Role of Circular Economy in the Indigenous Built Environment: An Assessment of Design and Construction Potential of Circular Building Materials in an American Indian Community

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2020 by the
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ARIZONA STATE UNIVERSITY

August 2020

ABSTRACT

This thesis intends to help inform American Indian nations' decision making related to housing. The study recognizes the urgent need for housing solutions that fit the needs of a community as well as benefit the overall ecosystem. One model that can offer guidance is the Circular Economy (CE) model. A well-thought-out CE process can provide housing solutions that are economically, socially, and environmentally sustainable. It also stimulates the local economy by strategically introducing positive changes. This research identifies the construction potential of available circular materials as compared to more contemporary building materials. It then recommends a closed-loop circular model that utilizes the community's existing infrastructure to develop affordable housing. The proposed CE model operates within the built environment, stimulating local employment while catering to the needs of the residents. Such an approach can prove to be beneficial for the local community and perhaps scalable to the global economy.

I offer flowers of gratitude to Dattatreya and Ambama. I dedicate this thesis to my parents Virendra and Arti, and my parents' in-law Naresh and Smita for their blessings and sacrifices. It is a privilege for me to dedicate this work and convey my appreciation to my husband, Arshey Patadia, who has always been a source of strength and happiness in my life. I am grateful for his endless love, care and support, which has brought me to this esteemed stage. This would not have been possible without him.

ACKNOWLEDGEMENTS

I am incredibly thankful to my advisor Dr. Mounir El Asmar, for his continuous guidance and support for this research. I am grateful to Dr. El Asmar for encouraging me to work on this project and for his constant motivation. I thank him for giving me an excellent foundation in my construction management study. I want to express my gratitude to Professor Philip Horton and Dr. Marc Neveu from the department Architecture at Arizona State University. I thank them for being a part of my committee and providing valuable feedback regarding my research. I do want to thank Professor Philip Horton for all his help during my architectural graduate studies and for his expert guidance on prefabrication construction methods.

I am indebted to my industry mentor, Richard K Begay Jr, AIA, Architect, SPS+ Architects, for sharing his experiences and giving me the basis for my research. I want to acknowledge Richard's counselling and for enlightening me about the indigenous American Indian community's culture, and their traditional design practices. I am extremely grateful for his unparalleled assistance in making this research possible. I also want to thank the entire team of SPS+ Architects for equipping me with the experience, knowledge, and resources that I needed for my professional development.

Thanks, are also due to Professor Darren Petrucci for his inspiring conversations on innovative sustainable practices and for believing in me. My gratitude goes to Dr. Harvey Bryan and Dr. Rajesh Buch for introducing me to the sustainable built environment framework of circular economy and green building practices.

I want to acknowledge my friend Ladawn Bentley in particular, for helping me understand the Navajo culture and for her guidance throughout my research. I would also like to thank my friends and colleagues Rhonda Harvey, Namho Cho, Jeffrey Feghaly and Marcus Denetdale for their help and encouragement during my graduate studies. I appreciate the inputs of all my colleagues from the School of Sustainable Engineering and the Built Environment and The Design School at Arizona State University. None of this work would have been possible without their generosity and contributions in bringing this thesis to fruition.

And finally, I would like to express my gratitude to my parents for always having faith in me, supporting me in everything I did, and for making me the person I am today. I am grateful to my parents-in-law, for giving me boundless love, care and blessings, and for supporting me throughout my graduate studies and in life. I am thankful to my brother Harsh for keeping my eyes on the stars with my feet on the ground, and to my sisters Zankar and Rakshita, for their love and efforts in supporting me. I thank my husband, Arshey, for all his guidance and perseverance, for sharing my dreams and supporting me through thick and thin. I thank him for continually reminding me that together we can overcome any challenge we face. I am grateful for all his sacrifices, for making me a better person and for always being by my side.

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CHAPTER 1

INTRODUCTION

The selection of construction materials and the practices employed during the design and the construction stages of a building have the biggest impact on its overall carbon footprint as well as on the local community (ARUP 2016). A closed loop relationship with raw materials and available goods that promotes reuse and extends the life of manufactured components by repair, recycle, remanufacture can not only create local jobs but also benefit the overall sustainability of newly constructed projects (Stahel 2016). A demand for accelerated growth has led to the quicker completion of projects and higher profit margins within the design and the construction industry (Ellen MacArthur Foundation (EMF) 2013). This leads to the adoption of ecologically destructive development activities which are unsustainable (EMF 2015). By utilizing a Circular Economy (CE) model, the above issues can be addressed. CE aims to recognize the three pillars of sustainable development which are Economy, Ecology and Society. EMF defines CE as a framework that is restorative and regenerative, seeking to rebuild and conserve financial, manufactured, human, social, or natural capital.

1.1 Background

Implementation of CE practices within a built environment should be able to benefit the local community (Stahel 2016). Tribal communities in particular have been shown to benefit from adoption of sustainable housing practices (Blosser et al. 2014). In addition, due to sparsely populated regions, many tribal communities lack access to affordable housing options. Blosser et al. (2014) also highlight a shortage of employment opportunities in the tribal regions.

Many tribal residents lack basic infrastructure due to their remote location (NHA et al. 2011). They tend to utilize easily available low-cost materials for building houses (GAO 2014). Homes typically are constructed using standard materials, mobile trailers and have various other structures that make up a homogenous landscape within the tribal lands. (Begay 2005). The material selection can restrict creative ideas and confine these houses to old building techniques. Their traditional structures include hogans, livestock corrals, sweat lodges, among other standard dwellings (Jett et al. 1981). Their remote location can result in the absence of professional contractor services which may result in poorly constructed houses and unsafe living conditions (Seltenrich 2012).

1.2 Thesis Scope

A sustainable off-grid high performance housing option can be beneficial for tribal residents, but it is neither affordable nor available. Establishing a circular approach for providing low cost housing and accessible amenities can help create jobs and boost the local economy. This is one of the motivations of this thesis.

Since trained construction professionals may not be readily available in many remote locations, prefabricated building modules can equip the design and construction teams with creative approaches. This can not only result in affordable buildings, but also facilitate speedy construction in remote locations (Smith 2010). Building using prefabricated materials can have up to a 40% lower carbon footprint as compared to traditional building practices (Quale et al. 2012). Prefabrication enables easier adoption of sustainable materials while assuring reliable quality, which is necessary to maintain the building’s structural integrity. Since the necessary training for assembly is relatively easy and fast, utilizing prefabricated elements in the construction process can also lead to higher participation from the local community further enhancing the local economy (EMF and ARUP 2019). Prefabricated modules can be easier to assemble and dissemble, enhancing their reusability and facilitating a circular process. This concept will be explored and implemented in this study.

The context of the research will be the American Indian Community of Navajo Nation (NN). The Housing Needs Assessment and Demographic Analysis report (NHA et al. 2011) identifies the housing needs as well as the lack of employment options for the tribal residents. This study draws inspiration from the centuries-old closed-loop process of corn harvesting and utilization followed by the Diné families of the Navajo Nation. The closed-looped process reflects traditional teachings of limiting food waste, in which the loop begins with corn harvesting and gathering of the pollen. The corn stalk is considered sacred and used in many traditional ceremonies. During winters, the remaining stalk is used to feed livestock (Begay 2005). The manure and the leftover corn stalks decompose and return to the earth as they are not overly processed. This tradition seems to be closely aligned with CE principles. The Diné (Navajo) people have also explored strawbale as a building material. It is readily available as a regional material since it is grown and harvested near the Four Corners region of the United States through the Navajo Agricultural Products Industry (NAPI).

Moreover, the U.S. Agriculture Improvement Act of 2018 (also known as the 2018 Farm Bill) enabled NAPI farms to further expand their portfolio into growing hemp locally. They are experimenting with hemp farming for the possibility of commercialization. The development of hemp into a building material also provides work opportunities for community members who lost their jobs due to the recent closure of the

Salt River Project's Navajo Generating Station (NGS), a major employer in the region (SRP 2019).

The local availability of hemp and its versatility as a carbon negative building material makes it an appropriate and perhaps natural choice of material to use in the development of affordable housing (Arrigoni et al. 2017; Elfordy et al. 2008). Using circular materials that are grown and processed within the community's infrastructure create job opportunities as well as recognizes longstanding farming practices. With an established prefabrication ability of hempcrete (Magwood 2016), it has the potential to answer many of the issues discussed above, hence laying the groundwork for this thesis.

1.3 Thesis Outline

This thesis identifies a potential circular ecosystem within the NN, by utilizing hempcrete as an economically viable and ecofriendly building material. This thesis will analyze and select circular building materials for construction from locally available options. After choosing the building materials, the thesis will review cultural aspects affecting the housing styles of the tribal community. In order to develop the CE model, a few customizable and affordable dwelling designs will be suggested. The construction process of these dwellings will also be discussed with a focus on the prefabrication, assembly and disassembly process. The sustainability of this dwelling will be analyzed and finally the value proposition of the CE model will be discussed.

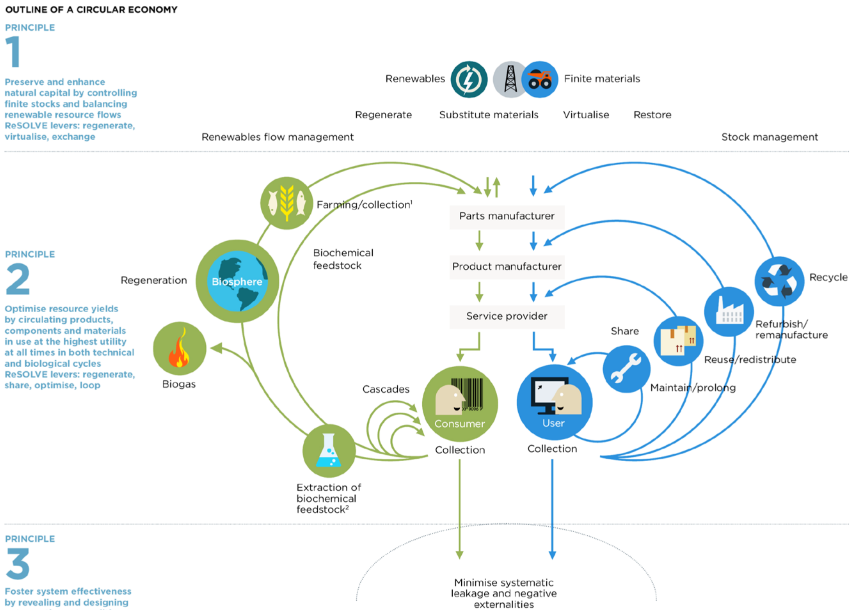
CHAPTER 2

THE CONCEPT OF CIRCULAR ECONOMY

This chapter presents a comprehensive literature review of CE and its role within the multiple facets of a built environment. After determining the built environment domain for this thesis, this section further identifies the impact of CE at different phases of the design and construction process. The basis of this section is to set the groundwork and study the advantages of employing CE during the early design and construction phases. This can not only lead to a reduction in GHG emissions but also result in faster building times and potential cost savings.

The Brundtland Report states that development that meets the needs of the present generation without compromising the ability of the future ten generations to meet their own needs categorized as sustainable development (Keeble 1988). The pursuit of growth and development during the industrial revolution resulted in a fast-paced expansion across all industries. United Nations reports that population growth has fuelled an ever-increasing demand of natural resources which are being extracted unsustainably (Gálvez-Martos et al. 2020). A never-ending demand caused the global supply chains to adopt a make-use-waste ‘linear production’ model (EMF 2013). CE is centered on the three main principles: Reduction, Reuse, and Recyclability (3R).

Figure 1 outlines this concept. EMF defines CE as an amalgamation various approaches to sustainability following the 3R approach.



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Figure 1. Outline of Circular Economy by Ellen MacArthur Foundation (2013)

A CE refers to an economy that is restorative and regenerative. It's an economy that is focused on the future, and in turn focused on positive society-wide benefits. To help achieve this, Elkington (2013) suggests that corporations follow the "Triple Bottom Line" (TBL) approach instead of thinking just about profit as the bottom line for a product or a process. TBL consists of profit, people and planet, thereby looking not only at the financial performance of the corporation but also at the social and the environmental performance over the given period. The CE design and construction approach aims to do just that (Ghisellini et al. 2016). The concept is based on three principles: 1) Eliminate waste and pollution; 2) Maximize the use of products and raw materials; 3) Regenerate the natural systems. A CE aims to do this by distinguishing between both technical and biological cycles. Consumption takes place in biological cycles, where items like food, cotton, and wood are designed to ultimately be fed back into the system at the end of their use through processes like composting. Technical cycles refer to the recovery, restoration or simply reuse of products, components, and materials. Recycling is often considered as a last resort since it would entail additional resources. The circular model is centered around several schools of thought, which are summarized in detail below.

William McDonough and Michael Braungart are the visionaries behind the concept of Cradle-to-Cradle design approach and the Cradle to Cradle Certified^{TM} Product Certification. (In the following study referred to as Cradle-to-Cradle Program (C2CP) as per Minkov et al. (2018)). This method considers all materials involved in commercial and industrial processes to be nutrients. The idea of “biological metabolism” eliminates the concept of waste, maximizes the use of renewable energy, and controls the impact on natural systems (McDonough and Braungart 2010).

Janine Benyus defined her philosophy of Biomimicry in her book, Biomimicry Innovation Inspired by Nature. This concept relies on three principles: (1) Nature as model, (2) Nature as measure, (3) Nature as mentor. Nature as model refers to studying nature’s models and applying these forms to human problems; Nature as measure refers to using ecological standard to judge human innovations; and nature as mentor refers to viewing and valuing nature based on what we can learn from the natural world (Benyus 1997).

Amory and Hunter Lovins and Paul Hawken are the three authors behind the book Natural Capitalism: Creating the Next Industrial Revolution. From this book came their concept of Natural Capitalism, which applies the human world of stocks and assets to the natural world. According to Natural Capitalism, nature’s assets include soil, air, water, and all living things (Hawken et al. 1999).

Walter Stahel is an architect and industrial analyst who started the concept of Performance Economy, in which emphasis is placed on selling services rather than goods (Stahel 2008). Reid Lifset and Thomas Gradel started the Industrial Ecology school of thought, which is focused on connections between operators within the industrial ecosystem. This approach is centered on using waste as input, to create closed-loop processes (Lifset and Graedel 2002). Gunter Pauli started the Blue Economy movement, which refers to using available resources to create new cash flow. The concept is based on 21 founding principles that link solutions to local environment (Pauli 2010). Lastly, regenerative design, or circular economy is said to be started by John T. Lyle, who applied the idea of recycling and reusing materials to all systems, beyond agriculture (Lyle 1996).

These various guidelines of CE follow similar principles and have the same end goal. EMF (2015) identify six different methods to apply circularity: Regenerate, Share, Optimize, Loop, Virtualize, and Exchange. Every CE school of thought mentioned above fall into some or all of these six categories. Regenerate focusses on maintaining as well as enhance the overall biocapacity of earth. In the built environment this is done by utilization of renewable energy and focusing on land restoration and resource recovery. Share guides to utilize the available resources (buildings) to their maximum. Optimize directs to optimize processes and material utilization employing off-site production techniques like prefabrication. Loop advises to reuse resources after they have been recycled and replenished which is commonly seen in modular buildings. Virtualize instructs to dematerialize, both directly as well as indirectly in order to reduce the overall material dependency. In the built environment this can be done by using BIM modeling to assist with faster building times and use of smart home systems to increase house performance. Exchange guides users to update, upgrade, and evolve the older methodologies and materials to utilize more efficient, greener options for an overall sustainable design and construction process.

2.1 Literature Review on Circular Economy in the Built Environment

The literature on CE in the built environment and in construction sector is still in its early stages. Crowther (2001) provides a built environment scenario with a circular business model where the 3R strategy is applied to a linear building construction process. This model encourages design for disassembly in order to establish a circular process. This can result in repurposing of the entire building, reuse of building components, manufacture of components from waste materials and recycling of existing components into raw materials. Figure 2 illustrates the proposed circular loops that can be applied at the end of life stage of this process. A recent study analyzes the economic potential of construction and demolition waste by implementing a similar closed loop process for a building (Aldaaja 2019).

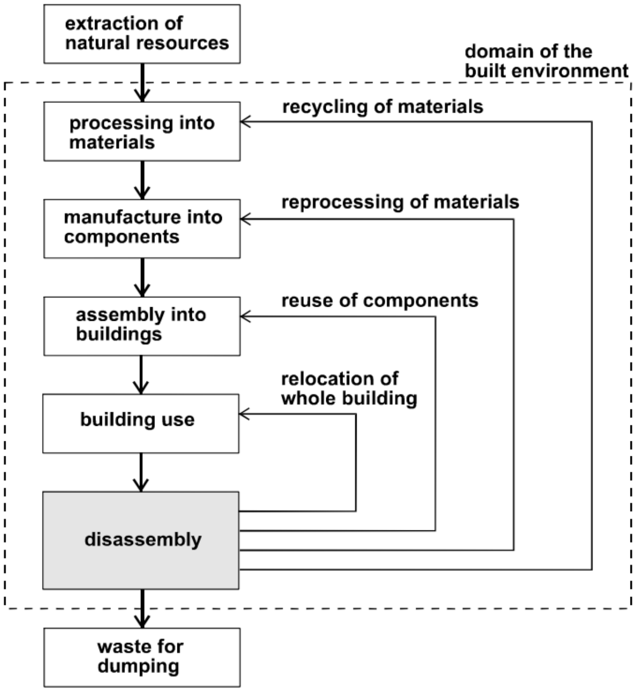


Figure 2. Possible End of Life Scenarios for the Built Environment (Crowther 2001)

A holistic circular ecosystem can be only be achieved when sharing and collaboration between various stages and their stakeholders of a construction process is enabled (ARUP 2016). This systems level thinking closely works with the local and global economic cycles. This enhanced circular model of a built environment is the outcome of having an ecosystem system wide perspective during construction like design of the building, sourcing of raw materials, construction process, operation of the building, renewal and repurposing of spaces, end of use demolition or disassembly and finally repurposing of raw materials in order to maximize their use. Such a closed loop economy can result in a 70% reduction in greenhouse gas (GHG) emissions while providing employment opportunities within the economy (Stahel 2016). Figure 3 depicts an implementation of circular economy at a systems level by closing as many loops as possible within a built environment.

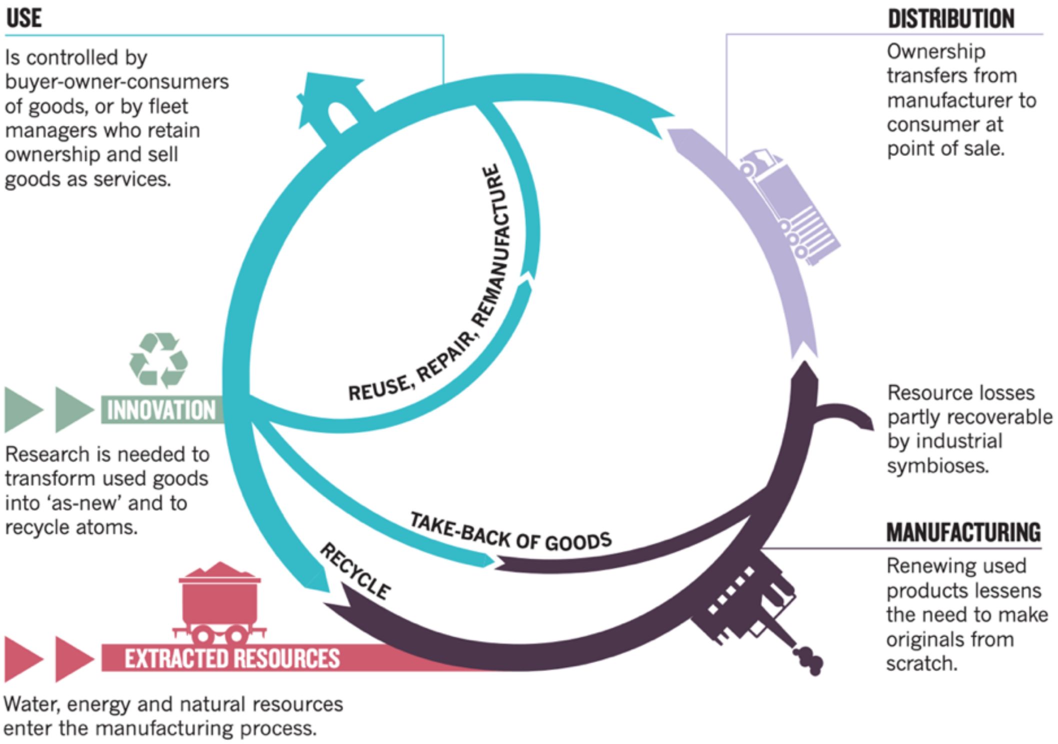


Figure 3. Systems Level CE Loop (Stahel 2016)

A recent article attempts to provide a framework that categorizes various domains within a built environment from a circular economy perspective (Pomponi et al. 2017). It presents a systemic perspective classifying buildings at a meso-level and its building components at a micro-level of the frame of reference. As seen from the

Figure 4, the urban infrastructure of neighborhoods or cities that encompasses various smaller level localized processes, is classified under the macro-level of the framework within the built environment.

