability of modular habitat can be customized to meet specific needs to ensure the comfort and productivity. Adapting the design to be sustainable and is crucial for the successful construction and operation of habitats in extreme environments. ISS is one of the great examples that illustrate effective strategies for building sustainable habitat. The strategies include advanced life support system to recycle air, water, and waste, the use of environmentally friendly materials and construction techniques. Moreover, the study suggests using local and recyclable materials to reduce the environmental footprint. Incorporation passive heating and cooling systems can improve the energy efficiency of habitats. Finally, self-sufficient design like developing agricultural systems like aeroponic system for food production can help to reduce the need of external assistance.(Dziaduła & Fross, 2022) Deployable structure like Desert Mars Analog Ramon Station (D-MARS) can provide fast shelter for crew members while giving the possibility of expansion depending on the mission (Rubinstein et al., 2019).

5.3.7 Ecosystem, water management and resource optimization

Green roofs are one of the strategies that can be used in habitat in extreme environments to balance between nature and engineering, by offering a good thermal regulation, stormwater management, and aesthetic benefits. Droz, Coffman, Fulton, et Blackwood (2021) have compared different types of green roof system: quasi-traditional green roof, conventional green roofs, and blue-green roofs. Also, the study evaluated two types of plants, restoration and horticultural, and two arbuscular mycorrhizal fungal treatments. The result of the study reveals that blue-green roofs provide high stormwater retention capacity, reduced nutrient runoff and improve thermal regulation. The results also show the importance of selecting appropriate plant communities. Moreover, in the context of space habitats, space greenhouses are important in providing fresh food and supporting crew nutrition. However, to maintain them required time and resources, for this reason several key parts for improvements, such as automation of routine tasks, integration of artificial intelligence (AI), standardization of methodologies, and crew training. The principal of green roof optimization can be used in the design of the life support system to maximize ecosystem services like nutrient recycling and water retention (Poulet et al., 2021).

The table presented below is a comparative analysis of 8 analog habitats: HERA, Lunares, Lunark, HI-SEAS, MDRS, MARS 500, Mars Dune Alpha, and FMARS. The table is divided into categories such as structural elements, utilities, comfort, safety measures, technology, EVAs, and climate zone. Each category is decomposed into subcategories for clarity, detail, and communication of specific aspects.

5.4 LunAres research station

LunAres Research Station (figure 5.1), established in 2017 in Pila, Poland, is an analog habitat designed to simulate crew space missions and accommodate up to 8 crew members for two weeks durations. It is designed to simulate the physical and operational conditions of extraterrestrial environments like Mars and the Moon and provide an interdisciplinary environment to support different types of research topics can be conducted at LunAres habitat. The research topics include extreme medicine, psychology, robotic and engineering, biotechnology, sustainability, extreme plant cultivation, and architecture.

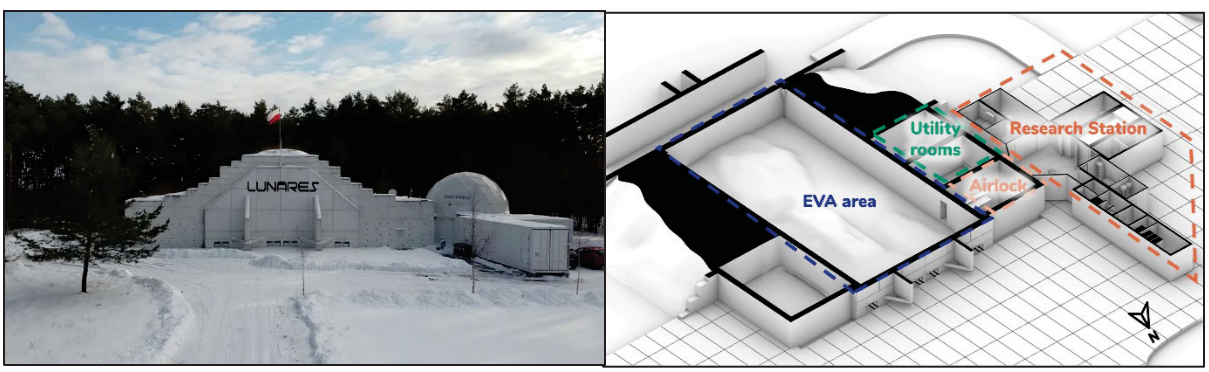

Figure 5.1 LunAres research station

5.5 Mission context

The "Space Bears " mission, conducted from May 15 to June 1,2024, was a two-week analog mission at LunAres Research Station. The objective was to study the implications of living and working in an isolated environment. Five analog astronauts have participated to this mission, each one of them assigned with different roles. The Executive Officer coordinated research and projects, supervised the daily tasks, and communicated with Mission Control. His second role was to manage the biolab research and projects. The commander was responsible for observing the well-being and productivity of crew members, give them support, keeping contact with the Mission Control, and deciding if an emergency occurs during the mission. The Mission Engineering was responsible of maintaining the habitat, engineering projects conducted during the mission, monitoring and collecting environmental data. The Communication Officer, document mission procedures and tasks and support the habitat. Finally, the Medical Officer supervises the medical and psychological research, data collection, and sustained crew health and well-being during the mission. The figure 5.2 illustrates the crew members of the Space Bears mission and its patch.

(a) Crew members (b) The mission patch

Figure 5.2 The crew members of the Space Bears mission and mission patch

The Figure 5.3 illustrates some of the activities carried out over the LunAres analog mission. It gives an idea about daily operations, social interactions, technological application, EVA activities, and germination at LunAres habitat. Figure 5.3a, the crew members are collaborating, planning, and managing daily tasks, this step is crucial for mission success. Figure 5.3b illustrates team members testing some equipment to ensure the functionality. The use of 3D printing shows in Figure 5.3c is a great tool for onsite manufacturing and fast problem solving that can occur during the mission. In Figure 5.3d, astronauts are involved in an EVA exploration outside the habitat using some equipment to collect samples, on the other hand, figure 5.3e shows astronauts simulating the rescue prototype. Germination and cultivation are essential during the mission to maintain food production. Figure 5.3f shows germination, this step is critical because it is important to test different nutrient regimens to promote plant health. The aeroponic (Figure 5.3g) and hydroponic (see Figure 5.3h) system are two agricultural techniques that support plant growth. Health monitoring is illustrating in figure 5.3i, promoting crew well-being within frequent evaluations. Finally, Figure 5.3j and figure 5.3k illustrate the crew socializing during dinner and movie night.

(a) Mission Control Team (b) Equipment Testing (c) 3D Printing
(d) EVA Exploration (e) EVA Rescue Simulation
(f) Plant Cultivation (g) Aeroponic (h) Hydroponic
(i) Health Monitoring (j) crew meal (k) Movie Night Socializing

Figure 5.3 Overview of various activities during the LunAres analog mission

5.6 Research methodology

The methodology used in this study is a combination between qualitative and qualitative methods to present a thorough knowledge of the Space Bears mission at Lunares research station. This mixed-method approach referred as Convergent Parallel Design was chosen to effectively collect both the crew's experience and operational data required for an in-depth examination. The qualitative approach including survey and interview, help for exploration of psychological and dynamics within the habitat. On the other hand, the quantitative approach includes health monitoring data, resource consumption, and waste management data, offers indications of how mission affects the well-being of the crew members and the functionality of the habitat. By integrating mixed-method approach, we can cross-validate our findings from different data sources.

5.6.1 Qualitative method

The primary objective of the survey and interviews was to collect opinions and behaviors from five analog astronauts. The data includes emotional stability and overall well-being of the crew members during the LunAres analog mission. The survey is a mixed and open-ended questions to gather a diverse group of data. The questions include psychological impact, organization of the habitat space, lighting and colors, social dynamics, and physical environment. Five crew members of the Space Bears mission have participated in the survey, in, and each crew member has a unique identification from A1 to A5. The survey, covering 45 questions and was shared at the end of the mission via Google Form link, allowing for a more comprehensive understanding of the mission. On the other hand, the interviews were semi-structured and conducted at the end of the day for real-time feedback and to examine astronauts' experiences and reactions as the mission progressed.

5.6.2 Quantitative method

During the mission, quantitative data was gathered using tools like systematic health monitoring, trackers for energy and water consumption. Medical equipment allowed a consistent monitoring of some health parameters, such as body temperature, blood pressure, pulse rate, weight, and more. Moreover, precise measurement equipment was used to collect resource consumption data, and waste production was classified and measured daily to conclude the effectiveness of waste management. On the other hand, it is important to mention that the LunAres Research Station was the only responsible for collecting all the quantitative data, which was then shared with the authors for the purpose of this research.

5.6.3 Data integration

The qualitative and quantitative data were examined independently and the results were compared and integrated during the analysis phase. The results let as identify the patterns and correlations between qualitative themes and quantitative and provide a clear understanding of the impact that the mission had on the analog astronauts and the performance in the habitat. The discussion section presents the correlation between the methods and the interconnections between different characteristics of the mission. The fig. 4 presents the research process, beginning with the research question, following by a literature review. The research methodology combines qualitative and quantitative methods, and the findings are integrated and cross-validated to have a better understanding and interactions of the results.

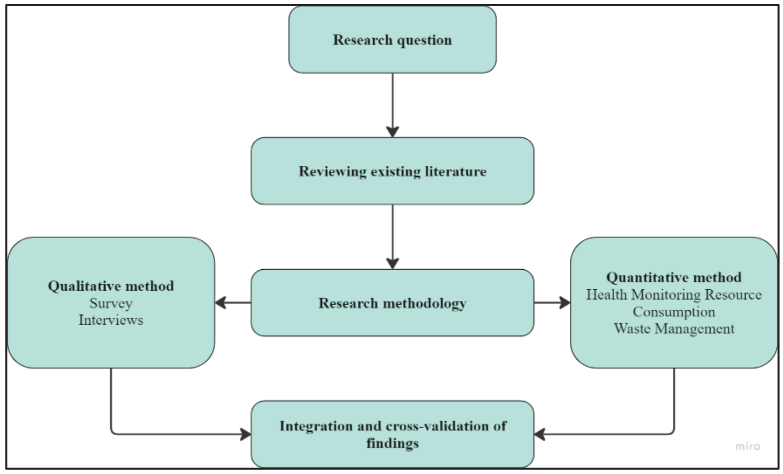

Figure 5.4 Research methodology

5.7 Results

5.7.1 Qualitative method

5.7.1.1 Psychological Impact

Participants were questioned about the emotional stability, 60% said they felt always emotionally stable, 20% reported often feeling stable and 20% felt sometimes stable. This suggests that the crew generally feeling happy. In terms of loneliness, 40% of the participants said that they felt isolated rarely, 40% reported never felt lonely, and 20% feeling alone sometimes. This indicated that loneliness was important but controllable for the crew. In terms of stress, 40% of the participants said they felt isolated, 40% reported workload, and 20% for college duties, which demonstrates the complexity of stressors in an isolated environment. Work (60%) and engaging in bobbies (20%), followed by socializing with team members (20%) were the most coping mechanisms to control stress and maintain mental health. About mental health support offers during the mission, 40% reported it was adequate and 60% rated as fair. This indicates that mental heal support should be improved. The participants suggest the need for online therapists, virtual reality, and online mental health counseling.

5.7.1.2 Organization of the habitat space

The following data highlights the level of satisfaction of participants with the organization of the habitat space during Space Bears mission. 40% of respondents said their living quarters were very comfortable and useful, while 60% said both helpful and functional, demonstrating great satisfaction with the living conditions. The kitchen (20%), the center (40%), and analytical lab (40%) were the most appreciated aspects of living quarters. When it came to balancing work and leisure, all the participants were satisfied with the comfort and functionality of furniture. In terms of sustainability, 80% of participants evaluated the materials used in the habitat's construction as sustainable, and 20% rated them as very sustainable. Also, waste management was effective.

The effectiveness of thermal insulation was rated as follows: 20% of participants thought it was effective, 60% said it was very effective, and 20% believed it was ineffective. 40% of respondents rated the habitat's integration with the natural environment as well integrated, 40% as very well integrated, and 20% as neutral. The interior design of the habitat was very pleasant and the ability to personalize living spaces was very important. Moreover, all the participants stated the habitat was extremely well prepared for emergency and the space was reconfigurable. Only 40% of the participants reported the habitat design did a great job of maintaining a balance between public and private areas, and 60% said it was neutral, which enhanced their sense of privacy. In general, respondents said they had adequate privacy, rating it as either important or neutral.

5.7.1.3 Lighting and colors

The lighting and color scheme used in the habitat can influence the crew's mood and overall well-being. The participants' responses were affected by the lighting settings in the Lunares habitat, as seen in the table below.

Table 5.1 LunAres habitat lighting settings

Time	Lighting settings
6:00 6:29	Dark Grey
6:30 6:59	Dark Blue/Gray
7:00 7:59	Light Blue/Gray
8:00 19:29	White
19:30 20:29	Yellow/White
20:30 21:29	Red/White
21:30 21:59	Violet/Black
22:00 23:00	Dark Grey/Black

80% of the participants expressed a preference for natural light that mimic sunlight which helps to create a favorable environment, while 20% prefer the adjustable lighting. In terms of color scheme's effect, 80% reported a positive influence on their emotional well-being, while 20% had a neutral impact. Participants picked neutral tones (such as beige, gray, and white) as the most calming colors. Nevertheless, the participants noticed that yellow, green, and red were each considered frustrating or uncomfortable.

5.7.1.4 Social dynamics

Sixty percent of participants rated the overall social dynamics within the team as good, while 40% said it was excellent. In terms of frequency of social activities, 60% of participants were engaged daily, following by 20% did so several times a week, and 20% engaged rarely. Regarding the effectiveness of conflict resolution, all participants did not face any conflict within the team.

5.7.1.5 Physical environment

Interpreting the issues related to temperature and air quality, each participant rated differently, 20% said it is too hot, 20% too cold, and 40% reported no issues. However, the temperature was controlled by the crew members, we believe that it is because of the personal comfort level, what feels comfortable to one person might feel too hot or too cold to another. The team was not affected by noise level, and the main sources of noise were from external environment, movements of team members, and conversations.

