SOLAR HARBOR: NURTURING NATURE IN INDUSTRIAL DESIGN

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By

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Solar Harbor: Nurturing Nature in Industrial Design

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DEDICATION

To my wife, Shania, for encouraging me and cheering me on through all my years at NDSU, and to my parents, whose support has been evident throughout my entire academic career, and without whom, I would never have made it this far.

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ABSTRACT

Warehouses are places where productivity and cost reduction meet to create highly profitable, efficient structures. At this intersection, however, there also lies a concrete box with little regard for the employees that toil within. These boxes, in addition to their disregard for human needs, interrupt nature in a massive way, destroying ecosystems for various lifeforms and leaving a large carbon footprint. These large, intrusive structures pose many problems regarding modern design, and contain outdated and unsustainable building practices that lead to many natural and societal problems.

A thorough investigation of current warehouse design indicates all the afore-mentioned issues. This thesis strives to address some of these issues and provide solutions to problematic design practices. Specifically, this thesis focuses on a warehouse residing in the Fargo/Moorhead area, designing a warehouse that provides an update to the current structure, integrating natural lighting, sustainable design practices, and improvements on the building's current program and layout.

Chapter 1 – Introduction

1.1 Problem Statement

I have worked in a warehouse for the past 3 years. In these three years, I have worked and toiled in this building in Fargo, entirely surrounded by concrete, steel, and no green space. My thesis idea is centered on warehouse design, or in my case, a redesign of these structures, to address the problems that I see daily within the industry. Many people are forced to work in sub-standard conditions, spending upwards of 20 hours at a time working in a place that provides no natural lighting, no escape from concrete and cement, and in general is not designed for extended periods of human stay. This leads to my main question posed: How can architects improve the design of modern warehouses in a way that is both sustainable, energy efficient, improves a worker's efficiency and enlightens the work area with daylight, and improves the overall aesthetic of a warehouse?

My thesis idea hopes to tackle some of the aspects of warehouse work that I, and others, find so depressing. The first aspect is finding ways to provide more natural lighting in the actual areas where employees work. It is common knowledge that daylight boosts a person's mood, increases efficiency and productivity, and, most importantly, provides a building with some sense of comfort. This poses a challenge, as warehouses are known to use high amounts of electricity, and more openings in a building's skin lower the energy-efficiency of a building of that size. This leads me to the second aspect of my thesis, which is to provide more daylighting to a warehouse while *increasing* energy-efficiency, through the use of alternative energy sources, sustainable building practice, and creative integration of vegetation to the building. The final aspect of my thesis is simply to generate a final design that is actually appealing, a beautiful piece of architecture that strays from the typical concrete rectangle jammed onto a plot of land.

1.2 Objectives

With this thesis, I have three main objectives that I hope to accomplish, as I have listed above. The first, and most important, is the integration of daylight into the work environment. As a worker, I have been subjected to long shifts with only 15-minute breaks to experience the sun and fresh air. This is a major problem. Much of the preliminary research that I have done has shown that human health and energy decline with increased periods without sunlight. Serotonin and melatonin drop, increasing a person's feelings of apathy and depression. Lowered levels of serotonin also result in sluggishness, increased fatigue, and, notably, lowers the efficiency of workers. Seasonal depression is something that many people suffer from, and working in a warehouse that provides little access to daylight throughout the day only sets this seasonal change on early. This lowers the efficiency of workers, and, in turn, the productivity of the entire warehouse. This issue is a far-reaching one, touching not just the lowest level of workers in the industry. My thesis will bring some resolve to this current oversight in the design world.

The second objective that my project will accomplish is finding ways to introduce and increase the sustainability of warehouse design. This poses a challenge, as my goal to add more natural lighting into a warehouse would result in more holes in the buildings skin, leading to more heat loss and gain in the winter and summer months, respectively. Be that as it may, I have placed these two goals upon myself. My final design will hopefully be able accomplish both at once, utilizing an area of warehouse design in which there lies another huge oversight: the rooftop. These large buildings cover many square feet of land, and yet the roof is left mostly empty, with only portions of it allotted for the use of mechanical systems. This unused real estate can be utilized for solar energy harvest by covering it with photovoltaic panels. In addition to this, I have a few ideas/products that I believe may be useful and will investigate further into the process. These thoughts include the following:

- Vertical Farming: Vertical farming is a method of using empty walls within the building to grow all varieties of vegetation. This technology allows a large corporation to provide vegetables and other naturally grown resources to its building's users. This interior vegetation also helps to clean the air within the building, providing a scrubber for air that does not add, but rather diminishes the carbon use of a building.
- Solar Facades by SolarLab: These highly advanced panels are photovoltaic in nature, which provide a way to utilize the exterior vertical surfaces on the building. They hide

easily when placed next to the common aluminum paneling, so they do not affect the aesthetic of a building in a major way. Most importantly, these panels harvest energy, so the use of them could help to accomplish a warehouse design that not only lowers energy bills, but could, in an ideal world, produce a warehouse that becomes energy positive.

- Geothermal Heating System: Geothermal heating systems are an amazing energy source that provides heating and cooling to a building in a low-impact, high-payoff manner. Utilizing the natural insulation and heat of the earth provides a low-cost energy source for heating and cooling within a building.
- Green Roofs: Green roofs are a technology that has been around for many years, but is still, sadly, underused. A warehouse, as previously mentioned earlier, has a lot of underused space on the roof level. The integration of a green roof onto a warehouse will help with many aspects of my design goals, but most importantly, they can help to reduce heat gain and loss within a structure, which will be vitally important to my final design.

Finally, my thesis will hope to accomplish what, in my opinion, no one has been able to do to this day: creating an aesthetically pleasing, architecturally engaging warehouse design. Most warehouses that we see today are concrete boxes, with little to no articulation added to the exterior to provide interest. This style has proven to be effective, keeping construction costs and costs low. I am under the belief, however, that just because something works and has been that way for decades does not mean that it cannot still be improved. Whether it be through fabric form casting or the integration of a few more textural skin types, many design decisions can help to improve the boring facades of warehouses, and that is something that I hope to accomplish with my final thesis.

Chapter 2 – Background

2.1 Natural Lighting in Warehouses

Natural lighting in warehouses is a critical element that transcends conventional notions of illumination, emerging as a pivotal factor in optimizing both the physical workspace and the well-being of those who inhabit it. Recognizing the multifaceted advantages, this section will delve into the importance of natural lighting for human well-being, shedding light on its physiological and psychological benefits. Additionally, this review will explore the intricate connection between daylight exposure and employee mood and productivity, unveiling the profound impact that a well-lit environment can have on workforce dynamics. However, the journey towards integrating natural lighting in large warehouses is not without its challenges, so this section will also navigate through the complexities that arise during implementation. To illuminate the practical aspects of this endeavor, the exploration will culminate with a review of case studies showcasing successful instances of natural lighting integration, providing valuable insights and inspirations for warehouse managers and designers alike.

2.1.1. Importance of Natural Lighting for Human Well-being

Natural light, provided by the sun, is an indispensable element for life on Earth. Beyond its ecological significance, exposure to natural light has profound implications for human health and functioning. As our lifestyles increasingly shift indoors, understanding the importance of natural light becomes paramount for creating environments that support optimal human well-being.

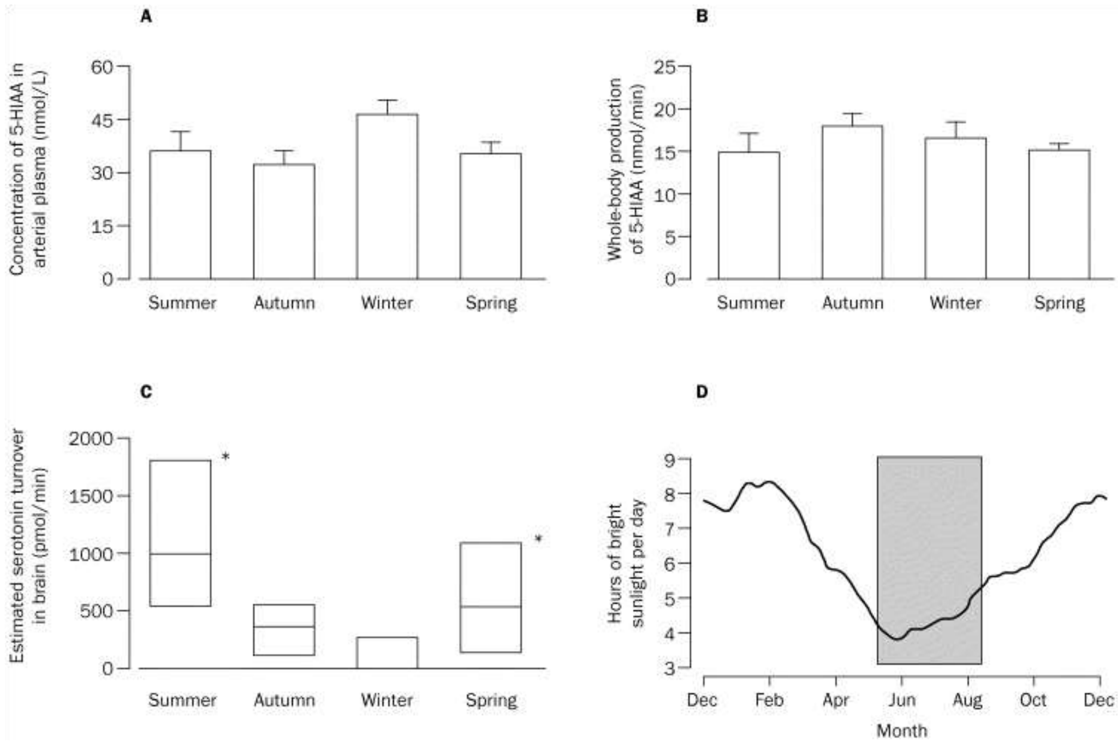
Exposure to natural light is linked to the regulation of the circadian rhythm, the internal biological clock that governs sleep-wake cycles. Adequate exposure to natural light during the day helps synchronize the circadian rhythm, promoting better sleep quality and overall health. Insufficient exposure to natural light has been associated with disruptions in sleep patterns, contributing to conditions such as insomnia and circadian rhythm disorders (Kopec, n.d.). Furthermore, natural light is a rich source of vitamin D, essential for maintaining bone health, immune function, and overall well-being. Adequate exposure to sunlight enables the skin to produce vitamin D, mitigating the risk of deficiencies and related health issues.

Natural light has a profound impact on mental health and well-being. Sunlight stimulates the production of serotonin, a neurotransmitter associated with mood regulation and feelings of happiness. Conversely, lack of exposure to natural light has been linked to an increased risk of mood disorders such as depression and seasonal affective disorder (SAD) (Kopec, n.d.). In architectural design, incorporating natural light into spaces has been shown to enhance occupant satisfaction and reduce stress levels. Sunlit environments create a positive ambiance, fostering a sense of connection to the external world and promoting psychological comfort.

Research suggests that exposure to natural light positively influences cognitive performance and productivity. Well-lit spaces have been shown to enhance concentration, alertness, and overall cognitive function. In educational settings and workplaces, optimizing natural light exposure can lead to improved learning outcomes and increased productivity. Architectural design that prioritizes natural light through features such as large windows, skylights, and open layouts contributes to creating vibrant and stimulating environments that support cognitive engagement and creativity.

A study conducted in Australia by doctors at the Human Neurotransmitter Laboratory, which focused on the relationship between serotonin metabolizers and the 4 seasons we experience on earth. This study found correlation between the levels of daylight during the 4 seasons and how they directly relate to increased or decreased levels of serotonin production and metabolization in the human body. This study, along with others, prove the importance of sun light in regards to mental health, and, in turn, physical health.