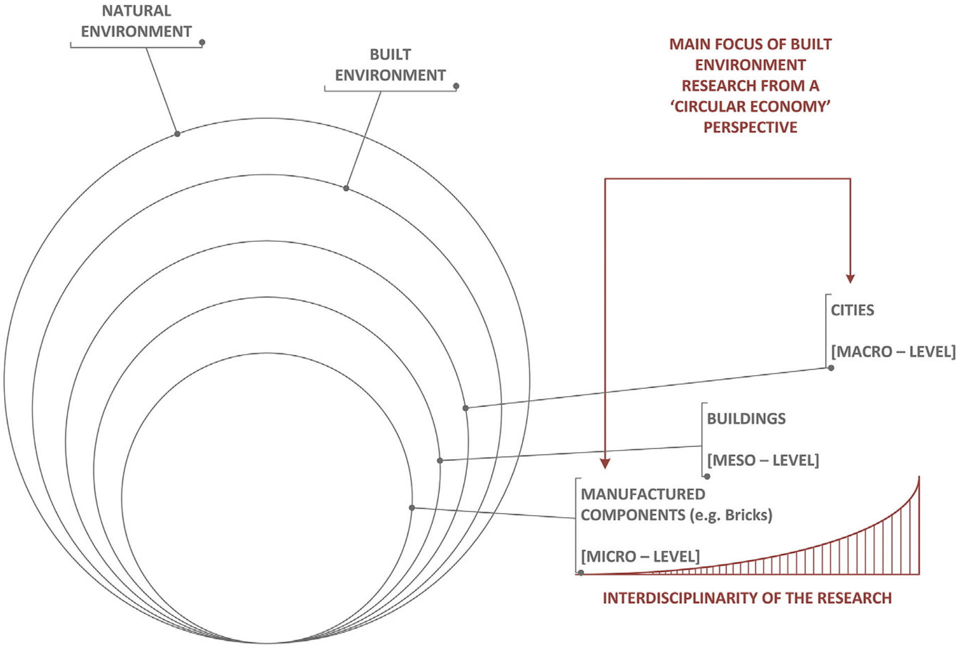


Figure 4. Framing of Built Environment Research (Pomponi et al. 2016)

The authors explain how most of the current research about CE in built environment can have varying theoretical boundaries due to absence of well-defined framework and lack of interdisciplinary research. The built environment boundary for the purpose of this thesis will be at a neighborhood level or a community level similar to the one discussed by Stopwaste and ARUP (2018). This can be scaled up to the macro level as shown above in the chosen context due to the sparsely populated nature of tribal communities. This thesis will adopt an interdisciplinary approach in applying CE principles for a chosen built environment domain.

2.2 Role of Architecture and Material Selection in a CE

Designers and architects support a circular economy by selecting sustainable products, including researching those with recycled content and avoiding those that cannot be recycled (Lauritzen 2018). Designers and architects can recommend materials that are certified by programs such as Extended Producer Responsibility (EPR) and C2CP thereby increasing the ability for materials to be reclaimed. Architects can develop sustainable designs that can be disassembled during demolitions, and with materials that can be recycled. When the reclaim of waste materials is appropriate, manufacturers are able utilize them for future production. A CE is a result of designers executing their decisions with a futuristic vision that ensures a holistic solution to all sustainability pillars. Figure 5 shows how the carbon reduction potential of a process or a product at various stages of its life cycle.

Tackle carbon early

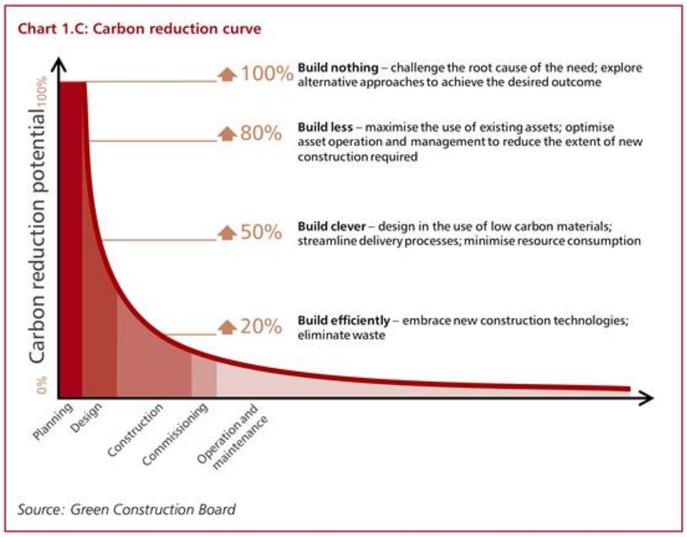


Chart 1.C: Carbon reduction curve

Source: Green Construction Board

1.8 You can reduce carbon at any point in the delivery process, but the opportunities are greater the earlier you start. Adopting the concepts of Chart 1.C above may require clients, consultants, contractors and suppliers to rethink some of their business models, many of which are fundamentally based on creating assets. However, helping clients to avoid construction, with its attendant cost and emissions, opens up new business opportunities.

Figure 5. Carbon Reduction Curve (Infrastructure Carbon Review 2013)

Designers and architects can help divert waste by utilizing sustainable practices. Effective planning from beginning stages of a project can result in divergence from the make-use-waste model. Design professionals with the knowledge about circular economy can advocate for closed-loop systems whereby reusing, recycling, and repairing can increase the life span of a product. Proper planning of waste disposal from demolition materials ensures the ability of materials to be recycled as they will not get contamination with food and liquid waste (Lauritzen 2018). Disposal of wastes in bulk adds expenses to the recycling company; therefore, architects and designers should plan appropriately for the disposal of waste. When building companies have consistent practices in recycling, they build a good relationship with the recyclers. The reuse and recycling of waste can bring change in an economy at the first step. The waste from construction is usually voluminous making them one of the offenders facilitating to filling the land with waste. According to the United States Environmental Protection Agency, approximately four hundred and eighty-four million tons of debris comes from construction and demolition more than the waste from the municipal council (USEPA 2014).

Due to population growth, there is an increase in the extraction of natural resources unsustainably, according to the United Nations reports (Gálvez-Martos et al. 2018). Materials that are sourced globally have the issue of generating heavy carbon dioxide emissions and have a negative impact on the environment. The International council on clean transportation (2017) reports that shipping activities constitute to eighty-seven percent emissions whereas as domestic transport result in nine percent. The global market fluctuations dictate the markets for recycled materials, thus creating challenging times for the companies. By selecting locally available materials, designers can help improve the environment as well as the economy since it results in job creation within the local communities. Correct implementation of a circular economic model in the conduct of daily transactions can generate long term benefits.

Products from a closed economy are durable, safe, and easily reused or claimed at the end-use stage. Healthy Building Network provides guidelines for making safe products by limiting and optimally displacing all prospective hazardous chemicals. The whole process is to ensure that reduced negative impacts on consumers. By utilizing prefabricated units in their designs, architects can help reduce the carbon footprint of the construction while achieving faster built times. Practicing sustainable manufacturing and designing for quicker manufacturing of products can further save time during recycling processes. A circular design can result in sustainable production of durable, quality, and recyclable products. The increased life cycle is due to designing for durability when manufacturing products that have a long life will ease recycling in a closed-loop economy (Gálvez-Martos et al. 2018).

Design professionals can include recycled goods during their developmental phase of a project. With the choice of durable goods, their reclaim and reuse value is increased. Therefore, designers can improve reclaiming of discarded materials. Designers with knowledge about the circular economy are able to better plan for the future of a project. By choosing materials that are easy to assemble and disassemble they can ensure material reuse. The choice of prefabricated materials can help with this (Smith 2010). All sectors of the economy need to be made aware of circular economic practices through education about choosing a sustainable product. Standards like Living Building Challenge (LBC) implores design professionals, contractors, and building owners to create a foundation for a sustainable future.

Property owners can be guided by architects to become aware about their choices as well. By investing in circular practices, they create long-lasting positive impact on the environment and can also reap a better future reward. When organizations select durable components in the process of construction it ensures longer life cycle of the building

(McKinsey 2014). With a focus on future demolition or disassembly, use of biodegradable or recyclable products should be encouraged. Operations that contribute to vast profits may be hard to change even if they are not sustainable (Lauritzen 2018). Therefore, managers should consider the circular economy principles when planning for the future, resulting in companies to compete efficiently. Practicing responsible business socially and environmentally differentiates an organization from others and promotes similar practices by others in the sector (Stahel 2008).

Transparency by designers to the consumers can drive essential market developments in the circular economy. Transparency in the products allow the consumers to evaluate every purchase they make with a sustainable mindset. Eco-friendly options are associated with a higher price, which is the primary factor for one to make a purchasing decision. Therefore, consumers usually research on all decisions made about prices. Designers and architects facilitate in selecting building materials that are sustainable. While, transparency can impose an initial financial burden, but it assures stakeholders that their building is healthy, safe, and environmentally friendly (Stahel 2016).

Architects have a responsibility to not only design for profitability but also for sustainably. In a CE Architects can encourage selection of building materials that are reusable and recyclable. They minimize raw material consumption by efficient design and select green certified components. A CE can reward designers by offering credits based on the selection of sustainable components (ARUP 2018). By including prefabricated materials in their designs, Architects can ensure low GHG emissions, cost savings as well as high components reuse (Smith 2010). By offering solutions to similar problems that owners might not be aware of, these projects stay up to the code and do not harm the environment. Restrictions and planning for the recycling of building materials in the demolition phase is a priority because it directly reduces contributions to landfills and increases the likelihood reclamation is done correctly within time restrictions (Aldaaja 2019). By including prefabricated materials in their designs, Architects can ensure low GHG emissions, cost savings as well as reuse of components after end-of-life of a building (Infrastructure Carbon Review 2013).

2.3 Role of Prefabrication in Sustainable Construction

While design and development teams pursue more reliable, cost-effective approaches to meet the demand for affordable housing, both Architects and Contractors are becoming more cognizant of the selection of materials and their impact on our planet. According to the World Economic Forum (2016), the construction industry is the world's largest raw materials consumer. It is also one of the largest wastes generating and carbon-producing industries (Kucukvar et al. 2013). In a world facing the imminent issue of global warming, the idea of the CE is becoming increasingly relevant in the construction industry by means of materials and components being used. Modular construction, or prefabrication, has evolved from this concept, in which the manufacturing process takes place within a facility rather than on site, to allow for various materials to come together in a controlled environment (Minunno et al. 2018). Smith (2010) details about how the availability of prefabricated materials can result in sustainable low-cost homes. He further points out that CE theories like C2CP, waste=food and biomimicry have a greater chance of success when incorporated in a prefabricated module. Some of the benefits of modular construction are discussed below (Wilson 2019).

Because modular construction takes place in a controlled setting, there is more opportunity for Higher Efficiency and Quality-Control. The three-fold process of design, manufacturing, and construction can be streamlined within a single controlled environment to heighten efficiencies and improve quality (The Modular Building Institute 2010). With the construction process taking place indoors, there is less risk of moisture collecting in materials and a longer period of off gassing of VOC's from adhesives, sealants, and finishes before occupants enter the building (Wilson 2019).

The conventional construction process often results in unforeseen obstacles that can significantly impact budget and resources. With modular construction, net waste can potentially be cut in half. With the process taking place in an optimized, controlled environment, there are fewer errors resulting in less damage and costly hurdles. Within factories, this process can also help with inventory control, and utilize lean production principles (Boston Consulting Group 2019).

Modular construction allows for a longer life cycle of the building. Over a long period of time, it also helps in reducing the energy and carbon costs. While this type of construction will require more materials, the amount of waste is decreased, resulting in higher cost efficiency in the long-term (Faludi et al. 2012).

One of the bigger benefits of modular construction is its reduced impact to the environment and energy used for construction. Factories have more control over energy use and emissions than traditional construction sites. In addition, factory settings require fewer workers needing transportation and accommodation and fewer power tools and lighting, all of which contribute to overall energy use (ARUP 2010). Performance and operational efficiency are improved with modular construction, as the factory setting allows for increased quality and precision of functions. Thermal insulation is improved with air-tight joints and seams, when manufactured under factory conditions, potentially resulting in 15 to 20% of reduced operational costs (MGI 2014; Buildoffsite 2013).

Fewer workers are needed on site in modular construction. This results in less transportation-related impacts, including emissions, noise, and air pollution. The impact is significant, with a reduction of 90% of total deliveries to sites and 75% of travel distance of workers travelling on site (WRAP 2007). On conventional construction sites, workers are subject to many risks, including environmental factors like heat, the operation of heavy machinery, and working at dangerous heights. Modular construction result in lesser worksite risks and injuries. Factory workers face less safety issues as compared to construction site (Buildoffsite 2013). There is less disruption to the community with modular construction, as the construction process is generally shorter, noise is decreased indoors, and pollution is minimized without the use of trucks and material storage (Pomponi et al. 2017).

Modular construction is more flexible than conventional construction in that buildings can be easily adapted or modified into components that can be reused and recycled. This type of construction is better designed to accommodate the needs of the future (Minunno et al. 2018). Modular construction can result in higher resilience. Buildings can be constructed with more affordable design features to withstand environmental factors, such as wind and earthquakes. Like conventionally constructed buildings, modular buildings can be designed to be wind and earthquake resistant, with the added benefits of ease, flexibility and affordability (Keeffe et al. 2014).

A study by McKinsey Global Institute (MGI) (2014), compared conventional construction to the modular construction approach. They found that a multi-family housing project, can be constructed in half the time it would take with traditional construction. This can increase the number of houses being built while helping with the rising cost of ownership. Modular construction approach can be the solution to affordable housing. Being much faster, and more cost-efficient approach, often reporting a 25-30% reduction in the time required to construct and commission a building. This naturally reduces financing costs, as the process requires less time to complete (MGI 2014).

This chapter demonstrates the potential increase in construction efficiency and sustainability of a project by implementing the CE model right from the early planning stages of a project. Some pieces of literature show the direct link between the material selection, GHG emissions and the carbon footprint of the building, which will be further explored in Chapter 4 of this thesis. Many reports discuss the importance of construction using prefabricated materials in CE.

The chapter recognizes a gap in CE studies that are focused on tribal built environments. Even though most of the literature is based on contemporary settings, it shows that the implementation of CE could be a potential solution for some of the issues discussed in the previous chapter. The next chapter studies the circular potential of the locally available materials in the Navajo tribal region and their potential for the reuse as building components.

CHAPTER 3

RESEARCH OBJECTIVE AND METHODS

The objective of this research is to investigate circular construction materials, including their design and construction methods, to inform tribal nations as they remedy current housing shortages while identifying opportunities for local residents. Even though many aspects of tribal family life seem to be aligned with circular concepts, there is a noticeable absence of research on how CE can benefit housing in tribal communities. This study will attempt to provide a path to bridge that gap and utilize CE principles to provide an affordable, sustainable, versatile and customizable housing solution.

The background of this report focuses on the latest developments within the NN that were obtained via published reports and media articles. The study although not done in partnership with the Navajo Housing Authority (NHA) or any tribal representative of the NN, aims to serve as a report in identifying the potential opportunities within their community. The intent is to support the Navajo community with the study as a theoretical proposal.

The thesis identifies a potential circular ecosystem that can be economically viable, culturally representative and environmentally beneficial for the Navajo community. A successful circular process has the potential to benefit the local economy, the tribal society and the overall ecology of the region. This study aims to follow CE guidelines to achieve the research objectives. Table 1 illustrates the step by step approach of this study.

Table 1. Research Method

Role of Circular Economy in Indigenous Built Environments	
Step 1	**Circular Economy review**
	Comprehensive review of CE in the built environment
	Review the literature on the role of architecture and material selection in a circular economy
	Review the literature on the role of prefabrication in sustainable construction
Step 2	**Identifying locally available materials and review their properties**
	Literature review of circular building materials available in Navajo Nation
	Compare the construction capability with contemporary building materials
	Study C2CP potential of the local materials
Step 3	**Design for a Circular Economy**
	Prioritize a material system for design and construction
	Perform case studies of Navajo architecture
	Propose a dwelling design using CE guidelines
Step 4	**Investigate social, environmental and economic impacts**
	Identify the cultural values desired by tribal members resulting in social sustainability
	Utilize green building practices for environmental sustainability
	Implement prefabrication practices for an efficient, responsible and profitable construction process resulting in economic sustainability
Step 5	**Propose a circular model within the local economy**
	Identify the strategies used in the proposed CE model
	Identify the potential value created due to the proposed CE model

The first step was to thoroughly review various CE guidelines and their implications from the available literature. This included identifying the various approaches to a CE for a built environment. It also included identifying various entities within a built environment that allows for a top-down or a bottom-up CE approach. The literature was then searched for roles played by various entities while developing a CE process and identified their key contributions.

The second step identifies locally available building materials. The intent was to collect data accessing their construction viability and compare them to commonly used contemporary building materials. After that, further research was done accessing their potential to be certified by green product standards like the C2CP or the Living Product Challenge (by the International Living Future Institute).

The third step determines the material system that would be best suited to establish a CE within the chosen ecosystem. Then, two case studies identifying the cultural factors affecting Navajo architecture are reviewed. Finally, a conceptual design for a residential dwelling is proposed which follows CE principles.

In step four, an analysis of the proposed building with respect to the three sustainability pillars is conducted. Stage one discusses the cultural relevance of the design in order to achieve social stability. Stage two focusses on the achieving environmental stability by means of implementing green building practices. Stage three analyzes for the economic viability of the construction process.

The final step of the study will identify the value that can be created within the proposed CE process. It will also explain the CE strategies used at various levels within the built environment domain.

CHAPTER 4

FINDINGS PART 1: PROPERTIES OF THE AVAILABLE MATERIALS

Indigenous communities have built homes using locally available materials throughout history. Utilization of native materials in construction has a significant impact on the carbon footprint of the project. It also benefits the local economy and hence further enhancing the overall sustainability (Stahel 2016). A few environmentally low-impact materials that are currently being used in tribal housing are timber logs, sage bush branches, clay, adobe brick, strawbale, rammed earth, and recycled wood (Corum 2005; Grant 2018). This chapter will study adobe brick, rammed earth, strawbale, and wood, to analyze their potential for a green product certification like C2CP.

Another environmentally low impact material that is being manufactured and used in tribal construction in northern Arizona is the Navajo Flexcrete. The U.S. Agriculture Improvement Act of 2018 (also known as the 2018 Farm Bill) has enabled the NAPI farms to grow hemp for various applications. This provides an opportunity for development and manufacture of Hempcrete as an ecofriendly alternative building material. Both Navajo Flexcrete and Hempcrete will be included in the study of circular potential of along with the construction materials mentioned earlier.

4.1 Literature Review of Locally Available Eco-friendly Materials

The following literature review analyzes the potential of these materials to be certified in one of the many green product certifications available. The scope of this research focus on their ability to follow the C2CP guidelines. Table 2 gives a brief outlook on the materials in focus and the literature related to their potential in being C2CP certified construction materials. The physical properties of these materials differ from each other; but their building components can be compared with those made from contemporary materials. This comparison is explored later in this chapter based on the similarity in the applications of each component.

Table 2. Selected Relevant Articles from Literature Review

Material	**C2CP Potential References**	**Construction Potential References**
Navajo Flexcrete	Ackerman et al. (2014) Malnar et al. (2018)	Creamer et al. (2004) Huber et al. (2016)
Adobe Brick	Christoforou et al. (2016)	Austin (1984)
Rammed Earth	Kitriniaris (2018)	Ben-Alon et al. (2019)
Strawbale	Hall (2019)	Rodrigues (2015) Corum (2005)
Wood/Timber	Vogtländer (2010) Van-der-Lugt et al. (2016)	Bongers et al. (2013)
Hempcrete	Bedlivá (2014) Berni (2019) Elfordy et al. (2008)	Isohemp (2019) Yu et al. (2005) Justbiofiber (2012)

4.1.1 Navajo Flexcrete

Thoughtful steps must be taken to choose products with fewer environmental impact. It is necessary to understand the materials' typical building application along with their entire lifecycle analysis, including production, distribution and recyclability. Navajo Flexcrete guarantees Navajos' supply of building materials while building social and cultural resources, helping to advance energy-efficient housing. This material offers an opportunity to use waste generally returned to surface coal mines. Its use as a building material not only reduces the stress on mining and manufacturing other building materials, but also reduces the use of other natural resources associated with them (Malnar et al. 2018).

One hundred twenty-five million tons of ash was being created every year by the coal-fired power plants like the Navajo Generating Station in Page, Arizona. NHA manufactured the Navajo Flexcrete building blocks by using the fly ash from NGS power plant. Every year, half a million tons of fly ash is collected from the combustion airstream. Sixty percent of the fly ash collected at power plants is generally landfilled or re-buried in the coal mines nationwide. But all the fly ash that was being created at the NGS power plant was trucked three miles down the highway to manufacture a unique building material called Navajo Flexcrete (Creamer et al. 2004).

Navajo Flexcrete is rigid and lighter in weight in comparison to concrete. Because of its aerated nature it has better insulation properties and fire resistance with an effective R-value of 23 F°sq.ft.hr/Btu (Huber et al. 2016). It is robust and also has an ability to act as a noise barrier. Flexcrete is a local and convenient option, making it a potentially good fit for construction.