5.7.2 Quantitative method

5.7.2.1 Daily health and activity metrics of analog astronauts

Table 5.2 presents the daily health and activity metrics of the analog astronauts, the data was collected by the medical officer and includes body temperature, blood pressure (systolic and diastolic), pulse rate, weight, and pulse oximetry. Furthermore, astronauts provided their own self-reported information on tea consumption, total water consumed, calories consumed, and whether they completed their MaxForce workout. However, during the mission, the body temperatures are maintained in a normal range, with only some low variations that may be related to the daily activities. Regarding the blood pressure, the data shows that astronauts maintained appropriate levels during the mission. However, some astronauts experienced increase readings, which may indicate that they were experiencing times of stress and cardiovascular problems. Also, astronauts consistently showed a higher pulse rate due to the increase of physical activity or stress. This information was mentioned during the interviews. The weight of the astronauts showed slight variations during the mission which reflect their consistent body mass. The astronauts were able to take enough calories and their pulse oximeter showed that they had oxygen saturation levels, which confirmed that their respiration was in good condition during the mission. Also, astronauts have filled their daily water consumption, tea consumption, calories intake, and workout. The table shows a variability in tea consumption. As an example, astronaut A5 had the highest water intake in day 13 which may be a result of physical activity or higher metabolism rate that causes the hydration. Same causes can explain the fluctuation of the number of calories consumed. MaxForce training was proposed for the mission and as we can see all the astronauts were performing it during the mission which demonstrate their commitment to maintain their physical conditioning.

Table 5.2 Daily health and activity metrics of analog astronauts

	Filled by Medical Officer							Filled by the analog astronaut			
Astronaut Number	Days	Body Temperature (°C)	Blood Pressure SYS (mmHg)	Blood Pressure DIA (mmHg)	Pulse Rate (/min)	Weight (kg)	Pulse Oximetry (%)	Tea Consumption (cups = 300 ml)	Total amount of water (ml)	Calories	MaxForce Workout
A1	D1	36.4	104	71	62	97.5	99	0	2000	1800	Yes
	D7	36.2	111	99	62	95.8	98	0	1500	2000	Yes
	D13	35.2	120	80	68	94.9	98	0	1800	2300	Yes
A2	D1	36.2	115	73	60	118.3	99	0	1920	2388	Yes
	D7	36.1	141	85	69	115.2	98	0	1600	2217	Yes
	D13	36.5	127	88	80	114.6	97	0	1800	2781	Yes
A3	D1	36.5	125	89	75	70.6	99	0	1030	1952	Yes
	D7	36.2	139	95	66	69.8	98	0	1200	1719	Yes
	D13	36.7	123	90	62	69.8	99	0	1570	1808	Yes
A4	D1	36.3	117	57	49	70.3	100	0	1830	2290	Yes
	D7	36.2	122	72	57	68.9	99	0	1010	2323	Yes
	D13	36.5	117	68	63	69	99	0	1800	2368	Yes
A5	D1	36.1	118	83	84	75.1	99	3	1500	1826	Yes
	D7	36.6	116	83	80	73.4	99	4	2170	2538	Yes
	D13	36.5	112	77	71	73.8	98	4	2500	2065	Yes

5.7.2.2 Health and body composition changes

Table 5.3 presents a visual presentation of health and body composition changes of the analog astronauts from day 0 to the end of the mission (day 14). This data presents an understanding of the psychological impacts of the mission, including body temperature, blood pressure, pulse rate, weight, pulse oximetry, body mass index (BMI), percentage of body fat, percentage of skeletal muscle, resting metabolism, and visceral fat levels. However, we can see a small increase in body temperature by the end of the mission, although, all values remained in the usual range, and this stability is because of the habitat environment was controlled, maintained, and the temperature was adequately regulated. Astronaut A4 had an increase in both systolic and diastolic blood pressure and this can be a reaction to the accumulated stress or other factors. Furthermore, all the astronauts experienced a clear drop in weight, especially A2 with a variation of 4.5 kg, which can suggest for more additional research to be conducted to understand the causes, which may include nutrition intake, stress, or metabolic changes. In addition, the oxygen saturation levels of the astronauts remained high due to their respiratory function despite the isolated environment, and BIM levels remained consistent. Also, the percentage of skeleton muscle showed a small improvement maybe due to the regular physical exercise to increase muscle mass.

During the rest metabolic rates varied, indicating the fact that individuals have different metabolic responses. This irregularity is influenced by diet and exercise, highlighting the importance of personalized health monitoring. Moreover, the levels of visceral fat were relatively stable, revealing that efficient internal fat management was achieved under the mission's dietary and physical activity. Finally, this study highlights the complex relationship between physical activity, diet, and metabolic health in an isolated environment, by examining the variance in resting metabolic rates as well as the stability of visceral fat levels. These findings show the importance of continuous monitoring and individual treatments during the mission.

Table 5.3 Health and Body Composition Changes

	Filled by Medical Officer							Filled by the analog astronaut				
Astronaut Number	Days	Body Temperature (°C)	Blood Pressure SYS (mmHg)	Blood Pressure DIA (mmHg)	Pulse Rate (/min)	Weight (kg)	Pulse Oximetry (%)	BMI	Body Fat (%)	Skeletal Muscle	Resting metabolism	Visceral fat level
A1	D0	36.5	124	82	64	97.9	99	31.1	34.2	30.9	1988	14
	D14	36.7	119	85	62	94.6	99	29.9	34	30.9	1931	13
A2	D0	36.5	125	84	83	118.6	98	35.9	36.5	30.5	2259	15
	D14	36.7	124	73	81	114.1	96	35.2	37.1	30.1	2227	15
A3	D0	36.9	127	82	70	71.6	99	25.4	24.4	38.1	1670	8
	D14	36.7	120	83	61	69.1	98	24.6	21.8	39.7	1650	7
A4	D0	36.7	136	75	61	70.6	99	23.1	18.3	41.5	1676	5
	D14	36.7	117	65	54	68.3	99	22.3	18.1	41.5	1635	5
A5	D0	36.7	116	81	86	74.3	99	22.5	18.8	40.2	1690	5
	D14	36.5	126	73	72	73.2	99	22.6	17.6	41.1	1690	5

In general, quantitative findings presented in tables 5.2 and 5.3 provide an idea about the health and physical status of the astronauts before, during and after the mission. The results show the effectiveness of health monitoring and the capability to maintain physiological stability in a controlled and isolated environment. This indicates the astronauts' adaptability and perseverance in dealing with mission challenges.

5.7.2.3 Energy consumption

The figure 5.4 illustrates the energy consumption of different areas of the habitat and the total daily energy consumption during the mission. The areas monitored include the kitchen, dormitory, operations, gym, workshop, biolab, and hygiene areas. However, the first diagram shows the variability in energy consumption by area. For example, Day 8 had the highest energy use across all areas, especially in the operations, the, gym, and the biolab. In the biolab the high energy consumption was due to the aeroponic and hydroponic systems that required lighting and electricity for plant growth and germination during the night, necessary for optimal conditions for the plants. Moreover, the high energy consumption shown in the workshop was due to the use of 3D printers and other electronic devices, it was common practice to keep these devices operating during the night to complete the daily tasks. Also, the workshop area was used as a charging station for LEO rover, walkie-talkies, and other items needed for the EVA. Additionally, there were days with lower energy consumption, indicating that astronauts did not engage in much activity or adopted an effective energy saving. Finally, the second diagram is the total energy used during each day of the mission and aligns with the first diagram.

Figure 5.5 Energy consumption across habitat areas during the 14-day mission

5.7.2.4 Water Usage

The figure 5.5 shows the quantity of water usage each day for every equipment, gray water produced, and the amount of water left during the mission. The first diagram in the figure represents the water usage per equipment measured in cubic meters (m^3), and includes the toilet, multiple sinks (kitchen, next to the shower, and toilet), shower (warm and cold), and laundry. However, the days 4 and 5 had the highest water use for the kitchen. We used the kitchen sink to fill the aeroponic and hydroponic tanks located in the biolab with 75 liters of water, to successfully maintain the ideal conditions for plant growth. The only time the laundry machine was used during the mission was on day 9, this decision was made the first day of the mission by the astronauts to manage and respect the limited water consumption given for the mission.

The second diagram presents the total water usage, gray water production, warm water, and cold water per day measured in liters. In the first days of the mission crew members were had to use clean water as the gray water tank was empty. To fill the gray water rapidly, astronauts decided to take more time in the shower, and a switcher was used to switch between clean water and gray water. A sensor was connected to the tank for monitoring its level to prevent damaging devices by avoiding being totally empty or full.

The last diagram shows the amount of water that is still available as well as the daily water consumption during the mission. From 2000 liters day 1 to 289 liters on day 14, which mean that astronauts were able to manage the water supply. To achieve this, the astronauts had meetings every morning and after the daily tasks to discuss about what different topics and review the water consumption and to plan for the next day. They investigated the areas in which the most water was used and find an effective solution to control the situation. For example, astronauts found out that the kitchen used a substantial quantity of water, and one of the strategies was to clean the dishes only once a day after the dinner. This proactive approach of daily meetings and strategic planning appeared to be very effective to minimize potential problems that can occur during the mission.

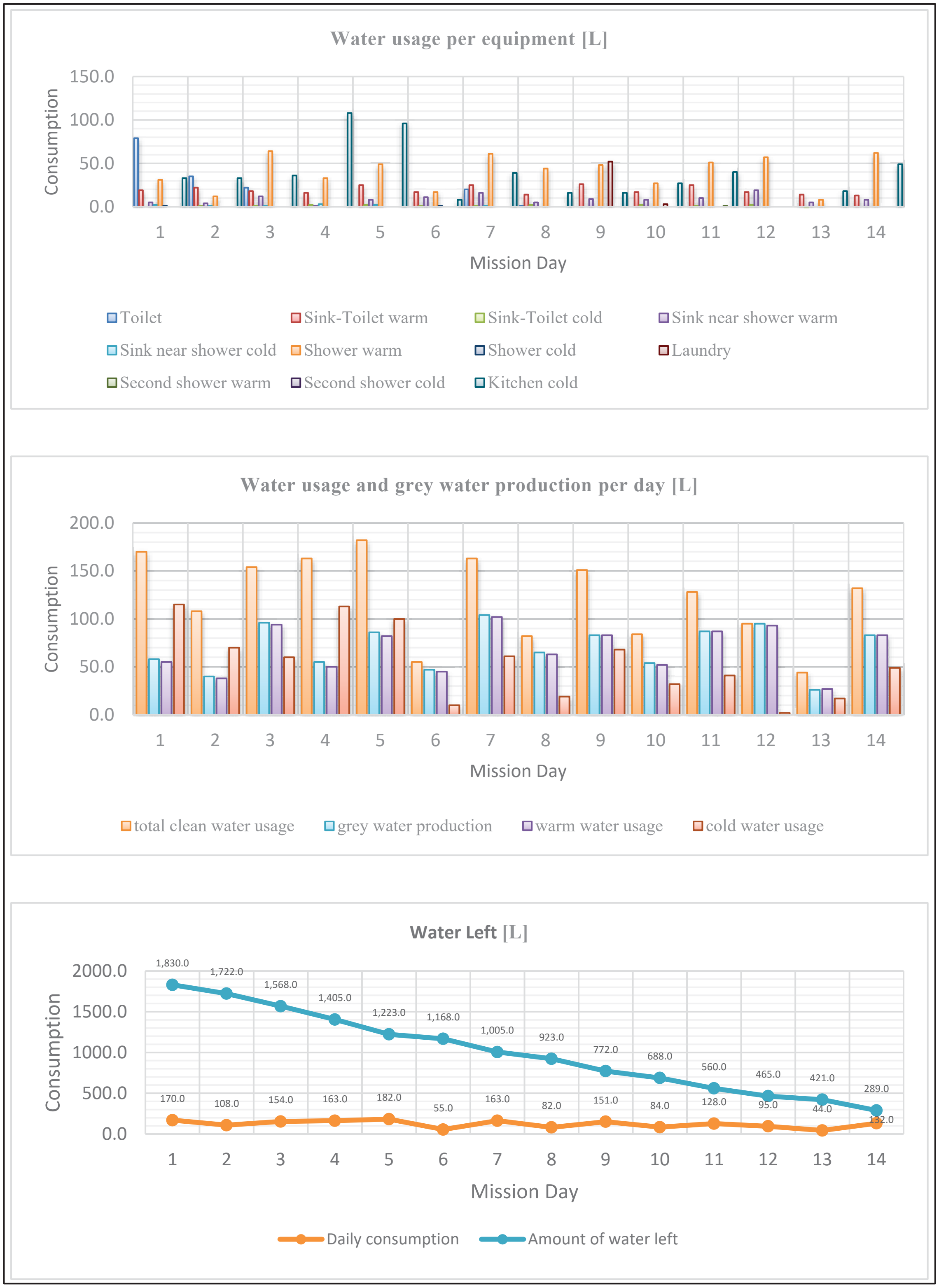

Figure 5.6 Water usage analysis during the 14-day mission

5.7.2.5 Waste Production

The sustainability of the mission is correlated with the successful waste management in an isolated environment. The figure 5.6 illustrates the waste production in kilograms (kg) during the mission, classified into plastic, mixed, paper, glass, and electronic waste. The first realization is that mixed waste had the highest production, peaking on days 3 and 14. Indication periods of waste generation and increase of the activities inside the habitat. Plastic waste showed an increase and was generally from a water bottle, discarded 3D printed items, packaging, and consumables. Also, paper waste stayed stable and glass waste was generated from used bottles for hot sauce and some electronic waste. The findings underline the need for better waste management, especially with mixed and plastic waste. For more sustainability is it crucial to improve recycling and reduction strategies.

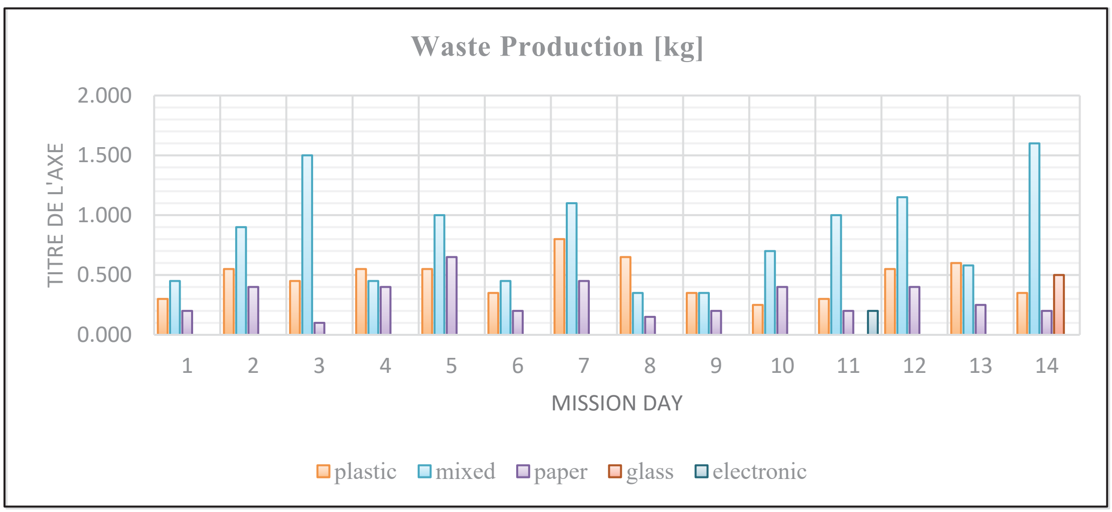

Figure 5.7 Waste production during the 14-day mission

5.8 Discussion

Integration and cross-validation of findings refer to the process of combining and verifying research results from different methods. This study adopted a mixed method which refers to a collection and analyzing both qualitative and quantitative data from the LunAres analog mission. However, the quantitative data was collected by LunAres Research Station and shared for research proposes. The objective of this study was to understand the effects of the mission on the crew members and the functionality of the habitat by combining the qualitative data collected from surveys and interviews with the quantitative data obtained from resource consumption, waste management, and health monitoring.