Table 1 – Human Neurotransmitter Laboratory Study (Lambert, Reid, Kaye, Jennings, Esler, 2002)



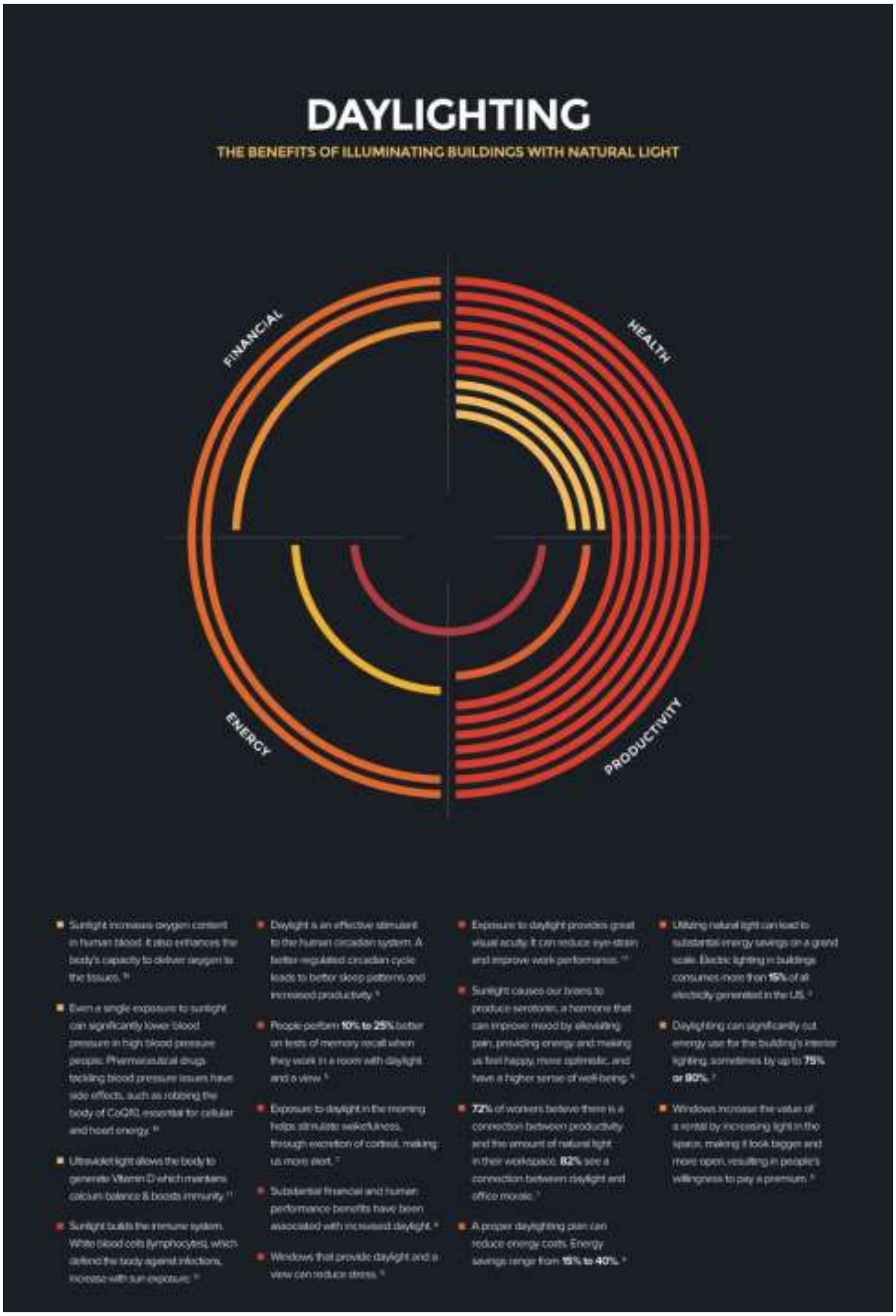


Figure 1 – Daylighting Benefits (Bendheim, 2015)

In addition to its physiological and psychological benefits, the incorporation of natural light in architectural design aligns with principles of sustainability and energy efficiency. Designing spaces that maximize natural light reduces the reliance on artificial lighting and, consequently, decreases energy consumption. By adopting sustainable design practices that prioritize natural light, architects and urban planners contribute to the creation of environmentally friendly spaces that align with global efforts to mitigate climate change.

The importance of natural light for human beings extends beyond mere illumination; it is intricately linked to our physical health, mental well-being, and overall productivity. Recognizing the pivotal role of natural light in shaping our environments can guide architects, urban planners, and individuals in creating spaces that prioritize human flourishing. As we continue to shape the built environment, a holistic approach that integrates natural light into our living and working spaces is essential for fostering a healthier and more sustainable future.

2.1.2. Impact of Daylight on Employee Mood and Productivity

As the modern workforce places a growing emphasis on employee wellness and productivity, attention is turning to the physical workspace and its influence on mental and physical health. Among various environmental factors, the role of natural daylight in shaping the mood and productivity of employees has gained prominence. This section examines the interconnected relationship between exposure to daylight, employee mood, and overall work performance.

Exposure to natural daylight has been consistently linked to improvements in mood. Sunlight stimulates the production of serotonin, a neurotransmitter associated with feelings of happiness and well-being (Wang et al., 2023). Employees working in environments with ample daylight report reduced feelings of stress and anxiety, fostering a positive and conducive atmosphere. Natural light exposure helps regulate the body's circadian rhythm, influencing the sleep-wake cycle and overall energy levels. Proper alignment with circadian rhythms has been shown to enhance alertness and concentration during working hours, contributing to increased productivity.

Daylight exposure has a direct impact on alertness and productivity. Employees working in well-lit environments experience heightened levels of alertness and concentration, leading to improved task performance (Wang et al., 2023). This effect is attributed to the suppression of melatonin, a hormone associated with sleep, during daylight hours. Adequate natural light can reduce visual discomfort and eye strain, common issues associated with artificial lighting. Natural light promotes visual comfort and reduces the likelihood of headaches and fatigue, contributing to sustained focus and productivity throughout the workday.

Workplace design should prioritize access to natural light for all employees. Open floor plans, strategically placed windows, and glass partitions can help distribute natural light evenly throughout the workspace, ensuring that employees across various areas benefit from daylight exposure. Integrating biophilic design elements, such as indoor plants and outdoor views, can enhance the overall impact of natural light. These elements not only contribute to aesthetic appeal but also support the connection between employees and the natural environment, further promoting a positive mood and well-being.

The impact of daylight on employee mood and productivity is a critical consideration for organizations seeking to create healthy and productive work environments. Recognizing the psychological and physiological benefits of natural light exposure, employers can implement design strategies and policies that prioritize access to daylight. As the workplace continues to evolve, fostering a balance between the built environment and the natural elements becomes essential for cultivating a thriving, engaged, and productive workforce.

2.1.3. Challenges of Implementing Natural Lighting in Large Warehouses

Large warehouses, essential components of modern supply chains, pose specific challenges when it comes to integrating natural lighting. Unlike traditional architectural spaces, warehouses demand unique considerations due to their sheer size, functional requirements, and operational complexities. This section investigates the challenges encountered in the endeavor to maximize natural lighting within these expansive industrial settings.

The vast roof structures of warehouses, often designed for optimal storage and loading configurations, pose challenges in integrating skylights. Maximizing natural lighting without compromising the structural integrity of the roof requires innovative design solutions and collaboration between architects and structural engineers. The layout and arrangement of storage racks and shelving within warehouses can obstruct the penetration of natural light. Designing a spatial layout that allows for light distribution while maintaining operational efficiency is a delicate balance.

Efficient warehouse operations involve densely packed storage areas, potentially obstructing the path of natural light. Placing and rearranging inventory to allow for adequate daylight penetration without disrupting logistics requires careful planning and coordination. Warehouses often have strict safety regulations, including fire codes and emergency egress requirements (Haran, 2009). Integrating natural lighting solutions must comply with these regulations, sometimes limiting the placement and design of windows, skylights, or other daylighting elements.

Large expanses of glass, while allowing for ample daylight, may introduce issues of glare and heat gain. Implementing technologies such as smart glass or automated shading systems is necessary to mitigate these challenges and maintain a comfortable working environment. The dynamic nature of warehouse operations requires flexible lighting control systems. Implementing effective systems for adjusting artificial lighting in response to changing daylight levels, occupancy, and operational needs poses a technological challenge.

Integrating natural lighting solutions may involve higher upfront costs, such as installing skylights or advanced glazing systems. Balancing these costs against long-term energy savings and potential improvements in employee productivity is a critical consideration for warehouse operators. The wear and tear typical in warehouse environments can impact the longevity and effectiveness of daylighting solutions (Haran, 2009). Ensuring that these systems are durable, low-maintenance, and compatible with the operational demands of the facility is a key concern.

The challenges involved in integrating natural lighting into large warehouses are complex and multifaceted. Addressing these challenges requires a holistic approach that considers structural, operational, technological, and financial aspects. While the obstacles are significant, the potential benefits in terms of energy savings, employee well-being, and sustainable operations make the pursuit of effective natural lighting solutions in warehouses a worthwhile endeavor. Future advancements in technology and design strategies may offer further opportunities to overcome these challenges and create warehouse environments that are both illuminated and efficient.

2.1.4. Case Studies of Successful Natural Lighting Integration

The Edge – PLP Architecture

Figure 2 – The Edge (PLP Architecture, 2016)

This structure, completed in 2015, displays one of the best integrations of natural lighting of any building in the entire world. The Edge, designed by PLP Architects, is a 15 story office building that stands in the business district of Amsterdam, The Netherlands. It contains an atrium that spans all 15 stories, which floods the entire structure with daylight though most of the day. In addition to its triumph of natural lighting and sustainability, The Edge has revolutionized the idea of an office space. It boasts a completely customizable work experience, successfully hazing the line between work and play. Workers can choose which natural and social environments they would like to work in, all within the same building (PLP Architecture, 2016).

Applicability – This structure, while not within the realm of industrial architecture, has many applications to a thesis related to sustainable redesign and renovation. The daylighting aspect of this project is the most striking, as it displays one of the best examples of maximizing daylight of any building in the world. The articulation of the glass that envelopes the atrium is a huge success and a prominent learning opportunity.

Marion Fire Station No. 1 – OPN Architects

Figure 3 – Marion Fire Station No. 1 (Pintos, 2023)

This fire station, designed by OPN Architects, was completed in 2021. Made for the people of Marion, Iowa, this fire station takes a modern approach to design. The new fire station accommodates 3 apparatus bays, 6 offices, training and fitness rooms, 10 sleeping quarters, and dining and living areas. This design was centered on two principles: the first, establishing ways to maximize the user's mental and physical health; the second, to create a public service building that makes itself open to the public. These design constraints led to the creation seen in Figure 2, with the large amount of glass serving as a means to increase natural light intake as well as open the space up to the public. The use of biophilic design and a green roof increases the building's stability while also adding a mental health boost to users (Pintos, 2023).

Applicability – This structure represents an interesting dynamic. Its use of natural lighting in an area with large equipment poses a challenge that the architects well exceeded at overcoming. Much like a warehouse, this building typology is not typically associated with large windows and natural lighting. However, this structure realizes these features, and, as a result, has made a beautiful structure that considers the mental and physical health of its users.

Vlissingen – Rodeca

Figure 4 - Vlissingen (Rodeca, n.d.)

This warehouse in The Netherlands, constructed using translucent, modular panels produced by Rodeca, displays a unique take on integrating natural lighting into an industrial environment. The panels allow for workers to experience all the benefits of natural lighting while still maintaining sight lines and glare control within the building (Rodeca, n.d.).

Applicability – This warehouse does not have much information to be found on the internet; however, the panels, a product produced by Rodeca, are largely informative and can be applied to many different typologies of design. The translucent nature of the panels is unlike most products that can be found in the design world, and can be highly useful when designing sustainably.

2.2 Energy-Efficient Design Strategies

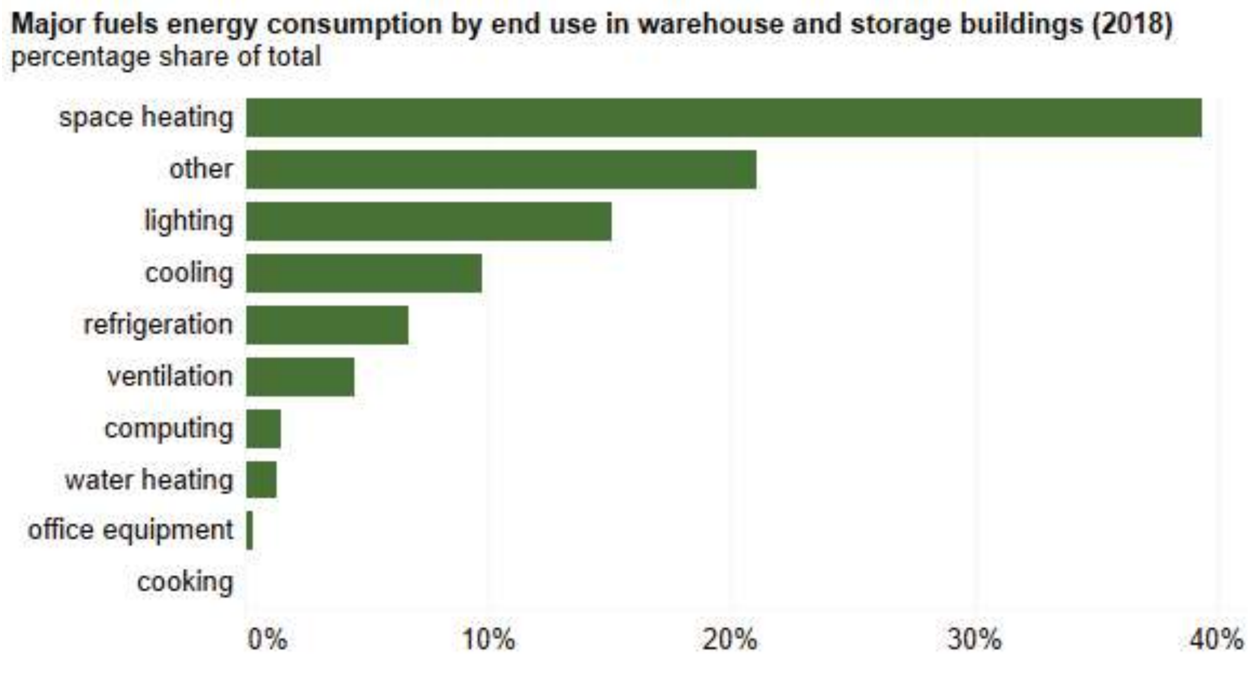
In the realm of industrial infrastructure, the pursuit of energy-efficient design strategies stands as a cornerstone for responsible and forward-thinking development. This exploration weaves through the intricate landscape of energy consumption in warehouses, dissecting the current state of affairs. This section then transitions into the delicate equilibrium between harnessing natural lighting and maintaining energy efficiency within these expansive spaces. As the discourse continues, attention turns towards the adoption of alternative energy sources for warehouse operations, presenting an array of sustainable solutions that can redefine the conventional power paradigm. Finally, the review delves into the realm of sustainable building practices tailored to industrial structures, encapsulating a comprehensive overview of approaches that promise to reshape the landscape of energy consumption in warehouses, illustrating the industry's commitment to a greener and more sustainable future.