About sixty to seventy percent of Flexcrete is comprised of fly ash, and the rest is an amalgamation of nylon and conventional cement. Even though nylon is not a recommended material due to its being sourced from crude oil, Flexcrete still has the potential to be certified if appropriate recyclability is achieved (Ackerman et al. 2014).

The NGS plant used to recycle about eighty to ninety percent of its fly ash in contrast to up to forty percent by an average US coal-burning plant. The recent closure of the NGS plant has forced the Navajo Flexcrete manufacturers to source the required fly ash from other nearby power plants.

4.1.2 Adobe Brick

Next, adobe bricks are discussed. Christoforou et al. (2016) examine different production scenarios that focus on the cradle to site Life Cycle Assessment (LCA) of adobe brick production. The scenarios include on-site production with locally available soil with transported straw or sawdust, on-site production with transported soil/straw and sawdust, and in factory production. They reported the results in terms of embodied energy and carbon per kg of adobe bricks produced. The results confirmed that transportation needs minimization, and locally available resource utilization significantly affects an adobe production system's environmental footprint. They also showed sawdust use instead of wheat straw leads to improved end-product environmental performance (Austin 1984). According to the authors, the application of LCA to construction materials provides a useful insight into the energy embodied in their production. It contributes towards informed decision-making regarding the choice of the most environmentally friendly product.

Adobe bricks have been in use as building materials since Neolithic times. Currently, they are used for restoration and traditional architectural conservation. The authors also claim it can promote contemporary sustainable architecture. Adobes are eco-friendly, cost-efficient, have high thermal mass, and are biodegradable — the potential of being energy efficient increases if renewable energy utilized. Wheat straw and sawdust are used in the adobe mixture as fiber additives to allow a comparative assessment of their effect in the environmental performance of the final product (Austin 1984).

To analyze and document technical options and alternatives to minimize the environmental impact of any process, the authors approached the use of LCA. LCA takes into consideration all the 'cradle-to-grave' inputs and outputs, starting from raw materials extraction to the disposal or recycling of the end-product. The author states the adobes or unfired clay bricks can be used as load-bearing materials in masonry. They are produced by mixing clay/silt-rich soil, organic fibers (e.g., straw or animal hair), and water to a plastic consistency. The mixture consists of volumes of roughly 20-25% sand, 60-70% clay/silt, and 20-30% organic material. The LCA of adobe brick production was implemented based on the principles described in the ISO 14040 standard and GaBi software was used to model the adobe production system in Cyprus and to investigate its environmental performance (Christoforou et al. 2016).

For environmental performance, the impact categories of GWP 100 (i.e., the Global Warming Potential in 100 years, measured in kg of equivalent CO2), ADP-fossil and MAETP present the higher values in the production process of adobe bricks. Christoforou et al. (2016) found that in all scenarios, transportation played a significant role in emissions, hence indicating the importance of establishing local economies for utilizing indigenously available resources. They also suggest sawdust as an additional additive to improve the physical and environmental benefits further. Overall, adobe bricks were a much better sustainable solution to other load-bearing construction materials.

4.1.3 Rammed Earth

Kitriniaris (2019) aims to adopt cradle-to-cradle regenerative design processes by using renewable energy sources as a solution to combine production efficiency with a healthier environment. The author discusses rammed earth as a sustainable building material through the example of the project “Earthwood.” The demonstration, along with renewable energy, utilizes other raw materials from sustainable recycling sources, including sewage sludge produced by Wastewater Treatment Plants, lightweight aggregates, and cement or lime generated by cement factories and structural timber fabricated by wood industries. This “Earthwood” attempts to integrate traditional building design methods with sustainable construction technology. Increased production of goods and multiplication of wastes simultaneously deplete the earth’s resources.

According to Ben-Alon et al. (2019), the increased sewage sludge global production from wastewater treatment plants has raised vital questions regarding the most efficient environmental and economical methods of managing the final product. It takes limited time to construct, i.e., 2-4 days; solar energy and sound water management make it self-sufficient; it is composed of recyclable construction materials that include structural cross-laminated timber and sewage sludge ash stabilized rammed earth. It, therefore, promotes economic viability and social responsibility, improving living conditions, ecological footprint minimization and ensures a positive impact on the environment and the community (Kitriniaris 2018).

In this paper, Kitriniaris (2018) connects the design’s reproductive process with environmental management, the circular economy, and waste management for the provision of sustainable buildings and landscapes. The author ultimately asserts that long-term and sustainable progress requires the balanced achievement of economic development, environmental performance, and social advancements. Rammed earth constructed wall is fully recyclable, no fume emission, fire resistance, and maintains humidity levels, enhancing microclimate, and improving living conditions. Using sewage sludge ash as rammed earth stabilizer mixed with cement or lime enhances pozzolanic properties of the loam to increase strength, reduce shrinkage, and create a waterproof layer. The construction process takes place in situ using a sliding formwork. The layers of moist earth, i.e., a mixture of clay, silt, sand, gravel, a 5% proportion of SSA, and a 5% proportion of cement or lime are added and compressed with compacting equipment. The construction gets finished with the removal of the sliding formwork, leaving visible layers of compacted earth (Ben-Alon et al. 2019).

The presented production model considers the increase in population, leading to a constant increase in product manufacturing to meet the technical and biological needs. This addition, in turn, leads to increased waste production, consequently diminishing natural resources. Therefore, the recommendations lie in an effective production process in combination with a healthier environment by adopting circular reproductive design processes and the exclusive use of renewable energy and raw material sources. Here, harmless ingredients and byproducts for the raw material for the manufacture of rammed earth walls, while waste is reused as biological or technical resources stay within the system. The biological and technical production cycles complement and interact with each other to produce improved and more productive construction material.

4.1.4 Strawbale

Next, this section discusses straw bale as a bio-based site construction material. The stalks remaining after the grain harvest are considered a renewable resource grown annually. According to the U.S. Department of Energy, over 200 million tons of straw remains unused every year within the United States. Rodrigues (2015) examines the viability of straw bale as a sustainable construction material.

Rodrigues (2015) also explores concepts related to building science that include straw stalk, structural system, stud framing, pony wall, wall cavity, and base plaster. The author also examines the most critical characteristics in terms of building performance, which are thermal capacity, fire resistance, and moisture performance. Rodrigues then explains the properties of straw bale. Straw bale relies on vapor permeability for its thermal performance, whereby the base plaster functions as the essential vapor permeable air barrier. Integrating vapor permeable air barriers on both sides of the wall assembly maximizes thermal performance while enhancing moisture mitigation. In the straw bale wall system, moisture build-up in the form of vapor inside the building may diffuse through the wall membrane to the outside, depending on the direction of the vapor drive. Plastered straw bale wall systems possess superior fire resistance qualities compared to standard fiberglass-insulated stud walls. Unplaster straw bales within the wall assembly, when exposed to fire, smolder in a low-oxygen state, once the exterior layer of straw has charred. In this regard, unplaster straw bales possess fire-resistance capabilities similar to those of heavy timber (Hall 2019).

Research has shown that straw bale buildings are energy-efficient, durable, and non-toxic (Corum 2005). Straw bale walls are resistant to thermal, acoustic, fire, and insects. They are culturally relevant, have low maintenance, improved indoor air quality, high longevity, and are aesthetically intangible, which make them environmentally responsible and contribute to the sustainable development of the built environment (Ecococon 2019). Modern natural building in the form of strawbale may be experiencing its re-emergence as a valuable design-construction strategy but it faces several challenges with respect to practical application.

4.1.5 Wood/Timber

Accoya® wood (referred to as AAW) is a high acetylated timber with properties matching tropical and tread hardwoods but sourced from FSC wood (Accoya® 2019). In the Netherlands, the UK and Germany, it is primarily used for non-structural applications such as cladding, joinery, decking and light civil works. Bongers et al. (2013) summarize that using forest and wood products can help reduce the effects of severe problems like climate change. The characteristics of wood, its sourcing and its operation can vary from place to place. Microtec Viscan graded timber modulus of elasticity of 8000 N mm-2 and more if manufactured sustainably by Accoya Technologies. Bongers et al. (2013) establish AAW products equivalent to class C24 strength.

Based on the wood density, 1 cuber meter of wood may store over 1 ton of CO2 for its lifetime. Wood not only helps in reducing the CO2 level from the atmosphere but also has excellent insulation properties when used as a building shell. It also helps save overall energy of the building. To reduce the pressure on rainforests and to meet the growing demand for wood, modified wood helps overcome the supply gap. Modified woods are manufactured from poor quality, but abundantly available wood. It helps to improve the performance of the wood from its durability to dimensional stability. From various chemical and thermal modification techniques, one of the best methods used to modify wood is acetylation, which helps to increase the stability and durability of the wood significantly (Van Der Lugt and Vogtländer 2014).

The co-product of this process is vinegar which is widely used across the world. Acetylated wood can be used for external joinery, decking, cladding, and even structural applications. This wood is popularly known as AAW. Radiata pine, alder and Scots pine are the species used for manufacturing the AAW which is the most durable and stable replacement to the tropical hardwoods. The World Business Council for Sustainable Development (WBCSD) reports the cradle-to-gate scenario of this acetylated wood, including their raw materials, transportation and production. The core ingredients of the AAW are timber and acetic anhydride. Two co-products developed during the manufacture of AAW are waste wood from sawmills and acetic acid from acetylation of wood, thus substituting the acetic acid industries (Bongers et al. 2013).

This wood is resistant against fungal decay and offers dimensional stability under varying moisture conditions resulting in extended life. They can serve as structural components for buildings that need structural elements while still being circular. At the end of its life cycle, it can be recycled for its secondary use such as MDF or particleboard. It can also be burnt at the end of its lifecycle. Idemat 2014 database (6) states generating electricity can heat up to 0.819 kg CO2eq for softwood and 0.784 kg CO2eq for hardwood (Van-der-Lugt 2016). The process starts with extracting biogenic CO2 from the air through the photosynthesis process. The extracted CO2 stored in the woods and its products return to the atmosphere, at the end of its lifecycle. Therefore, the net value of the CO2 is zero, if not burnt for the production of energy to replace fossil fuel. Storing 6.97 kg of CO2 in the forests can be comparable to using 1 kg of wood product. AAW and azobe constructed from scots pine sourced sustainably tend to be carbon negative over its lifecycle, but if sourced unsustainably, the carbon sequestration value of the AAW becomes negative (Van Der Lugt and Vogtländer 2014). Thus, circular sourced wood can lead to the conservation of tropical rainforests, which is a significant carbon sink in the global carbon cycle.

4.1.6 Hempcrete

The UK HEMP association discuss the technical properties of the hemp building materials in their article “Hemp for Construction.” They also discuss current industry practices related to manufacture of hemp materials, notable building projects involving them, and the factors that will see the industry thrive. According to the authors, hemp has natural insulating properties and is astonishing durability, making it a viable alternative in terms of technical quality to traditional materials (Berni 2019). There have been many companies that have successfully demonstrated the use of hemp in structural building blocks, as wall insulation and as non-structural building materials in construction and design (Elfordy et al. 2008).

The report discusses the impressive properties of hemp building materials. The core mix of these products for building and insulation are made by combining the shiv-the woody inner core of the hemp plant with lime and water, to make a bio-compositable cement. This mixture is used as a type of concrete in removable wood shuttering to provide structural stability and insulating benefits (Bergen et al. 2011). Also known as ‘Hempcrete’, it is lightweight, highly insulating, resistant to pests and molds, has good acoustics and is able to moderate humidity. Therefore, it is perfect for the renovation and retrofitting of old buildings to new energy efficiency standards. It can also act as a carbon sink as hemp plant absorbs carbon dioxide in the growth phase and is locked into the material which continues to absorb carbon from the atmosphere. Bedlivá et al. (2014) estimate that lime-based hempcrete can sequester 249 kg of Carbon dioxide over a 100-year lifecycle (Isohemp 2019).

A Canadian hemp-based construction block manufacturing house (Justbiofiber 2012) suggest that their hempcrete blocks can sequester 110-130 kg per cubic meter which is just 32 blocks. Greencore Construction Group in association with the University of Bath have developed prefab panels to help dry the hempcrete. Just these panels are easy to assemble and keep the vapor-regulating property of hempcrete. Industrial nature in Scotland is producing hemp bricks (Indie Blocs) using a complex mix of minerals with industrial hemp fibers to form a good insulating material having an impressive heat/ retention capacity. The hemp fibers can also be entwined into loft insulation that is recyclable and free from harmful materials and chemicals. This material is antimicrobial, resistant to rotting and, again, carbon fixing (Bedlivá 2014).

Many hemp projects discussed by the UK hemp association (2018) noting that although being an expensive to manufacture material as compared to traditional concrete, hempcrete offers more value in long term with respect to savings form insultation and environmental benefits. However, to encourage the use of hemp as a building material, there has to be a reduction in production costs by reducing transportation costs. Making the costs, or ‘externalities’ of the current materials clearer is another way of reducing competitiveness of hemp (Yu et al. 2005). More work is needed to help identify, publish, and broadcast the less tangible benefits of working with hemp (Turnbull 2017). The material has gained significant popularity in the UK and in Australia. Due to policy restrictions hemp was not a material of choice in the United States until 2018.

4.2 Comparing the Construction Capability with Contemporary Building Materials

The section below compares the properties of the selected eco-friendly building materials with typical contemporary building materials. The comparisons are shown in Tables 3, 4, 5, and 6. This also includes a comparison of Navajo Flexcrete and Hempcrete. Flexcrete is currently being used in the Navajo Nation due to its ecological properties and structural and thermal capabilities. But the closing of the NGS resulted in a need for its by-product, fly ash, used for Flexcrete manufacturing. Another material, in addition to the Navajo Flexcrete building material used for housing, may be needed. Hempcrete could play a significant role in bridging this gap.

4.2.1 Hempcrete vs Navajo Flexcrete

Navajo Flexcrete, with Portland cement as one of its components, is a carbon intensive material. Hempcrete made from lime is biodegradable and offers comparable structural strength as Navajo Flexcrete. Both materials work well for dwellings up to 2-3 floors, but the added agricultural and insulation benefits of Hemp make a clear case of Hempcrete potentially yielding some advantages over Navajo Flexcrete. Table 3 offers a comparison of construction potential between Hempcrete and Navajo Flexcrete.

Table 3. Comparison of Hempcrete and Navajo Flexcrete

	Hempcrete	**Navajo Flexcrete**
Strength	550 psi compressive	290 psi compressive
Potential Advantages	Hemp blocks ensure humidity regulation, acoustic insulation, as well as protection and fire resistance. It's ten times stronger than concrete and one sixth of the weight, Product development based on C2CP	Good Structural Strength, Economical, Available and Inexpensive, Versatile, Durable, Seismic Resistance, Ease of Construction
Durability	100 years, durable, sustainable, healthier for the occupants, affordable, carbon negative	50 - 60 years
Limitation	Not ductile, Hemp concrete cannot be used underground or underwater applications. The cost of building with hempcrete is a little expensive in comparison to the other conventional methods.	Not ductile, exhibits a strain softening behavior, Low toughness, Quasi Brittle
Application	Walls, Walls – Timber frame infill, Insulation – Retrofit against existing walls	Walls, Degraded, Damp and Wet Insulation under Metal Cladding or Bulk Heads
Fire Resistance	4 hours	4 hours
R-value / U -Value	2.08 per inch/ 0.02 per inch	3.75 per inch / 0.03 per inches
Carbon Sequestration	108 kg per m^3	(-)100/ kg per m^3
Raw Materials / Source	Hemp stalk, hurd, lime/ Farms	Fly ash, Cement, Nylon / Power plants, lime mines
References: Ackerman et al. (2014), Malnar et al. (2018), Creamer et al. (2004), Huber et al. (2016), Bedlivá (2014), Berni (2019), Elfordy et al. (2008), Isohemp (2019), Yu et al. (2005), Justbiofiber (2012), Turnbull (2017)		

4.2.2 Adobe Brick vs Kiln Fired Masonry Brick

Traditional masonry bricks require a lot of energy to be manufactured which can in turn results in higher GHG emissions and an unsustainable development. Adobe bricks do not need external energy during their manufacture process but fail to offer similar structural properties as masonry bricks. Adobe are locally manufactured with easily available raw materials which is one of the major reasons of it being extensively adopted in tribal housing. It is highly insulating material and does not require additional insulation. It has comparable fire resistance properties to masonry bricks. This material is durable can be recycled by breaking it down into its raw materials but like masonry bricks it is hard to reuse after the first build is completed. Table 4 below compares construction potential of Adobe brick and Masonry brick.

Table 4. Comparison of Adobe Brick and Masonry Brick

	Adobe Brick	**Kiln fired Masonry Brick**
Strength	13 psi compressive	1600 -10000 psi compressive
Potential Advantages	Relatively easy and cost-efficient to install, low- embodied energy, Durable construction	Easy to use, and transport
Durability	100 years	20-50 years
Limitation	Poor heat insulation	Poor heat insulation, brittle, not
Application	Walls, Insulation	Walls, Structural wall for 2-3 floor
Fire Resistance	2 hours	3.5 hours
R-value/ U -Value	0.3 per inch / 0.01 per inch	0.4 h ft2 / 0.263 per inch
Carbon Sequestration	170 kg per m³	(-)255 kg per m³
Raw Materials/ Source	Straw from Wheat, Rice, Rye and Oats / Local Farms	Clay/ locally available
References: Rodrigues (2015), Austin (1984), Christoforou (2016), Apoh (2013), Forbes (1998), Lertwattanaruk et al. (2011)		

4.2.3 Timber vs Steel

No other construction material compares to steel in its adaptability. It is strong and relatively light weight, malleable while offering flexibility without being brittle. It is offers versatile joinery customizations. Wood, especially timber, has similar structural properties as steel and is commonly used as a cheaper replacement for steel in low rise structures. Steel manufacturing is one of the most carbon intensive processes which is one of its major disadvantages. Wood offers a suitable replacement since it is able to capture carbon during its growth and is renewable while being easily available. Table 5 compares wood/timber construction with steel as a construction material.

Table 5. Comparison of Timber (Wood) and Steel

	Timber	**Steel**
Strength	4020 psi - 4920 psi compressive	22000 psi compressive
Potential Advantages	Natural Insulator, Cost-effective, Versatile, Elastic, Seismic Safety, help reduce energy needs, Easy to Work	High strength/weight ratio, Good ductility and fatigue strength, Predictable material properties, fast construction times due to prefab, easy to repair and reuse, expanding structures.
Durability	50 years	30 - 60 years
Limitation	frames are pressure treated with preservative, not soundproof, will rot, wood has structural weakness and sensitivities	Cost intensive and energy intensive to produce, susceptible to buckling, not fireproof, corrosive material and need regular weather resistant coating, maintenance and corrosion proofing needed
Application	formwork carpentry, engineering purpose, framing	Structural material, long-span bridges, structures located on ground with low soil bearing and in areas with high seismic activity
Fire Resistance	1/2 inch per 10 minutes	0.34 inch per 60 minutes
R-value/ U -Value	1.41 per inch / 0.64 per inch	3.3 per inch / 0.30 per inch
Carbon Sequestration	140 kg per m³	(-)10⁶ kg/m³
Raw Materials/ Source	Timber / Forest	Iron and Carbon / Iron mines at specific locations
References: Vogtländer (2010), Van der Lugt (2015), ACCOYA (2019), Bongers et al. (2013)		

4.2.4 Rammed Earth vs Poured Concrete

Concrete is another widely used material in construction industry. It is extremely strong and is easily moldable. It is also a carbon intensive material which is hard to repair and poor biodegradability. Precast concrete blocks and panels can be reused but the manufacturing process requires high amounts of energy. Rammed earth can be manufactured locally and although being environmentally friendly, it is a heavier building material which is not suitable for prefabrication. Like concrete, construction with rammed earth is a time intensive process and the material is not easily reusable.

Table 6 compares rammed earth with concrete as a construction material.

Table 6. Comparison of Rammed Earth and Concrete

	Rammed Earth	**Poured Concrete**
Strength	290 psi compressive	4,500 psi compressive
Potential Advantages	Strength, Durability, Temperature regulating, Noncombustible, Humidity of building is maintained, Sustainable, Recyclable, Airtight Construction	High Compressive/tensile strength, Durability, Rigid, User friendly, easy to source, cost effective, fire resistant, modality
Durability	30 years	100+ years, Low maintenance
Limitation	Easily identifiable appearance, On-site weather dependency, for low carbon emissions, Prefab associated with delivering the building material results in high emissions.	Long-term Storage not possible and it has a 30-day Curing time. The cost of the forms used for casting RC is relatively higher. Shrinkage causes crack development and strength loss, poor temperature regulation
Application	Walls and Structural elements	Walls, Structural elements, footings, damns, piers,
Fire Resistance	11 inches per 90 minutes	4 inches per 90 minutes
R-value/ U -Value	0.06 per inch / 0.15 per inch	0.52per inch/ 0.16 per inch
Carbon Sequestration	16 kg /m^3	(-)410 kg/m3
Raw Materials/ Source	Sand and Clay/ Local Soil	Water, cement and aggregates / Local Source
References: Austin (1984), Kitriniaris (2019), Ben-Alon et al. (2019), Aggarwal (2020)		

4.3 Investigate C2CP Potential of the Selected Materials

The above literature review suggests that sustainability complements the components of cost, function, aesthetics, time, and local community benefits. The CE in the building industry seeks to address the environmental effects of building materials and define the consumption limits of resources while considering future needs. A CE process encompass the three basic principles of Reduce, Reuse and Recycle (EMF, 2013). The section below compares the properties of the selected eco-friendly building materials with typical contemporary building materials.