This integration matrix facilitates the cross-validation of findings from the data. The table 5.4 illustrates the correlation between qualitative and quantitative data, providing us a deep insight of different aspects of the mission. For example, the emotional stability of crew members indicated in the survey, demonstrates a relation with blood pressure and pulse rate. Another example is the feeling of loneliness which is correlated with social activity frequency. Through the examination of these interconnections, we may pinpoint specific areas that require focus and improvements such as mental health support, workload management, and the design of living quarters to promote privacy and public spaces. This analysis, which combines both qualitative and quantitative methodologies validate the findings and provide more recommendations for future mission and habitat designs. The following table provides a comprehensive overview of the relationships between qualitative and quantitative data.

Table 5.4 Cross-validation matrix

Qualitative Data	Quantitative Data	Observation
Emotional Stability	Blood Pressure	Some Astronauts had higher blood pressure in response to higher stress levels, which suggests a physiological reaction to stress
Feeling of Loneliness	Social Activity frequency	The importance of social interaction is illustrated by decreased loneliness with increased social activity.
Satisfaction with Living Quarters	Resource Consumption (Water/Energy Usage)	Promoting sustainable living conditions leads to high living quarters satisfaction and resource efficiency.
Mental Health Support	Health Metrics (Body Temperature, Wight, etc.)	Psychological resources are needed for stable health metrics and adequate mental health support.
Social Dynamics	Health Metrics, Social Activity Frequency	Social well-being correlates to physical health via positive social dynamics and regular social activities.

Table 5.4 Cross-validation matrix: connecting qualitative themes and quantitative metrics in the LunAres analog mission (Cont'd)

Qualitative Data	Quantitative Data	Observation
Lighting and Colors	Sleep Quality, Productivity Levels	Lighting and color schemes influence mood and well-being, including mental health.
Physical Environment (Temperature, Air Quality, Noise)	Pulse Rate	Qualitative data such as temperature, air quality, and noise discomfort indicate the need for appropriate conditions in the environment.
Workload and Stress	Blood Pressure, Pulse Rate, Resource Consumption	High workload is associated with increased stress, blood pressure, and energy consumption, indicating the importance of task management.
Privacy and Personal Space	Satisfaction Rating	Qualitative data reveals that lack of privacy lowers satisfaction, highlighting the need of personal space.
Resource Management Efficiency	Resource Consumption (Water/Energy Usage, Waste production)	Resource management efficiency reduces resource usage and waste, promoting sustainability.
Physical Health and Workout	Weight, pulse, exercise frequency	Weight and pulse rate stability with regular exercise indicate good physical health, emphasizing the need of fitness regimens.
Adaptation to Habitat	Health Metrics, Resource consumption	Faster adaptation generally corresponds with stable health measures and efficient resource use, indicating the need of support.
Team Cohesion	Social Activity Frequency	Team-building exercises improve team cohesion, which leads to more social activities and healthier living.
Nutritional Satisfaction	Health Metrics (Weight, Energy Levels)	High nutritional satisfaction is related to stable weight and energy,
Task Satisfaction	Productivity Metrics, Health Metrics	Task satisfaction promotes productivity and health, showing the necessity for meaningful work.
Sleep Quality	Health Metrics	Better sleep quality for some astronauts is associated with stable health metrics and increased mood, highlighting the significance of accommodating sleep environments.
Innovation and Problem Solving	Resource Utilization	Effective problem-solving eliminates occurrences and optimizes resource use, illustrating the importance of innovation.
Environmental Awareness	Resource Consumption, Waste Production	Sustainability supports resource optimization and minimizes waste, bringing out the necessity for sustainable habits.
Coping Mechanisms	Health Metrics, Resource Consumption	Psychological training is important because effective coping mechanisms improve health parameters and resource use.

Table 5.4 Cross-validation matrix: connecting qualitative themes and quantitative metrics in the LunAres analog mission (Cont'd)

Qualitative Data	Quantitative Data	Observation
Cultural Sensitivity	Social Activity Frequency, Health Metrics	Respect for differences in culture improves social dynamics and health, underlining the need of cultural knowledge.
Motivation Levels	Health Metrics	Motivational techniques are essential since high motivation increases productivity and health indicators.
Recreation and Leisure	Health Metrics	Leisure activities improve mental health and health metrics, highlighting their value.

5.9 Conclusion

The "Space Bears" mission at the LunAres Research Station provided a valuable data about challenges and solutions associated with building and living in an extreme and isolated environment. Our findings focus on the requirement of optimizing resource management, constant health monitoring, and effective waste management, crucial for sustainability in construction in the extreme environment on Earth and space.

The results of qualitative and quantitative data reveal a connection between psychological well-being, resource consumption, and environmental conditions. However, emotional stability, social dynamics, and habitat design has a substantial impact on the crew members' experience as well as the effectiveness and productivity with the daily tasks, to maintain the functionality of the habitat. The results emphasize the importance of individualized support for mental health, management of workload, and the design of public and private space.

Furthermore, the study's findings on energy consumption, water consumption, and waste production offer valuable recommendations for more sustainable practices and resource management for the next missions. Daily meetings and strategic planning are strong practices for reducing possible problems and improving resource use.

For future research, further exploration can be done such as the long-term psychological effects, advanced waste management technologies like the implementation of closed loop, resource optimization strategies like renewable energy, water recycling, and health monitoring innovations such as virtual reality therapies and remote counseling services.

To finish, the “Space Bears” mission has not only improved our understanding of human aspects of analog missions but also added valuable information for next space exploration projects and for sustainable construction in the extreme environment. However, the integration of these findings can influence future habitat design for more resilience, adaptability, and well-being of future astronauts on Earth and beyond.

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The Bibliography section is presented at the very end of the thesis.

CHAPTER 6

DISCUSSION

6.1 Introduction

This final chapter builds upon the findings from the previous chapters and discusses the implications for architecture and construction in extreme environments. It brings out space architecture as an interdisciplinary field to promoting a new perspective on building homes in Northern Canada and addressing global challenges such as climate change and potential natural disasters. In this chapter, ChatGPT was used to refine the language and correct grammatical errors.

6.2 Discussion of the proposed design

The proposed house design presented in this thesis was primarily influenced by the findings from the case studies analysis of 6 different projects located in different climate zones in chapter 1. The results indicated the importance of choosing high quality materials suitable for specific climate zone, employing prefabricated elements, and modular construction. However, the need of sustainable construction practices and the potential of prefabrication solutions inspired the integration of 3D printing technology and CLT to address the housing crisis in Northern Canada's permafrost region.

The analysis of the housing crisis in Nunavut and Inuit Nunangat presented in chapter 2 showed the need for housing solution to face the overcrowding, the environmental challenges, and the deterioration of health caused by the poor house conditions that indigenous communities are facing. The design aims to rethink by creating housing that demonstrates structural resilience in permafrost environments while addressing socio-economic challenge. However, the cultural context of the Inuit people and their historic relationship with the land were taken into account, this is reflected in the design approach and the choice of materials, which align with Inuit values while incorporating modern technology.

In chapter 3, the design process was informed by a comparison between conventional construction and 3D printing technology. This analogy highlights the benefits of 3D printing for remote regions. However, the combination of 3D printing and CLT emerged as a promising strategy for reducing the logistical issues of transporting materials to Northern Canada by combining onsite and offsite construction techniques. The chapter explores the different configuration scenarios of 3D printing and prefabrication to determine the optimal combination of the two construction techniques, prioritizing the transportation costs, and maximizing onsite assembly.

The computational tools used in this study, including Grasshopper, Karamba 3D, and Ameba, were selected for two reasons main reason: their ability to explore structural configurations and optimize the use of materials, and secondly because of my previous experience with these tools in different workshops I attended. These tools offer functions for environmental and structural impact simulations, making them highly suitable for this thesis. Their adaptability to make iteration in the design process leads to a constant improvement for material selection and building solutions to address the challenges faced by permafrost regions. In addition, the use of Ladybug enriched the analysis by incorporating climate data like snow loads, wind pattern and temperature fluctuation to know if the proposed design can withstand the Northern Canada's extreme environment.

The next research design incorporated data from my participation in analog mission at LunAres Research Station. The mission named *Space Bears* provided practical knowledge of how analog astronauts interact with habitat and resources available in isolated and extreme environments. The qualitative data gathered during and after the mission showed how human factors such as psychology, ergonomics, physical fitness, and team dynamics are important during the design process. The findings were crucial to ensure that the proposed house can provide long-term living in the extreme in remote areas.

Nevertheless, there were some limitations in this research that are also mentioned in the conclusion and recommendation sections of the thesis. First, the integration of 3D printing and

CLT is still theoretical, and no real-world example currently demonstrates its performance. Also, the logistics needs to be used to build in remote regions and building in cold weather is challenging, and the durability of 3D printing and material under the freeze-thaw conditions is in doubt. Regarding these limitations, the research provides a strong basis for more studies, providing a framework for concrete application and validation.

6.3 Discussion of key findings

One significant finding of using 3D printing in construction is the optimized use of materials, which achieved through the machine's precision, this optimization considerably reduces waste compared to conventional construction methods. This method is beneficial in remote regions, where transportation is expensive, limited, and taxing. The use of ISR as a material for 3D printing can offer a more adaptable method for building in extreme environments. However, the findings were evaluated in the context of existing 3D printing technology acknowledging that some required materials may not be locally available or suitable for Northern Canada.

The integration of CLT as a complementary material for 3D-printed structures was another important exploration. CLT is with its natural insulation properties and structural resilience, proves to be an excellent solution for the upper structure in cold climates. The synergy between CLT and 3DCP indicates how combining traditional and modern materials can result in energy efficiency and durable structure. These findings not only support the use of CLT in extreme environments but also encourage the subject of the feasibility of developing designs and building houses in areas where CLT production is less accessible.

Sustainability and environmental impact are central themes in the findings, particularly in terms of minimizing the carbon footprint of buildings in remote regions. The capacity to prefabricate components offsite and assemble them onsite significantly reduces energy consumption and pollution associated with transportation. The findings support the current literature on prefabrication and sustainability, and confirm that offsite construction minimizes waste and accelerates the building process. Yet, the findings suggest that concrete implementation of both technologies require further exploration.

Human Factors is an important aspect of the thesis, supported by qualitative and quantitative data collected from the LunAres analog mission. The study reveals that housing in extreme environments must support the well-being of its occupants. The focus on space design and the psychology reports a critical gap in the current housing solution in Northern Canada. While the design proposed in chapter 4 shows promise in addressing these aspects. More detailed studies on long-term habitation are required to completely understand how the structures may affect the occupant's well-being over time.

In conclusion, the key findings of the thesis indicate the potential of combining 3D printing and CLT to develop sustainable, adaptable, and stable housing solutions in extreme environments. Moreover, the thesis contributes to the discussion of how advanced construction technologies and combining other materials with 3D printing can be used to meet the specific needs of communities in remote regions and particularly Northern Canada.

6.4 Space architecture

It is becoming evident that climate change is making construction in extreme environments and remote regions more challenging, necessitating innovative approaches to overcome the resource limitations and unexpected events. In these circumstances, the field of space architecture provides technology and interesting design solutions that improve sustainability, resilience, and adaptability. The concept of space architecture was developed at World Space Congress in Houston in 2002 by members of the Technical Aerospace Architecture Subcommittee of the American Institute of Aeronautics and Astronautics (AIAA):

> « As a discipline comprises the design of living and working environments in space and on planetary bodies, such as the Moon and Mars, and other celestial bodies. This includes space vehicles and space stations, planetary habitats, and required infrastructure. Earth analogs for space applications, simulation and test facilities are also included in the field of Space Architecture. Earth analogs may include Antarctic, airborne, desert, high altitude, underground,

> undersea environments, and closed ecological systems. » (Sandra Hauplik-Meusburger & Olga Bannova, 2016, p. 1)

the parallels between space architecture and extreme architecture on Earth allow for a transfer of knowledge between the two fields, From the definition, we can understand that space architecture is not just about theory but also is a practical field offers practical solutions to pressing challenges on Earth, including climate change. The technology developed for space like autonomous construction, new materials, and security protocols, holds the potential to revolutionize the construction industry and push the boundaries of innovation and creativity.

Space habitats are often designed to minimize energy, recycle water, and minimize material waste. The same strategy has become a must while designing houses in regions with limited resources and harsh environmental conditions. My participation at LunAres analog mission in Poland, where I lived and worked in an isolated environment with four more analog astronauts for two weeks, gave me a new perspective of how space architecture principles can be beneficial and how the psychology, well-being, and the availability of resources can be considered when designing and building in regions like Northern Canada in our case. During the mission, each astronaut has a specific role and task to accomplish daily, and the schedule was carefully structured to maintain the balance between task, rest and personal time.

My interest in space architecture and my participation in the analog mission have shown me the importance of combining different disciplines and prioritizing 3Dprinting, sustainability, adaptability, resource availability, human well-being. However, in the next lines we will give some examples of projects to explore how technologies like 3Dprinting and resource availability can be used to develop the next generation of housing.

The first example shown in Figure 6.1a is Mars Dune Alpha proposed by ICON and BIG in collaboration with NASA is a 3D printed habitat developed for the CHAPEA mission. What make this project special is the use of Lavacrete for the 3D concrete, as an excellent material for extreme environment. In the case of Northern Canada, it can offer a solution by taking the same principles and maybe study if the ISRU available in the permafrost region could be used to create the Lavacrete. Also, the principal of lightning and organization of different spaces in the habitat can be incorporated as well to improve the human well-being. Moreover, the habitat focuses on automatization or the process and the flexibility as a solution for remote regions. By applying these principles, it will streamline the construction process and reduce the need of external resources.

The second project called Marsha by AI SpaceFactory (Figure 6.1b), introduces the use of biopolymer basalt composite, a recycling material made from Martian basalt. The use of recyclable materials is a great choice to reduce construction waste, environmental impact, and for circular economy principles in construction. In regions like Northern Canada, where the construction is challenging. Creation a similar material could offer ecological and practical advantages. By integrating these principles, 3D printing technology will help to reduce the carbon footprint.