2.2.1. Current Energy Consumption in Warehouses

Warehouses are integral components of the logistics and supply chain infrastructure, serving as hubs for the storage and distribution of goods. As the demand for efficient and sustainable practices continues to grow, the energy consumption trends within warehouses have come under scrutiny. This section examines the current state of energy consumption in warehouses, identifying key trends, challenges, and innovative solutions.

The surge in e-commerce has indeed sparked a significant rise in the demand for warehouse spaces, creating a domino effect on various aspects of the supply chain. As online shopping continues to reshape consumer habits, warehouses have become critical nodes in the distribution network, handling the storage, processing, and dispatch of a vast array of products. One of the notable consequences of this e-commerce boom is the substantial increase in energy consumption within these warehouse facilities. The need for constant lighting, heating, and cooling to support extended operating hours and ensure optimal storage conditions has become a significant contributing factor to this trend. The table below shows the energy consumption of warehouses, and breaks down the facilities by how much energy they each consume.

Table 2 – Warehouse Energy Consumption (U.S. Energy Information Administration, 2018)



Firstly, the requirement for consistent and well-distributed lighting is paramount in warehouses to facilitate efficient navigation, order picking, and inventory management. In many cases, warehouses operate around the clock to meet the demands of a 24/7 online market, resulting in a continuous need for artificial lighting (Lewczuk et al., 2021). This constant illumination not only contributes to increased energy consumption but also raises environmental concerns as traditional lighting systems are often energy intensive.

Secondly, the need for adequate heating and cooling systems within warehouses is crucial to preserve the quality of stored goods. Depending on the nature of the products, maintaining specific temperature ranges is essential. This requirement leads to the deployment of energy-consuming HVAC (Heating, Ventilation, and Air Conditioning) systems. As warehouses expand to accommodate growing inventories, the energy demand for these systems escalates proportionally.

Moreover, the growing trend of automated storage and retrieval systems, along with the use of robotics in warehouses, adds another layer to the energy consumption challenge. These technologies, while enhancing efficiency and speed, often require continuous power and contribute to the overall energy demand. Addressing the environmental impact of the increasing energy consumption in warehouses has become a priority for many companies. Some are exploring sustainable alternatives such as energy-efficient lighting solutions, solar panels, and advanced insulation technologies to mitigate the environmental footprint of their operations.

The widespread adoption of automation technologies in modern warehouses has revolutionized the logistics and supply chain industry, bringing about a paradigm shift in operational efficiency. Robotic systems, automated conveyors, and other advanced technologies offer the promise of faster processing times, increased accuracy, and round-the-clock operations (Lewczuk et al., 2021). However, this shift towards automation brings forth a multifaceted challenge that revolves around energy consumption, costs, and the delicate balance between upfront investments and long-term benefits.

The integration of robotic systems and automated conveyors often demands substantial energy inputs. Robots and machinery require continuous power to operate efficiently, contributing to an increased overall energy consumption within the warehouse. While these technologies are designed to optimize processes, reduce errors, and enhance productivity, the energy demand they impose poses a notable environmental and financial challenge for warehouse operators.

One of the primary hurdles in warehouse design is the high upfront costs associated with implementing automation technologies. Investing in state-of-the-art robotic systems and automated conveyors requires a significant capital investment, making it a substantial consideration for businesses, especially smaller ones. The challenge lies in justifying these upfront costs, as they often outweigh the immediate cost benefits derived from manual labor.

Additionally, the maintenance and upkeep costs of automated systems can be substantial, further complicating the cost-effectiveness equation. Warehouses must contend with the need for specialized technicians and regular maintenance schedules to ensure the smooth functioning of these sophisticated technologies. Balancing the benefits of increased efficiency against the ongoing operational and maintenance costs becomes a pivotal factor in determining the feasibility of automation adoption.

Comparatively, manual labor, while requiring ongoing wage expenses, doesn't involve the same level of upfront investment and operational complexities associated with automation. The challenge, therefore, is to strike a balance between the long-term advantages of automation, such as improved accuracy, reduced labor costs over time, and increased throughput, and the immediate financial constraints of implementation.

In response to these challenges, warehouse operators are increasingly exploring ways to optimize energy consumption in automated systems. This includes the implementation of energy-efficient technologies, incorporating renewable energy sources, and developing smart systems that can adapt to varying workloads, thereby minimizing unnecessary energy consumption during periods of lower demand.

Ultimately, the challenge with warehouse design lies in navigating the trade-off between the undeniable benefits of automation and the associated costs, both upfront and ongoing. Striking the right balance and implementing sustainable practices in the adoption and operation of automated technologies are key considerations for warehouses looking to stay competitive in an ever-evolving landscape.

Warehouses often serve as the backbone of supply chains, storing a diverse range of products that can be sensitive to temperature and humidity fluctuations. Maintaining optimal environmental conditions within these facilities is crucial to preserve the quality and integrity of the stored goods. However, the necessity for precise climate control introduces a significant challenge in terms of energy consumption, with heating, ventilation, and air conditioning (HVAC) systems playing a central role in addressing this need.

Temperature-sensitive products, such as pharmaceuticals, electronics, certain foods, and other perishable items, require storage conditions that fall within specific temperature ranges. The HVAC systems in warehouses are designed to regulate temperature and humidity levels, ensuring that these goods remain in a controlled environment (Lewczuk et al., 2021). This demand for climate control translates into a substantial energy requirement, contributing significantly to the overall energy consumption of warehouse operations.

During the warmer months, the need for air conditioning to cool the warehouse becomes imperative to prevent products from degrading due to excessive heat. On the other hand, in colder seasons, heating systems are deployed to maintain a stable temperature and protect goods from freezing. The continuous operation of these HVAC systems, especially in warehouses with extended working hours or those that operate 24/7 to meet the demands of e-commerce, results in a continuous energy draw.

The challenge is exacerbated by the large and open spaces characteristic of warehouses, which often have high ceilings and expansive floor areas. Maintaining uniform temperature and humidity levels throughout these spaces requires robust HVAC systems that can handle the volume and scale of the facility, further intensifying energy consumption.

To address this challenge, warehouses are exploring various strategies to optimize the energy efficiency of their climate control systems. This includes the adoption of advanced HVAC technologies with energy-saving features, such as smart sensors and controls that can adjust settings based on real-time environmental conditions and occupancy (Lewczuk et al., 2021). Additionally, warehouses are increasingly investing in insulation and building design that minimizes heat exchange with the external environment, reducing the workload on HVAC systems.

In some cases, warehouses are incorporating sustainable practices such as the integration of renewable energy sources, like solar panels, to partially offset the energy demand of their climate control systems. Implementing energy-efficient lighting and insulation solutions also contributes to the overall goal of reducing the carbon footprint associated with temperature-sensitive storage.

In the evolving landscape of warehousing and logistics, compliance with environmental regulations has emerged as a top priority for warehouse operators. Governments and international bodies are increasingly implementing stringent measures to address climate change, promote energy efficiency, and reduce carbon emissions. Warehouses, being integral components of supply chains, have a substantial impact on energy consumption and environmental sustainability. Consequently, adhering to environmental regulations is not only a legal obligation but also a strategic move that aligns with broader sustainability objectives and provides multifaceted benefits.

One key area of focus for warehouses is energy efficiency standards. Governments worldwide are introducing regulations that mandate the adoption of energy-efficient technologies and practices. Warehouses are often energy-intensive operations, with lighting, heating, ventilation, air conditioning (HVAC) systems, and various machinery contributing to significant energy consumption. Compliance with energy efficiency standards involves the implementation of advanced technologies, such as LED lighting, smart HVAC systems, and energy-efficient appliances, to minimize energy usage. This not only helps warehouses meet regulatory requirements but also results in long-term cost savings and a reduced carbon footprint.

Emissions reduction targets are another critical aspect of environmental regulations that warehouses are increasingly addressing. Governments and environmental agencies set ambitious goals to mitigate greenhouse gas emissions and combat climate change. Warehouses contribute to emissions through their energy consumption, transportation activities, and, in some cases, refrigeration systems. In response, warehouses are adopting sustainable practices, such as optimizing transportation routes, incorporating electric or hybrid vehicles, and investing in renewable energy sources like solar panels. Meeting emissions reduction targets not only positions warehouses as responsible corporate citizens but also contributes to global efforts to combat climate change.

Beyond avoiding penalties and legal consequences, compliance with environmental regulations aligns with the broader trend of corporate sustainability. Many businesses recognize the importance of environmental stewardship in maintaining a positive public image, meeting customer expectations, and attracting environmentally conscious investors. Warehouses that proactively embrace sustainability not only contribute to a healthier planet but also enhance their brand reputation and competitiveness in the market.

The current energy consumption trends in warehouses are shaped by a complex interplay of operational demands, technological advancements, and sustainability imperatives. Warehouses that strategically embrace energy-efficient technologies, optimize operational practices, and align with regulatory and sustainability goals are better positioned to navigate the evolving landscape of energy consumption (Cook & Sproul, 2011). As the industry continues to innovate and prioritize sustainability, the integration of advanced technologies and best practices will play a pivotal role in shaping the future of energy-efficient warehousing.

2.2.2. Balancing Natural Lighting with Energy Efficiency

Architectural design plays a pivotal role in the quest for sustainable and human-centric built environments. Balancing energy efficiency with the integration of natural daylight is a central challenge for architects seeking to create spaces that are environmentally responsible and promote the well-being of occupants. This section investigates the principles, strategies, and technologies that facilitate the harmonious coexistence of energy efficiency and daylighting in architecture.

Passive solar design principles leverage the sun's path to optimize natural light and heat. By strategically positioning windows, skylights, and shading devices, architects can harness daylight while minimizing the need for artificial lighting and heating. The orientation of a building in relation to the sun is critical for effective daylighting. Proper alignment allows architects to maximize exposure to natural light, reducing the reliance on electric lighting during daylight hours (Sari et al., 2021). Utilizing advanced building materials with high thermal resistance can contribute to energy efficiency by reducing heating and cooling demands. Energy-efficient envelopes also play a role in controlling glare and optimizing daylight distribution. Integrating intelligent lighting systems that respond to daylight levels can further enhance energy efficiency. Automated lighting controls adjust artificial lighting based on available daylight, ensuring that electric lights are used judiciously.

Advanced simulation tools allow architects to model the impact of daylight at various times of the day and throughout the seasons. This enables a more precise design approach, ensuring that spaces receive optimal daylight without compromising energy efficiency (PLP Architecture, 2016). Technological advancements in glazing materials provide architects with options that balance transparency, insulation, and solar control. Dynamic glass that adjusts its tint based on external conditions is one such innovation that enhances daylighting while managing solar heat gain.

Balancing energy efficiency and maximizing daylighting is not merely a technical challenge; it is a fundamental aspect of creating architecture that is responsive to both environmental concerns and human needs. As architects continue to innovate and integrate sustainable practices into their designs, the synthesis of energy-efficient technologies and thoughtful daylighting strategies becomes a hallmark of responsible and forward-thinking architectural practice. By striking this balance, architects contribute to the creation of built environments that prioritize energy conservation, occupant well-being, and a harmonious relationship with the surrounding natural environment.

2.2.3. Alternative Energy Sources for Warehouse Operations

The logistics and supply chain industry, driven by the rise of e-commerce and global trade, faces the imperative of reducing its environmental impact. Warehouses, as key components of this industry, play a crucial role in this endeavor. This section examines the various alternative energy sources available for powering warehouse operations, emphasizing the potential benefits and challenges associated with each.

The following headers and descriptions are taken from B.K. Hodge, author of Alternative Energy Systems and Applications.

Solar Power:

a. Photovoltaic (PV) Systems: Solar power, harnessed through photovoltaic systems, is a widely adopted alternative for warehouses. Solar panels installed on the roof or in open areas generate electricity from sunlight, providing a clean and renewable energy source. Advances in solar technology and decreasing costs make this an increasingly viable option for warehouses.

b. Energy Storage Solutions: Integrating energy storage solutions, such as battery systems, allows warehouses to store excess solar energy for use during periods of low sunlight. This helps address the intermittent nature of solar power generation and ensures a more reliable energy supply.

Wind Energy:

a. Wind Turbines: Wind energy, harvested through wind turbines, can be an effective alternative for warehouses situated in areas with consistent wind patterns. While large-scale wind farms are common, smaller-scale turbines can be integrated into warehouse facilities to supplement energy needs.

b. Hybrid Systems: Combining solar and wind energy systems into hybrid solutions provides a more consistent and reliable power supply. Hybrid systems leverage the strengths of both technologies, maximizing energy generation and minimizing reliance on the grid.

Biomass:

a. Biogas and Biomass Power Plants: Biomass, derived from organic materials such as agricultural waste or wood pellets, can be used to generate electricity or heat through biogas and biomass power plants. Warehouses with access to organic waste streams can leverage biomass as a locally sourced and renewable energy option.

b. Combined Heat and Power (CHP) Systems: CHP systems, also known as cogeneration, simultaneously produce electricity and useful heat from a single energy source, often biomass. Warehouses with a demand for both electricity and thermal energy can benefit from the efficiency gains provided by CHP systems.

Emerging Technologies:

a. Kinetic Energy Harvesting: Emerging technologies in kinetic energy harvesting, which capture energy from movement or vibrations, hold promise for warehouses with high levels of material handling equipment. The energy generated from machinery movements can be converted into electricity, contributing to a more sustainable energy mix.

b. Piezoelectric Flooring: Warehouses with significant foot traffic can explore the potential of piezoelectric flooring. This technology converts the pressure generated by footsteps into electrical energy, offering a unique way to harness energy within the operational space (Hodge, 2017).