In order to achieve micro-level circularity within the built environment (Pomponi et al. 2016), it is advised to used building materials that follow CE principles. One efficient way of doing this, is by using materials that have already received certification from the C2CP (Braungart et al. 2007; McDonough et al. 2010; CradletoCradle Product Innovation Institute 2020). Any material that aims to achieve strict certifications like LPC can certainly achieve C2CP certifications due to its more flexible rating system (Basic, Bronze, Silver, Gold, Platinum). This further ease the path for the building to achieve a building level certification like Living Building Challenge or the Leadership in Energy and Environmental Design (LEED) Certification.

Table 7 displays the material properties and the potential of obtaining a circular product certification like C2CP for the six building materials (Navajo Flex Crete, Adobe brick, Rammed Earth, Strawbale, Wood, Hempcrete) discussed in the previous section. Adobe Brick, Strawbale and Accoya Wood already have the C2CP certification, and the rest have the potential to achieve it.

Table 7. Comparison of Materials with respect to their C2CP Potential

Circular achievements possible	**Rammed Earth**	**Adobe Brick**	**Navajo Flexcrete**	**Wood/ timber**	**Strawbale**	**Hempcrete**
Material Health	Product development based on C2CP with clay raw material certified	Product choice based on C2CP (certified materials exist)	Ash from coalfired plants used as a raw material along with aerated cement	Product choice based on C2CP (certified materials exist)	Product choice based on C2CP (certified materials exist)	Product development based on C2CP and many companies are aiming certification
Material Reutilization	can be repaired but not reutilized unless prefab friendly	can be repaired and reutilized but hard to remanufacture	high recyclability but poor reusability	reconstruction, recycle and potential to be reused	biodegradable, low reutilization	high reuse, reutilization, biodegradable and remanufacture
Renewable Energy and Carbon Management	16 kg/ m^3	170 kg/ m^3	100 kg/ m^3	140 kg/ m^3	490 kg/ m^3	108 kg/ m^3
Water Stewardship	water can be substituted, Water-saving schemes established	water is required during manufacturing process with new saving schemes established	no untreated wastewater discharge from production	high amount of water is required during forest growth, Water-saving schemes established	almost no water required since it is made from crop waste	low quantity of water is needed during crop growth, No untreated wastewater discharge from production
Social Fairness	Introduce training for local manufacturing	Indigenous community upliftment from localized production	Prefab only but locally available	Local manufacture and sourcing common	High Prefab and local manufacturing potential	High Prefab and local manufacturing potential with locally grown raw material
C2CP Potential	Basic	Bronze or Silver	Silver or Gold	Gold or Platinum	Silver or Gold	Silver or Gold

References for table 3-7: Ackerman et al. (2014), Malnar et al. (2018) Creamer et al. (2004), Huber et al. (2016), Christoforou et al. (2016), Austin (1984), Kitriniaris (2018), Ben-Alon et al. (2019), Hall (2019), Rodrigues (2015), Corum (2005), Vogtländer (2010), Van-der-Lugt (2015), Bongers et al. (2013), Bedlivá (2014), Berni (2019), Elfordy et al. (2008), Isohemp (2019), Yu et al. (2005), Justbiofiber (2012), Elfordy et al. (2008), Justbiofiber (2019), Hempitecture (2020), Turnbull (2017)

Table 7 suggests that strawbale material or hemp-based concrete for construction are up-and-coming and environmentally sustainable alternatives to conventional concrete. These materials can also be used as an insulation filler in the hollow part of the bricks. Hemp-based bricks result in carbon sequestration of over 108 Kg per meter cube along with providing fire resistance and improved temperature regulation.

Overall, adobe bricks are probably a more sustainable solution compared to other load-bearing construction materials. If the energy demands of adobe brick manufacturing are met from a renewable source, then it also becomes a viable alternative. Adobe bricks are especially attractive due to their potential for creating local manufacturing economies. To improve the deconstruction, all these can be modified in design to include hollow "Lego"-like bricks that can result in faster construction and deconstruction of the structure. Rammed earth is another promising material if its prefabrication and transportation capabilities can be improved.

Wood if treated appropriately can withstand harsh conditions while being carbon neutral. Accoya wood has demonstrated how to successfully achieve the C2C certification while being commercially and structurally viable. Table 7 thus shows that the six indigenous materials discussed in this thesis not only have the potential of being C2C certified but are also viable from an architectural and construction perspective. These indigenous materials, if chosen for construction, have resulted in a positive impact on the overall life cycle of the constructed building. The study of these indigenous materials emphasizes that they not only possess a sustainable life cycle; but are also competitive from design and building standpoint.

Utilizing CE and LBC principles to develop and construct sustainable designs can provide notable environmental and societal benefits while contributing positively to the traditional ingenious design process. The interconnected systems theory model is essential, and one of the most relevant and pertinent approaches to addressing sustainable construction materials for the future (Rodrigues 2015). There is a demonstrated urgency in future material technology research to re-examine natural, traditional, and sustainable building techniques, resulting in a more holistic approach towards the building process and design.

Co-owned by the NN, Navajo Flexcrete blocks are frequently used for construction in and around the NN region. Since it is made from locally sourced materials and manufactured within the region, it plays an important role in the NN local economy. Flexcrete is not certified under the C2CP but definitely has the potential to get certified. Since it is sourced from carbon intensive raw materials like coal ash and cement, this study will not consider Navajo Flexcrete as one of the building material choices.

Adobe brick, straw bale and rammed earth are commonly used building materials in traditional tribal houses, and they do contribute to the local CE. In comparison, hempcrete is a newer alternative; it will be used in this thesis to explore how CE fundamentals can be applied and integrated easily within built environments of the NN.

CHAPTER 5

FINDINGS PART 2: DESIGNING FOR A CIRCULAR ECONOMY

True sustainability can be only achieved by balancing the economic, environmental and social benefits, which can be strongly supported by a functioning CE. By designing with circularity in mind, we can build lesser and cater to more people. Designers can repurpose older buildings and reuse their original structure or rearrange the existing space to avoid waste and generate cost benefits. The space can be shared by different entities to increase its usage and efficiency. By utilizing natural elements like recycling water and solar energy the operation would not become a burden on the environment. Designing for material reuse, can help smaller systems to be inculcated into urban systems and achieve a true CE. A circular ecosystem heavily relies on collaboration and sharing and advocates not from self-sufficiency.

Circular economy concept aligns with indigenous people's traditional practices and how existing social structures can play a role in multi-generational housing patterns. For example: A single bedroom house is expanded by addition of rooms when a family grows. Many cases have seen a small culture form around a single house as the demand of space increases. By doing this repurpose, the use of the same building is extended. They rely on locally available low-cost material and local labor for their construction.

The study suggests a design process, that follows a closed-loop circular model with its surroundings. All components and materials required for construction are sourced from the locally available resources within the context of the Navajo Nation's tribal region. The design process accounts for the community's cultural values (DLR 2012; Begay 2005) while using available green building guidelines like LBC in order to have a sustainable indigenous built environment. The recommended raw materials used during this process have the potential of acquiring green product certifications (like C2CP or LPC). Furthermore, utilization of prefabricated modules results in faster construction, cost savings and an overall reduction in carbon footprint of the building resulting in qualification for green building certifications programs (like LBC and LEED).

5.1 Prioritize a Material System for Design and Construction

Material choice could further reduce the energy and carbon contained in a project's life cycle. For example, in addition to the fact that it stores carbon, wood is also lighter than steel or concrete. In modular construction lightness of material has significant advantage as it can reduce energy consumption and pollution associated with the transport and lifting of modules. The weight of structural elements also influences the type of material needed for the building foundation. Kedir et al. (2019) address the value of integrating super-and substructure design based on environmental impact assessment. It found that the nature of the super-structure of modular buildings affects the quantity of material required for the foundation considerably. The use of wood or other light-weight materials for the super-structure decreased the need of carbon heavy sub-structure materials.

In the context of this study, these indigenous materials, if chosen for the construction, result in a positive impact on the overall life cycle of the constructed building. Hemp hurd from the hemp plant is an extremely versatile light weight material, which can be used in various building applications due to its unique properties. In a study of UK cotton production against hemp, the Stockholm Environment Institute found that approximately 10,000 liters of waters are used to grow cotton with around 1 kg of soil, compared to about 300-500 liters, providing 1 kg of hemp with a fiber content of 30 percent. Hemp growth does not require any agrochemicals, pesticides and needs comparatively less nitrogen fertilizer. Hemp farming is helpful to land and livestock and does not hinder food production. Hemp has high carbon sequestration potential. Like all other plants, it absorbs carbon dioxide through fast growth and traps carbon, releasing oxygen to the atmosphere. Hemp can be used to make standalone insulation material like hemp wool or can be combined with other materials like lime to form hempcrete blocks or panels. Hempcrete further absorbs and "locks up" this carbon dioxide in the building's insulation. Hempcrete is fire resistant with great acoustic properties and has a high R-value which allows it to keep the interior temperatures regulated. As insulation, it substitutes conventional fossil-fuel-based materials that absorb energy and release harmful chemicals during processing. Due to hempcrete’s fire resistant properties, no toxic chemicals such as phosphates or PBDEs (bromine-based materials) are needed as fire retardants. Hemp can be used as 'aggregate' substituting quarried minerals in construction and reducing harm to the environment due to mining.

The combination of one or more materials can prove to be more efficient and has a potential to become more competitive with the contemporary building materials. Hempcrete in combination with ceramic studs can be formed into interlocking blocks that make them structurally stable. This combination overcomes the structural limitation of regular hempcrete block by means of a distributed load passing through the interlocking ceramic studs down to a spread foundation (Radford 2018). Another popular structurally stable combination is wood and hempcrete. They complement each other in terms of their building properties, hence overcoming each other’s limitations. When used as prefabricated building components like blocks or panels they become viable from an architectural and construction perspective.

5.2 Identify Cultural Values of the Community

The thesis considers a hypothetical site for an affordable residence located in northern region of Navajo Nation, Shiprock, NM. The building design aims to derive its cultural inspiration from the culturally sensitive design of local traditional and modern vernacular such as The Senator John Pinto library, Diné College, in the Navajo community, which is located in Shiprock, New Mexico. The second case study analyzed here is a tribal Navajo residence by Arizona State University Stardust Center, called the Nageezi House, located in rural Navajo community. This section highlights the lifestyle of the Diné (Navajo) people and their culture influences on Navajo Architecture. The thesis aims to reflect these culturally significant elements in its building design to achieve social sustainability.

In seeking cultural relevancy in Diné buildings, Begay (2005) talks about his approach in design which is based on the responsive design on cultural sites and delves into individuals' boundaries with the place. indigenous design is naturally composed of the human cultural aspect, the spiritual, and a treasured relationship with the natural world where there exists living in balance with nature (Denetdale 2017). The construction of the dome type of structure, the Hogan, is generally done with cedar logs, tree bark, and soil mixed with water to provide a workable mortar to hold the joints (Jett et al. 1981).

Begay (2019) describes ways to design and construct with readily available natural eco-friendly materials. Taking inspiration from nature, the building design is straightforward and has a natural flow. For design aspects, the natural environment is where a natural order of rain clouds, the trees, and the rocks exist in nature with the understanding of a spiritual connection to Diné Bikeyah’s six sacred mountains and the universe. The design is inspired to be a symbiotic link to nature, the seasons and the cosmos creates beyond the three-dimensional structures. Furthermore, nature-based organic forms inspire and create a foundational framework for regional values, which can support new techniques or methods for construction. These traditional structures are intended to stay for a long time and tell a story about people and their origins. It is also the most ecological and economical way to construct while maintaining cultural authenticity.

5.2.1 Case Study of Diné Library

Located in Shiprock, New Mexico, The Senator John Pinto library of Diné College has its architecture inspired from the Diné culture. This project by DLR group (2012) is located near the Four Corners area, and is a well-recognized tribal facility rooted with traditional Diné concepts. The building is modern and unique with secular spaces that are well lit along with Hogan-inspired room. It seeks to restore the important link between language and education and storytelling traditions. Diné college has done well in chasing and gaining accreditation by blending modern with traditional concepts of learning and teaching with its mission being to provide educational opportunities. Furthermore, they offer critical education through self-determination by incorporating social, political, and economic concepts with Diné language and history. The library has a unique design with highly visible structures representing the Diné values. Figure 6 highlights the cultural aspects of its design.

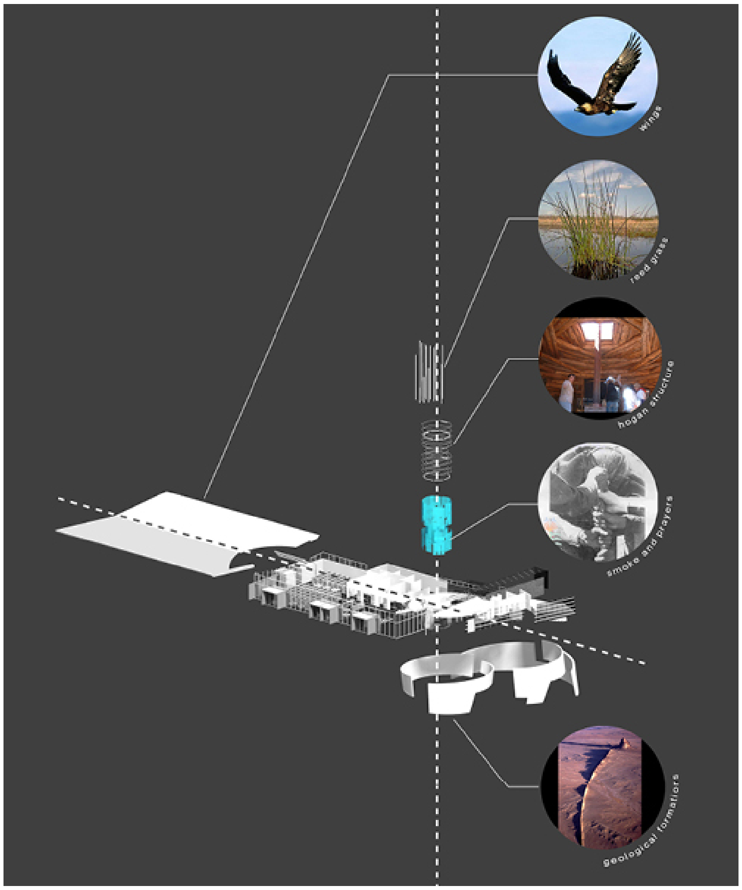


Figure 6. Cultural Aspects of the Diné library Design (DLR group 2012)

The concept of the design explains that in order to transcend the ordinary to be really unique, one must understand the phrase hozhoogo naashaa doo (In beauty I walk); the phrase conveys internalizing principles of the Diné knowledge towards sa’ah Naaghai Bik’eh Hozhoon which means living in balance with nature to a Hozho (Beauty) at a place that harmony exists between, nature, self, and the universe’s natural order.

The campus arrival is from the east that leads to a roundabout and a parking lot. In this sense, the campus entry follows the clockwise, cyclical movement of the sun to reinforce ideological values related to each cardinal direction. The site of the library is north of the classroom building to act as wisdom elders for the community and students.

At the entry of the library, traditional plant field patterns and building’s curve forms organize the landscape and hardscape plantings. The use of a clockwise spiral was meant to represent harmony while the gentle circular landscape forms representing the traditional cornfields to provide a welcoming spirit and to honor the past.

Through integrating the Hogan, the building responds to Diné’s teachings holistic world view. There is also the inclusion of a central gathering space also called the storytelling room which is shaped to the Hogan and is uniquely clad in blue panels that are translucent to evoke the color of ceremonial smoke that rises from a fire in daylight and also transcends to the sky’s color. The doorway of the room faces east in order to allow the penetration of sunlight to the interior.

The steel columns anchor the Center Place to show the Diné’s emergence story with the columns to signify the long reed grass stems. To further reinforce the Diné’s teachings of the importance of the concept of family and the seasons, light fixtures are purposely arranged in star constellation patterns outside the storytelling room.

5.2.2 Case Study of Nageezi House

Senator John Pinto's Diné College Library offers an outstanding example of how architecture can be influenced by culture. The purpose of this study is to suggest a housing solution for the NN, which is why this section will analyze a culturally-inspired housing unit for NN clients —The Nageezi House. It was designed and developed in collaboration with Arizona State University and the tribal representative of NN.

The Diné people understand the interconnection and the delicate ratio among the canyons, junipers, and water as they sustain life in their way. Begay (2005) shares the story behind the dwellings at the Navajo Nation. He describes how several homes mostly belonging to the mother's daughters cluster next to each other at the Diné settlements.

However, the most important structure is the female hogan which is the center place that represents the spiritual center. Its doorway aligns with the direction of sunrise, and the smoke hole sits at the center on top of the fire hearth. The top opening allows for the spiritual threshold that connects the earth to the sky. Furthermore, its floor plan represents special points that relate to duality, night and day, lifeways, and cardinal direction (Emerson 1983; NHA et al. 2012). Seeking cultural relevance is a socially driven practice that starts with listening to the people who will use the structure.

The form of Nageezi house represents and honors the indigenous culture of Navajo. The house design exhibits the conventional structures of the Navajo Nation like the hogan (house) and the chahash'oh (shade structure). The clients of the Nageezi house grew up in traditional hogans; however, they lived in a typical western style home for the last 40 years and were used to that lifestyle. The architect of the house established a style that appreciates and expresses the values of the Navajo culture while also providing the scale, privacy, and compartmentalization of contemporary housing.

The same as a hogan, the door faces east, and movement through the home is in a clockwise flow, from more public areas like living and kitchen to private rooms like bathrooms and bedrooms. The rooms of the house enclose an indigenous material, Hogan shaped courtyard. The living room, kitchen, restaurants, and south-facing space are merged for larger family gatherings that reflects the hogan's central location. A south-facing shade system protects the southern windows and deck from the harsh light of the summer sun. It also symbolizes the traditional chahash'oh that the Navajo uses as summer shade and for the outdoor cooking. In the center of the east-facing courtyard, the outdoor fireplace represents the hogan's heart. The windows of the house allow you to view the four cardinal directions from the yard through the building.

Throughout the design period, the Nageezi House was designed to comply with the USGBC's Leadership in Energy and Environmental Design (LEED) for Homes criteria. It did not pursue accreditation though. During the testing, it was concluded that the house's energy consumption was reduced 50 percent compared to a conventional home. Some of the key features considered during the design phase were a low-cost approach, passive cooling and ventilation, passive solar heating. The biggest lesson learned from this case study was that the collaboration between the tribal housing authority and an academic institution led to a design that was not only sustainable but acceptable to the tribal community.

Figure 7. Nageezi House (Blosser et al. 2014)

5.3 Proposed Design

Recognizing the need for housing on NN and the potential opportunity of applying CE for the benefit of the indigenous community, and with the limited understanding from the literature of local regions and traditions, this study proposes a mix of housing prototypes.

These designs follow the directional symmetry, as well as the clockwise circulation of a traditional hogan as seen in the traditional designs of the Diné Culture.

The entrance door faces the east direction with the idea of having the first light of the sun entering the house. The fire god is in the central part of the hogan as per the traditional principles, which can also be seen in this design by means of placing a central fireplace. The white area on the right side of the figure represents the bright light of the sun. Again, the circulation of the house is in the clockwise direction representing the circle of life. It also describes the movement of the sun and the change of its light intensity. Figure 8 highlights this Hogan style symmetry to the design's site plan (Corum 2005).

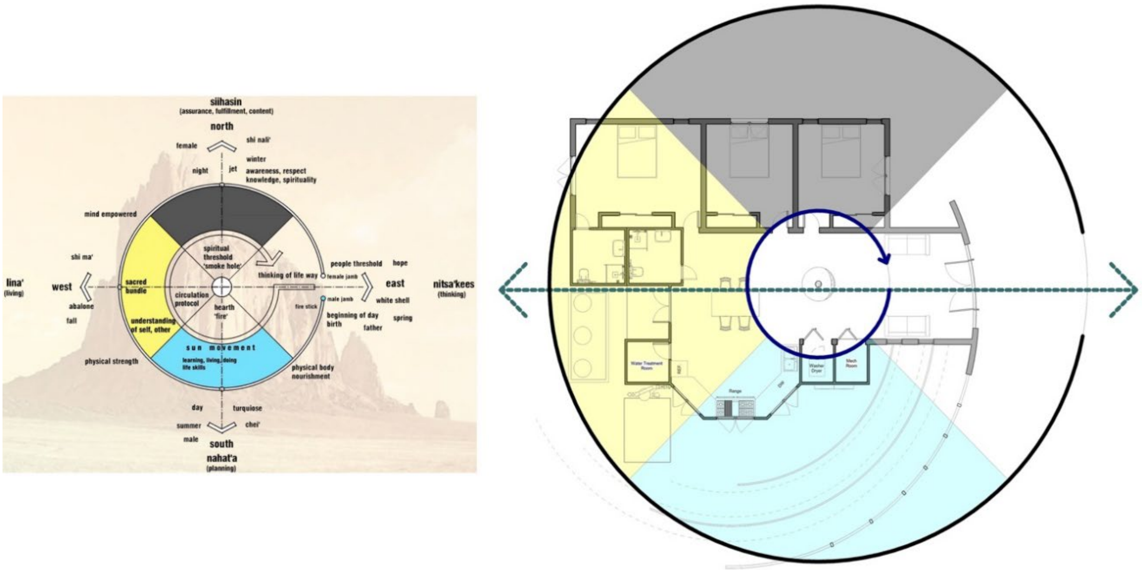


Figure 8. House Circulation in the Proposed Design

The blue light represents the south and turquoise stone and displays activity zones like the kitchen outdoor and gathering to coincide with planning. The yellow color displaying values such as evening light areas. The circulation further moves toward more private spaces like the bedrooms in the north direction. The pleasant and warm northern light enhances the privacy of the bedroom. The directions are also significant with respect to the Diné Bikeyah's six sacred mountains (Begay 2005). Figure 9 displays the floor plan and the perspective views of an expandable 3-bedroom 1300 square feet (SF) house. Figure 10 shows the floor plan and the perspective views of an expandable 2-bedroom, 800SF Hogan style house designs and their exterior. The outdoor landscaping outlines the traditional cornfields. The patterns of the corn field radiate to honor traditional patterns and the house circulation represents harmony. The circular pergolas represent the crop fields of the Navajo people, while providing microclimate area which can be used for outdoor gatherings and celebrations (Corum 2005).