The third example is Relativity Space, the first company to 3D print an entire rocket autonomously, and what is fascinating is that the company wants to use this technology to produce large structures in space and in orbit. The material used for the printing is advanced metal alloys, particularly aluminum and titanium. However, these materials are not only lightweight but also durable, making them ideal to withstand the harsh conditions of Northern Canada. Also, Relativity Space’s 3D printing technology can be used for different types of projects including public and commercial buildings, bridges and walkways, energy facilities, cold storage facilities, emergency shelters, and greenhouses. Figure 6.1c shows the use of this technology.

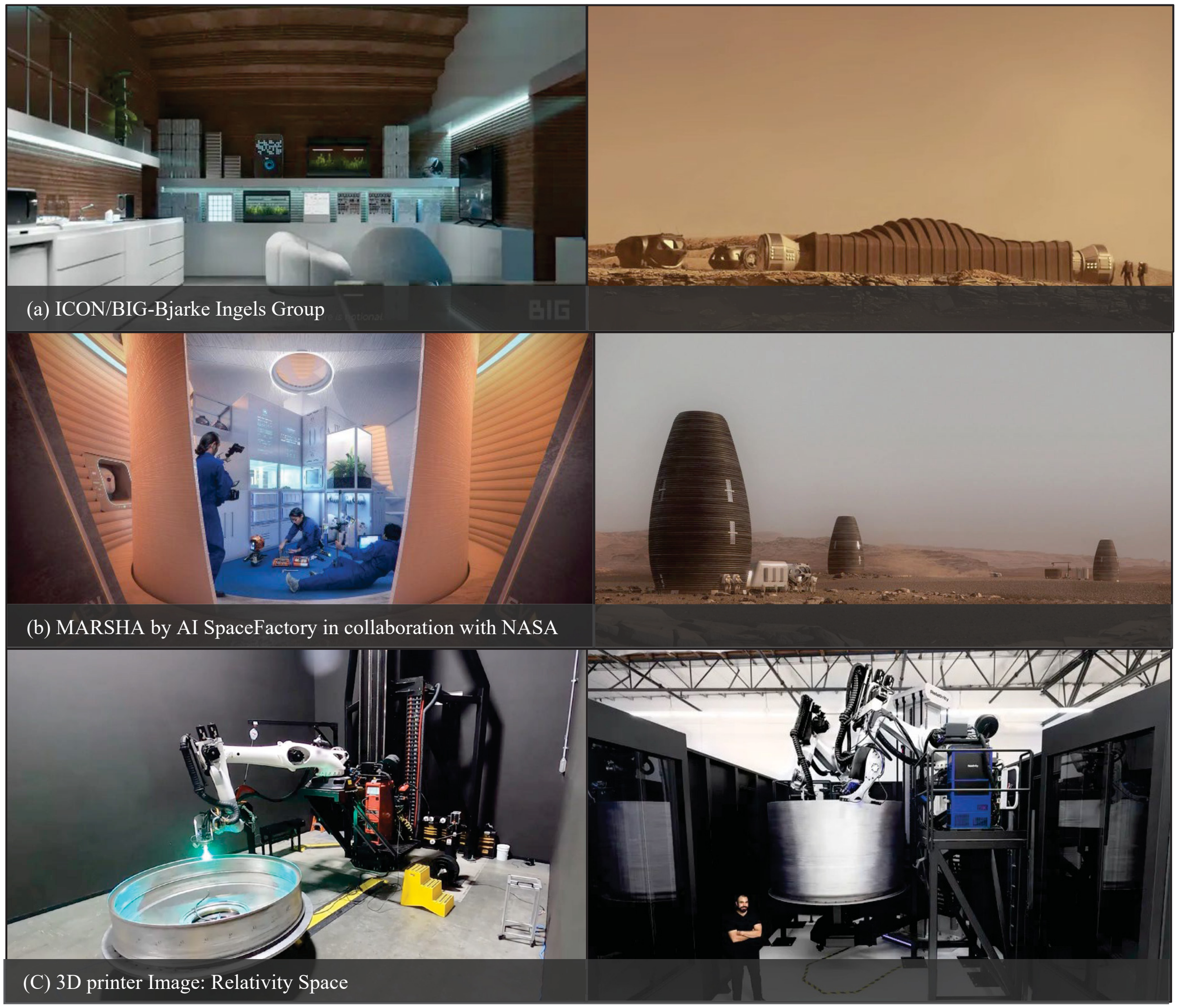

Figure 6.1 Examples of space architecture projects and technologies
Taken from Bjarke Ingels Group (2020); AI SpaceFactory (2023); Space (2024)

In summary, the different projects presented above are the transformative potential of space architecture not only for space exploration but also for climate change and extreme environments. In the words of Bjarke Ingels, Founder and creative director of BIG:

> To explain the power of architecture, "formgiving" is the Danish word for design, which literally means to give form to that which has not yet been given form. This becomes fundamentally clear when we venture beyond Earth and begin to imagine how we are going to build and live on entirely new worlds. With ICON we are pioneering new frontiers – both materially, technologically and environmentally. The answers to our challenges on Earth very well might be found on the Moon. (Bjarke Ingels, Founder and Creative Director, BIG-Bjarke Ingels Group.)

This viewpoint supports the idea that space architecture can drive the development of new materials and technologies, which not only influence the future construction of the future construction of habitats for an interplanetary species but also to provide innovative solutions to the environmental challenges here on Earth.

6.5 Originality and contribution to the knowledge

This thesis brings a new perspective by integrating space architecture ideas into the housing design extreme environment and particularly Northern Canada. While current actual architecture discussions focus of conventional approaches, this thesis bridges space architecture and extreme architecture to contribute to the development of innovative construction strategies to deal with Canada's housing crisis.

The thesis demonstrates the possibility of combining 3D printing and CLT to create sustainable, adaptable, and cultural considerations. This hybrid approach provides a modern solution to logistical challenges, environmental constraints, and the cultural needs of indigenous communities in Northern Canada. By using 3DCP for the ground floor and CLT for upper structure, the research creates a new opportunity for building in remote regions, where traditional methods are inadequate.

Furthermore, the research adds to the ongoing understanding of sustainability in construction and architecture by explaining how digital fabrication tools may optimize the use of renewable materials like CLT to reduce the carbon footprint of construction projects and being more environmentally responsible.

6.6 Comparison with existing research

The thesis presents a new approach for solving housing needs in extreme environments by combining 3D printing technology and CLT. This research suggests a hybrid strategy combines prefabricated offsite and onsite construction to increase the profitability of material transport and manufacturing process crucial for remote regions such as Northern Canada, where logistical barriers are considerable. Moreover, this approach will reduce transportation expenses and material waste that are frequently addressed in the literature.

Furthermore, this thesis explores the possibility of using indigenous architecture as a solution that is rarely addressed in existing studies on remote housing. Also, this research proposes the construction of regional factories capable of processing resources into construction materials, and creating local jobs and becoming economically self-sufficiency and more sustainable. However, this strategy minimizes the need for long-distance material transportation and reduces the carbon footprint, which is highlighted in current research on sustainable building for isolated regions.

In addition, this thesis integrated socio-economic and cultural factors into the proposed house to ensure that the design can respect the indigenous communities' values. Compared to the existing literature that focuses on environmental and logistical challenges, our research addresses the cultural context by providing a design approach that combines the recent construction technology with the Inuit values and perspectives.

6.7 Steps toward optimizing home construction in the extreme north of Canada

A clear path to transform home construction in Canada is revealed by building on the findings of this thesis. First, the logistical and environmental challenges unique to remote regions can be addressed by using the hybrid technique of combining the CLT for upper building and 3D printing for ground floors. This strategy will minimize material waste and transportation costs by combining offsite and onsite construction techniques. However, one of the most important steps is to localize material manufacturing, local job opportunities and economic sustainability can be promoted while logistics expenses and carbon emissions are reduced by transforming resources into building materials closer to project sites. Moreover, the integration of advanced energy solutions like renewable energy systems can support these efforts.

Finally, advancing policy support and funding for innovative construction technologies is crucial for successful implementation. The idea may be tested, improved, implemented by starting with pilot projects in regions like Nunavut. This will guarantee that the housing problem is effectively and sustainably addressed.

6.8 Lessons from analog missions for Northern Canada

The findings from LunAres analog mission offer important lessons for housing construction in Northern Canada. The need to improve psychological well-being through modular designs, adaptable spaces, and the choice of materiality inside the house. Additionally, resource management systems, such as renewable energy sources and closed-loop water recycling, have proven effective in reducing logistical dependencies in isolated environments. Finally, to meet the requirements of construction in Northern Canada, these lessons highlight the importance of integrating sustainable and adaptive strategies to meet the needs of affordable housing in Canada.

CONCLUSION

The present thesis has offered a comprehensive analysis of the challenges and potential advantages involved in construction in extreme environments, particularly in Northern Canada's permafrost regions. By integration computational design and digital fabrication methods, including 3D printing and CLT, this research presents an innovative approach that addresses logistical, cultural and environmental challenges. These technologies provide important benefits in terms of sustainability, adaptability, rapidity for remote and extreme conditions. However, it is crucial to acknowledge that the integration of both technologies is still purely theoretical, and no real-world projects have been realized.

To answer the research questions, this thesis has explored the potential integration of CD and 3D printing with CLT t develop adaptive and sustainable housing solutions for permafrost zones in Northern Canada (Q1). Moreover, it explored CD's capacity to improve materials and construction systems to withstand extreme weather conditions (Q2). Furthermore, the thesis underlined the need of developing houses that are culturally sensitive and that properly integrate indigenous values, and to deal with the housing crisis in Nunavut, it is required for a deep awareness of the social and cultural context (Q3).

Moreover, the thesis integrates results from analog mission named *Space Bear*s conducted at LunAres research station in Poland. The mission led to a significant understanding of the physical and psychological impacts of living in isolated environments (Q4). The findings highlight the need for designing habitats that prioritize comfort, privacy, and social engagement to improve mental well-being and long-term sustainability, where isolation and extreme conditions can influence the health and productivity of the users.

This thesis provides a new perspective on housing solutions in extreme environments. However, some limits must be acknowledged. Firstly, the present research shows a new opportunity of combining between CLT and 3D printing technology to solve the unique housing crisis in Northern Canada. This combination is still in the theoretical phase, and required further exploration, testing, and collaboration between developers, indigenous communities, government, and investors. Secondly, the lack of empirical data for long-term performance of the proposal design in Arctic climates durability and life cycle materials, and its ability to withstand extreme conditions. Thirdly, the research used computational design tools to optimize the use of material and maximize the structural integrity of the house. However, computational models cannot fully predict real-world environmental factors. Moreover, the input data used in the design may not reflect the behaviors of materials under specific stress which required some pilot projects to validate the results provided by digital tools. Finally, the combination of 3D printing and prefabrication technologies is still in the development phase, while Canada is still far away from building homes using 3DCP, future research can create potentials to use local materials to transform and use them in the 3D printing process.

RECOMMENDATIONS

Based on results of this thesis, several recommendations can be suggested for further research, policy, and real application in the field of construction in extreme environment, specifically in northern areas of Canada:

1) Initiate pilot projects that combine the 3D printing and CLT. These projects will be a small-scale preliminary experiment designed to refine construction methods, evaluation the performance of materials, testing the assembly and junctions between the two technologies for best thermal insulation, and analyze the speed and cost effectiveness in remote regions like Nunavut.

2) Collaborative research with indigenous communities to participate in the design phase to ensure the cultural compatibility and effectiveness of housing solution in Northern Canada. Active participation of local populations to understand their housing needs, traditions, and values. It is important to include indigenous perspectives from the initial design phases to the construction phase, to ensure that the user is satisfied and all the requirements have been respected.

3) While the CD tools such as Karamba 3D and Ameba have proven their efficiency in optimizing structural configurations, there is a need for more advanced tools that already existed to address specific challenges for building in extreme environments. This includes the optimization of material usage for temperature fluctuations, advanced simulations to test the stresses and displacement of different materials, especially the mixture of concrete and other compositions.

4) The results from LunAres mission should be considering in future housing design, because it provides an important insight for psychological well-being and promote mental health, privacy, natural lighting, public space, and overall comfort.

5) It is important that any projects involve the 3D printing and CLT should be evaluated and monitored for a long-term use. This way we can learn if there are any problems occur and find the best solution and use it as data for the next construction projects, for more durability and performance.

6) Future research should prioritize more precise environmental data into computation design tools. The inclusion of permafrost dynamics, direct and indirect loads, and wind pattern can provide information to successfully build an adaptable and durable structure in extreme environments.

7) Highlight the importance of adaptability, modular construction, and standardization of the process to integrate the climate change and fluctuation of environmental condition. With the standardization, it will be easy to expand, reconfigure, and relocate the buildings. This adaptability will reduce long-term expenses and allow housing to deal with different climate conditions.

8) To deal with logistical challenges and transportation cost to build in northern regions, future research can study localized supply chains and local manufacturing facilities for in-Situ resource for 3D printing and CLT. This will help to have a map or different zones where materials are available and contribute to local economic growth.

9) Finally, to successfully implement CLT and 3D printing, coordination between different disciplines, such as engineering, architecture, indigenous study, and environmental science will create creative and innovative solutions to address challenges in the extreme environment.

APPENDIX A

CONFERENCE PAPER 1 – CHAPTER 1

CONSTRUCTING IN EXTREME CLIMATES: AN IN-DEPTH EXAMINATION ACROSS VARIED ENVIRONMENTAL CONDITIONS WITH A FOCUS ON CANADA

Yakine Zerrad[1] ; Ivanka Iordanova[1]

[1] Department of Construction Engineering, École de Technologie Supérieure
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
yakineer@gmail.com

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Abstract

This research explores the link between harsh climate conditions and adaptive building methods in various extreme environments, with a particular emphasis on Canada. This paper offers an examination of six different projects located in distinct climate zones: polar, Alpine, desert, marine, vacuum space, and Tundra. The study highlights the importance of adaptive strategies, sustainability initiatives, and new technologies required to address the unique barriers associated with extreme environments. Although the projects did not employ the 3D printing concrete or autonomous robotics, the study shows that these technologies represent a promising path toward improving building techniques in terms of environmental sustainability, safety, and efficiency. The discussion includes conceptual exchanges between space architecture and terrestrial architecture, indicating a multitude of opportunities to improve building practices in extreme environments. The findings indicate to a possible strategy for encouraging a more robust, sustainable, and technologically advanced building industry, capable of effectively addressing the environmental challenges presented by extreme climate conditions.