These alternative energy sources, though highly beneficial in many ways, face many challenges in the industrial world. The first and most major is the upfront costs of installing alternative energy systems, although decreasing technology costs are mitigating this challenge. Another challenge is a constant and highly reliable supply of energy. Solar and wind energy sources can be intermittent, requiring supplementary energy storage solutions to ensure a continuous power supply. The last major challenge is the space requirements; implementing certain technologies, such as large-scale solar arrays, may require significant available space.

The adoption of alternative energy sources for warehouse operations represents a critical step toward achieving sustainability goals and reducing the environmental impact of the logistics industry. As technology continues to advance and costs decrease, warehouses have a growing array of options to choose from. By strategically integrating solar, wind, biomass, and emerging technologies, warehouses can not only enhance their operational resilience but also contribute to a more sustainable and responsible future.

2.2.4. Sustainable Building Practices in Industrial Structures

The built environment significantly impacts the planet's sustainability, making it imperative for industrial designers to adopt eco-friendly practices. This paper begins by outlining the current challenges associated with traditional construction methods and materials, highlighting the need for a paradigm shift towards sustainable building practices.

Key Principles of Sustainable Building in Industrial Design according to Cook and Sproul:

a. Life Cycle Assessment (LCA): Evaluating the environmental impact of products and materials throughout their entire life cycle is essential for making informed design decisions. LCA allows designers to consider factors such as raw material extraction, manufacturing processes, transportation, use, and end-of-life considerations.

b. Energy Efficiency: Incorporating energy-efficient design principles can substantially reduce the environmental footprint of buildings. Industrial designers can explore innovative solutions, such as passive heating and cooling systems, smart lighting, and renewable energy sources.

c. Material Selection: Opting for sustainable and locally sourced materials, as well as considering recycled and upcycled materials, is crucial in minimizing the environmental impact of industrial design projects.

d. Circular Design: Embracing circular design principles involves designing products and spaces with the end goal of reusing, repurposing, or recycling materials to create a closed-loop system, reducing waste and resource consumption (2011).

Strategies for Sustainable Building in Industrial Design according to Cook and Sproul:

a. Green Building Certifications: Industrial designers can pursue and integrate green building certifications, such as LEED (Leadership in Energy and Environmental Design), into their projects. These certifications provide guidelines for sustainable construction and offer a structured framework for implementation.

b. Biophilic Design: Incorporating elements of nature into industrial design promotes human well-being while reducing the ecological impact of buildings. Strategies such as green roofs, natural lighting, and indoor plants contribute to a healthier and more sustainable built environment.

c. Collaborative Design Processes: Engaging in interdisciplinary collaboration throughout the design process ensures that sustainability considerations are integrated from the early stages. Architects, engineers, and environmental experts working together can create more comprehensive and effective sustainable solutions (2011).

Sustainable building practices in industrial design are essential for mitigating the environmental impact of the built environment. By adopting a holistic approach, industrial designers can contribute to creating more resilient, efficient, and environmentally friendly structures. As the world moves towards a sustainable future, the role of industrial designers becomes increasingly crucial in shaping a built environment that harmonizes with the planet's ecological systems.

2.3 Creative Integration of Vegetation

The exploration of the creative integration of vegetation within industrial environments unfolds as an intriguing journey into the transformative potential of green spaces. This section commences with an exploration of the myriad benefits that green spaces impart to industrial settings, delving into the ways in which vegetation contributes to the well-being of both the environment and its inhabitants. As the discussion progresses, the focus pivots towards the challenges and opportunities that arise when introducing vegetation into warehouses, unraveling the complexities of seamlessly blending nature with industrial functionality. Finally, the review concludes with an examination of the profound impact such creative integration has on employee well-being and the overall environmental ethos, providing insights into how strategically placed greenery can foster a harmonious coexistence between industry and nature.

2.3.1. Benefits of Green Spaces in Industrial Environments

Industrial environments are often associated with the hustle and bustle of manufacturing processes, machinery, and structures. However, the integration of green spaces within these settings presents a compelling opportunity to address environmental, social, and economic concerns. The benefits of green spaces extend beyond aesthetic appeal, encompassing ecological restoration, improved employee well-being, and positive contributions to the surrounding community. Green spaces play a crucial role in mitigating the environmental impact of industrial activities. They act as carbon sinks, absorbing pollutants and mitigating the urban heat island effect. The introduction of vegetation in industrial areas helps enhance air quality by filtering pollutants and particulate matter. Moreover, green spaces contribute to biodiversity conservation, creating habitats for various plant and animal species, and supporting overall ecosystem health.

Integrating green spaces into industrial environments has been shown to have positive effects on employee well-being. Exposure to nature has been linked to reduced stress, increased productivity, and enhanced overall job satisfaction. Access to green spaces provides employees with opportunities for relaxation, physical activity, and improved mental health. Additionally, green spaces can serve as communal areas for breaks and social interactions, fostering a sense of community among industrial workers (Doğmuşöz, 2023).

Green spaces in industrial settings can be designed to engage the surrounding community. Open and accessible green areas provide opportunities for recreational activities, community events, and educational programs. This integration fosters a positive relationship between industries and their neighboring communities, promoting transparency and collaboration. Community engagement can lead to shared benefits, such as improved local aesthetics and increased pride in the industrial ecosystem.

Green spaces act as buffers, helping to mitigate the negative impacts of industrial activities on surrounding ecosystems. Properly designed green infrastructure can absorb and filter runoff, reducing soil erosion and preventing pollutants from entering nearby water bodies. This not only protects local ecosystems but also contributes to the sustainable management of natural resources.

The incorporation of green spaces in industrial environments can lead to economic advantages. Enhanced employee well-being and satisfaction can result in increased productivity and decreased absenteeism (Kafka, 2023). Moreover, the positive image associated with environmentally conscious industrial practices can attract investment and clients who prioritize sustainability, creating a competitive advantage for businesses.

The benefits of incorporating green spaces in industrial environments are far-reaching, positively impacting the environment, employee well-being, community relations, and the overall economic sustainability of industries. As the global shift towards sustainable practices continues, the integration of green spaces in industrial settings emerges as a practical and holistic solution. Policymakers, industrialists, and urban planners should collaborate to promote and implement these green initiatives, fostering a harmonious coexistence between industrial progress and environmental stewardship.

2.3.2. Challenges and Opportunities for Adding Vegetation to Warehouses

Warehouses are traditionally characterized by large, utilitarian spaces that prioritize functionality over aesthetics. The inclusion of vegetation within these environments has the potential to enhance indoor air quality, reduce energy costs, and create a more pleasant and productive atmosphere. However, this transition comes with unique challenges that must be carefully considered.

Opportunities for incorporating vegetation into warehouses include the potential for improved indoor air quality. Vegetation can filter and purify indoor air, absorbing pollutants and releasing oxygen, creating a healthier working environment and potentially reducing respiratory issues among employees. Additionally, the introduction of plants can contribute to overall well-being.

Energy efficiency is another potential benefit, with green roofs and walls acting as natural insulation. This regulation of indoor temperatures can reduce the need for excessive heating or cooling, leading to significant energy savings and fostering a more sustainable operation. Beyond environmental advantages, the inclusion of vegetation can aesthetically enhance warehouses, creating a more pleasant and inviting atmosphere for both employees and visitors (Semeraro et al., 2021). Moreover, integrating greenery into warehouses provides an opportunity to support local biodiversity by attracting and sustaining a variety of plant and insect species.

However, challenges arise in the limited availability of natural light in warehouses, often designed with minimal windows or openings. Innovative lighting solutions may be necessary to ensure the health of vegetation in such environments.

Space constraints present another challenge, as warehouses prioritize efficient storage and logistics, leaving limited room for incorporating vegetation. Creative design solutions that maximize vertical space and utilize unused areas must be explored to address this constraint. Thoughtful maintenance and irrigation strategies are essential for ensuring the well-being of plants in an industrial setting. Implementing automated systems and choosing low-maintenance plant varieties can help overcome this challenge. Finally, cost considerations pose a potential barrier for businesses looking to integrate vegetation into warehouses due to the initial investment required (Semeraro et al., 2021). However, a comprehensive analysis of long-term benefits, including improved employee productivity and energy savings, may outweigh the initial costs.

The integration of vegetation into warehouses presents a promising avenue for sustainable industrial design. By addressing challenges and capitalizing on opportunities, businesses can create more environmentally friendly, aesthetically pleasing, and employee-centric warehouse environments. The transformation of traditionally sterile spaces into green hubs reflects a commitment to a greener future, balancing industrial functionality with ecological responsibility. As the world embraces sustainable practices, the inclusion of vegetation in warehouses represents a significant step towards a more harmonious coexistence between industry and nature.

2.3.3. Impact on Employee Well-being and Environment

The industrial landscape, often characterized by concrete structures and machinery, is undergoing a paradigm shift towards more sustainable and employee-focused practices. This section examines the impact of green spaces within industrial environments, exploring the dual benefits of promoting employee wellbeing and contributing to environmental sustainability.

Green spaces within industrial settings provide employees with access to nature, offering a respite from the often demanding and stressful work environment. Studies consistently demonstrate the positive impact of nature on mental health, including reduced stress levels, improved mood, and enhanced cognitive function (Semeraro et al., 2021). Incorporating green spaces provides employees with areas for relaxation and rejuvenation, ultimately contributing to better mental wellbeing.

Access to green spaces encourages physical activity and exercise, crucial components of maintaining good health. Employees who engage in regular physical activity are not only healthier but also more productive. Green spaces within industrial environments serve as venues for exercise, whether through walking paths, recreational spaces, or organized fitness programs, promoting a healthier and more active workforce. The presence of green spaces also contributes to overall job satisfaction. Employees who feel connected to nature at their workplace tend to express higher job satisfaction levels. This positive sentiment can lead to increased loyalty, reduced turnover rates, and a more motivated and engaged workforce.

Related to the benefits that green spaces bring to employees are the benefits that they bring to the work environment. Green spaces act as natural air purifiers, absorbing pollutants and releasing oxygen. The introduction of vegetation within industrial environments helps mitigate the impact of industrial emissions on air quality. This not only benefits the immediate surroundings but also contributes to the overall improvement of regional air quality. Green spaces promote biodiversity within industrial landscapes, creating habitats for various plant and animal species (Semeraro et al., 2021). This contributes to the preservation of local ecosystems and fosters a balanced and resilient environment. Biodiversity also plays a critical role in pollination and soil health, supporting sustainable agricultural practices. Vegetated areas serve as effective stormwater management systems, reducing runoff and preventing soil erosion. Green spaces help absorb and filter rainwater, preventing pollutants from entering water bodies and contributing to the sustainable management of water resources.

The integration of green spaces within industrial environments is a holistic strategy that not only prioritizes the wellbeing of employees but also contributes to environmental sustainability. As industries increasingly recognize the interconnectedness of human health and ecological balance, the implementation of green initiatives emerges as a practical and impactful solution. Policies that encourage the creation and maintenance of green spaces within industrial settings should be promoted, fostering a workplace culture that values both the health of employees and the preservation of the environment.

2.4 Aesthetics and Architectural Design

This section on aesthetics and architectural design in industrial settings unfolds into the convergence of form and function. The review begins by underscoring the significance of aesthetic appeal in industrial architecture, recognizing it as a potent catalyst that transcends the utilitarian aspects of warehouses. As the exploration deepens, the focus shifts towards the compelling need to break away from conventional warehouse designs, heralding a new era where industrial structures seamlessly merge functionality with artistic expression. Within this context, case studies emerge as beacons of inspiration, illustrating instances where industrial spaces transcend their utilitarian origins to embody both beauty and functionality. The section concludes with an examination of design principles essential for creating appealing warehouse spaces, offering a roadmap for architects and designers eager to infuse industrial landscapes with a heightened sense of aesthetic allure.

2.4.1. Importance of Aesthetic Appeal in Industrial Architecture

Historically, industrial architecture has prioritized utilitarian aspects, emphasizing functionality and cost-efficiency over aesthetics. However, as industries evolve and societal expectations shift, the importance of aesthetic appeal in industrial architecture is gaining recognition. A visually appealing industrial landscape can have far-reaching benefits, influencing not only the well-being of those within the industrial environment but also shaping the perception of industry in the broader community.

The work environment significantly impacts the well-being and productivity of employees. Aesthetically pleasing industrial spaces contribute to a positive and inspiring atmosphere, fostering a sense of pride and motivation among workers. Natural light, green spaces, and thoughtfully designed common areas can improve the overall quality of the work environment, leading to increased job satisfaction and employee retention (Kopec, n.d.). Studies have shown that aesthetically pleasing surroundings can reduce stress levels and enhance the mental well-being of workers. Incorporating elements of design, such as attractive facades and landscaping, can create a more inviting workplace that promotes a healthy work-life balance.

The aesthetic appeal of industrial structures has a profound impact on how industries are perceived by the surrounding community. Traditionally, industrial sites were considered eyesores, associated with pollution and environmental degradation. However, aesthetically pleasing industrial architecture can change these perceptions, fostering positive relationships between industries and communities.

Architectural designs that prioritize aesthetics demonstrate a commitment to responsible and sustainable practices. By integrating industrial structures into the surrounding landscape with sensitivity to design, industries can contribute to the creation of visually appealing, harmonious environments that coexist with their communities.

Aesthetic considerations in industrial architecture often go hand-in-hand with sustainable design practices. Modern industrial structures are increasingly incorporating green building techniques, energy-efficient technologies, and environmentally conscious materials (Herriott, 2021). These design elements not only enhance the visual appeal but also contribute to the overall sustainability of industrial facilities.