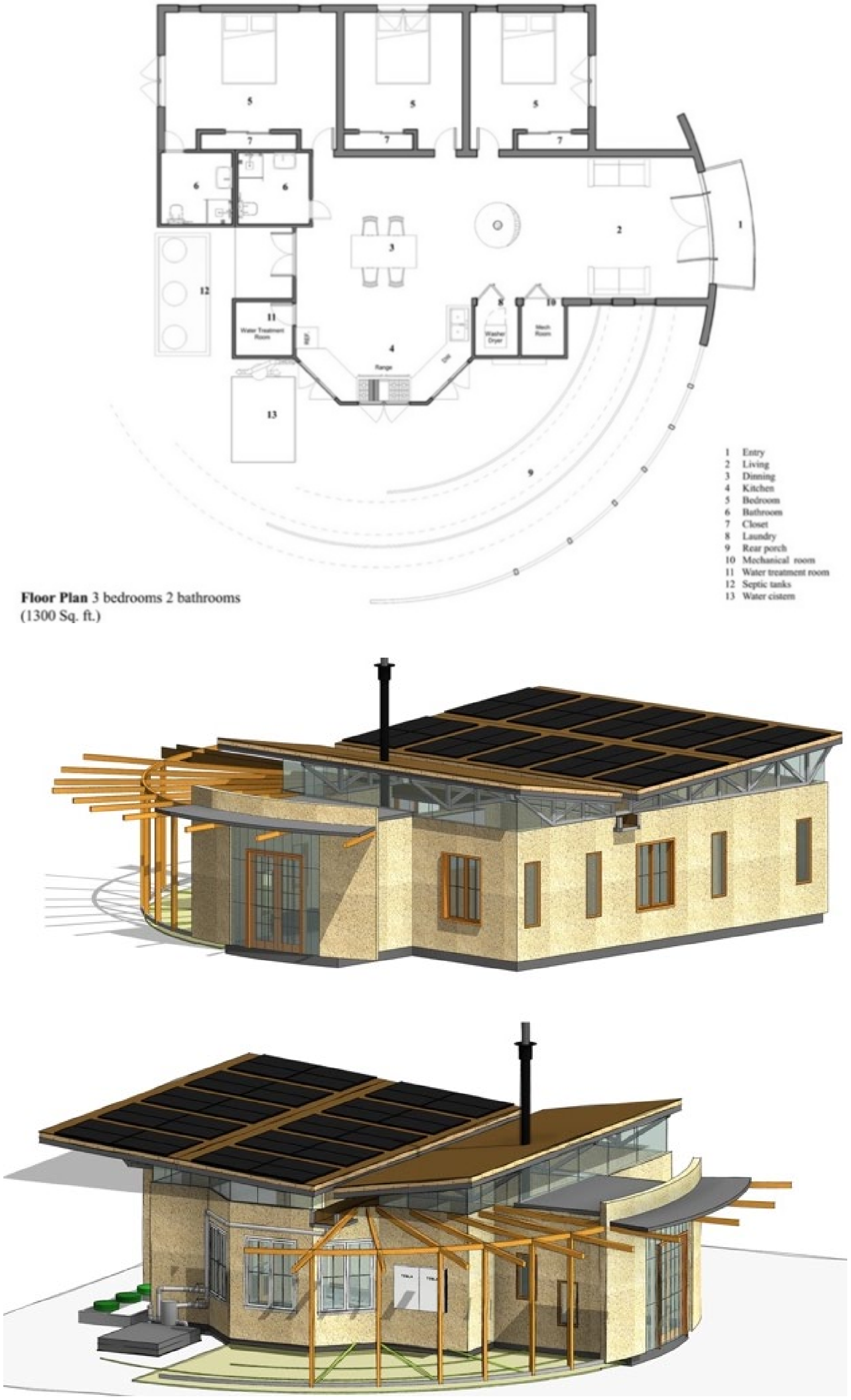


Figure 9. Floor Plan and Perspective Views of the Proposed 3-Bedroom House Design

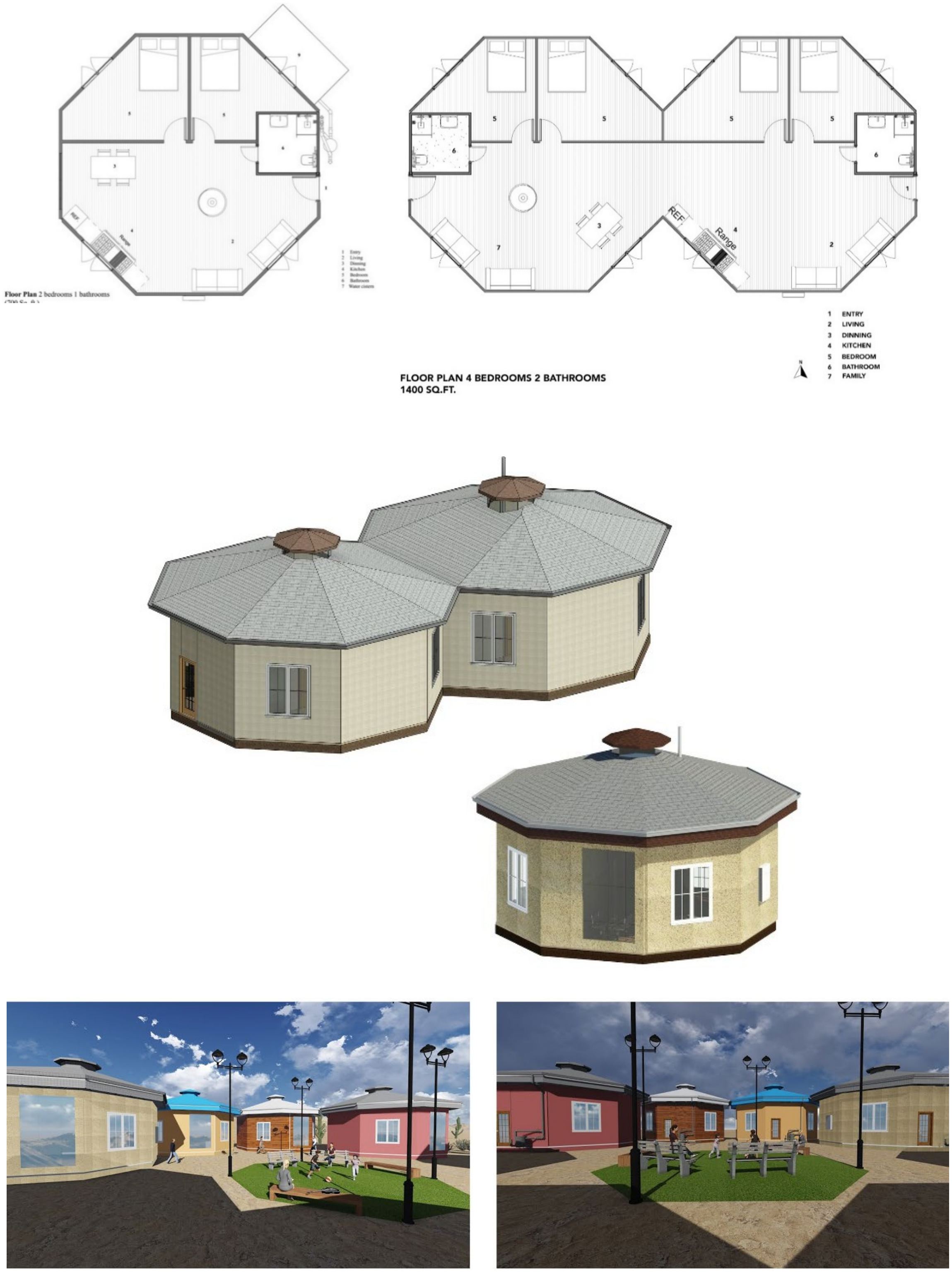


Figure 10. Floor Plan and Perspective Views of the Proposed Hogan Style House Design

The contemporary design allows both the residences to be expanded as per the family needs within the urban setting, which can be seen in Figure 11. This growth and expandable design encourage repurpose of the space and reuse of the structure. The families often include nuclear families, clan groups, and or homesteads. The nuclear structure is located near the matriarch. When a family grows the design encourages reuse and recycle by means of home expansion instead of relocating or building a new house. Expansion can be easily achieved by adding new prefabricated panels to add more rooms in the house or any other desired space that meets the occupants' needs. The same follows in the Hogan style design. The flexibility due to the use of same sized prefabricated wall modules in the Hogan style house plan provides possibilities for growth and expansion according to the family needs. Not only does it help to grow houses by forming groups, but it also helps to grow the housing community at the urban scale. The octagon shape allows for more wall interactions, thus increasing the possibilities of growth.

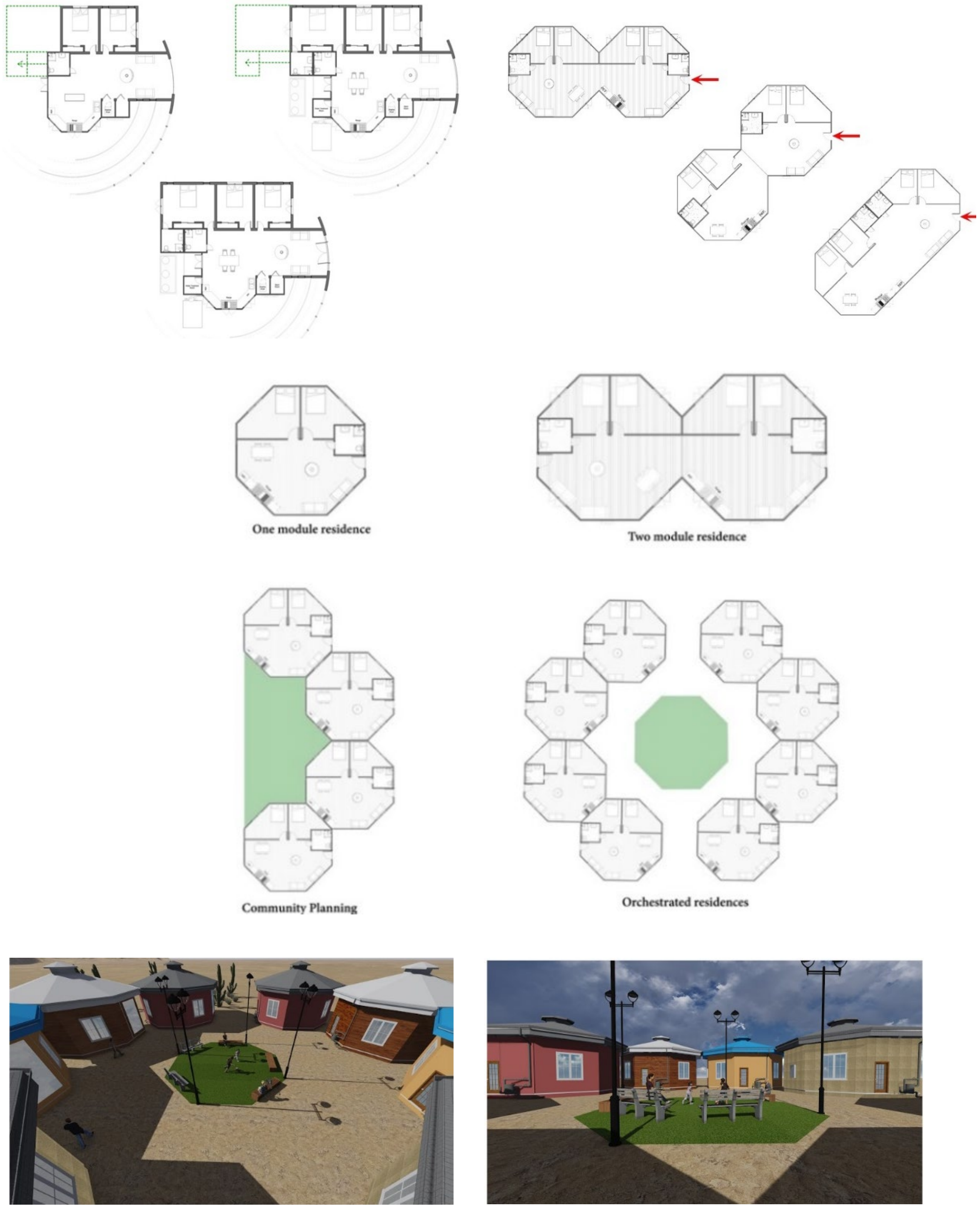


Figure 11.Expandable Layout Allowing Repurpose and Reuse

CHAPTER 6

FINDINGS PART 3: ECONOMIC, SOCIAL, ENVIRONMENTAL IMPACTS

A true CE is only achieved when a building achieves social, environmental and economic sustainability (Keeble 1988). This chapter explores impacts of the proposed design with respect to the three main pillars of sustainability.

6.1 Culturally Representative Design for Social Sustainability

In the Navajo creation myth Diné Bahane', it is said that the creator placed the Diné on land between four mountains, ranges, reflecting the four cardinal directions. Figure 12 shows these four sacred mountains of the Navajo Nation and the cultural significance of the directions in the Diné community.

In the east direction, there is the holy mountain of Sisnaajiní which is also called the "white shell mountain" associated with the color white. The blue mountain – Tsoodził, is in New Mexico. This sacred mountain of the south, also known as "turquoise mountain," is associated with the color blue. The sacred mountain of the west –Dook' o' oosłíid is in the San Francisco Peak in Arizona. This mountain, on which snow never melts, is associated with the color yellow. The black mountain – Dibé Nitsaa is in Colorado. This sacred mountain of the north is also known as big sheep and is associated with the color black. The main entrance of the house should point towards the sacred mountain of Sisnaajiní, which is in the east direction. The windows of the proposed houses are looking towards these sacred mountains, thus making it more culturally relevant and allowing for natural light and ventilation.

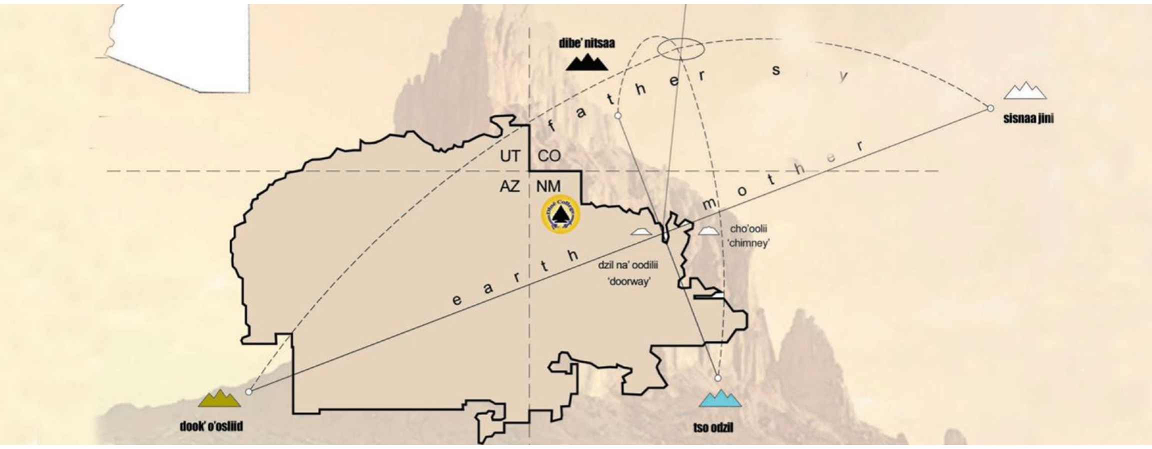


Figure 12. Cultural Significance of Directions (Begay 2005)

The architecture idea is derived from cultural ideals and beliefs of the Diné community. The landscape resembles typical corn farming. The central fire area in the family house and the octagonal shape used in house architecture recalls the traditional Hogan. Outdoor pergolas reflect community basket weaving patterns. The butterfly roof represents the bird eagle which is an extremely significant bird for the tribal people.

Placing rooms and events in the house explains the sun movements directions. The design offers access to the natural surroundings throughout. The landscape and the trellis create a green space in shape of a cornfield which is one of the main farming crops for the community. It offers gathering and celebration spaces outside the residence. The modules also allow forming semi-open and open spaces in a central area between the houses creating an opportunity for farming, outdoor activities, and community celebrations.

Traditional settlement planning is preferred by the community members against the typical row house style of housing development projects. The house design and community planning allow for cultural discourse among the community kids. The culturally sensitive architecture allows for refined, natural, and balanced interiors, biophilic interactions. The design celebrates culture and offers a community-friendly sustainable built environment. The house serves as a future generation storekeeper representing various cultural aspects of the Diné (Navajo) community.

6.2 Green Building Practices Resulting in Environmental Sustainability

The design embodies several environmental sustainability strategies. For instance, the butterfly-style roof traps rainwater in the rainwater channel. The collected water is filtered in the water treatment room, and then stored in a water cistern for reuse. No toxic materials are used for construction, and no materials from the C2CP's red list (hazardous and non-biodegradable) are used. Wood is used for the structure; hempcrete is used for walls; and rammed earth for the foundation.

The residence is a net positive energy building that produces 120 percent of energy needs along with the ability to produce over 200 percent of its energy requirements. It is designed to utilize 1500SF (10 – 15kW) of Solar PV (800SF – 7kW in Hogan) along with a battery pack offering 7 days' worth of energy storage (Huber et al. 2016). Solar water heaters and energy efficient hempcrete walls are used. There is an abundance of natural light as well as efficient ventilation resulting in effective passive cooling/heating. Rainwater harvesting as well as water storage and treatment systems along with the solar energy modules result in a nature powered living. The landscape is designed to mature and evolve to emulate the functionality of the habitat with regards to density, plant succession, water use, and nutrient needs. Figure 13 shows the energy and water circulation.

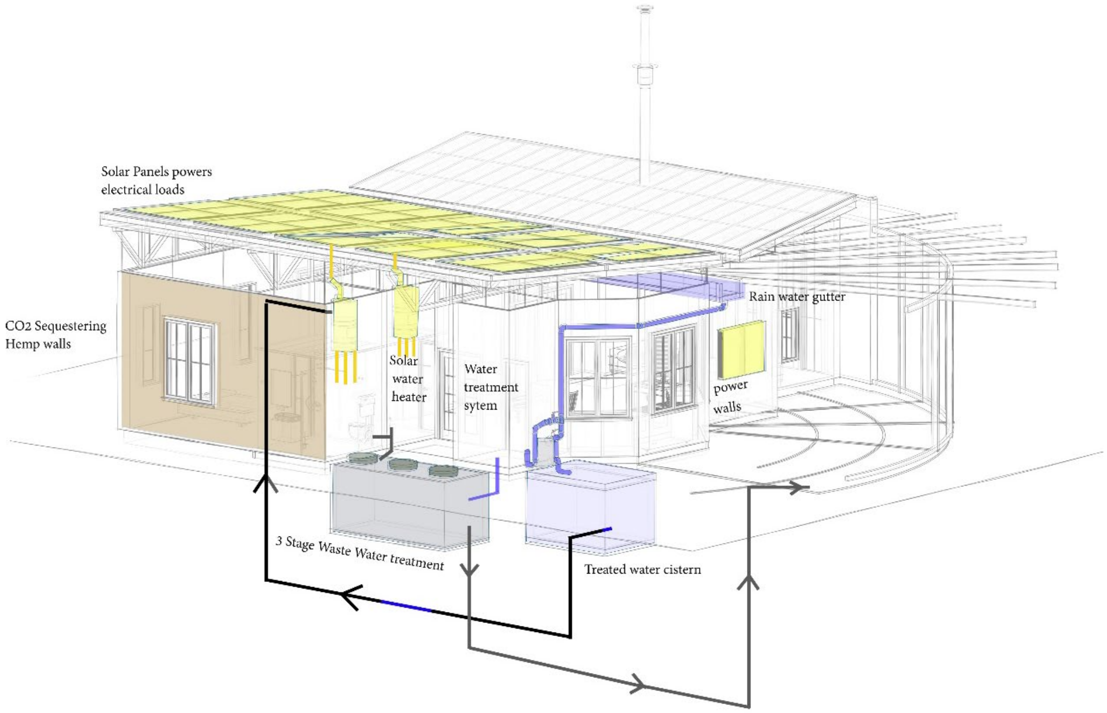


Figure 13. Solar Energy and Rainwater Circulation Plan of the Proposed Design

Figure 14 gives a detailed view of the eco-friendly and recycled materials that are being used in the building. Precast hempcrete panels and blocks are carbon absorbing (carbon sequestration during hemp farming and during curing of lime), insulating and structurally stable (Justbiofiber 2012). Biodegradable lime finishes on the interior and exterior walls allow the hempcrete to remain breathable. The rammed earth foundation in combination with the hemp insulated wooden floor provide structural stability to the overall lightweight building.