Keywords: Extreme environment, Adaptive strategies, Technological Advancements

Introduction

Building in extreme climates brings difficulties that involve the creation of innovative solutions. The objective of this study is to analyze six projects situated in diverse challenging climates and explore strategies employed to adapt to environmental challenges. Moreover, this research turns its focus to the Canadian context. Studying the projects indicates that the construction techniques used in these climate zones are very efficient at dealing with the problems caused by cold temperatures and permafrost conditions in Canada. In particular, the Canadian High Arctic Research Station (CHARS) project, located in Cambridge Bay, Nunavut's harsh tundra climate, serves as a case study showing how innovative strategy and construction technology can be effectively applied to control extreme environments. This includes reducing the carbon footprint, the use of new insulating materials, specific foundation designs for the permafrost region, and renewable energy sources. This research aims to examine these strategies in detail, reviewing their possible adoption and benefits in the Canadian construction industry.

Definitions

Extreme Environment

An extreme environment refers to a place with conditions that are very different from the usual ones, such as extreme heat or cold, unusual pressures, intense radiation, and corrosive substances. These factors make it difficult for humans to be present and carry out activities. Such locations may have pH levels, wide temperature ranges, or high salt content, requiring engineering for safety and proper functioning. Despite being inhospitable to life forms, extremophiles, organisms adapted to these environments, thrive in such conditions. This concept also extends to space, where unique engineering solutions are necessary to cope with the conditions found on celestial bodies and in outer space orbits. In the expanse of space, the field of space architecture plays a crucial role.(Gómez, 2011)

Space architecture

Space architecture focuses on creating living spaces that can withstand the challenges of space, such as extreme temperatures, radiation, and limited oxygen. This is essential for supporting life in locations like the Moon, Mars, and low Earth orbit. The field explores building methods that utilize materials and tackles unique obstacles like space debris. Additionally, analog missions conducted on Earth simulate these conditions to test the feasibility of construction techniques and approaches in such environments. This helps advance practices, habitat design, and our ability to live and thrive in space and other hostile places. These missions act as a link between concepts in space architecture and the practical requirements for living beyond Earth's boundaries.(S. Hauplik-Meusburger & O. Bannova, 2016)

Permafrost

Permafrost is ground that stays frozen for two or more years. About half of Canada, in the Arctic Archipelago, Yukon, the Northwest Territories, and Nunavut, sits on this permafrost layer. When it comes to engineering projects in these areas, special attention is needed to deal with permafrost. This involves creating and executing plans during the design and construction phases for structures like foundations, dams, pipelines, roads, railways, airports, and essential services for communities in the north.(N. R. C. Canada, 1981)

In Canada, when it comes to building homes, the methods and materials chosen are influenced by factors like land features and geological details. Looking at the land's characteristics helps determine the construction approach. This includes studying things like soil quality, water presence, terrain incline, and rock makeup. These factors all contribute to selecting the ways to build and what materials to use in an area, making sure structures are safe, long-lasting, and environmentally friendly.(Slaymaker, 2015)

Methodology

The research methodology is based on an approach that involves analyzing case studies by following a series of steps. We initially selected projects located in different temperature zones, each facing its own environmental challenges. To aid in comprehension, we created table -A I-1 to display the typology and types of spaces for each project, such as bedrooms, control rooms, living areas, and research modules. Furthermore, Figure AA.1 and table AA.2, which include line connections and checkboxes, complement the table by summarizing the aspects of each project and offering a representation to understand the distinct context of every study.

It's worth mentioning that although this structure may suggest a framework, the objective of this research is not to compare these projects against one another. Instead, the focus lies in examining each project within its context. This method allows for an investigation into how each project addresses and adapts to its climate-related obstacles. Our structured methodology facilitated an in-depth analysis of these climate zones, capturing the characteristics of each case study. The projects selected incorporate a range of categories from the expanses of Antarctica to the harsh conditions of Cambridge Bay, Nunavut. This diverse selection offers perspectives on how each project tackles the challenges caused by its climate and the innovative approaches taken in its development. Looking at how each project responds to its climate conditions, as shown in Table AA.3, tells a story of sustainability, adaptability, and technological advancement. This narrative highlights how the design and operational strategies of each project are influenced by its surroundings, demonstrating the creativity needed to thrive in environments.

The importance of this concept becomes particularly clear when applied to construction in extreme environments. For example, the Canadian High Arctic Research Station (CHARS) in Cambridge Bay exemplifies design and operational solutions aimed to overcoming environmental limitations. This case study, along with others studied in this research, offers insights into construction practices in challenging environments by emphasizing the significance of considering environmental factors rather than making comparisons across different locations.

While the case study method provides a great perspective, it is essential to acknowledge its constraints. Every project faces challenges due to its unique conditions, making it complex and unpredictable. The variability, in environments makes it difficult to generalize findings across climate zones. While the case studies are diverse, they may not cover all aspects of conditions. By focusing on analyses of direct comparisons, this study might miss out on valuable insights that a comparative approach could provide. It's important to recognize these limitations to understand the study results and guide research in this field.

Table AA.1 Case studies analysis

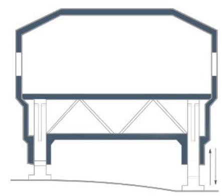
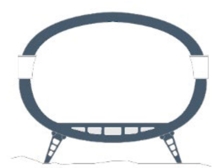
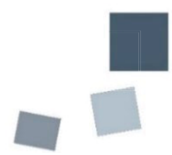
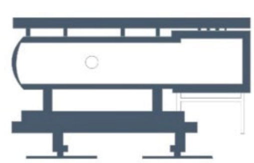
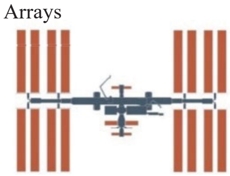
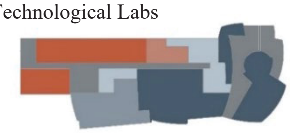
Project	**Typology**		Ref.
Halley VI Research Station		Sleeping Module Command Module Living Module Generator & Plant Module Science Module 	(Building, 2007) (Hughet, 2017)
The New Refuge Gervasutti by LEAPfactory		Living space Sleeping Space, Bathroom 	(LeapFactory, 2023)
Desert Nomad House		Living Space Office Bedroom 	(Naser Nader, 2020)
The Aquarius Underwater Habitat - NEEMO		Main Lock with Bunks and Counter Entry Lock with Science Area Wet Porch and Entry-Exit Hatch 	(Sarah A., 2015) (oneworldoneocean, 2012)
International Space Station (ISS)		Habitable Modules Solar Arrays 	(Kitmacher G., 2010)
CHARS – MRB		Public Space Offices Rough Labs Field and Maintenance Services Circulation Technological Labs 	(AANDC Arctic Science Policy Integration et al., 2012)

Table AA.2 Evaluation of the projects based on architectural and structural considerations

		Projects	Halley VI Research Station	The New Refuge Gervasutti	Desert Nomad House	Aquarius underwater habitat - NEEMO	International Space Station (ISS)	(CHARS) – (MRB)
Location	Climate Zone	Polar	✓					
		Tundra						✓
		Alpine		✓				
		Marine				✓		
		Desert			✓			
		Vacuum Space					✓	
Performance and Resilience	Energy Efficiency	Materials/Orientation	✓	✓	✓	✓	✓	✓
		Photovoltaic Integration	✓	✓			✓	
		Renewable Energy Tech.	✓	✓			✓	
	Sustainability	Environmental Protection	✓	✓	✓	✓	✓	✓
		Resource Recycling	✓	✓			✓	
		Sustainable Building Practices	✓	✓	✓		✓	✓
		Sustainable Materials	✓	✓	✓		✓	✓
	Adaptability	Environmental preservation	✓	✓	✓	✓		✓
		Location-specific adaptation	✓	✓	✓	✓	✓	✓
		Relocation Capability	✓					
		Mission Flexibility	✓			✓	✓	✓
		Modular Adaptability	✓	✓			✓	
	Safety Measures	Life Support measures	✓	✓		✓	✓	
		Safety Emphasis	✓	✓		✓	✓	✓
		Communication Measures	✓	✓		✓	✓	✓
		Training Measures	✓			✓	✓	✓
		Emergency Measures	✓			✓	✓	✓
		Structural Safety Measures	✓	✓		✓	✓	✓
	Water mngt	Wastewater Treatment	✓	✓			✓	
		Water Recycling	✓				✓	
		Biological Waste Treatment	✓	✓			✓	
	Thermal Insulation	Insulation Materials	✓				✓	✓
		Temperature Control	✓		✓		✓	✓
		Building Design	✓	✓	✓	✓	✓	✓
		HVAC Systems	✓				✓	✓
Technology	Construction Systems	Modular Construction System	✓				✓	✓
		Robotic Assembly					✓	
		Inflatable Technology					✓	
		3D print						
		Wood Framing						✓
		Steel Framing	✓		✓	✓	✓	✓
		Reinforced Concrete and Steel Support	✓					
		Prefabricated Construction	✓	✓			✓	
Cross-Industry Construction Innovation	Cross-Industry Construction	Aerospace Technology		✓		✓	✓	
		Aeronautical / Nautical Fabrication		✓		✓		
		Environmental & Material Science	✓	✓	✓	✓	✓	✓
		Software & IT	✓			✓	✓	✓
		Communications & Electronics	✓			✓	✓	✓
		Chemical Industry					✓	

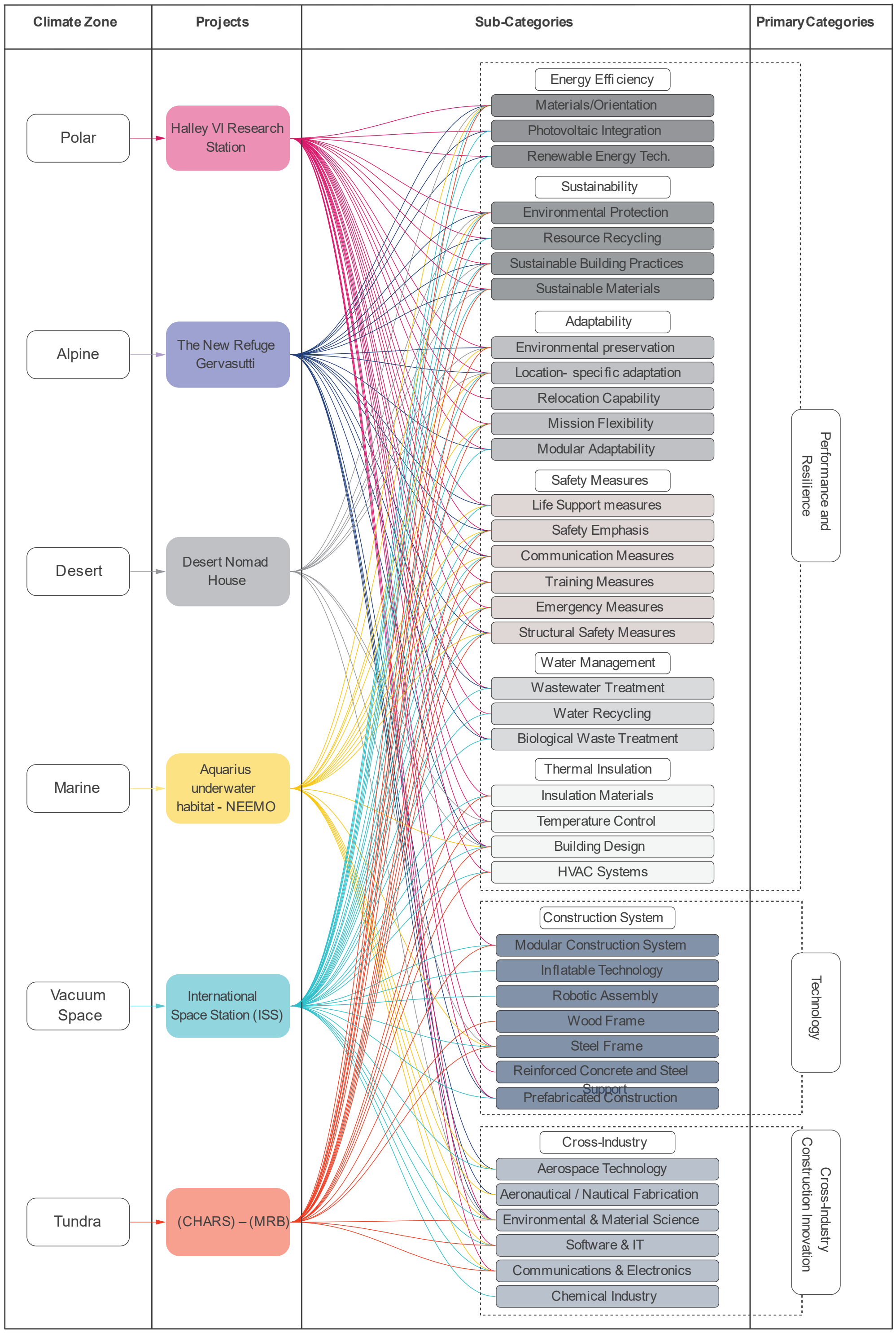


Figure AA.1 Presentation of Similarities Across Climate Zones

Results and discussion

The Categorical Overview Chart and the Similarities Across Climate Zones table show how various climate zones are analyzed, along with the design approaches used in projects for each zone to address their environmental challenges.

Presentation of Categorical Overview Chart

The 'Categorical Overview Chart' is a tool designed to outline and showcase the features of every selected project, aligned with the respective climate zones. This chart acts as a resource for recognizing the strategies for adaptation, sustainability initiatives, and technological advancements utilized in each project. It offers a view of the methods implemented to tackle the climate-related obstacles particular to their surroundings.