Architectural features such as green roofs, sustainable landscaping, and the use of recycled materials not only improve the aesthetics but also align industrial practices with global efforts to reduce environmental impact (Theodosiou, 2009). Aesthetic appeal, when integrated with sustainability, reinforces the image of industries as responsible stewards of the environment.

Aesthetically pleasing industrial architecture can have a positive economic impact on regions. Attractive industrial zones can attract investment, tourism, and skilled labor. The visual appeal of industrial areas contributes to a positive economic climate, enhancing the overall development and attractiveness of the region.

The importance of aesthetic appeal in industrial architecture extends beyond visual pleasure; it influences employee well-being, community perception, and the economic vitality of regions. Recognizing the value of aesthetics in industrial design allows for the creation of industrial spaces that are not only functional and efficient but also visually captivating and environmentally responsible. As industries evolve in the 21st century, embracing a holistic approach to industrial architecture that balances aesthetics with functionality is essential for fostering a positive and sustainable future.

2.4.2. Breaking Away from Conventional Warehouse Designs

Conventional warehouse design has been the cornerstone of logistics and supply chain operations, emphasizing stability, predictability, and storage efficiency. While effective in its time, the limitations of this approach have become increasingly apparent in the fast-paced and dynamic business environment of the 21st century.

Current Conditions of Warehouse Design according to Baker and Canessa:

Static Layouts: Traditional warehouses are characterized by fixed layouts that prioritize storage capacity over adaptability. This static nature makes it challenging to accommodate changes in product demand or operational processes.

Manual Processes: Labor-intensive processes, such as manual order picking, packing, and inventory management, have been the norm in conventional warehouse design. This reliance on human labor can lead to inefficiencies, errors, and limited scalability.

Storage Optimization: Conventional warehouses prioritize maximizing storage space through methods like stacked racking systems. While effective for storage, this approach may hinder accessibility and slow down order fulfillment (Baker & Canessa, 2009).

Challenges of Conventional Warehouse Design according to Baker and Canessa

Lack of Flexibility: The static nature of traditional layouts makes it difficult for warehouses to adapt swiftly to changes in product lines, order volumes, or market demands.

Inefficiency: Manual processes are prone to errors, and the reliance on human labor for tasks that could be automated can result in increased operational costs and slower fulfillment times.

Limited Visibility: Conventional warehouses often lack real-time visibility into inventory levels, order statuses, and overall warehouse performance, making decision-making more challenging (Baker & Canessa, 2009).

Conventional warehouse design has played a crucial role in the history of logistics, providing a foundation for efficient storage and distribution. However, the limitations of this approach are becoming increasingly evident as businesses face heightened customer expectations, shorter product life cycles, and the need for greater operational agility.

Recognizing the challenges posed by conventional warehouse design opens the door to exploring alternative strategies and innovative technologies that can revolutionize the way warehouses operate. As businesses strive for increased efficiency, accuracy, and adaptability, breaking away from the conventional warehouse design becomes not only a strategic choice but a necessity for sustained competitiveness in the evolving landscape of supply chain management.

2.4.3. Case Studies of Beautiful and Functional Industrial Structures

Boulevard Brewing Company – El Dorado

Figure 5 – Boulevard Brewing Company (El Dorado, 2012)

This structure, completed in 2012 and designed by El Dorado architects, displays a beautiful example of aesthetic design in industrial architecture. BBC selected a project team assembled by an architect-led design-build delivery process to execute a complex assembly of components within very tight quarters. From the onset of the design process, the architect-builder had to plan the project to allow all adjacent space to remain open throughout construction. The addition utilizes beautiful, glazed facades protected by sun-shading devices, making this space both aesthetically pleasing and functional (El Dorado, 2012).

Applicability – This structure displays one of the best uses of natural light in industrial architecture. The giant glazed brewery area of this design integrates natural lighting for the laborers' health, and does so in a way that makes an otherwise boring typology of building a piece of art that catches the eye of a passerby. The design choices made by El Dorado architects are important to the industrial world, making this building a design that should be studied for successful industrial design.

038 Ricola Storage Building – Herzog and DeMeuron

Figure 6 – 038 Ricola Storage Building (Herzog and DeMeuron, n.d.)

Herzog & de Meuron, a renowned architectural firm, is known for their innovative and distinctive designs, and their warehouse design is no exception. This particular warehouse, created in 1987, is a masterpiece of contemporary industrial architecture, blending functionality with a unique aesthetic vision. The warehouse is a bold and striking structure that challenges traditional notions of industrial design. Its exterior is characterized by a dynamic interplay of materials and shapes. The architects have taken a minimalist approach, employing a combination of glass, steel, and concrete to create a visually captivating facade. The structure is massive, yet it seems to defy gravity, giving the impression of a floating, almost ethereal presence (Herzog and DeMeuron, n.d.).

Applicability – The 038 Ricola Storage Building is a triumph in industrial design. While the building's only function is for storage of Ricola sweets and cough drops, the design was not just mailed in or overly basic. It has a simple design, but one that does not leave it to blend in with the cityscape. The gentle stacking and articulation of the wall components gives this building a floating appearance. This project has many aesthetic design choices that are applicable to the design of a warehouse.

2.4.4. Design Principles for Creating Appealing Warehouse Spaces

Warehouses, once perceived solely as utilitarian structures, have undergone a transformation in design philosophy. Beyond their conventional role in storage and logistics, contemporary warehouse spaces are now recognized as integral components of the industrial landscape. The following section delves into the multifaceted design principles essential for creating appealing warehouse spaces, where functionality converges with aesthetics to enhance the overall user experience.

Efficient spatial planning lays the foundation for appealing warehouse design by minimizing travel distances, optimizing storage, and facilitating streamlined workflows. Adopting vertical storage solutions and incorporating mezzanines maximizes cubic capacity. The integration of natural lighting is pivotal for energy efficiency and employee well-being. Strategically positioned skylights and windows reduce energy consumption, contributing to a positive working environment. Concurrently, thoughtful ventilation systems enhance air quality and maintain a comfortable atmosphere.

An adaptable design is imperative to accommodate the dynamic nature of warehouse operations. The incorporation of modular shelving and storage systems ensures flexibility, allowing easy reconfiguration to meet evolving storage needs and operational requirements. The visual appeal of warehouse spaces is a critical aspect often underestimated. Utilizing color schemes that enhance visibility, architectural features that captivate, and landscaping that complements the industrial setting contribute to an aesthetically pleasing environment, fostering employee pride.

Acknowledging the significance of employee comfort is vital. Designing accessible and comfortable break areas, lounges, and restrooms contributes to a positive work environment. Ergonomic workstations and the incorporation of green spaces within or around the warehouse enhance overall well-being. Safety is paramount in warehouse design (Kafka, 2023). Clear sightlines, proper signage, and well-defined pedestrian and vehicle pathways contribute to a secure environment. Integrating advanced security measures seamlessly ensures both safety and visual harmony.

The seamless integration of technology is integral to modern warehouse design. Automated storage and retrieval systems, IoT sensors, and real-time tracking solutions optimize operational processes without compromising the aesthetic appeal of the space. Sustainable design practices should be considered to minimize the environmental impact of warehouse operations. Energy-efficient lighting, the use of recycled materials, and implementation of rainwater harvesting systems contribute to a greener and more sustainable warehouse.

Warehouse design should extend beyond its physical boundaries, considering its impact on the surrounding community. Incorporating elements such as community spaces, public art installations, or sustainable landscaping fosters positive community engagement (Herriott, 2021). Reflecting the identity and values of the brand in warehouse design reinforces corporate image and employee morale. Incorporating brand colors, signage, and elements that align with the overall brand identity contributes to a cohesive and representative warehouse space.

The design of appealing warehouse spaces is a holistic endeavor that balances functionality, aesthetics, and the well-being of its occupants. By adhering to these design principles, warehouses can transcend their traditional roles, evolving into dynamic and inviting spaces that contribute positively to the overall success of the organization and the satisfaction of its workforce.

Chapter 3 – Methodology

3.1 Site Analysis and Surveys

3.1.1 Site Selection

Macro-Scale

The process of selected a site started with finding an area in the United States that poses a challenge when it comes to implementing daylighting throughout all times of the year. This will allow the thesis to be an example for all areas of the US. Moving into the micro-scale site, I selected the area of the United States Midwest, specifically the northern area, as it poses challenges in regards to natural lighting and sun paths.

Micro-Scale

The process of site selection for this thesis is quite simple. The goal is to address the problems that can be found in the design of current warehouses. As such, the site selected is in Fargo, and the current warehouse that is owned and operated by UNFI. It is slightly outdated, having been built in the 1970's. This is an ideal location for a warehouse redesign, as its outdated design and sustainability standards ask for an upgrade. Figure 1 below displays the existing site, located at the address of 3501 12th Ave N, Fargo, ND 58102.

Figure 7 – Site, from Google Earth, 2017

3.1.2 Site Analysis

The site, located at the intersection of 12th Avenue N and Interstate 29, this site has quite a few design opportunities for sustainability, while also posing many challenges to making a final design that has to contain many different environments. The site's proximity to the interstate is largely important, as its accessibility to that major road makes it highly ideal for a warehouse that has over 30 semis going in and out in a day. 12th Avenue North is another major road in the Fargo/Moorhead area; combining with the fact that many grocery stores in the Fargo and Moorhead cities are supplied by UNFI, this intersection is an ideal location for the warehouse redesign.

The site also contains a large amount of green space. While currently underused and undeveloped space, this untouched space allows for cheap renovation and reuse. The large empty space to the east has solid ground, leaving it open-ended for what it could be used for. The green space on the north of the property, however, is swamp. While a good natural habitat for ducks and other species, this space cannot really be used for infrastructure, as the cost to build on the ground would blow up an already high budget. Moving forward, this area of the site will be protected in site design, maintaining, and possibly expanding this sanctuary.

The site has little vegetation. The existing building is surrounded by plains of grass, with a few saplings lining the vehicle paths. Vegetation is largely important in providing habitat regeneration, lowering carbon footprint, and providing wind buffers (especially on the plains of the Midwest).

3.2 Analysis of Existing Sustainable Warehouse Practices

Conducting an analysis of existing sustainable warehouse practices involves a systematic review of the environmental, social, and economic aspects of warehouse operations. Here’s a brief guide on how this will be conducted for this thesis:

Define Scope and Objectives: Clearly outline the scope of your analysis and define the specific objectives you aim to achieve. Identify key performance indicators (KPIs) related to sustainability, such as energy consumption, waste management, and carbon emissions.

Data Collection: Gather relevant data on current warehouse practices. This includes energy bills, waste disposal records, transportation logs, and any other information pertinent to sustainability. Consider conducting on-site visits and interviews with warehouse staff to gain insights into daily operations.

Energy Consumption Analysis: Evaluate energy usage within the warehouse. Assess lighting systems, heating, ventilation, and air conditioning (HVAC) systems, as well as the efficiency of equipment and machinery. Look for opportunities to implement energy-efficient technologies and practices.

Waste Management: Examine the warehouse’s waste generation and disposal methods. Identify opportunities for waste reduction, recycling, and reuse. Assess the effectiveness of current waste management practices and explore partnerships with recycling facilities.

Transportation and Logistics: Analyze transportation practices, including the efficiency of delivery routes and the environmental impact of the vehicle fleet. Consider alternative transportation modes, such as electric vehicles or optimized route planning, to reduce carbon emissions.

Water Usage: Assess water consumption within the warehouse. Identify areas where water efficiency can be improved, such as optimizing irrigation systems, fixing leaks, or implementing water recycling initiatives.

Employee Engagement and Social Impact: Consider the social aspects of sustainability by examining employee engagement and well-being. Evaluate existing training programs, safety measures, and employee initiatives that contribute to a positive and sustainable workplace culture.

Cost-Benefit Analysis: Conduct a cost-benefit analysis for proposed sustainability initiatives. Consider both the initial investment and the long-term operational savings. This analysis will help prioritize actions that provide the most significant environmental impact with a reasonable return on investment.

Benchmarking: Compare your warehouse's sustainability performance against industry benchmarks and best practices. This will provide insights into areas where improvement is needed and help set realistic targets.

Report and Recommendations: Compile the findings into a comprehensive report. Present a set of actionable recommendations with clear timelines and responsibilities. Highlight the potential benefits of adopting sustainable practices, both in terms of environmental impact and operational efficiency.

Implementation and Monitoring: Work with relevant stakeholders to implement the recommended changes. Establish a monitoring system to track the progress of sustainability initiatives over time and make adjustments as needed.

Continuous improvement is crucial in the pursuit of sustainability. Regular assessments and updates to this analysis to stay aligned with evolving industry standards and technological advancements will be important.

3.3 Programming

A warehouse constitutes a large amount of square footage, most of which is used for product storage and distribution. Beyond this, the building requires many different spaces, from shipping offices to conference rooms to locker rooms. The following is a rough program for the building, leaving room for advancement and change in the program.