Removable low emissivity glass windows and panels allow for reuse of these parts. Reclaimed wood and lumber are used were possible in conjunction with C2CP conformal wood for structural applications. Hemp insulation is also used in the roof which is covered either with solar PV or PV shingles. The storage batteries and inverter system placed on the exterior walls of the house save the excess generated power and supply back to the house when needed.

The design prevents GHG emissions at three levels: by utilizing carbon negative and temperature regulating material in the form of hempcrete, by using prefabricated modules which save on equipment emissions during construction, and by utilizing solar energy during the building's operation.

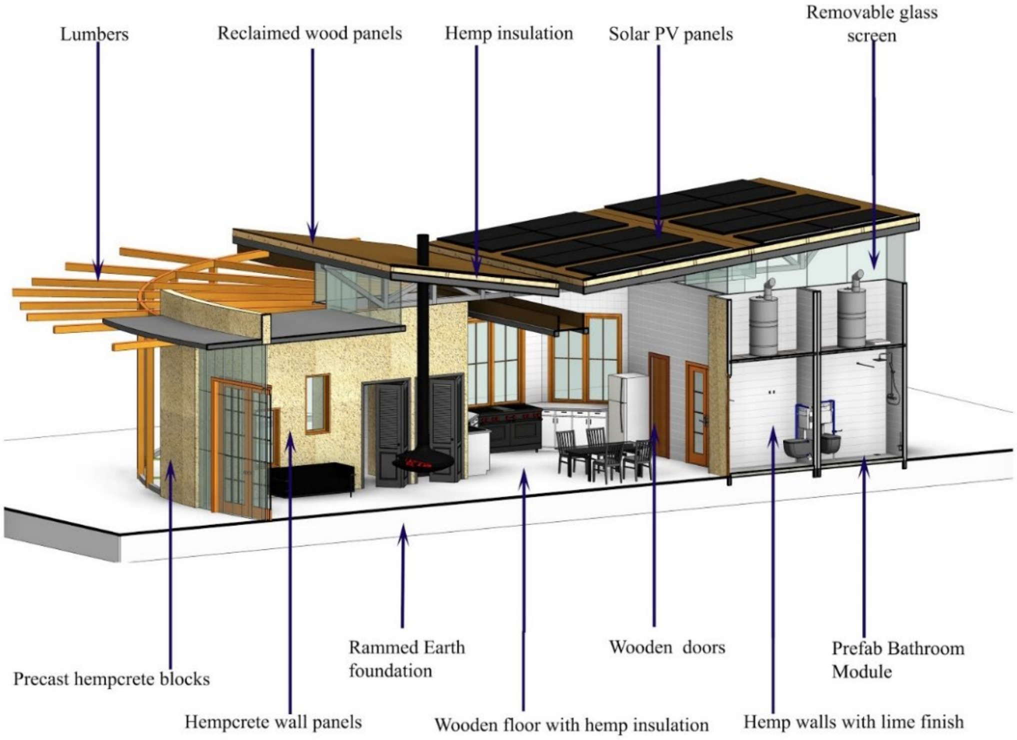


Figure 14. Eco-Friendly Materials Used in the Construction System in Proposed Design

Hempcrete sequesters roughly 110kg CO_2/m^3 (Justbiofiber 2012). The 1300SF house with a 1500SF roof and 1500SF wall area uses a total of ~4000 ft^3 of hempcrete. By using hempcrete as a building material, at least 12,000kg CO_2 can be sequestered over the lifetime of the building. Hempcrete is also an insulating material with the ability to maintain ambient indoor temperatures during extreme weather conditions. This reduces the energy needed during operation, and without a central HVAC system the energy demands of the entire house can easily be supported by the installed solar PV panels. Prefabrication and modular construction results in a roughly 43% reduction in GHG emission as compared to onsite construction for an average sized residence.

Table 8 below summarizes the carbon savings due to the modular design of the house (Quale et al. 2012). A 15kW solar PV can reduce ~21,900 kg CO_2 emissions in a year. Due to hempcrete's CO_2 sequestration the building becomes carbon neutral and the use of PV can lead to a carbon negative operation of the dwelling unit. The material choice and the energy source result in further improvements in GHG emissions that are seen in Table 8 (Quale et al. 2012).

Table 8. GHG Emissions Modular Construction vs On-Site Construction

Energy consuming activities	**Consumption at stages of construction**	**Environmental Impact (GHG Emissions/kg CO2)**	
		Modular	On-site
Transportation	Resource supply	-	-
Transportation	Material transport to factory	10	11
Transportation	Worker transport to factory	831	0
Heating and cooling, Equipment and appliances	Material production and manufacturing	613	780
Transportation, Equipment and Appliances	Module transport to site	1800	0
Transportation	Worker transport to site	1110	7160
Equipment and appliances, Heating and cooling, lighting	On-site energy use	3160	11500
Equipment and appliances	Waste management	2	3
	Average	**13,600**	**19,500**
Material selection	Hempcrete **Carbon Footprint**	(-)12,000 **1,600**	(-)9,000 **10,500**

6.3 Prefabrication Resulting in Economically Viable Construction

The proposed design utilizes prefabricated elements in the building construction. These include hempcrete wall panels, floor panels, roof panels, glass and window panels along with bathroom and kitchen modules. While these components are prefabricated and manufactured in the respective factories, the site work is done in parallel resulting in lower overall construction time. The building components can be shipped to be assemble on-site as soon as the site is ready. It can take about 50% less time to assemble the building than constructing them on site (Smith et al. 2010).

6.3.1 Assembly

In case the occupants decide to increase their living space, they simply need to add new modules to the current layout. Modular construction can help in providing affordable housing. Prefabrication and assembly when done by local businesses boost the local economies and provide employment opportunities for the surrounding community (Mckinsey 2019). Figure 15 shows the details of the building modules used in the construction of the Hogan style house. The details of the prefabricated panels can be seen in Figure 16 which shows an exploded view of the prefabricated panels that are being used in the construction.

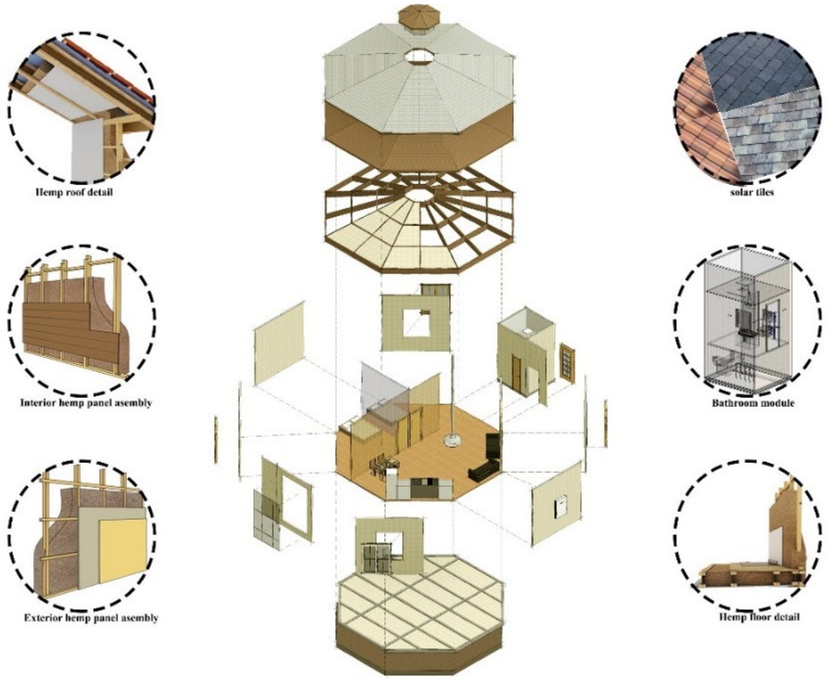


Figure 15. Details of Prefabricated Modules in Hogan Style House (Hempitecture2020)

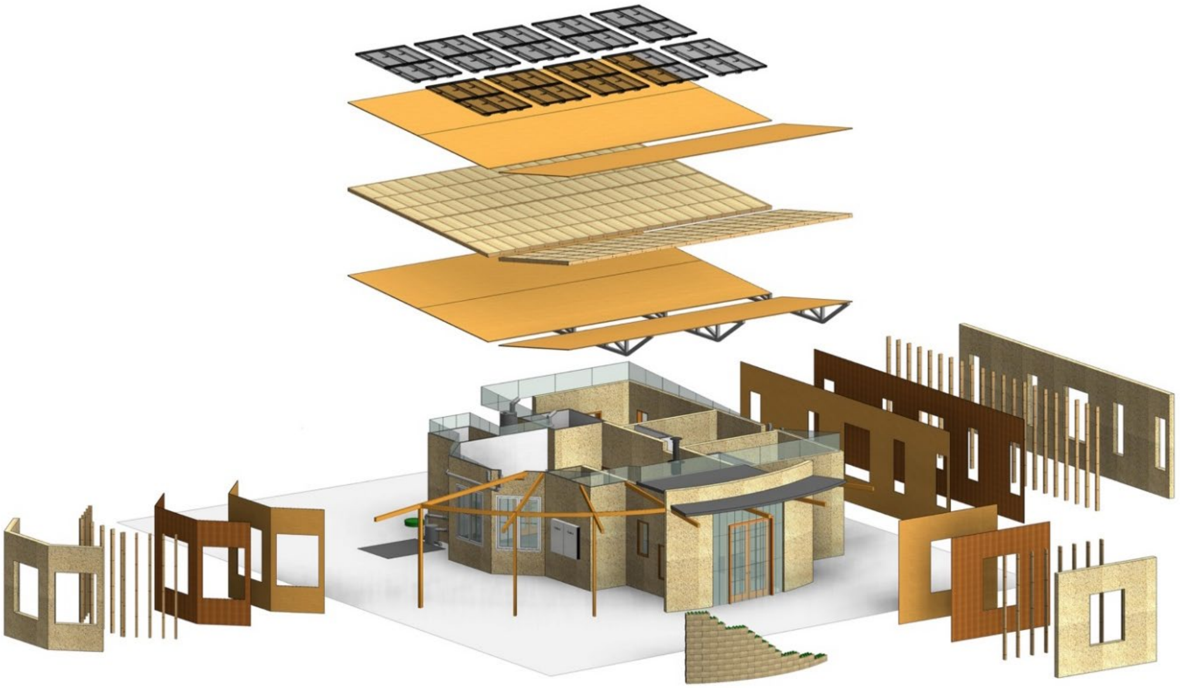


Figure 16. Exploded View Showing the Panel Layers in the Proposed-3 Bedroom House

The prefabricated hempcrete wall panels have several layers. The layers consist of packed hempcrete, structural timber, and optional cladding. Manufacturing of these panels takes place in a factory setting. They are then delivered to the site for assembly. The curved entry wall in the front is made of the precast structural hempcrete blocks, delivered with the panels and assembled on site. These blocks are stackable and interlocking to form a structurally stable wall. They can be cut in the field per the design requirements. The brick wall can be replaced by a panel if needed. A layer of bio lime scratch can be added on the walls, followed by the bio lime brown and bio lime finish for the final finish.

Each roof panel has a specific size (here approximately 38’ x 14’), which are assembled on site. The roof panels have wooden sheets on the top and bottom insulated with hemp wool and structural timber sandwiched in between the two layers. The roof panels are laid on the timber structural trusses which are manufactured in the factories and installed on-site. The number of roof panels required depends on the interior floor space. The topmost layer of the roof consists of the solar panels or solar tiles (shingles).

As seen in the Figure 17, the two bathrooms and the kitchen are fully functioning modular “kits” with all the necessary fixtures, plumbing, cabinets, and appliances. Utilization of such modules can result in significant savings of construction time and cost (McKinsey 2019). The wall section details for assembly and disassembly are discussed in the section 6.3.3. The Hempcrete panels can be flat packed, and the bathrooms and kitchen are modular. Both the flat packed and modular blocks are transported by truck since they can fit inside the trailer of a common semi-truck (14’ W x 52’ D x 15’H). The three-bedroom and two-bathroom house requires two trucks, while the two-bedroom and one-bathroom Hogan style house can fit in one truck.

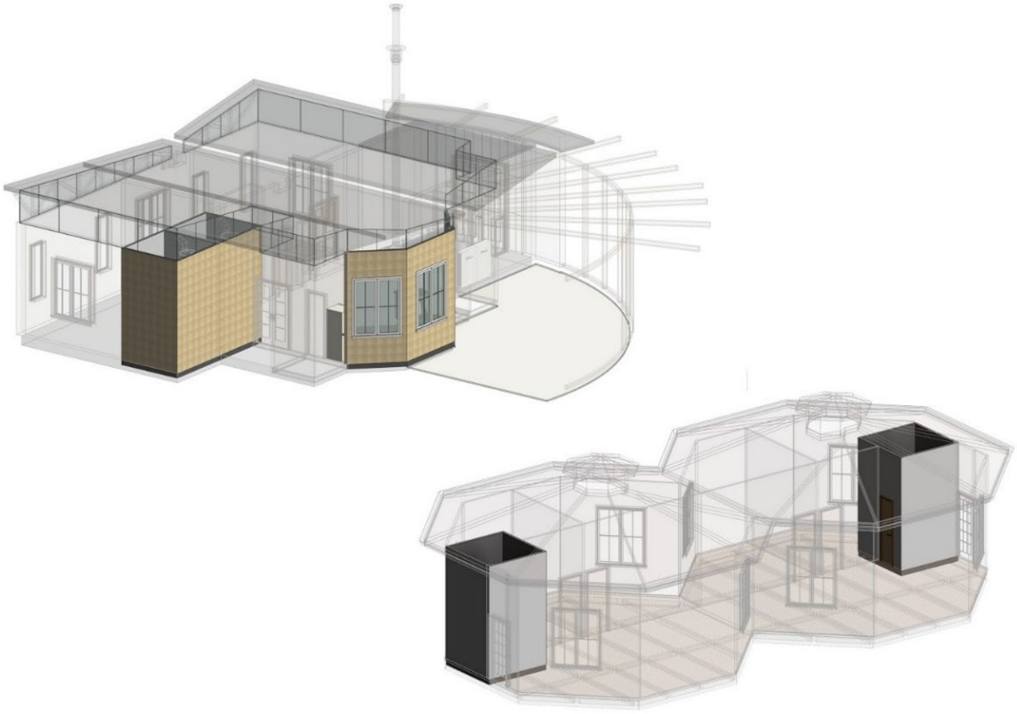


Figure 17. Modules within the Construction System within the Proposed Designs

The construction process illustrated in Figure 18 and Figure 19 (for each of the two respective designs) can be described in nine steps. (1) The foundation is prepared, and the septic and water recycling system are installed. In the meantime, the wall, roof and floor panels are manufactured and shipped. Kitchen and bathroom modules are prepared and shipped. (2) After the individual components arrive on site, the bathroom and the kitchen modules are first to be installed. (3) Next, the floor and all the wall panels are installed. (4) The roof trusses are places and preparation for roof installation begin. (5) Roof panels are installed (6) The plumbing, electrical and solar PV set up begins. (7) Doors, windows and other remaining elements are next to be put in their respective places. (8) All the services are connected and tested. (9) Interior and exterior finishes are completed as the site is finalized.

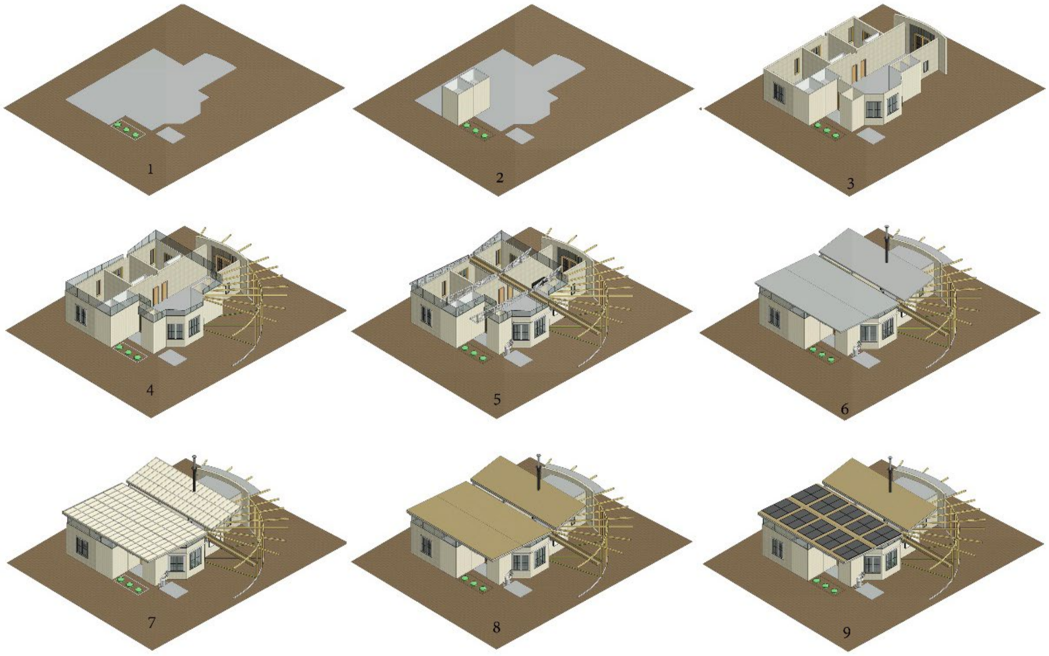


Figure 18. Construction Steps of the Proposed 3-Bedroom House Design

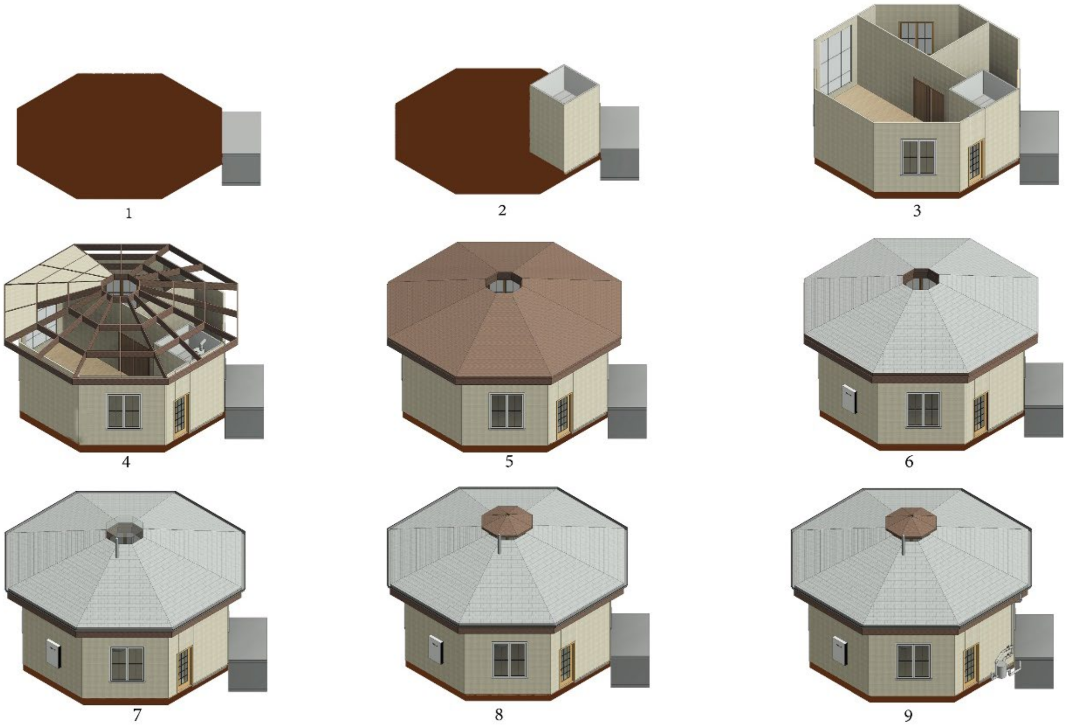
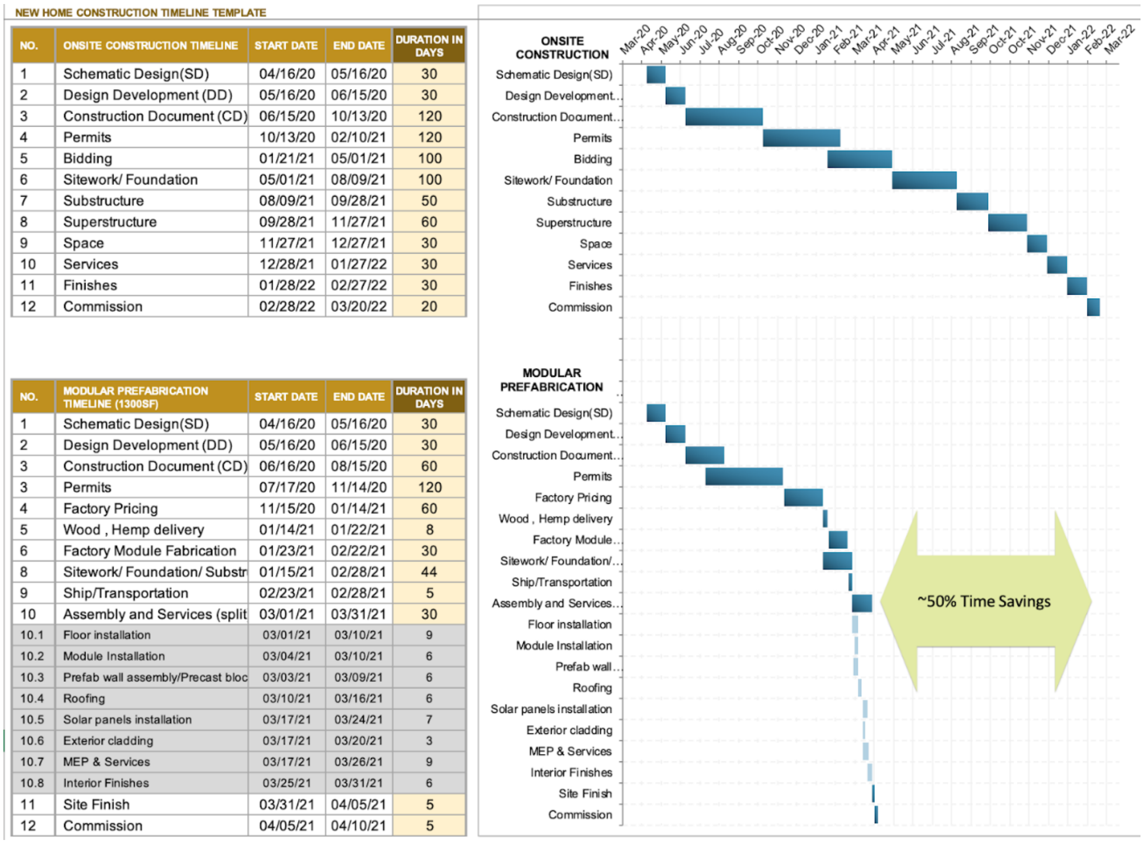


Figure 19. Construction Steps of the Proposed Hogan Style House Design

6.3.2 Cost and Scheduling

Smith (2010) discusses the time savings that can be achieved during modular construction. Figure 20 provides a rough timeline for the construction of the proposed 1300SF house and compares it with the time required for the on-site construction of a similar sized dwelling unit (Smith 2010). Modular construction using prefabricated units can offer significant cost savings (MGI 2014).