Table AA.3 Categorical Overview Chart

Category	Antarctica	Alpin	Desert	Underwater	Outer Space	Tundra
Climate-Specific Challenges	Snowfall, moving ice, severe cold, logistics, and inaccessibility	Harsh temperatures at high altitudes, Transport logistics	Climate control and landscape conservation	Isolation and a harsh environment	Microgravity, Radiation, Isolation, Extreme environment	Blending with Arctic environment, HVAC efficiency, Equipment heat management, Adaptation to Arctic storage conditions
Solutions for Energy Efficiency	Renewable energy (solar, wind), Insulation (nanoaerogel panels, PIR), Heat recovery	Photovoltaic panels, Excellent insulation	Ventilated façade, material selection, and orientation	Life support system	Solar panels, Battery storage	High-efficiency equipment, Exhaust air energy recovery, Occupancy-based controls
Sustainability Measures	Waste heat repurposing, Bioreactor for sewage treatment, Renewable energy	Prefabrication offsite, recyclable materials (GFRP)	Integration with the surrounding	Mooring system, Environmental disruption minimization	Water and air recycling (ECLSS)	Silver-Level LEED certification, LABS21 Environmental Performance Criteria adherence

Table AA.3 Categorical Overview Chart (Cont'd)

Category	Antarctica	Alpin	Desert	Underwater	Outer Space	Tundra
Adaptability	Hydraulic legs, ski-based foundations, and fully relocatable legs	Prefabricated components, location-based adaptation	Minimal disturbance, preservation of untouched landscape	Internal space modification, adaptable research platform	Modular design, Standardized interfaces	Adaptable design to accommodate evolving research goals
Safety Measures	Snow drift management, Base split for life safety	Weather data integration and two-way escape paths	Elevated structure for water flow, Landscape preservation	Life support buoys, Emergency evacuation	Emergency training, Lifeboats (Soyuz or Crew Dragon)	WHMIS regulations, Specific lab containment levels, Safety equipment and protocols
Innovative Construction Methods	Aerospace technology (aerogels), prefabricated elements	Aeronautical and nautical engineering, Methyl Methacrylate-Based Adhesives	Reinforced concrete piers, ventilated façade, steel beams	Underwater assembly, Welding and fabrication underwater	Modular construction, In-space assembly, Robotic systems	Steel frame structure, Elevated pilings, Thermosyphons for slabs
Water Management	Water management system that includes UV disinfection and sewage treatment	Melting and boiling snow for drinking water, biological lavatory system	(Information not provided)	Waste treatment, freshwater sink	Water recycling (ECLSS)	Closed-loop water system, Water-efficient equipment, Strict waste disposal protocols
Thermal Insulation Techniques	Polyisocyanurate foam Insulation (PIR) and a highly insulated glass fiber system	Controlled ventilation and constant interior temperature maintenance	Air gap between perimeter wall and exterior cladding	Thick metal shell	Multi-Layer Insulation (MLI), Active Thermal Control System (ATCS)	ASHRAE 55 adherence, Separate HVAC zones, UV-protected exteriors, R20 insulation, Low-E windows

Structure and purpose

The chart arranges each project based on its climate zone, aiming to offer a structured representation of how different environmental obstacles demand distinct adaptive approaches and creative solutions. Its primary goal is to compare and categorize, aiding in recognizing trends, unique methods, and notable advancements that showcase the project's efforts to achieve sustainability, flexibility, and effective operations in demanding weather conditions.

Discussion of Projects

The Halley VI Research Station in Antarctica stands out for its reliance on energy, a movable design, and the use of aerospace technology for insulation. The installation of nanoaerogel panels effectively reduces energy loss, demonstrating technological innovation. Additionally, the New Refuge Gervasutti in the Alps showcases prefabricated construction methods, renewable energy production through panels, and fabrication techniques borrowed from the aerospace and maritime industries. An interesting aspect is the transportation of prefabricated parts by air to overcome hurdles in the alpine area. Moreover, the Desert Nomad House in a desert region emphasizes elements that blend with the environment, such as a ventilated façade for climate control and the use of building materials. The ventilated façade system effectively addresses the challenges posed by desert temperatures. Furthermore, the Aquarius Underwater Habitat NEEMO, demonstrates adaptability in setting up a mooring system designed to minimize impact and underwater communication technology. Notable advancements include welding and fabrication methods to ensure strength and operational efficiency. Similarly, the International Space Station (ISS) showcases a design for outer space conditions, an advanced life support system that recycles water and air, as well as incorporating robotics and spacewalks for construction and upkeep tasks. It incorporates technology, like the Bigelow Expandable Activity Module (BEAM) to expand operational space.

Finally, the Canadian High Arctic Research Station (CHARS), in the Tundra, achieved Silver Level LEED certification, showcasing its dedication to sustainability. It features cutting-edge HVAC systems tailored for Arctic conditions and encourages community involvement. Significant innovations, such as pilings and thermosyphons, in foundation building address the distinctive needs of the Arctic setting.

Presentation of Similarities Across Climate Zones Table

The table named 'Similarities Across Climate Zones ' is designed to present and contrast the shared characteristics and strategies of projects across climates. It classifies six projects: the Halley VI Research Station in Antarctica, the New Refuge Gervasutti in the Alps, the Desert Nomad House in a desert setting, the Aquarius Underwater Habitat. (Part of the NEEMO underwater project), the International Space Station in space, and the Canadian High Arctic Research Station in the Tundra. Each project is associated with its climate region, demonstrating how diverse environmental obstacles have led to approaches or solutions being implemented across different geographical areas.

Table AA.4 Similarities Across Climate Zones

Similarity Categories	Polar	Alpin	Desert	Underwater	Outer Space	Tundra
Renewable Energy	✓	✓	✓		✓	
Efficiency Systems	✓					✓
Prefabrication	✓	✓			✓	
Insulation	✓	✓	✓		✓	✓
Modular/Adaptable Design		✓		✓	✓	✓
Safety Protocols	✓	✓		✓	✓	✓
Water Management	✓	✓		✓	✓	✓
Sustainability Measures	✓	✓	✓	✓	✓	✓
Construction Techniques	✓	✓	✓	✓	✓	✓
Construction Materials			✓			✓
Technology Integration	✓	✓		✓	✓	
Certifications/Standards						✓
Community Interaction						✓
Environmental Blending			✓	✓		
Logistical Challenges	✓	✓				
Equipment Management	✓					✓
Operational Duration					✓	
Cost Management	✓					
R&D	✓			✓	✓	
Waste Disposal	✓	✓		✓	✓	✓
Emergency Preparedness	✓	✓		✓	✓	✓
External Collaboration	✓			✓	✓	
Occupancy Control						✓

Structure and purpose

The chart aims to highlight the similarities among projects in different weather conditions, emphasizing recurring trends and creative problem-solving approaches in harsh settings. Its primary objective is to display shared characteristics, like energy conservation, flexibility, and technological advancement, through a format that showcases successful tactics applied in varying climate regions.

Discussion on common features

One common feature seen in these projects is the focus on energy efficiency. Using energy sources, both the Halley VI Research Station and The New Refuge Gervasutti use panels to reduce their impact on the environment. The International Space Station (ISS) and the Canadian High Arctic Research Station showcase advanced resource management systems, highlighting a shared commitment to sustainability across climates.

The use of modular construction is another similarity found in both The New Refuge Gervasutti in the Alps and the Canadian High Arctic Research Station in the Tundra. These construction methods reflect a shift towards efficient, standardized, and eco-friendly building practices, especially important in harsh environments with limited resources. Across all projects, there is a recurring theme of leveraging technologies to tackle challenges to extreme environments. For instance, the Desert Nomad House incorporates a ventilated façade system for climate control, while the Aquarius Underwater Habitat NEEMO, uses cutting-edge communication technology for improved operational efficiency.

The impact of constructing buildings in environments like the Canadian High Arctic Research Station (CHARS) is substantial, based on studies of different climate zones. The unique challenges of the Arctic demand solutions, as seen in the case of CHARS, which showcases innovative HVAC systems and construction methods tailored to the region's characteristics. By examining these projects, we can gather insights on strategies for extreme environments throughout Canada. The use of construction techniques in structures like the International Space Station (ISS) and The New Refuge Gervasutti in the Alps shows promise for overcoming challenges in Canadian climates. Additionally, a focus on energy efficiency and renewable energy sources, as seen in projects such as Halley VI Research Station and The New Refuge Gervasutti, aligns with sustainability goals in CHARS, emphasizing a shared commitment to responsibility across various climatic settings.

Conclusion

This research marks an advancement, in comprehending construction practices tailored for climates with a specific focus on Canada. It delves into adaptation strategies, eco-friendly approaches and technological progressions expanding our knowledge on constructing in demanding settings. The key takeaways highlight the significance of adaptability, sustainability, and technology in improving efficiency, safety measures, and environmental preservation within Canada's diverse climates.

Exploring the utilization of onsite resources, autonomous robotics, and 3D printing unveils avenues for construction techniques that are well suited for Canada's challenging conditions. These breakthroughs do not just address the climate-related obstacles in Canada. Also contribute to a global conversation on construction practices in harsh environments. Nonetheless, the study's emphasis on individual case studies without comparisons might restrict the generalizability of its findings across the spectrum of extreme climates found in Canada. Looking to the future, it is evident that upcoming research should concentrate on applying these cutting-edge technologies within Canada's climate contexts. Understanding how these innovations can tackle the challenges posed by environments is essential.

Furthermore, there is opportunity to embrace approaches that blend global construction knowledge with specific Canadian scenarios. Examining the regulations that govern construction in Canada's environments is crucial for promoting progress, safety, and environmental responsibility. Looking into how construction is done in climates across Canada could offer valuable insights, pinpointing effective methods and creative ideas that can improve construction practices nationwide.

To sum up, this research paves the way for an understanding of building in weather conditions, focusing on the specific challenges faced in Canada. It lays the foundation for studies and practical implementations that seek to enhance construction practices in environments not only in Canada but also globally. This involves incorporating technologies, sustainable approaches, and adaptable strategies to push forward innovation, in the construction industry.

APPENDIX B

LUNARES ANALOG MISSION – CHAPTER 5

Table AB.1 Questionnaire Used to Collect Data After the Lunares Mission

N.	Psychological Impact	
01	Your astronaut number	○ AA01 ○ AA02 ○ AA03 ○ AA04 ○ AA05
02	How often did you feel emotionally stable during the mission?	○ Always ○ Often ○ Sometimes ○ Rarely ○ Never
03	How frequently did you experience feelings of loneliness or isolation?	○ Always ○ Often ○ Sometimes ○ Rarely ○ Never
04	What was the main source of stress for you during the mission? (Select all that apply)	□ Isolation □ Workload □ Social dynamics □ Living conditions
05	Which coping strategies did you use? (Select all that apply)	□ Work □ Meditation □ Socializing with team members □ Engaging with hobbies □ Food □ Other:
06	How adequate was the mental health support provided during the mission?	○ Excellent ○ Good ○ Fair ○ Poor ○ Very poor
07	What additional mental health resources would have been helpful? (Select all that apply)	□ Online therapist □ Online mental health □ Consol □ Virtual Reality (VR) □ Other:

Table AB.1 Questionnaire Used to Collect Data After the Lunares Mission (Cont’d)

N.	Organization of the Habitat Space	
08	How would you rate the comfort and functionality of your living quarters?	○ Very Comfortable and Functional ○ Comfortable and Functional ○ Neutral ○ Uncomfortable and Functional ○ Very Uncomfortable and Non-functional
09	What aspects of your living quarters did you find most helpful? (Select all that apply)	○ Bed and sleeping area ○ Storage space ○ Analytical lab ○ Kitchen ○ Operations ○ Bio lab ○ The center
10	How well was the habitat organized to balance work and leisure activities?	○ Excellent ○ Good ○ Fair ○ Poor ○ Very poor
11	How well was the habitat organized to balance work and leisure activities?	○ Very Satisfied ○ Satisfied ○ Neutral ○ Dissatisfied ○ Very Dissatisfied
12	How comfortable and functional was the furniture provided in the habitat?	○ Very Comfortable and Functional ○ Comfortable and Functional ○ Neutral ○ Uncomfortable and Functional ○ Very Uncomfortable and Non-functional
13	How sustainable were the materials used in the habitat's construction?	○ Very Sustainable ○ Sustainable ○ Neutral ○ Unsustainable ○ Very Unsustainable
14	How effective were the waste recycling systems in the habitat?	○ Very Effective ○ Effective ○ Neutral ○ Ineffective ○ Very Ineffective
15	How effective was the thermal insulation in maintaining indoor temperature?	○ Very Effective ○ Effective ○ Neutral ○ Ineffective

Table AB.1 Questionnaire Used to Collect Data After the Lunares Mission (Cont'd)

N.	Organization of the Habitat Space	
16	How well did the habitat integrate with the surrounding natural environment?	○ Very Well ○ Well ○ Neutral ○ Poorly ○ Very Poorly
17	How would you rate the interior design of the habitat in terms of creating a pleasant living environment?	○ Very Pleasant ○ Pleasant ○ Neutral ○ Unpleasant ○ Very Unpleasant
18	How important was the ability to personalize your living space to your well-being?	○ Very Important ○ Important ○ Neutral ○ Unimportant ○ Very Unimportant
19	How well was the habitat equipped for emergency situations (e.g., fire, medical emergencies)?	○ Very Well Equipped ○ Well Equipped ○ Neutral ○ Poorly Equipped ○ Very Poorly Equipped
20	How easy would it be to expand or modify the habitat to accommodate more people or additional functions?	○ Very Easy ○ Easy ○ Neutral ○ Difficult ○ Very Difficult
21	How useful were reconfigurable spaces (e.g., movable walls, modular furniture) in adapting to different needs?	○ Very Useful ○ Useful ○ Neutral ○ Not Useful ○ Very Not Useful
22	How well did the habitat design balance shared communal spaces with private personal spaces?	○ Very Well ○ Well ○ Neutral ○ Very Poorly
23	How did the design of the habitat impact your sense of privacy?	○ Very Positively ○ Positively ○ Neutrally ○ Negatively ○ Very Negatively

Table AB.1 Questionnaire Used to Collect Data After the Lunares Mission (Cont'd)

N.	Organization of the Habitat Space	
24	Did you feel you had enough privacy within the habitat?	○ Always ○ Often ○ Sometimes ○ Rarely ○ Never
25	How important was personal privacy to your overall well-being during the mission?	○ Very Important ○ Important ○ Neutral ○ Not Important ○ Not Important at All
N.	Lighting and Colors	
26	How did the lighting conditions affect your mood and productivity?	○ Very Positively ○ Positively ○ Neutrally ○ Negatively ○ Very Negatively
27	Which type of lighting works best for you? (Select one)	○ Natural light simulation (lighting that mimics sunlight) ○ Bright, cool light (intense, blue-tinted light) ○ Dim, warm light (soft, yellow-tinted light) ○ Adjustable lighting (lighting that can be changed to different settings) ○ Other:
28	How did the color scheme of the habitat impact your emotional well-being?	○ Very Positively ○ Positively ○ Neutrally ○ Negatively ○ Very negatively
29	Which colors did you find most calming or relaxing? (Select all that apply)	○ Blue ○ Green ○ Yellow ○ Red ○ Neural tones (like beige, gray, white)
30	Which colors did you find most annoying or uncomfortable? (Select all that apply)	□ Blue □ Green □ Yellow □ Red □ Neural tones (like beige, gray, white) □ Other:

Table AB.1 Questionnaire Used to Collect Data After the LunAres Mission (Cont'd)