Receiving Area: 50,000 ft^2

- Receiving Dock
- Inspection Area
- Storage for incoming goods awaiting processing

Storage Areas: 302,000 ft^2

- Dry Storage:
  - Shelving for non-perishable goods
  - Racking systems for efficient space utilization
- Cold Storage:
  - Refrigerated rooms for perishable items
  - Freezer rooms for frozen goods
- Non-Frozen Perishable Storage:
  - Climate-controlled area for meat and dairy
  - Climate-controlled area for fruits and vegetables
  - Shelving or bins designed for produce storage

Picking Area: 105,000 ft^2

- Shelving for easy access to commonly picked items
- Aisles for order picking
- Packing stations for preparing orders

Packing Area: 3,000 ft^2

- Packaging materials storage

- Packing stations equipped with scales, labeling machines, and packing supplies

Quality Control Area: 20,000 ft^2

- Inspection stations to ensure the quality of goods
- Space for quality control checks before dispatch

Shipping Area: 15,000 ft^2

- Shipping docks for loading trucks
- Staging area for orders ready to be shipped
- Documentation and labeling area

Office Spaces: 20,000 ft^2

- Administrative offices for managerial and administrative tasks
- Customer service area for order inquiries and issue resolution
- Shipping offices on selection and staging areas

Break Room: 3,000 ft^2

- Rest area for warehouse staff
- Kitchenette or cafeteria
- Outdoor and indoor options

Maintenance Room: 5,000 ft^2

- Storage for maintenance tools and equipment
- Space for equipment repairs and maintenance

Training Room: 1,500 ft^2

- Space for employee training sessions
- Equipped with audio-visual aids for presentations

Technology Room: 3,000 ft^2

- Server room for IT infrastructure
- Space for managing warehouse management systems (WMS)

Restrooms: 1,000 ft^2

- Adequate restroom facilities for warehouse staff
- Safety and First Aid Station:

First Aid: 800 ft^2

- Room with basic medical supplies
- Emergency equipment and signage throughout the warehouse

Parking Area: 50,000 ft^2

- Parking spaces for employee and visitor vehicles
- Loading and unloading zones for trucks

3.4 Environmental Impact Assessment

Conducting an Environmental Impact Assessment (EIA) for a conceptual warehouse design without specific clients or stakeholders involves a self-driven analysis focused on minimizing environmental harm and promoting sustainability. The following is a guide on how the EIA will be conducted:

Define Objectives and Criteria: Clearly define your objectives for the conceptual warehouse design. Establish criteria for environmental sustainability, considering factors such as energy efficiency, resource conservation, and ecosystem protection.

Regulatory Compliance: Research and understand applicable environmental regulations and standards. Ensure that the conceptual design aligns with these requirements, even if there isn't a client or external stakeholder pushing for compliance.

Conceptual Design Documentation: Develop detailed documentation of the conceptual warehouse design. Include architectural drawings, specifications, and plans. This documentation serves as a basis for evaluating potential environmental impacts.

Impact Identification: Use conceptual design information to identify potential environmental impacts throughout the lifecycle of the warehouse, including construction, operation, and potential decommissioning. Consider aspects such as energy consumption, water use, waste generation, and emissions.

Mitigation Strategies: Develop mitigation strategies to address identified impacts. Focus on design modifications and operational practices that minimize negative effects on the environment. Consider incorporating sustainable materials, energy-efficient technologies, and waste reduction measures.

Alternative Analysis: Explore alternative designs and technologies to identify options with lower environmental impacts. Assess different approaches to site layout, construction methods, and operational practices to minimize ecological disruption and resource consumption.

Visualizations and Modeling: Utilize visualizations and modeling tools to represent the conceptual design and its potential impacts. This may include 3D models, simulations, and renderings that help to visualize and communicate the environmental aspects of the warehouse.

Documentation and Reporting: Document the entire environmental impact assessment process, including methodologies used and results obtained. Create a comprehensive report summarizing potential impacts, mitigation measures, and alternative considerations. This documentation serves as a record and reference for future decision-making.

Continuous Improvement: Even without external stakeholders, adopt a mindset of continuous improvement. Regularly reassess the conceptual design, incorporate new technologies or sustainable practices, and refine the environmental impact assessment based on evolving knowledge and best practices.

By following these steps, you can conduct a self-driven environmental impact assessment for a conceptual warehouse design, aligning the project with principles of environmental sustainability and minimizing its potential negative effects on the environment.

3.5 Comparative Analysis

Within the context of the chosen site, it is highly useful to routinely conduct a comparative analysis between the existing building and the proposed design. The existing UNFI Distribution Center was built in the 1970's, and has an extremely outdated program that is, unfortunately, standard for this building typology. The current state of the building and site are abysmal, and a clear benchmark for which to compare my design solutions to is highly useful.

A comparative analysis in the context of this project is complicated. As the primary goal of this project is to increase daylighting levels, an analysis between the two is hard to quantify and put into numerical values. In addition, sustainable energy practices and environmental impact assessments will have to be done in the digital realm, making the process long and even more complex. To address this challenge, I will mostly be utilizing other projects that have data regarding their lighting levels and sustainable aspects of design. This, coupled with the visual and physical comparisons that can be made with the existing site, will prove to be highly useful when completing comparative analyses.

3.6 Case Studies

While the site provides import context and a solid benchmark for comparison, there is much that can be learned from other buildings in the industry. In particular, existing projects were investigated that hold a certain level of daylighting or sustainable design within a factory, warehouse, or manufacturing setting.

3.6.1 Daylighting Case Studies

The Mayoral New Warehouse Logistics Center

Figure 8 – The Mayoral New Warehouse Logistics Center (Alda, 2018)

Location: Intelhorce, Málaga

Year of Completion: 2018

Architects: System Arquitectura

Typology: Warehouse / Storage Facilities

Square Footage: 54,000

The new building, situated adjacent to a protected warehouse in Intelhorce, Málaga, is designed to harmonize with its surroundings while fulfilling high-storage requirements. Standing at 68 foot tall with a floor area exceeding 54,000 square feet, it necessitated careful integration with the existing 46-foot-tall warehouse. The project emphasizes urban planning within the campus and shares a textile industry-inspired design language with its neighbor. Distinctive features include curved facades to soften the height contrast and a facade design reminiscent of fabric, with large arches subdivided to create a textured appearance. Prefabrication and energy efficiency are key aspects, with the entire structure prefabricated off-site and assembled using BIM technology. The triangulated steel structure and folded zinc sheet facade contribute to both aesthetics and performance, providing natural light while minimizing energy consumption (Caballero, 2023).

Figure 9 The Mayoral New Warehouse Logistics Center Interior (Alda, 2018)

System Warehouse

Figure 10 – System Warehouse (Ettefagh, 2017)

Location: Karaj, Iran

Year of Completion: 2017

Architects: Olgooco

Typology: Warehouse / Storage Facilities

Square Footage: 16,000

The project reimagines the traditional warehouse and administration building structure with a focus on efficiency and innovation. A white cocoon envelops the structure, creating a dynamic form and a uniform expression. Inside, the administrative building is integrated within the warehouse space, resembling a box within a box concept. This layout fosters a fluid dialogue between the two spaces, offering users a unique spatial experience. The design employs a monochromatic color scheme, highlighting shades of white, while incorporating natural elements like plants and ceramics. The warehouse and administration spaces interact to provide light and views for each other, enhancing the overall functionality and aesthetics of the project (Rojas, 2018).

Figure 11 – System Warehouse Interior (Ettefagh, 2017)

3.6.2 Sustainability Case Studies

Warehouse Schiphol Trade Park

Figure 12 – Schiphol Trade Park (Base Photography, 2022)

Location: Schiphol, the Netherlands

Year of Completion: 2022

Architects: Denkkamer

Typology: Warehouse / Storage Facilities

Square Footage: 215,000

Schiphol Trade Park, located near Hoofddorp, aims to be Europe's most sustainable and innovative business park. The warehouse designed by Denkkamer serves as the entrance to the park and aims to redefine logistic landscapes by integrating with the environment. The logistics core is surrounded by a dynamic shell consisting of programmatic and nature-inclusive elements, distinguishing it from a typical distribution center. Office spaces are positioned around transparent volumes connected to roof gardens, while logistic operations are optimized at the building's core. Traffic flow is separated, with logistic-related activities at the back and parking decks for cars above. The shell incorporates various heights and green elements, providing habitats for wildlife and enhancing the surrounding environment, creating a unique and integrated space (Denkkamer, 2023).

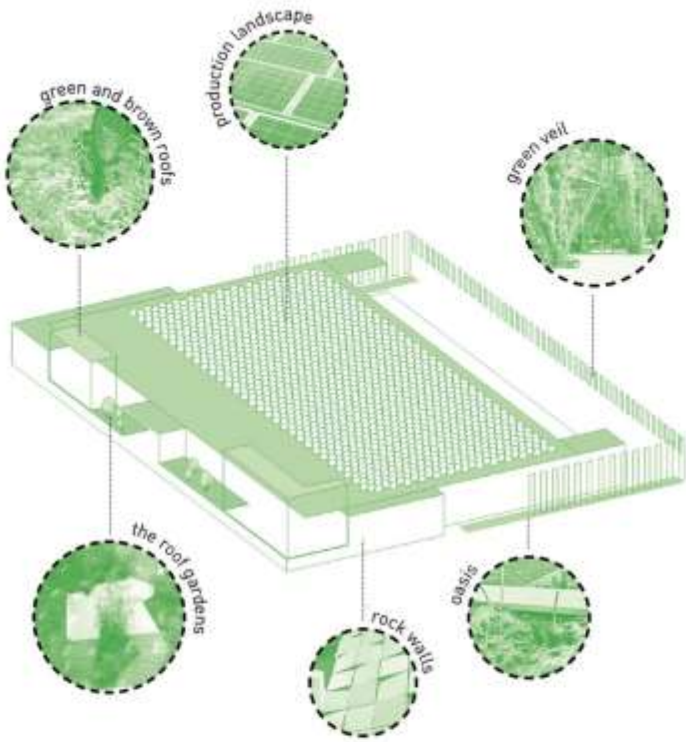


Figure 13 – Schiphol Trade Park Diagram (Base Photography, 2022)

Waste to Energy Campus

Figure 14 – Waste to Energy Campus (INI Design Studio, 2021)

Location: Jamnagar, India

Year of Completion: 2021

Architects: INI Design Studio

Typology: Manufacturing / Storage Facilities

Square Footage: 84,000

The waste management challenge is a global concern, with India generating 62 million tons of Municipal Solid Waste (MSW) annually, but only a fraction being treated, leading to open landfills. Abellon's Waste-to-Energy (WTE) project in Jamnagar, Gujarat, aims to process 50-100% of the city's waste using controlled combustion technology, compliant with environmental regulations. The project converts 2,20,000 tons/year of MSW into 7.5 MW clean energy, powering 15,000 homes, while transforming barren land into green space with social infrastructure. The design prioritizes functionality and sustainability, utilizing lightweight prefab structures and recyclable materials. Water conservation and landscaping efforts create a pleasant environment for citizens. The project also integrates additional value chains in the waste-to-energy sector, fostering a circular economy. Recognized for its sustainability, the campus has received prestigious awards for its design and environmental impact (INI Design Studio, 2021).

Figure 15 – Waste to Energy Campus Interior (INI Design Studio, 2021)

3.6.3 Employee-Driven Planning Case Studies

Yared Warehouse

Figure 16 – Yared Warehouse (Khoriaty, 2020)

Location: Beirut, Lebanon

Year of Completion: 2020

Architects: Halim Khoriaty

Typology: Warehouse / Storage Facilities

Square Footage: 34,000

The project revolves around the site's significance, aiming to blend functionality with corporate image for the Yared Headquarters. The warehouse's design is tailored to accommodate different access needs based on merchandise weight and handling methods. Internal space arrangements, such as ceiling heights, are determined by practical considerations like crane usage. Functionality is prioritized from the project's outset, resulting in an optimized volume. Utilizing an existing concrete structure on-site, office spaces are integrated, featuring a glass facade for natural light and signature louvers to enhance the corporate identity. The warehouse itself employs a steel structure for efficiency and speed, atop a concrete floor. Finally, a striking addition is the rooftop pool, catering to corporate events and leisure activities (Khoriaty, 2020).

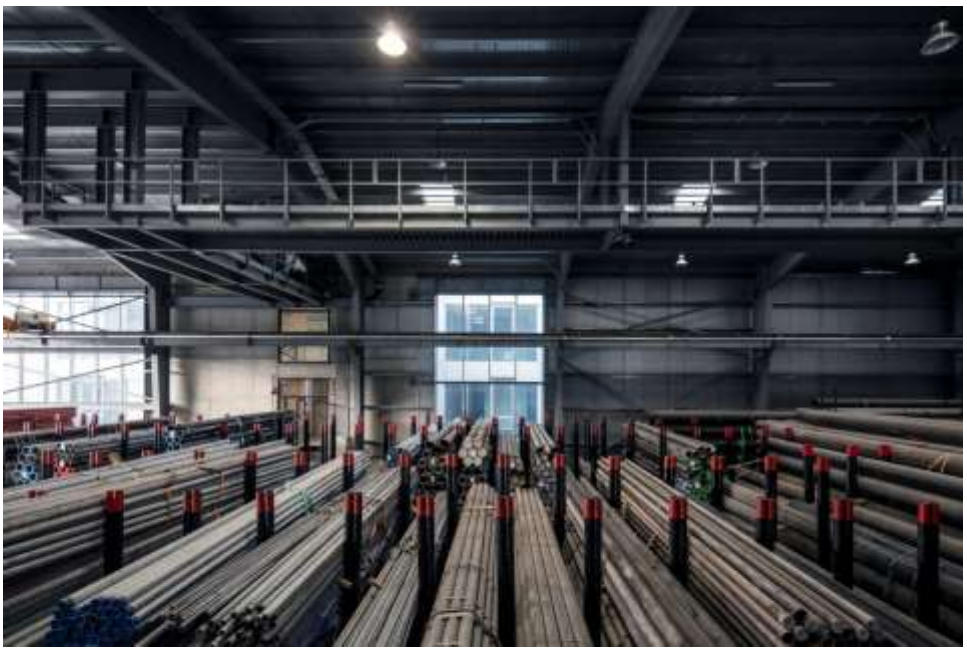


Figure 17 – Yared Warehouse Interior (Khoriaty, 2020)

3.7 Prototyping and Simulation

With the goals of implementing daylighting and sustainable energy into this warehouse redesign, it is paramount that the design be thorough and viewed through a highly critical lens. This investigation will be conducted through multiple iterations of design that take an in-depth look into employee-driven planning and aesthetically pleasing interior design. Additionally, these iterations will also be put through simulation software that analyzes natural lighting levels and sustainable design strategies.