The proposed design is about 30% cheaper to build using prefabricated modules instead of on-site construction. The 1300SF 3-bedroom 2-bathroom residence has a projected cost of construction between \$135,000 - \$170,000 for a newly built dwelling unit. The Hogan style 2-bedroom 1-bathroom is projected to cost between \$75,000 - \$100,000 depending on the customizations. On-site construction of similar sized house can range between \$175,000 - \$200,000.



NEW HOME CONSTRUCTION TIMELINE TEMPLATE

NO.	ONSITE CONSTRUCTION TIMELINE	START DATE	END DATE	DURATION IN DAYS
1	Schematic Design(SD)	04/16/20	05/16/20	30
2	Design Development (DD)	05/16/20	06/15/20	30
3	Construction Document (CD)	06/15/20	10/13/20	120
4	Permits	10/13/20	02/10/21	120
5	Bidding	01/21/21	05/01/21	100
6	Sitework/ Foundation	05/01/21	08/09/21	100
7	Substructure	08/09/21	09/28/21	50
8	Superstructure	09/28/21	11/27/21	60
9	Space	11/27/21	12/27/21	30
10	Services	12/28/21	01/27/22	30
11	Finishes	01/28/22	02/27/22	30
12	Commission	02/28/22	03/20/22	20

NO.	MODULAR PREFABRICATION TIMELINE (1300SF)	START DATE	END DATE	DURATION IN DAYS
1	Schematic Design(SD)	04/16/20	05/16/20	30
2	Design Development (DD)	05/16/20	06/15/20	30
3	Construction Document (CD)	06/16/20	08/15/20	60
3	Permits	07/17/20	11/14/20	120
4	Factory Pricing	11/15/20	01/14/21	60
5	Wood , Hemp delivery	01/14/21	01/22/21	8
6	Factory Module Fabrication	01/23/21	02/22/21	30
8	Sitework/ Foundation/ Substr	01/15/21	02/28/21	44
9	Ship/Transportation	02/23/21	02/28/21	5
10	Assembly and Services (split	03/01/21	03/31/21	30
10.1	Floor installation	03/01/21	03/10/21	9
10.2	Module Installation	03/04/21	03/10/21	6
10.3	Prefab wall assembly/Precast bloc	03/03/21	03/09/21	6
10.4	Roofing	03/10/21	03/16/21	6
10.5	Solar panels installation	03/17/21	03/24/21	7
10.6	Exterior cladding	03/17/21	03/20/21	3
10.7	MEP & Services	03/17/21	03/26/21	9
10.8	Interior Finishes	03/25/21	03/31/21	6
11	Site Finish	03/31/21	04/05/21	5
12	Commission	04/05/21	04/10/21	5

Figure 20. Proposed Construction Timeline Comparison

The cost analysis and comparison can be seen in Tables 9, 10, and 11 (cost-to-build 2019). The recommended construction process is developed to be efficient and socially responsible while being profitable, hence resulting in economic sustainability. The scope of this cost analysis and project execution analysis excludes the costs related to the initial project development, first-time cost as well as the initial documentation development required during the proposal phases. The projected costs in this study only considers the recurring construction costs of both the dwellings after these designs have been developed as well as the materials' sourcing and transportation routes are established. The contingency amount is also excluded from the total cost of these dwellings shown in Tables 9, 10 and 11.

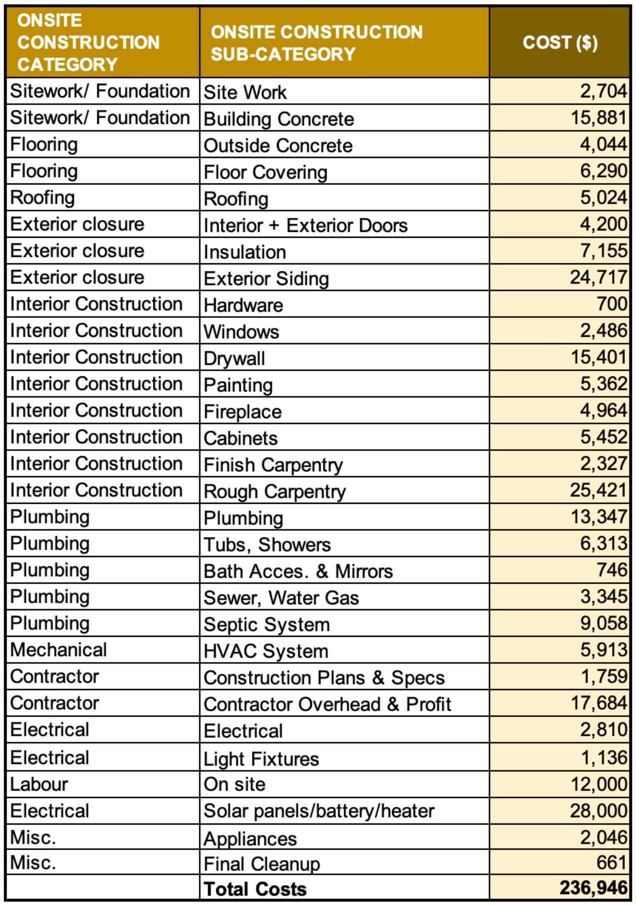
Table 9. Estimated Cost of 3-Bedroom Modular Dwelling (APPENDIX A)

MODULAR PREFABRICATION CATEGORY	MODULAR PREFABRICATION SUB-CATEGORY (Hogan)	COST ($)
Sitework/ Foundation	Demolition/Earthwork	1,500
Sitework/ Foundation	Foundation	8,781
Flooring	Floor construction	1,500
Flooring	Floor finishes	800
Roofing	Roof construction	3,000
Exterior closure	Wood structures	1,000
Exterior closure	Exterior wall panels	5,400
Exterior closure	Exterior windows	1,000
Exterior closure	Doors	1,000
Interior Construction	Interior wall panels	1,000
Interior Construction	Wall finishes	2,000
Interior Construction	Modular Kitchen with appliances	3,500
Interior Construction	Fire place	2,000
Plumbing	Toilet Modules + plumbing fixture	4,000
Plumbing	Rain water drainage systems	5,000
Plumbing	Plumbing	2,000
Plumbing	Septic tanks and sewage system	6,058
Mechanical	Fixed and moveable instruments	4,000
Electrical	Electrical system with fixtures	3,000
Electrical	Solar panels/battery/heater	20,000
Misc.	Landscape	2,000
Labour	On site	8,000
Contractor	Construction Plans & Specs	1,759
Contractor	Contractor Overhead & Profit	10,684
Transportation	Transportation	2,000
Total		**100,982**

Table 10. Estimated Cost of 2-Bedroom Hogan Style Modular Dwelling (APPENDIX A)

MODULAR PREFABRICATION CATEGORY	MODULAR PREFABRICATION SUB-CATEGORY	COST ($)
Sitework/ Foundation	Demolition/Earthwork	3,000
Sitework/ Foundation	Foundation	15,881
Flooring	Floor construction	2,500
Flooring	Floor finishes	1,300
Roofing	Roof construction	8,000
Exterior closure	Wood structures	5,000
Exterior closure	Exterior wall panels	10,401
Exterior closure	Exterior windows	4,000
Exterior closure	Doors	3,000
Interior Construction	Interior wall panels	4,800
Interior Construction	Wall finishes	6,000
Interior Construction	Modular Kitchen with appliances	7,000
Interior Construction	Fire place	2,000
Plumbing	Toilet Modules + plumbing fixtures	8,000
Plumbing	Rain water drainage systems	5,000
Plumbing	Plumbing	6,000
Plumbing	Septic tanks and sewage system	9,058
Mechanical	Fixed and moveable instruments	4,000
Electrical	Electrical system with fixtures	4,000
Electrical	Solar panels/battery/heater	28,000
Misc.	Landscape	2,000
Labour	On site	12,000
Contractor	Construction Plans & Specs	1,759
Contractor	Contractor Overhead & Profit	14,684
Transportation	Transportation	3,000
Total		**170,383**

Table 11. Cost On-Site House Construction (APPENDIX A)



ONSITE CONSTRUCTION CATEGORY	ONSITE CONSTRUCTION SUB-CATEGORY	COST ($)
Sitework/ Foundation	Site Work	2,704
Sitework/ Foundation	Building Concrete	15,881
Flooring	Outside Concrete	4,044
Flooring	Floor Covering	6,290
Roofing	Roofing	5,024
Exterior closure	Interior + Exterior Doors	4,200
Exterior closure	Insulation	7,155
Exterior closure	Exterior Siding	24,717
Interior Construction	Hardware	700
Interior Construction	Windows	2,486
Interior Construction	Drywall	15,401
Interior Construction	Painting	5,362
Interior Construction	Fireplace	4,964
Interior Construction	Cabinets	5,452
Interior Construction	Finish Carpentry	2,327
Interior Construction	Rough Carpentry	25,421
Plumbing	Plumbing	13,347
Plumbing	Tubs, Showers	6,313
Plumbing	Bath Acces. & Mirrors	746
Plumbing	Sewer, Water Gas	3,345
Plumbing	Septic System	9,058
Mechanical	HVAC System	5,913
Contractor	Construction Plans & Specs	1,759
Contractor	Contractor Overhead & Profit	17,684
Electrical	Electrical	2,810
Electrical	Light Fixtures	1,136
Labour	On site	12,000
Electrical	Solar panels/battery/heater	28,000
Misc.	Appliances	2,046
Misc.	Final Cleanup	661
	Total Costs	**236,946**

6.3.3 Disassembly

The model recommends local manufacture, and the main components of the dwelling are locally available within 500 miles of the location. The dwelling units are designed for easy disassembly and component recovery. Most of the materials used for construction are either circular or have the potential of being C2CP certified. The prefabricated hempcrete panels are used for both the exterior and the interior walls, which can be easily dismantled, reused as well as repaired. Figure 21 displays the joinery details of the panels and blocks. The “L” Plate channel helps to anchor the hempcrete panels. These can be easily screwed with the nails. These nails and channels not only support assembling the panels and blocks but also help for easy disassembly.

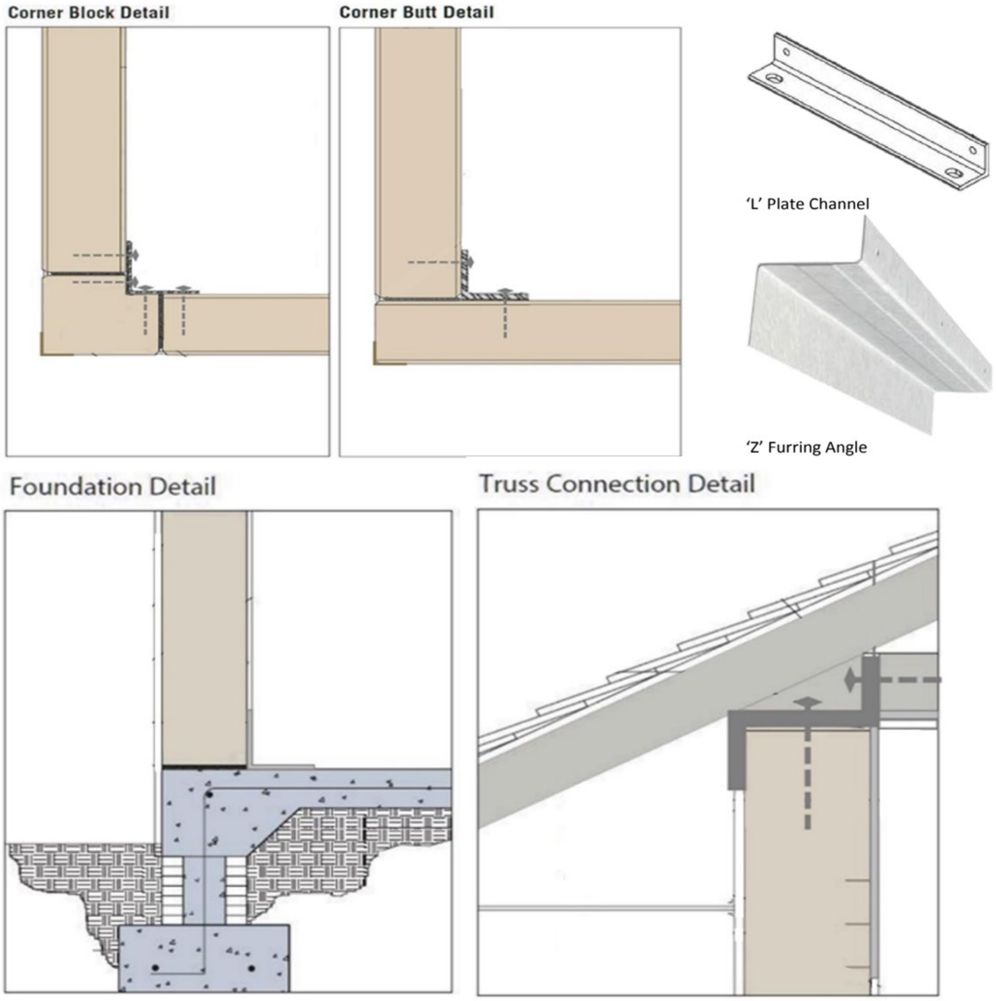


Figure 21. Assembly-Disassembly Details (Studiogreen 2016)

The exterior cladding, if needed by the owners, would also be cohesive components provided by the pre-fabricators. The toilet and the kitchen modules can be removed during disassembly and reinstalled at a new location. By keeping the hempcrete panel walls as the structural elements, the design allows for easy assembly and disassembly.

CHAPTER 7

DISCUSSION: CE PRINCIPLES APPLIED IN THE PROPOSED MODEL

The first section of this chapter will detail a possible governance model with respect to the tribal community, homeowners and builders. The next section brings all the entities together in a proposed circular loop and studies the circular principles implemented. The last section will analyze the value that can be created by means of the CE.

7.1 Governance Model

In this model, the Tribal Housing Authority discusses the issues and learning of the past and suggests the future actions benefiting the tribal citizens and their families. Their regular participation and representation are warranted, and it is suggested that the housing authority should continue their research and planning in support of the tribal communities.

The council of elders is the consulting body of the tribe and their wisdom and experience is critical for the growth of the community. Community leaders continue to foster an environment that encourages broad citizen participation. Final approvals needed by the tribal housing authority administration must be run through the council of elders.

The Tribal Housing Authority and the architects and contractors are suggested to work under a strategic alliance. The architects and contractors are responsible for providing culturally responsive, sustainable, and affordable home design and construction to assist with the Tribal Housing Authority to address housing shortages. Their partnership is mutually beneficial and results in the affordable nature of the housing. They encourage and require local participation of the community and train the tribal members on how to build the homes. The strategic alliance includes regular meetings, discussions, scheduling, and continuous goal alignment through constant communication.

The alliance also can initiate a localized facility management entity that helps the tribal families maintain and renew their dwelling units. This entity can be trained by professionals and work in conjunction with the local management, local manufacturers and local suppliers, including the Navajo Nation Forestry Department (NNFD) and NAPI farms. These local sources and the Tribal Housing Authority should also collaborate and communicate continuously to inform decisions. Figure 22 illustrates the proposed governance model.

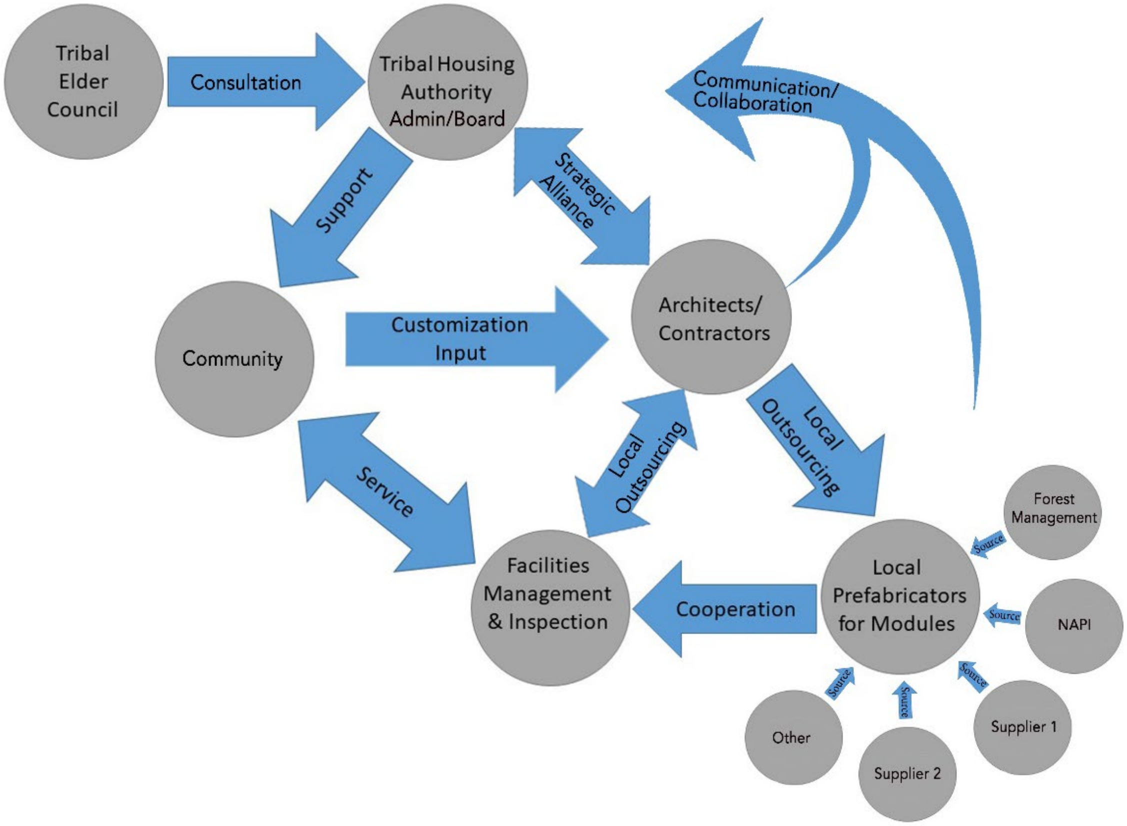


Figure 22. Proposed Governance Model and Interaction Patterns

7.2 Proposed CE Loop

This section will incorporate the proposed design's materials into a CE loop and discusses the flow of raw materials and interactions with the various entities within the system resulting in a CE. The proposed circular loop starts with the farming and harvesting of hemp. The next step is to supply hemp hurd to the local hempcrete manufacturing and prefabrication factories. During the design phase of the low-cost residence, utilization of prefabricated hempcrete panels and precast interlocking structural hempcrete blocks for construction is proposed. Once the required dimensions are sent to the manufacturing facility, they can start manufacturing the desired panels.