N.	Social Dynamics	
31	How would you rate the overall social dynamics within the team?	○ Excellent ○ Good ○ Fair ○ Poor ○ Never
N.	Social Dynamics	
32	How frequently did you engage in social activities with team members?	○ Daily ○ Several times a week ○ Weekly ○ Rarely ○ Never
33	How effective were the conflict resolution strategies within the team?	○ Very Effective ○ Effective ○ Neutral ○ Ineffective ○ Very Ineffective
34	What types of conflicts were most common? (Select all that apply)	□ No conflict □ Personal disagreements □ Work-related disputes □ Resource allocation □ Noise and space issues
N.	Physical Environment	
35	How would you rate the temperature and air quality within the habitat?	○ Excellent ○ Good ○ Fair ○ Poor ○ Very Poor
36	Did you experience any issues related to temperature or air quality? (Select all that apply)	□ Too hot □ Too cold □ Poor air circulation □ Humid air
37	How did the noise levels within the habitat impact your comfort and concentration?	○ Very Positively ○ Positively ○ Neutrally ○ Negatively
38	What were the main sources of noise within the habitat? (Select all that apply)	□ Equipment □ Conversations □ Movements of team members □ External environment

Table AB.1 Questionnaire Used to Collect Data After the LunAres Mission (Cont'd)

N.	Physical Environment	
39	How would you rate the overall design of the habitat?	○ Excellent ○ Good ○ Fair ○ Poor ○ Very Poor
40	What changes would you recommend improving the habitat design? (Select all that apply)	□ More personal space □ Better lighting □ Improved temperature control □ Enhanced privacy □ Better recreational facilities □ Other (please specify)
41	How well prepared did you feel for the isolation experience?	○ Very Well Prepared ○ Well Prepared ○ Neutral ○ Poorly Prepared ○ Very Poorly Prepared
42	What additional preparations would you recommend for future missions? (Select all that apply)	□ More training on coping with isolation □ Better mental health resources □ Enhanced team-building exercises □ Improved nutritional planning (better food options and diet plans) □ Access to recreational activities (games, hobbies, or entertainment to relax and have fun) □ Other:
43	Would you consider living in an isolated environment in northern Canada or other cold climates for an extended period?	○ Definitely ○ Probably ○ Not Sure ○ Probably Not ○ Not
44	What challenges do you anticipate in living in such cold climates? (Select all that apply)	□ Extreme temperatures □ Limited daylight □ Isolation from the outside world □ Limited access to resources □ Social isolation □ Other:
45	Overall, how would you rate your experience during the mission?	○ Excellent ○ Good ○ Fair ○ Poor ○ Very Poor

Table AB.2 Daily health and activity metrics of astronaut AA01

Astronaut Number	Filled by Medical Officer							Filled by the analog astronaut			
	Days	Body Temperature (°C)	Blood Pressure SYS (mmHg)	Blood Pressure DIA (mmHg)	Pulse Rate (/min)	Weight (kg)	Pulse Oximetry (%)	Tea Consumption (300 ml)	Total amount of water (ml)	Calories	MaxForce Workout
A01	D1	36.4	104	71	62	97.5	99	0	2000	1800	Yes
	D2	35.9	131	85	68	98	96	0	1200	1700	Yes
	D3	36.1	101	78	72	97.6	99	0	1700	1376	Yes
	D4	36	156	84	72	96.6	97	0	1800	2000	Yes
	D5	36.5	120	75	75	95.5	99	0	1800	2000	Yes
	D6	36	119	87	64	97.2	96	0	1900	2100	Yes
	D7	36.2	111	99	62	95.8	98	0	1500	2000	Yes
	D8	36.6	126	65	53	96.2	97	0	2000	2000	Yes
	D9	36.7	126	83	62	95.6	99	300	2000	2000	Yes
	D10	36.4	122	84	57	96	96	0	2000	2000	Yes
	D11	36.1	119	75	78	95.4	99	0	2000	2000	Yes
	D12	36.6	130	82	69	95.1	98	300	2000	2000	Yes
	D13	35.2	120	80	68	94.9	98	0	1800	2300	Yes

Table AB.3 Daily health and activity metrics of astronaut AA02

Astronaut Number	Filled by Medical Officer							Filled by the analog astronaut			
	Days	Body Temperature (°C)	Blood Pressure SYS (mmHg)	Blood Pressure DIA (mmHg)	Pulse Rate (/min)	Weight (kg)	Pulse Oximetry (%)	Tea Consumption (300 ml)	Total amount of water (ml)	Calories	MaxForce Workout
A02	D1	36.2	115	73	60	118.3	99	0	1920	2388	Yes
	D2	36.3	122	82	65	116.5	100	600	2100	1985	Yes
	D3	36.1	140	86	88	115.4	99	0	1800	2196	Yes
	D4	36.3	136	93	72	115.7	99	0	2310	2250	Yes
	D5	36.4	94	62	69	116.3	98	0	1180	2388	Yes
	D6	36.4	127	88	83	116.1	96	0	2575	2237	Yes
	D7	36.1	141	85	69	115.2	98	0	1600	2217	Yes
	D8	36.5	150	105	83	115.5	97	0	2000	2249	Yes
	D9	36.3	116	75	69	114.3	98	0	2000	1900	Yes
	D10	36.6	130	78	62	114.8	98	0	2000	1949	Yes
	D11	36.4	143	81	70	114.3	99	0	2000	1983	Yes
	D12	36.6	129	84	69	114.7	96	0	2200	1840	Yes
	D13	36.5	127	88	80	114.6	97	0	1800	2781	Yes

Table AB.4 Daily health and activity metrics of astronaut AA03

Astronaut Number	Filled by Medical Officer							Filled by the analog astronaut			
	Days	Body Temperature (°C)	Blood Pressure SYS (mmHg)	Blood Pressure DIA (mmHg)	Pulse Rate (/min)	Weight (kg)	Pulse Oximetry (%)	Tea Consumption (300 ml)	Total amount of water (ml)	Calories	MaxForce Workout
AA03	D1	36.5	125	89	75	70.6	99	0	1030	1952	Yes
	D2	36.3	123	86	70	71.1	99	0	1030	1925	Yes
	D3	36.5	126	85	75	71.2	99	0	2070	1993	Yes
	D4	36.6	126	80	74	70.4	96	0	2360	1789	Yes
	D5	36.1	118	75	78	70	98	0	1660	1730	Yes
	D6	36.6	132	91	77	70.3	96	0	2050	1871	Yes
	D7	36.2	139	95	66	69.8	98	0	1200	1719	Yes
	D8	36.5	123	89	56	70	100	0	1200	1719	Yes
	D9	36.6	126	80	60	69.8	98	0	1650	1629	Yes
	D10	36.4	120	82	57	69.9	99	0	150	1718	Yes
	D11	36.4	122	82	60	69.3	98	0	1250	1673	Yes
	D12	36.5	132	84	60	69.9	100	0	1786	1727	Yes
	D13	36.7	123	90	62	69.8	99	0	1570	1808	Yes

Table AB.5 Daily health and activity metrics of astronaut AA04

Astronaut Number	Filled by Medical Officer							Filled by the analog astronaut			
	Days	Body Temperature (°C)	Blood Pressure SYS (mmHg)	Blood Pressure DIA (mmHg)	Pulse Rate (/min)	Weight (kg)	Pulse Oximetry (%)	Tea Consumption (300 ml)	Total amount of water (ml)	Calories	MaxForce Workout
AA04	D1	36.3	117	57	49	70.3	100	0	1830	2290	Yes
	D2	36.2	126	71	50	69.9	99	0	1170	1730	Yes
	D3	36.2	138	85	66	68.5	99	0	2064	1967	Yes
	D4	36.6	122	65	52	69.8	97	0	1575	2420	Yes
	D5	36.4	103	57	56	69.4	100	0	2258	2292	Yes
	D6	36.6	125	76	50	69	99	0	1754	2311	Yes
	D7	36.2	122	72	57	68.9	99	0	1010	2323	Yes
	D8	36.5	122	70	57	68.7	99	0	1794	2408	Yes
	D9	36.8	111	71	56	69.1	98	0	1770	2047	Yes
	D10	36.7	121	78	48	69.2	99	0	1580	2430	Yes
	D11	36.4	138	72	48	69.3	100	0	1550	2136	Yes
	D12	36.5	121	79	55	69	100	0	1870	2256	Yes
	D13	36.5	117	68	63	69	99	0	1800	2368	Yes

Table AB.6 Daily health and activity metrics of astronaut AA05

Astronaut Number	Filled by Medical Officer							Filled by the analog astronaut			
	Days	Body Temperature (°C)	Blood Pressure SYS (mmHg)	Blood Pressure DIA (mmHg)	Pulse Rate (/min)	Weight (kg)	Pulse Oximetry (%)	Tea Consumption (300 ml)	Total amount of water (ml)	Calories	MaxForce Workout
AA05	D1	36.1	118	83	84	75.1	99	900	1500	1826	Yes
	D2	36.6	131	81	71	74.8	99	1500	2400	2088	Yes
	D3	36.3	112	85	83	74.7	100	900	1820	1973	Yes
	D4	36.6	115	73	74	73.6	99	1500	1810	1955	Yes
	D5	36.8	116	67	84	73.3	96	1200	2380	2073	Yes
	D6	36.4	109	74	65	73.3	100	900	2050	2528	Yes
	D7	36.6	116	83	80	73.4	99	1200	2170	2538	Yes
	D8	36.8	111	76	67	73.6	98	900	1820	2819	Yes
	D9	36.9	110	69	69	73.6	100	1200	2140	2973	Yes
	D10	37	118	79	74	73.6	100	900	2000	2760	Yes
	D11	36.4	142	65	83	73.5	100	1200	2140	2240	Yes
	D12	36.4	117	77	85	74.2	98	1200	2450	2119	Yes
	D13	36.5	112	77	71	73.8	98	1200	2500	2065	Yes

Table AB.7 Health and Body Composition Changes of Analog Astronauts: Pre- and Post-Mission

Astronaut Number	Filled by Medical Officer							Filled by the analog astronaut				
	Days	Body Temperature (°C)	Blood Pressure SYS (mmHg)	Blood Pressure	Pulse Rate (/min)	Weight (kg)	Pulse Oximetry (%)	BMI	Body Fat (%)	Skeletal Muscle	Resting metabolism	Visceral fat level
AA01	D0	36.5	124	82	64	97.9	99	31.1	34.2	30.9	1988	14
	D14	36.7	119	85	62	94.6	99	29.9	34	30.9	1931	13
AA02	D0	36.5	125	84	83	119	98	35.9	36.5	30.5	2259	15
	D14	36.7	124	73	81	114	96	35.2	37.1	30.1	2227	15
AA03	D0	36.9	127	82	70	71.6	99	25.4	24.4	38.1	1670	8
	D14	36.7	120	83	61	69.1	98	24.6	21.8	39.7	1650	7
AA04	D0	36.7	136	75	61	70.6	99	23.1	18.3	41.5	1676	5
	D14	36.7	117	65	54	68.3	99	22.3	18.1	41.5	1635	5
AA50	D0	36.7	116	81	86	74.3	99	22.5	18.8	40.2	1690	5
	D14	36.5	126	73	72	73.2	99	22.6	17.6	41.1	1690	5

Table AB.8 Daily energy usage in different sections of the LunAres habitat during the mission

Day	Kitchen [kWh]	Dormitory [kWh]	Operations [kWh]	Gym [kWh]	Workshop [kWh]	Biolab [kWh]	Hygiene [kWh]	Total Daily
1	2.5	1.4	0.74	0.4	4.51	3.86	2.1	15.51
2	2.62	1.49	0.77	6.56	5.25	3.92	1.5	22.11
3	2.84	1.04	0.74	-5.66	3.89	3.73	3	9.58
4	2.77	1.53	0.8	0.71	6.7	5.2	2.1	19.81
5	1.54	1.34	0.4	0.17	2.81	2.92	0.9	10.08
6	1.99	1.76	0.67	0.57	3.84	4.19	2.6	15.62
7	2.11	1.49	0.81	0.38	6.65	6.39	2.103	19.933
8	6.39	4.94	3.32	1.36	14.38	15.47	17	62.86
9	3.61	1.77	1.74	0.56	4.46	7.02	3.7	22.86
10	1.94	3.61	2.06	0.55	4.4	6.37	8.5	27.43
11	1.37	1.14	1.2	0.3	2.39	7.31	9.8	23.51
12	3.19	2.61	1.52	0.88	7.72	6.98	5.5	28.4
13	2.63	2.16	1.66	0.47	4.78	7.5	1.8	21
14	1.84	2.23	1.2	0.5	3.88	4.72	3.2	17.57
Total	37.34	28.51	17.63	12.91	75.66	85.58	63.803	316.273

Table AB.9 Total clean, warm, and cold-water usage with gray water production during the LunAres mission

Day	total clean water usage [L]	gray water production [L]	warm water usage [L]	cold water usage [L]
1	126.847	54.692	41.471	85.376
2	170.000	58.000	55.000	115.000
3	108.000	40.000	38.000	70.000
4	154.000	96.000	94.000	60.000
5	163.000	55.000	50.000	113.000
6	182.000	86.000	82.000	100.000
7	55.000	47.000	45.000	10.000
8	163.000	104.000	102.000	61.000
9	82.000	65.000	63.000	19.000
10	151.000	83.000	83.000	68.000
11	84.000	54.000	52.000	32.000
12	128.000	87.000	87.000	41.000
13	95.000	95.000	93.000	2.000
14	44.000	26.000	27.000	17.000
Total	132.000	83.000	83.000	49.000

Table AB.10 Daily water consumption and remaining water levels during the analog mission

Days	Daily consumption [L]	Amount of water left [L]
1	170.000	1830.000
2	108.000	1722.000
3	154.000	1568.000
4	163.000	1405.000
5	182.000	1223.000
6	55.000	1168.000
7	163.000	1005.000
8	82.000	923.000
9	151.000	772.000
10	84.000	688.000
11	128.000	560.000
12	95.000	465.000
13	44.000	421.000
14	132.000	289.000

Table AB.11 Waste production during the analog mission

Day	Plastic [Kg]	Mixed [Kg]	Paper [Kg]	Glass [Kg]	Electronic [Kg]
1	0.300	0.450	0.200	0.000	0.000
2	0.550	0.900	0.400	0.000	0.000
3	0.450	1.500	0.100	0.000	0.000
4	0.550	0.450	0.400	0.000	0.000
5	0.550	1.000	0.650	0.000	0.000
6	0.350	0.450	0.200	0.000	0.000
7	0.800	1.100	0.450	0.000	0.000
8	0.650	0.350	0.150	0.000	0.000
9	0.350	0.350	0.200	0.000	0.000
10	0.250	0.700	0.400	0.000	0.000
11	0.300	1.000	0.200	0.000	0.200
12	0.550	1.150	0.400	0.000	0.000
13	0.600	0.580	0.250	0.000	0.000
14	0.350	1.600	0.200	0.500	0.000

Figure AB.1 Visual Documentation of the Lunares Analog Mission: Research, Experiments, and Astronaut Activities