3.7.1 Employee-Driven Planning Investigation

In this section of investigation, I will utilize Revit and Rhino to create multiple iterations to find the floor plan that aligns with employee needs, warehouse safety standards, and storage solutions. This process will start with sketches, looking into the form in which the building will materialize. After determining the form, the focus will shift to the interior of the building. Referencing the existing building on the chosen site, the investigation of the floor plan will look at the existing building's plan, and highlight key areas for improvement, as well as the spaces that the current plan lacks. After determining the program for the building, the design will continue with creating iterations in Revit to ensure that all spaces are included in the final design and that the layout of said spaces is practical, efficient, and safe.

3.7.2 Aesthetic Design Investigation

This section of investigation is a little more complicated, as "aesthetic" is not an aspect of design that can be quantified or concretely established. To prototype this, the investigation will begin with a look at Pinterest and other sources that provide many images from which inspiration can be drawn from. After this step, Rhino, Lumion, and Photoshop will be utilized to generate images that portray multiple options for interior aesthetics.

3.7.3 Natural Lighting Analysis

A natural lighting analysis is vital for this thesis' investigation. As it is the primary goal, it is of the utmost importance that schematic design looks into many different types of daylighting implementation while completing an analysis of each. This investigation will utilize Rhino, Revit, and a software that can analyze many aspects of design (including daylighting levels), which is Cove.Tool. In the simulations that are completed on Cove.Tool, natural lighting will be measured in lumens per square foot. It is key to research the standard for lighting before these simulations are completed to ensure that the correct natural lighting solution is integrated into the final design.

3.7.4 Sustainable Design Analysis

Sustainable design is the standard for current architectural practices, and this warehouse will be no different. The utilization of sustainable energy sources and passive systems is currently lacking in the existing building's design. To improve on this, the proposed design will be run on at least 50% renewable energy sources. To ensure this, this phase of design will revolve around renewable energy research and implementation, utilizing Revit and Cove.Tool as well as other energy modeling software to provide a clear analysis of sustainable energy usage. The design will also implement other green design strategies, such as water collection, Low-E glazing, and green spaces. This area of design is less quantifiable, so it will be reflected in the design in diagrams and vignettes.

3.8 Energy Modeling

Energy modeling for an architectural warehouse design involves using computer simulations to predict and optimize the energy performance of the building. The following is a brief guide on how this thesis will conduct energy modeling for the final design:

Gather Design Information: Collect comprehensive information about the warehouse design, including architectural drawings, specifications of building materials, lighting systems, HVAC (heating, ventilation, and air conditioning) systems, insulation details, and any renewable energy sources planned for integration.

Choose Energy Modeling Software: Select a suitable energy modeling software tool. Choose a tool that aligns with the complexity of the warehouse design and the level of detail fit to incorporate into the analysis.

Create a Digital Model: Use the chosen software to create a digital representation of the warehouse design. Input detailed information about the building's geometry, materials, and systems. Accurate modeling is essential for reliable simulation results.

Climate Data Input: Specify the geographical location of the warehouse and input local climate data into the simulation tool. This information helps the model account for external factors like temperature, humidity, and solar radiation, affecting the building's energy performance.

Define Operating Schedules: Input occupancy schedules, lighting schedules, and HVAC operation schedules based on the expected usage patterns of the warehouse. Consider variations in usage during different times of the day and seasons.

Set Simulation Parameters: Configure simulation parameters, such as time step intervals and simulation duration. Adjust these settings based on the level of detail required and the available computational resources.

Simulate Energy Consumption: Run the energy model to simulate the warehouse's energy consumption under various conditions. The software will analyze how the building responds to environmental factors and occupant behavior.

Evaluate Results: Review the simulation results to identify energy consumption patterns, peak loads, and areas of inefficiency. Evaluate the impact of design features on energy performance, such as insulation, window placement, and HVAC system efficiency.

Optimize Design: Explore design modifications and alternative energy-efficient technologies to optimize the warehouse's energy performance. This may include adjusting insulation levels, incorporating natural ventilation, optimizing lighting systems, or integrating renewable energy sources like solar panels.

Life Cycle Cost Analysis: Conduct a life cycle cost analysis to assess the economic feasibility of proposed energy-efficient measures. Consider initial costs, operational savings, and payback periods to make informed decisions about the design.

Documentation and Reporting: Document the energy modeling process, assumptions made, and the results obtained. Generate reports to communicate findings with stakeholders, architects, and engineers. Include recommendations for optimizing energy performance.

Iterative Process: Energy modeling is an iterative process. Use feedback from simulations to refine the design, and rerun the analysis as needed. This iterative approach allows for continuous improvement and ensures the final design aligns with energy efficiency goals.

3.9 Comparing Laborer Selection to Automated Selection

Distribution centers play a pivotal role in the supply chain, serving as crucial hubs where products are received, stored, and shipped to meet consumer demands. One of the key operational processes within distribution centers is order selection, the task of picking and assembling products for outbound shipments. This section compares and contrasts manual order selection with automated order selection, considering various factors such as efficiency, accuracy, flexibility, and cost-effectiveness.

Manual Order Selection:

Process Description: In a manual order selection system, human operators physically navigate through the aisles of the warehouse to locate and pick items according to the order requirements. This traditional approach relies on human labor and is well-established in many distribution centers.

Flexibility: Manual order selection offers a high level of flexibility, allowing workers to adapt easily to changes in product demand or variations in order characteristics. Human adaptability is particularly valuable when dealing with diverse products or irregular order patterns.

Initial Cost: The initial investment for implementing a manual order selection system is often lower compared to automated alternatives. The costs are primarily associated with labor, training, and basic warehouse infrastructure.

Scalability: Manual systems may face challenges in scalability, especially during peak demand periods. As order volumes increase, maintaining efficiency may require additional labor, space, and resources.

Automated Order Selection:

Process Description: Automated order selection involves the use of advanced technologies such as robotic systems, conveyors, and automated storage and retrieval systems (AS/RS). These technologies work together to retrieve and assemble products without direct human involvement.

Efficiency: Automated order selection systems are renowned for their efficiency and speed. The precision and consistency of machines often result in faster order fulfillment, reducing lead times and improving overall operational efficiency (Jaghbeer et al., 2020).

Accuracy: Automation significantly minimizes the risk of errors associated with manual picking. Automated systems utilize advanced sensors and algorithms to ensure high accuracy levels, reducing the likelihood of mispicks and order discrepancies.

Initial Cost: The initial investment for implementing automated order selection systems can be substantial. Costs are associated with the purchase and installation of robotic equipment, software integration, and facility modifications to accommodate automation.

Scalability: Automated systems are inherently scalable and can handle increased order volumes more efficiently than manual systems. As demand grows, additional robotic units can be deployed to meet the requirements without proportional increases in labor (Jaghbeer et al., 2020).

The choice between manual and automated order selection in distribution centers depends on a variety of factors, including the nature of the products, order volumes, and budget constraints. While manual systems offer flexibility and a lower initial investment, automated systems excel in efficiency, accuracy, and scalability. Distribution centers may opt for a hybrid approach, integrating both manual and automated elements to leverage the strengths of each system. Ultimately, the decision should align with the specific needs and goals of the distribution center in question, recognizing that advancements in automation technologies continue to shape the landscape of order selection processes.

For a small distribution center, manual order selection can often present several advantages over automated alternatives. Firstly, the initial cost of implementing an automated system can be a significant barrier for smaller operations with limited budgets. Automated order selection involves substantial investments in robotics, conveyors, and sophisticated software, expenses that may outweigh the benefits for a smaller-scale facility. Manual order selection, on the other hand, requires less capital investment, primarily focusing on labor costs and basic infrastructure, making it a more financially feasible option for smaller distribution centers.

Secondly, manual order selection provides a higher degree of flexibility that is well-suited for smaller-scale operations with variable order patterns. Human operators can easily adapt to changes in demand, product mix, or order specifications without the need for extensive reprogramming or reconfiguration that automated systems might entail. Small distribution centers often deal with diverse product types and irregular order volumes, and the adaptability of manual order selection allows for efficient handling of these variations. Additionally, the learning curve for manual processes is generally shorter, enabling quicker implementation and reduced downtime during the transition phase for small distribution centers. In conclusion, the cost-effectiveness and adaptability of manual order selection make it a pragmatic choice for smaller distribution centers where operational agility and financial considerations play a pivotal role in decision-making.

Chapter 4 – Results and Conclusions

4.1 Project Description

Solar Harbor is a 430,000 square foot warehouse where tradition meets transformation. Nestled amidst the plains of North Dakota, this facility redefines the industrial landscape by prioritizing the well-being of its workforce and the health of the planet. Shifting the focus of the industry from efficiency and cost reduction to health is the undeniable way of the future, and this design places itself at the forefront of this revolution.

This structure is to be utilized for food and beverage distribution for grocery stores in the states of North Dakota, South Dakota, and Minnesota. With a total storage area of about 308,000 square feet, this structure creates a large amount of storage and selection space while maintaining safety and environmental standards.

This structure boasts a level of daylighting in competition with office buildings and apartments. It does so without bloating the energy consumption of the warehouse itself, producing half of the needed energy to keep the building running by means of over 2,000 solar panels and six vertical wind harvesters. This structure utilizes many sustainable practices, from KalWall-style paneling to keep insulation standards while improving daylighting to a water collection system that recycles rain water and snow collection.

4.2 Project Objectives and Goals

I established three main goals before moving into design. The primary goal was to increase the levels of natural lighting within the industrial environment. Given the many benefits found in the research phase related to natural lighting implementation, this goal was the primary driver going into design. The secondary goal was implementing sustainable practices within the design. Given the high energy consumption of warehouses, it was key that this design attempted to reduce the load of energy produced by nonrenewable resources, and provide a greener standard for industrial design. The third goal of design was simply to produce quality aesthetics that harbor a healthier, more productive work environment. The following breaks down how the final design meets the goals.

First, I investigated the lumen level that would be ideal for natural lighting levels. Part of this investigation brought me to Cove.tool, a software that can be used to display lighting levels in plan view. For comparison, I investigated average lumen levels required for different spaces that everyone can be familiar with, such as a kitchen, which requires around 70 lumens per square foot. This research helped to develop a standard that my design should reach. Given the typology of this warehouse, I determined that 20-40 lumens per sq. ft. was the minimum requirement to meet lighting conditions. The average lumens per sq. ft. for the selection areas that were accomplished through the use of solely natural lighting provided from a winter sun path, not including the artificial light that would be required to keep the building running, was 50 lumens per sq. ft., which exceeds the goals. The plan view that displays this study can be found in the following section.

Secondly, I designed ways to reduce the project's impact on the environment. The inclusion of solar panels and vertical wind harvesters produce over half of the structures energy needed to keep it running. I determined that the project needed around 10 kWh / sq. ft. / year for basic function needs. This means that the building needs about 4,000,000 kWh / year. The 2,000 solar panels produce around 1,000,000 of these kWh, and the vertical wind harvestors produce the other 1,000,000 kWh. In addition to energy needs, the structure lowers carbon footprint on the site by reducing property green space to concrete ratio to 60:40. The building also harvests rainwater and snow, cutting water needs for plumbing and irrigation by a third.

Finally, I investigated the cost of the project, and utilized some basic equations to develop a rough return on investment figure. A goal of the project was to increase energy efficiency, and the calculations I conducted show that a return on investment is improved with this design. Though it is low, the calculations were done with only a 10 year projection, meaning that further investment and development will only improve the ROI. The final ROI of 3.17% is displayed below, as well as the values and equations that were utilized to get the number.