In the meantime, the site is prepared for construction and the foundation is completed. As soon as the panels and other prefabricated modules (i.e., kitchen, bathroom, roof, solar, water) arrive, the house is assembled, and the services are connected within a short period of time as discussed in the previous chapter.

Once ready for occupancy, the house relies on solar energy for most of its energy demands. The design includes a water harvesting and recycling system which helps in achieving net-zero water. Hempcrete has a high R-value and is able to maintain ambient internal temperatures even with harsh external weather conditions. This reduces the energy required to operate the house especially when the site is off grid.

The energy storage batteries need renewal after they have reached a particular operational cycle. The battery disposal needs to be completed in an environmentally friendly manner in conjunction with the suppliers and recyclers. This again should be handled by the facilities management personnel. These repair and renewal efforts can also be localized in form of facility management services provided either by the tribal authorities or the local factories with a Public Private Partnership model. This localization of services further enhances the economic activity within the community (Turnbull 2017).

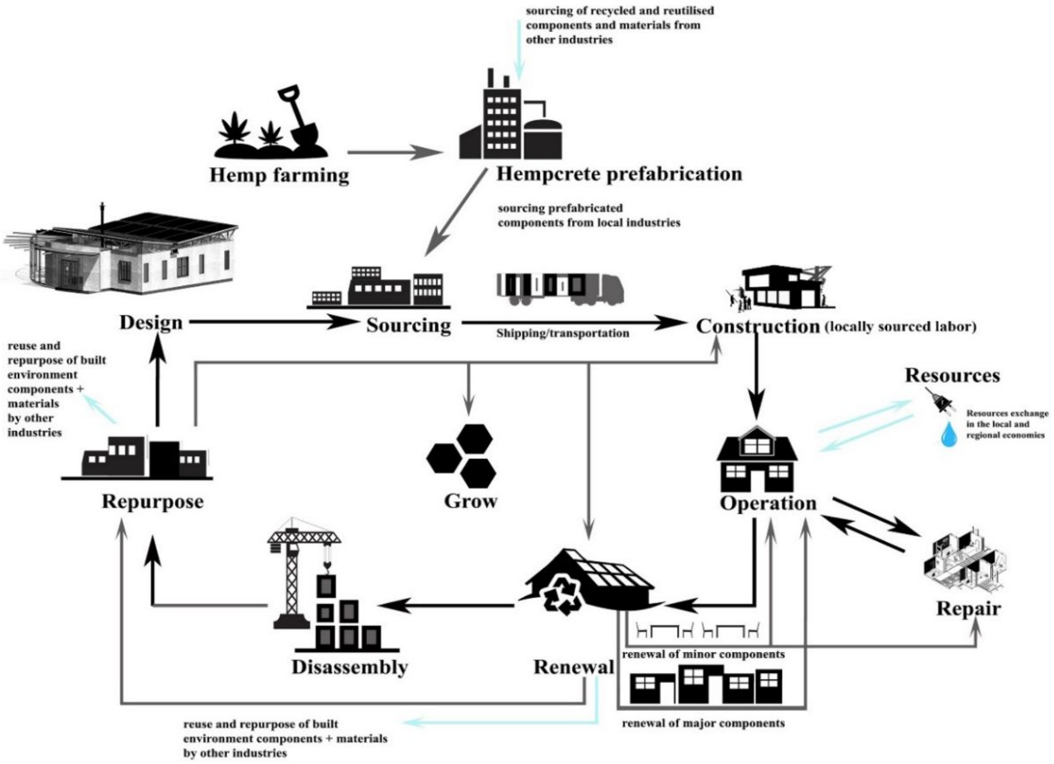
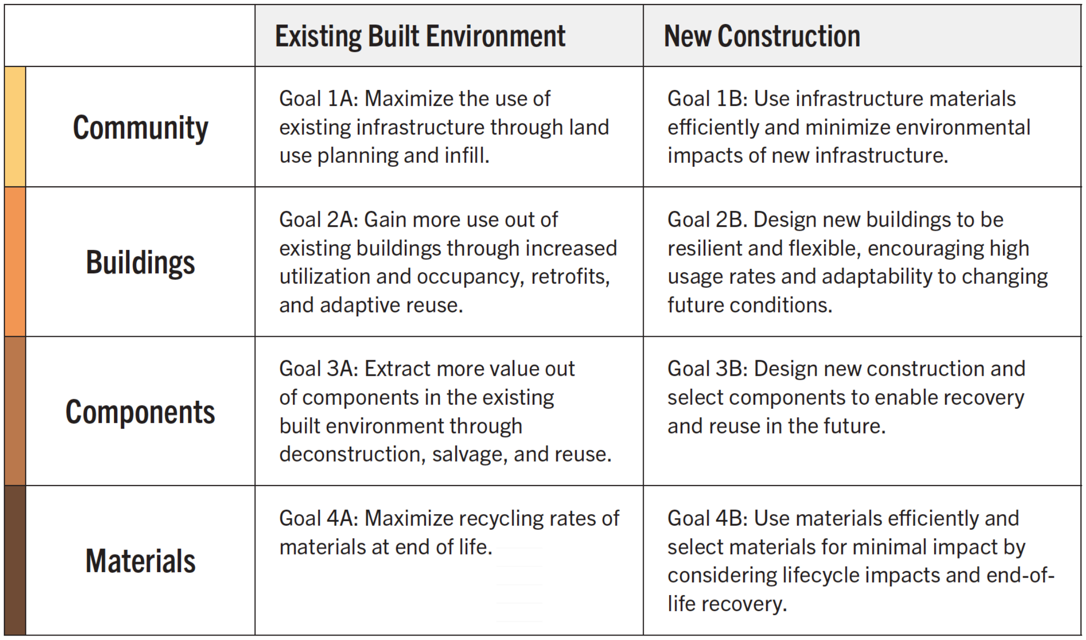


Figure 23. Proposed Circular Ecosystem

Repurpose and renewal of space can be seen during the occupancy by means of addition of rooms and modules. Hempcrete blocks and panels can have a life of over hundred years so they have a potential to be reused (Justbiofiber 2012). If there is need for relocation, the panels can be removed, and modules can be disassembled. This can be done with the assistance of the panel manufacturers. They can be either be repaired at the local factories and reassembled at a new location or reclaimed by the factory for material reuse. Figure 23 summarizes the proposed circular loop within the chosen ecosystem of the Navajo built environment near Shiprock, NM.

7.3 CE Desired Goals and Strategies Implemented

Stopwaste and ARUP (2018) identify the goals and strategies that can influence new construction within an existing built environment. Figure 24 below divides the built environment into four categories and explores strategies that can bring circularity in the built environment. The next step discusses the CE principles that are incorporated in the proposed model with respect to the goals mentioned by Stopwaste and ARUP (2018).



	Existing Built Environment	New Construction
Community	Goal 1A: Maximize the use of existing infrastructure through land use planning and infill.	Goal 1B: Use infrastructure materials efficiently and minimize environmental impacts of new infrastructure.
Buildings	Goal 2A: Gain more use out of existing buildings through increased utilization and occupancy, retrofits, and adaptive reuse.	Goal 2B. Design new buildings to be resilient and flexible, encouraging high usage rates and adaptability to changing future conditions.
Components	Goal 3A: Extract more value out of components in the existing built environment through deconstruction, salvage, and reuse.	Goal 3B: Design new construction and select components to enable recovery and reuse in the future.
Materials	Goal 4A: Maximize recycling rates of materials at end of life.	Goal 4B: Use materials efficiently and select materials for minimal impact by considering lifecycle impacts and end-of-life recovery.

Figure 24. Circular System Goals at Multiple Scales (Stopwaste and ARUP 2018)

The architecture and design process encourage social and ecologically inclusive decision-making becoming an economic guide to surrounding communities. The use of reusable and recyclable building materials supports the local economy by generating employment for the population. Since hemp can be easily grown within 4 months compared to timber taking 10 years, the local factories can produce and manufacture hempcrete panels relatively faster and at a lower cost compared to timber.

The proposed designs add value to creating a socially viable community by facilitating the community and family growth, as well as by enhancing common values through social integration, culturally responsive design, and material communication. The Material selection provides architectural experience enhanced by the cultural tactility of materials such as hemp (leaves) and wood (logs) to promote core values of the community. The design generates value with an acceptable rate of return that covers the operating costs in the initial stages of its lifetime. The proposed model assures continued positive effects on societies by intensified environmental responsibility and long-term sustainability. Table 12 summarizes the strategies employed in the proposed ecosystem.

Table 12. Circular Strategies Employed at Various Levels of Built Environment

	Existing Built Environment	New Construction
Strategy used at Community level	1A: Utilization of the existing NAPI farms to grow hemp.	1B: Hemp needs no agrochemicals, pesticides or insecticides to grow. It does not hinder food production.
Strategy used at Building level	2A: Flexcrete factory can be used to manufacture hempcrete panel. It does not need harmful raw materials like fly ash.	2B: The proposed building is designed for adaptability, reuse and expansion to meet the future needs of a family (i.e., nuclear, clan, homestead).
Strategy used at Component level	3A: Existing components (like appliances) can be utilized in manufacture of bathroom and kitchen modules. Repaired and repurposed modules are cheaper than brand new modules.	3B: Prefabricated modules and components allow easy deconstruction, recovery and reuse (e.g., bathroom modules, hempcrete wall panels).
Strategy used at Materials level	4A: Technology and policy for recycling and reuse of hemp, wood and glass components in building and in other applications.	4B-1: Hempcrete blocks can be structural and do not need additional insulation or fireproofing. 4B-2: During its lifetime, hempcrete absorbs more carbon than it emits. 4B-3: It is recyclable and biodegradable.

7.4 Potential Value Created with respect to the Sustainability Pillars

Not only does a CE unlash the contemporary styles of generally unsustainable construction, but it also offers creative methods to make architecture and construction smarter, more resilient and sustainable. The recommended circular economy model provided earlier in Figure 23 forms a broader trading framework within the community, resulting in a profitable sustainable development.

The CE loop developed this study perpetuates cultural traditions while also providing information and training around the built environment. It also increases awareness of recycling and reuse of functional components. The model advocates for a lower material waste and lower resource consumption achieved due to the disassembly potential of the prefabricated building modules. The choice of Hempcrete as a key building material from the locally available Hemp hurd enhances the economic value of the crop. It also creates opportunities for locals in the form of hempcrete production and prefabrication labor. The localized raw material production, manufacture of components and facilities management reduce the maintenance and building costs resulting in an affordable dwelling unit.

The choice of material also addresses many green building practices. Hempcrete is a biodegradable material with excellent insulation properties. It has the ability to retain heat and insulate from harsh outside climate due to its exceptional thermal efficiency. It is able to maintain healthy and comfortable indoor temperatures with minimal need of an HVAC system. The reduced energy demands result in an off-grid capable unit due to the presence of a solar PV module with a battery back-up system. The design also advocates for a water harvesting and an on-site water treatment system. Hempcrete panels are carbon negative resulting in a low carbon footprint of the dwelling unit. The building design thus has the potential to generate positive ecological effects in its natural built environment.

The above value additions are a result of sustainable design combined with modern construction methods. Nussholz and Milios (2017) studied the value chain benefits of applying CE principles to building materials. Table 13 summarizes the value proposition of the CE model developed in this thesis, presenting the benefits of a localized manufacturing and facility management loop.

Table 13. Value Creation through the Life Cycle of the Project

Lifecycle phases (Nussholz, J. & Milios, L. 2017)				
Value Dimension	**CE Model elements**	**Material and component production**	**Design**	**End-of-life**
Value proposition: What value is provided and to whom	1) Value proposition	1) Materials designed for durability.	1) Design and planning of buildings with high sustainability standards and social vision.	1) Competitive rates and certified quality standards
		2) Structurally stable withstanding extreme weather conditions.	2) Culturally sensitive housing allows for social sustainability	2) Focusing on clients who are environmentally conscious and who care about environmental
		3) The components are flexible and can be repaired, replaced, recycled and reused.	3) Enabling small scale to urban scale projects	
		4) Local farming of hemp and use of locally available wood results in cost savings and increased value within the local economy.	4) Designed for adaptability and flexibility.	
		5) Aims to invite the indigenous communities that values affordable housing, waste management, circular solutions and reduced environmental impacts		
	2) Value creation recipients	1) Targeted public housing associations are benefited as total costs of ownership is lowered.	1) Targeting organizations that are open to reuse and promoting reuse design choices	1) Sustainable organizations providing certifications are valued.
		2) Targeted customers are benefited as the houses are affordable, safe and durable.	2) Improved social and environmental sustainability performance	2) companies producing sustainable products using sustainable raw materials are valued
		3) The user group is benefited who value circular solutions, recycling and reusing	3) The designed houses are less costly, are more precise, have the same aesthetic value, and are equally functional than the conventional house designs.	3) Construction companies are benefited, and prefabricated manufacturers are valued.
		4) Manufacturers are benefited as the raw materials are locally available thus saving their cost.	4) Targeting organizations like Native American communities that are open to reuse and who make sustainable choices in design.	4) Clients are benefited for selling the damaged components and modules to the recycling industries
		5) Environment is benefited due to the use of sustainable materials and renewable and sustainable manufacturing process		
Value creation & delivery: How is value provided	1) Value chain activities	Developed supply base and sometimes get contacted with offers	Incorporating circular economy in every bid	Developing distribution network of recycled demolished hempcrete
	2) Resources and capabilities	1) Building material choice (hemp) allows for stability, safety and sustainability	1) The prefabricated panels and or blocks in the house design, allows for easy adding and removing of rooms as per the family needs.	1) The prefabricated roof panels have the same size, hence can be added or removed as per the customer needs.
		2) NAPI farming and Navajo Flexcrete generating factories allows for production and manufacturing of the components,	2) Culturally responsive architectural planning via community interaction	2) Technology development for sorting, piling up and cleaning of hempcrete
		3) Prefabrication techniques not only allows easy fabrication and deconstruction, but also helps in recycling and reusing of the building components and modules		3) Sorting of the building components and materials by the construction company for restoring.
	3) Partner network	1)Technology for manufacturing hempcrete panels, 2) Technology for recycling hempcrete panels 3) Development and application of building elements from reused building materials	Partner network to develop reuse solutions and certification standards	Partner network to develop certification
Value capture: How is profit made and other forms of value captured?	1) Financial structure	1) Developing networks of partners which lease technology and run their own production and sales units	1) Franchising fee 2) commission on sales of franchises 3) Offering to take disposed materials for a lower price	Offering higher than market price to acquire discarded materials and components (case-by-case basis)

CHAPTER 8

CONCLUSION

The architecture and construction industry have a role in devising a sustainable direction for all built environments, including indigenous built environment. Similar to working with any client, the only way designers and builders would be able to deliver the needed service effectively is when they work with the tribal communities to understand the culture and specific needs. Laban (2018) illustrates the importance of conforming to the cultural aspects of the community while designing a residence in an Indigenous community. Policy also plays an important role, and issues like land ownership should also be resolved before housing projects are initiated (GAO 2014). To effectively develop a circular ecosystem within a tribal built environment, it is imperative for the designers to collaborate with the tribal housing authority as well as the local construction industry.

The first stage of the thesis assessed CE at the micro-level. This was done by analysing the sustainable building materials that are commonly used for traditional tribal housing construction located in northern Arizona. The study initially consisted of five locally available materials, namely Navajo Flexcrete, adobe brick, rammed earth, straw bale, and wood. The study then considered Hempcrete as the sixth building material option due to recent Hemp farming developments in the community. The analysis shows that, with appropriate closed loop practices, Hempcrete can qualify for green product standards like C2CP and it is also able to provide new opportunities for the community. Hempcrete was hence selected as a key building material due to its multilevel benefits.

The study then reviews the cultural aspects of the community, at a meso-level, and recommends two culturally appropriate designs for tribal housing utilizing prefabricated modules, both using Hempcrete. With an already demonstrated ability of Hempcrete to be formed as high R-value structural bricks and insulating wall panels, the construction process with the prefabricated modules can be significantly faster and cost effective resulting in almost thirty percent savings when compared to on-site construction (as opposed to leveraging prefabrication) of a similar dwelling with contemporary building materials. The prefabricated modules can be shipped to remote locations and assembled at the site within a quick time frame with over a fifty percent construction time savings compared to full on-site construction of a similar sized building.

The inherent material properties of hempcrete along with use of solar PV result in a net-zero energy building. The proximity to the San Juan river along with the water recycling system can result in a closed-loop water cycle. The culturally sensitive design results in a high-performing, sustainable building that can be constructed for a cost that is comparable to the examined tribal housing case study.

Hempcrete can last for over 100 years (Justbiofiber 2012) and requires very low maintenance over its lifetime. The expandable design increases the life of the building and encourages reuse of the space. The choice of Hempcrete can help boost the local economy as well since farming is one of its major sources of income. Due to low training requirements Hempcrete panels can be manufactured locally and assembled fast. A circular ecosystem is hence conceived at a macro-level within the community that positively impacts the built environment.

The principles of a circular design provide a significantly positive outlook towards achieving a sustainable built environment in many tribal communities (Petit-Boix et al. 2018). Designs that are inspired by the cultural teaching and natural environment of an indigenous community, can bridge the gap between economic and cultural objectives as well environmental concerns (Blosser et al. 2014). With a clear framework and a localized infrastructure, the CE concept has the potential to adhere to some of the most aggressive design guidelines like the Living Building Challenge principles while still being economically viable (Ghisellini 2016).

Sustainability complements the components of cost, function, aesthetics, time, and the local community. CE in the building industry seeks to address the environmental effects of buildings and define the consumption limits of resources while considering future needs. Utilizing the CE design process in conjunction with the indigenous traditions helps in developing a sustainable built environment. Using many successful natural ecosystems as an example, we can conclude that resilience of circular resource loops is a result of mutual collaboration. Therefore, this new paradigm in the culturally inspired indigenous forms can result in an all-encompassing architectural and construction model which introduces an ecologically and financially feasible perspective to the tribal community.

8.1 Limitations

The implementation of a circular design and development scenario can face many challenges. Realizing a CE needs collaborative action on many different fronts. Due to a lack of familiarity with CE in the design and construction industry, CE adoption in this industry has been gradual and relatively conservative.

With 114 definitions of CE compiled (Kirchherr 2017), a clear-cut explicit model offering easy to understand guidelines is not readily available. Reike (2018) attempts to distinguish them into 3 versions while discussing their differences. In absence of a simple and easy to understand design framework like LBC, the design of a CE process can end up with an unsteady definition, conforming to only a given set of conditions.

Another significant factor that can influence CE development is the expectation of convenience. A sustainable design might require some form of compromise from the side of the user in terms of services offered with the circular loop. It needs a collective understanding of what is right for the planet, especially with respect to energy utilization, resource conservation or materials selection (Bjørn and Hauschild 2011).

A circular economy is heavily dependent on the supply chain and the availability of the required resources. Whether it is prefabricated building materials or raw materials that have notable cultural value, they can become challenging to obtain, transport, or even manufacture. The absence of waste management and recycling infrastructure can also significantly harm the reuse potential of indigenous or locally available materials. Many raw materials that are culturally notable might not be able to qualify for any green product certifications, whereas many materials that help in a circular design might not be completely sustainable (Homrich 2017). Designing for deconstruction offers another set of challenges since sustainable materials in structural arrangements are typically not the easiest to dissemble.

The absence of supporting regulations and incentives is another factor that can deter the development of a circular design process. There is no credit system in place that recognizes and awards the overall value of a circular design. Lack of economic motivation for designers as well as for the stakeholders including the end-users impedes adoption of sustainable design practices and eco-friendly material use.

Lack of public participation and poor involvement is the one of the biggest factors that can affect a CE loop. A sense of ownership is often needed to affect change. Land ownership in the Navajo tribal lands is another factor that also needs to be accounted for (Wagner and Harris 2016). A comprehensive understanding of local factors and cultural significance is often a foundational element for sustainable change.

8.2 Future Work

Future work that builds on this study can include other material combinations that result in a circular ecosystem, while also addressing urban scale issues. Development of eco-friendly building materials requires further research, in order to become economically and structurally competitive when compared to contemporary building materials. While enhancing overall sustainability of the project is the goal, research needs to be conducted on whether the indigenous communities consider this to be a priority in their built environments.

The built environment domain of the CE model proposed in this study was at the community-level of a tribal nation. The scope of the exploratory research was restricted to published resources only. It is recommended that in the next step of this research tribal representatives are involved from the early planning and design stages. Also, a partnership program that includes CE experts from academia, and design veterans who have intimate knowledge of the tribal nation, can prove to be beneficial. Blosser et al. (2014) discuss the advantages of a three-way partnership with academic-tribal-private involvement. The future of this study should similarly include an on-site partnership with the local housing entities and other tribally designated housing programs like the NHA to fully identify the possible opportunities. It should include significant community engagement to identify priorities and facilitate implementation and realization of the potential benefits that this study identified.

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APPENDIX A

COST ESTIMATION REFERENCES

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