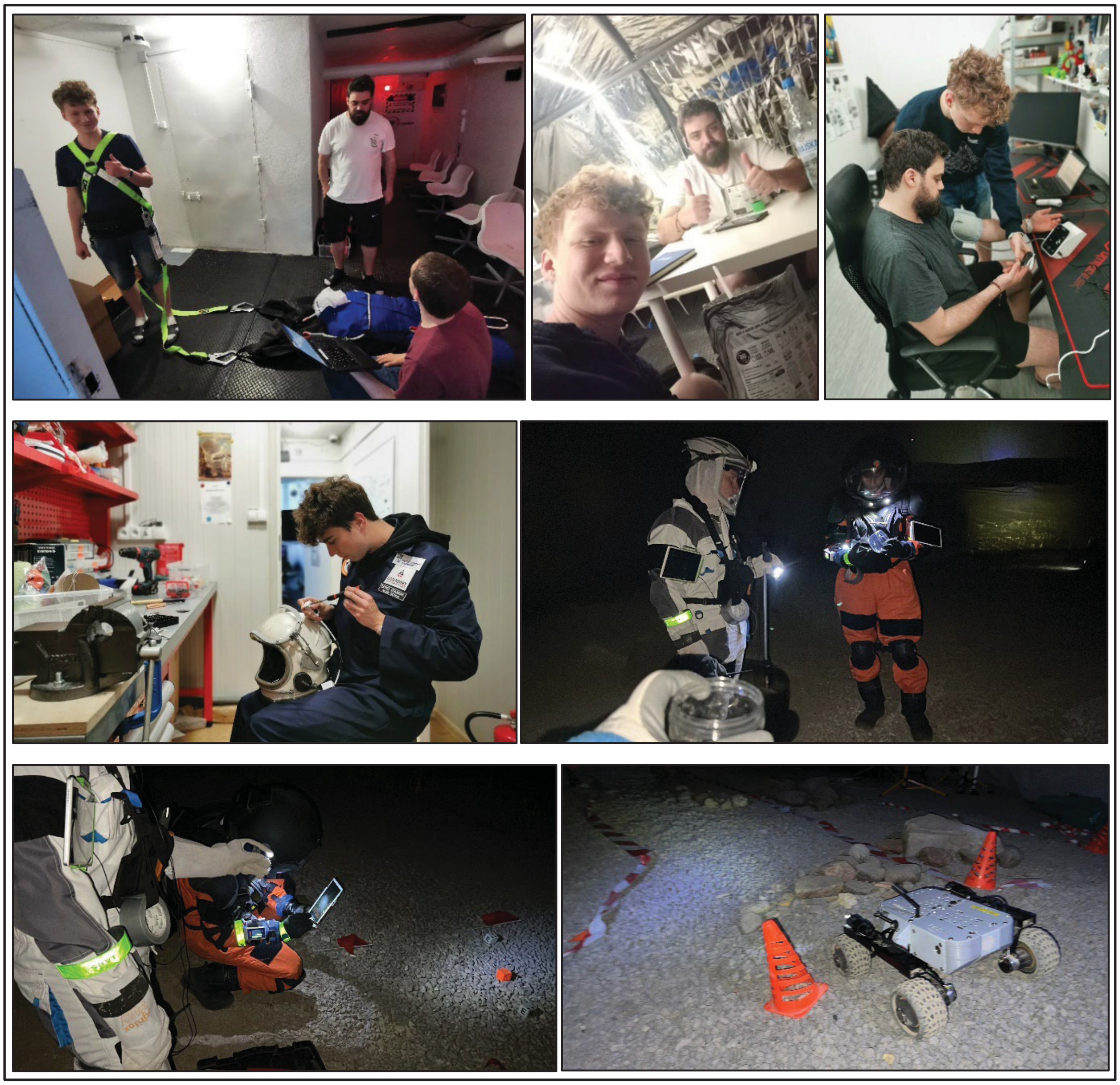


Figure AB.2 Visual Documentation of the Lunares Analog Mission: Research, Experiments, and Astronaut Activities

ANNEX I

CONFERENCE PAPER 2

DEAIGNING FOR THE EXTREME: COMPUTATIONAL STRATEGIES FOR ADAPTABLE AND SUSTAINABLE HOUSING IN NORTHERN CANADA PERMAFROST REGIONS

Yakine Zerrad[1] ; Ivanka Iordanova[1]

[1] Department of Construction Engineering, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
yakineer@gmail.com

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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 offsite 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.

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 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.

Background and Literature Review

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, 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 Eva Dyck et 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)

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. (Sadeghipour Roudsari & Pak, 2013; Zhou, 2020)

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, Thaddeus, & Scaccia, 2022)

Innovative Materials and Techniques

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 et 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 a complex building environment. These advancements play a role, in decreasing the impact of construction procedures while upholding top-notch levels of strength and flexibility.

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 onsite 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.

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 distinct structures: the Tupiq (figure AI.1a), a summer dwelling made from animal skins and supported by wood or whalebone, offering mobility for the following migratory game paths; the Igloo (figure AI.1b), constructed from snow with superb insulating properties to maintain warmth during freezing temperatures; and the Thule Winter House (figure AI.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 AI.1 Traditional Inuit Architectural Forms and Their Modern Relevance. (a), Tupic. (b), Igloo. (c), Thule winter house
Taken from Historica H. Canada (2020)

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.

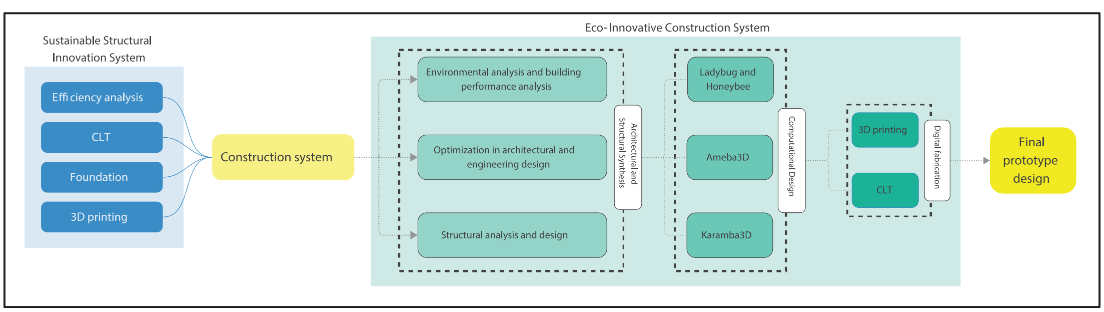

Figure AI.2 Schematic Overview of the Computational Design Workflow

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 AI.3, which showcases the Grasshopper script used in the design process.

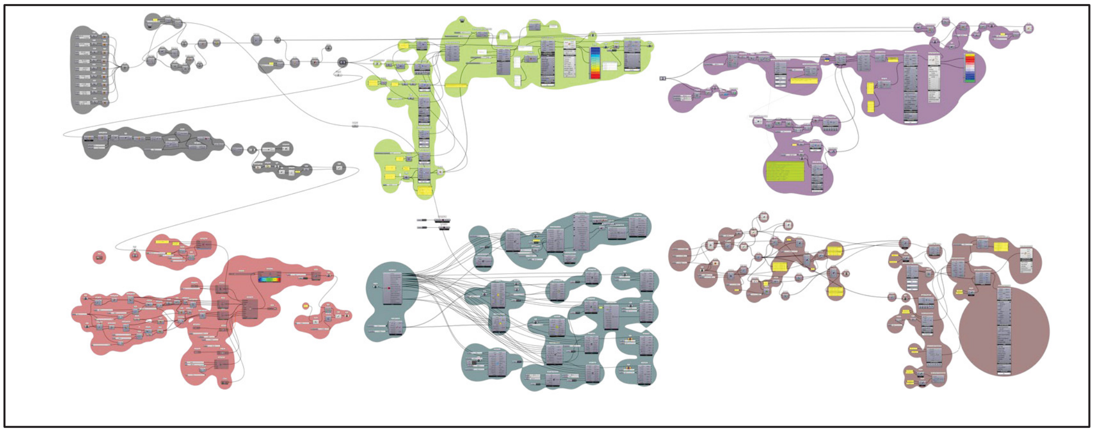

Figure AI.3 Parametric Design Workflow for Adaptable Housing in Arctic Environments

The envelope's optimization process utilizes stress and displacement analyses to guide material selection, as shown in Figure AI.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 AI.4b. Following the subframe construction, the steel structure designed to support mass timber beams is optimized for strength and durability, detailed in Figure AI.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 AI.4d. Simultaneously, environmental optimization by Ladybug, shown in Figure AI.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.

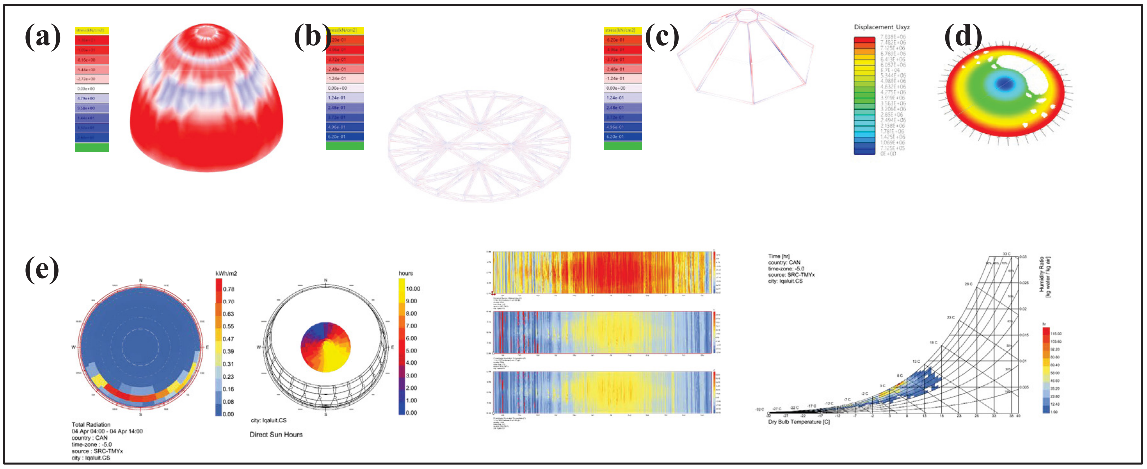

Figure AI.4 Computational Analysis of Building Design for Arctic Environments. (a), envelope. (b), steel subframe. (c), structure. (d), material. (e), energy.

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.

Design Proposal

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 AI.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.

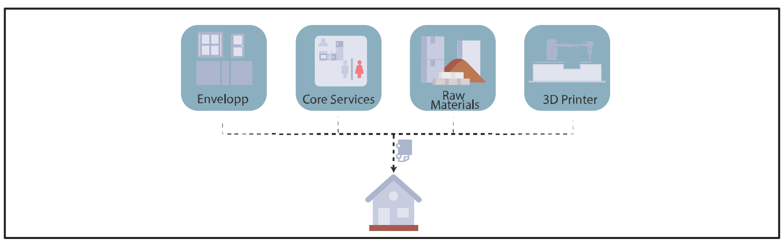

Figure AI.5 Integrated Construction Process Using Onsite 3D Printing and Offsite CLT Prefabrication.

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 AI.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.

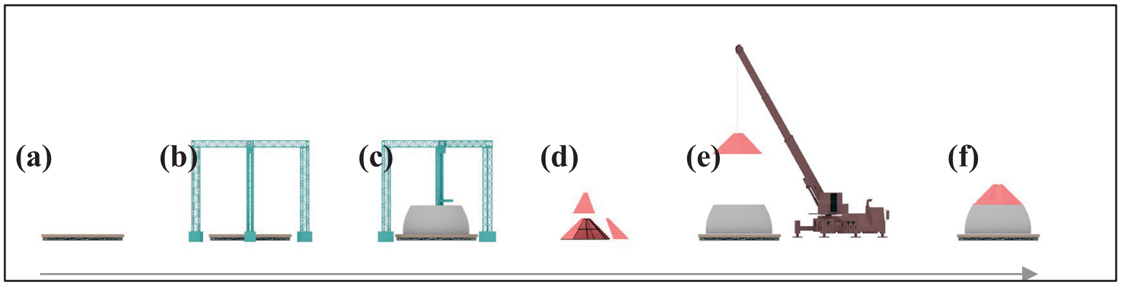

Figure AI.6 Sequential construction process. (a), base setup. (b), frame assembly. (c), 3D printing the structure. (d), assembling the prefabricated components. (e), installing the assembled structure. (f), final house

Program and Design

Figure AI.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.

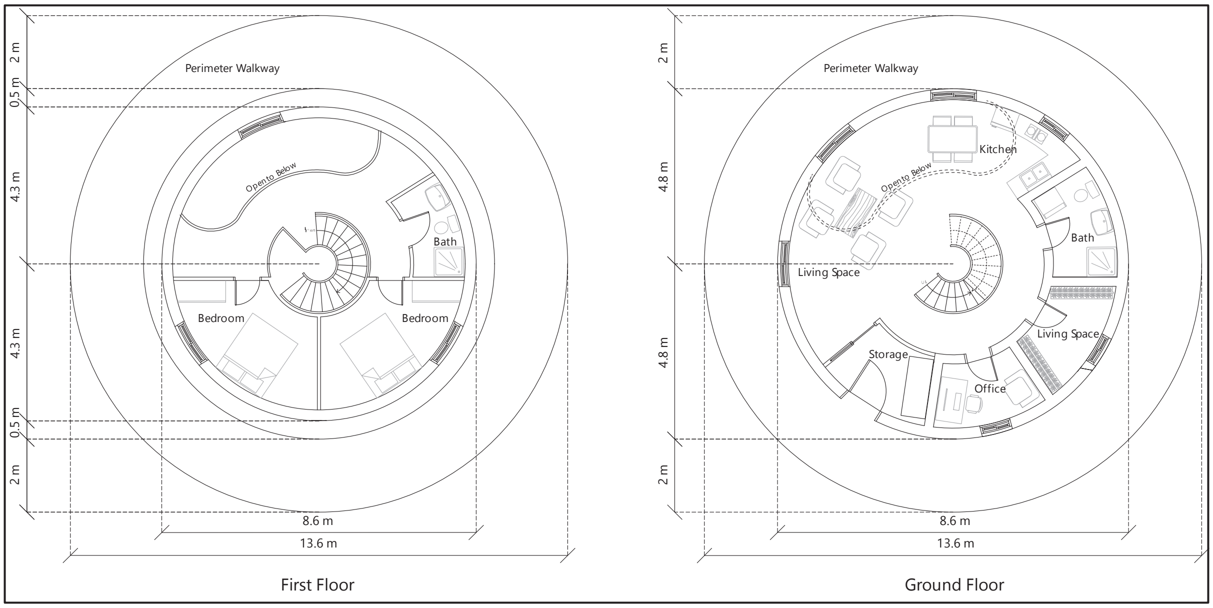

Figure AI.**7** Plans of the proposed design

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.

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, 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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