Table 3 – Project ROI

Project Costs					
Land Acquisition	Land Area (sf)		1,300,000	1	Area varies per lot
	Land Cost ($/sf)	$	300.00	2	Assessed Value / SF
Demolition Costs	Building/Lot Floor Area (sf)		40,000	3	Varies per lot
	Demolition Cost ($/sf)	$	10.00	4	Generally $15 or $10 for open lot (includes cut, hauling, landfill)
Building Construction	Proposed Gross Floor Area (sf)		430,000	5	Max allowable Zoning - Later use 'Actual'
	Building Cost ($/sf)	$	500.00	6	May range: $300-500/sf+ (Low to High)
Fees, Permits, & Misc (rate)	Fee Rate (%)		20%	7	Generally 20%
Construction Financing	Construction Interest Rate (per anum)		7%	8	Generally 7%
	Construction Length (yrs)		3	9	May vary by constr/type (prefab, precast?)
Total Land Acquisition		$	390,000,000.00	10	Line 1 x 2
Total Demolition Costs		$	400,000.00	11	Line 3 x 4
Total Building Construction		$	215,000,000.00	12	Line 5 x 6
Total Fees, Permits, & Misc		$	43,000,000.00	13	Line 7 x 12
Total Construction Financing		$	50,310,000.00	14	Lines (12+13) x line8 x line9
Total Project Cost		$	698,710,000.00	15	Total of Lines 10-14

Balance Sheet					
	Gross Floor Area (gsf)		430,000	22	Line 5
	Leaseable Area (Efficiency)		70%	23	Rentable Area vs Non (stairs,shafts,etc)
	Net Leasable Floor Area		301,000	24	Line 22 x 23
	Income Rate ($/SF/YEAR) - SEE NOTES	$	350.00	25	Composite of ALL Uses (Show calcs)
	Occupancy Rate		80%	26	Generally 80%+ is good
	Tax Rate		15%	27	Generally 15%
	Operating/Maint Cost (per GSF/Mon)	$	0.80	28	Generally $.80/gsf/month
Assets/Income per month	Income / Month	$	7,023,333.33	29	Line 24 x Line25/12 x Line26
Liabilities/Expenses per month	Debt Service (from above)	$	3,868,342.57	30	Line 20
	Operating Costs (total)	$	28,666.67	31	Line 22 x 28
	Total Liabilities	$	3,897,009.24	32	Total of Lines 30+31
	TOTAL Monthly Cash Flow	$	3,126,324.09	33	Assets minus Liabilities
	Monthly Depreciation ('Paper Loss')	$	(951,574.07)	34	Lines (12+13+14) div by 27/12mos
	Gross Profit	$	2,174,750.02	35	Lines 33+34
	Taxes on Gross Profits	$	326,212.50	36	Tax Rate (Ln27) x Gross Prof (Ln35)
NET PROFIT per month	Net Profit (per month)	$	1,848,537.52	37	(x) is loss, should be positive
	NET Profit (per YEAR)	$	22,182,450.21	38	Ln37 x 12mos
	ROI % per year		3.17%	39	Ln38/ Ln21

4.3 Project Design and Documentation

This section breaks down the final design of the project. Here, final drawings are displayed with a short text description explaining how each contributes to the translation of my thesis and the realization of the design goals and objectives.

4.3.1 Renders

Figure 18 – Southern Exterior Render

Southern Exterior Render- This render provides viewers with the general idea of what the final design looks like, showing materiality, glazing articulations, and the scale of the project.

Figure 19 – Grocery Selection Area Interior Render

Grocery Selection Area Interior Render – This render displays both the natural lighting that was achieved in the final design as well as the aesthetic practice that was employed in the project's final design. It also illustrates (partially) the custom structure that was used to accomplish the lighting goals.

Figure 20 – Greenspace Interior Render

Greenspace Interior Render – This image displays some of the green design practices that were utilized in the project's design, as well as one of the many accommodations that were made to make employee work life better.

4.3.2 Site and Floor Plans

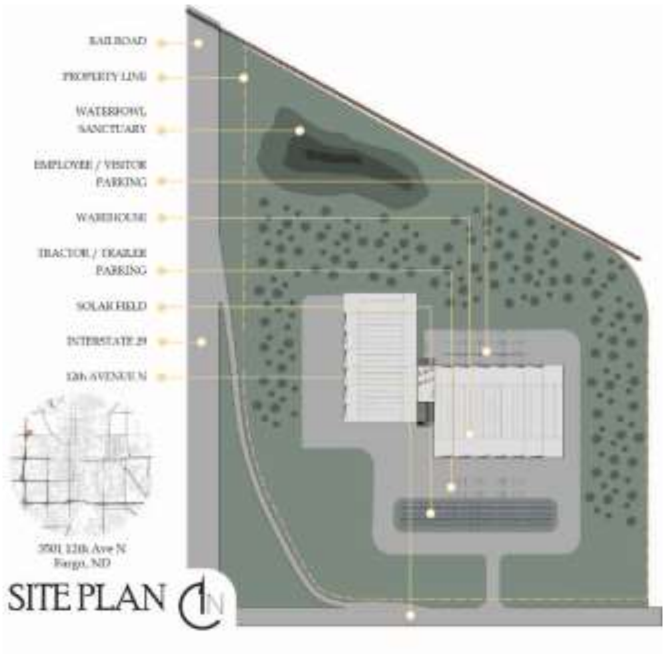


Figure 21 – Site Plan

Site Plan – This image displays the site, including surrounding context and the design choices that were made in order to improve the site conditions.

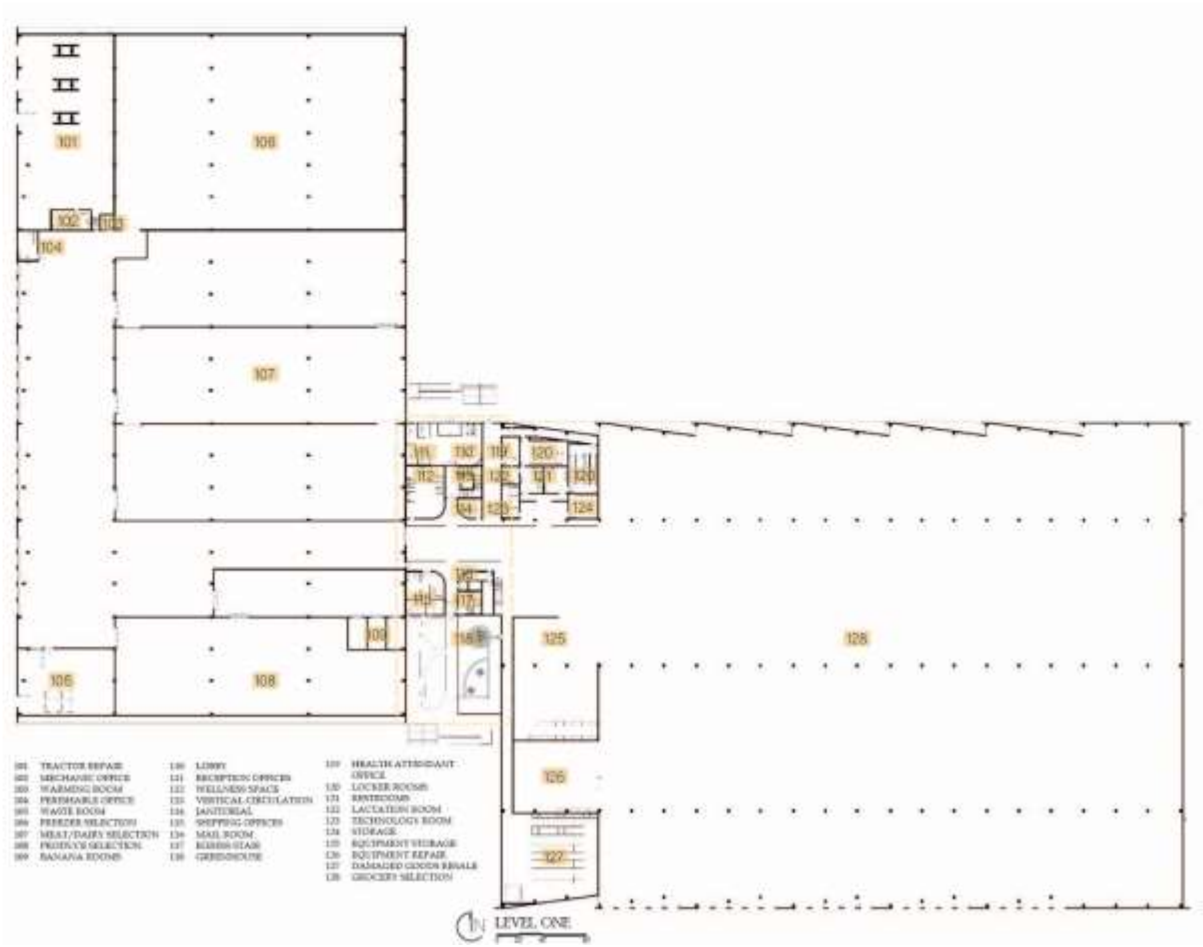


Figure 22 – Floor Plan, Level One

Floor Plan – Level One – This floor plan, taken from Revit, displays the main selection spaces, loading docks, and health and wellness amenities that were integrated into the final design.

Figure 23 – Floor Plan, Level 2 & 3

Floor Plan – Levels 2 & 3 – These floor plans display the office spaces in this design. The offices and break spaces were separated by floor to reduce noise pollution from the main work space.

Figure 24 – Circulation Plan

Circulation Plan – This image displays the common circulation patterns of the different traffic types within the design. It further displays the attention to detail when it came to the planning of the building, including the investigation of the existing plan and the corrections made to make a cohesive, inclusive plan.

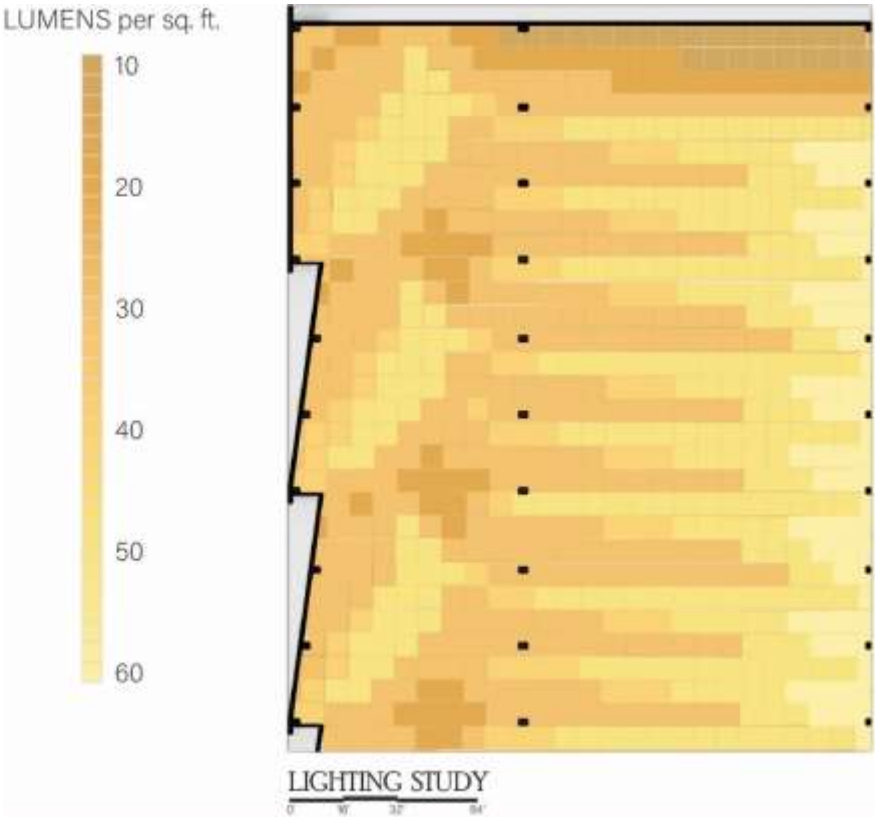


Figure 25 – Lighting Plan

Lighting Plan – This plan view was taken from Revit and plugged into Cove.Tool, which provided the lumen levels per square foot achieved in the final design.

4.3.3 Sections

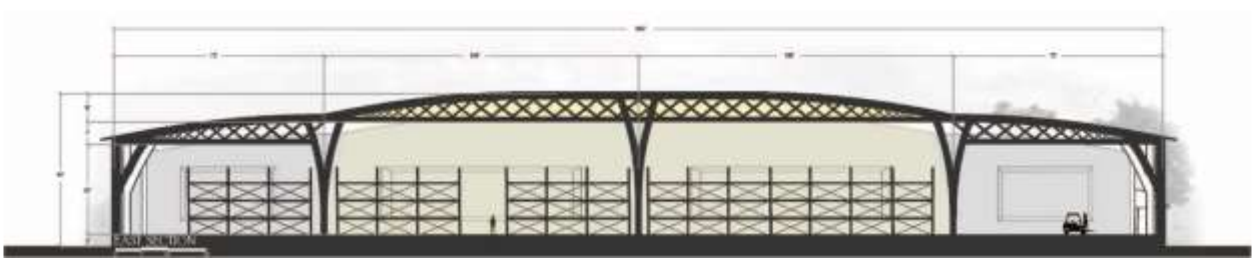


Figure 26 – East Section

East Section – This image displays the intricacies of the structure that was used in the final design to achieve lighting and aesthetic goals.

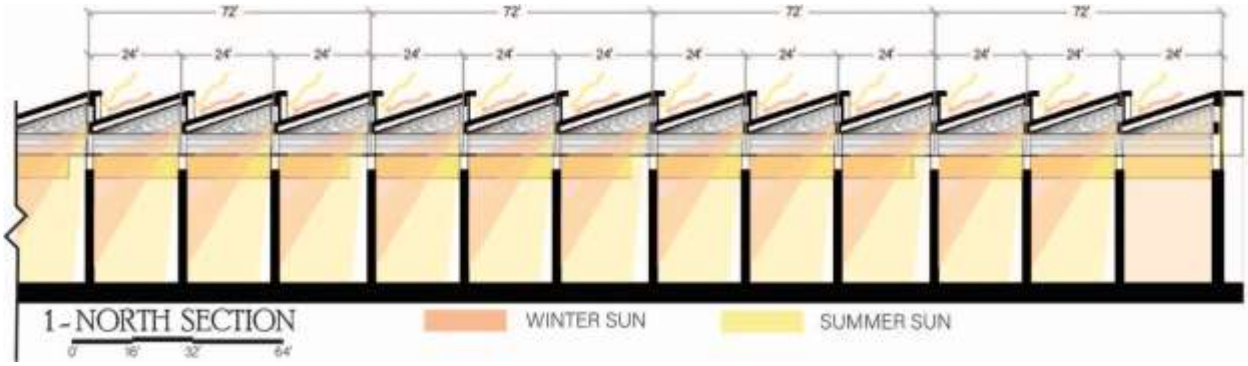


Figure 27 – North Lighting Section

North Lighting Section – This image displays, in section view, the diffusion and dispersal of natural lighting in the summer and winter months.

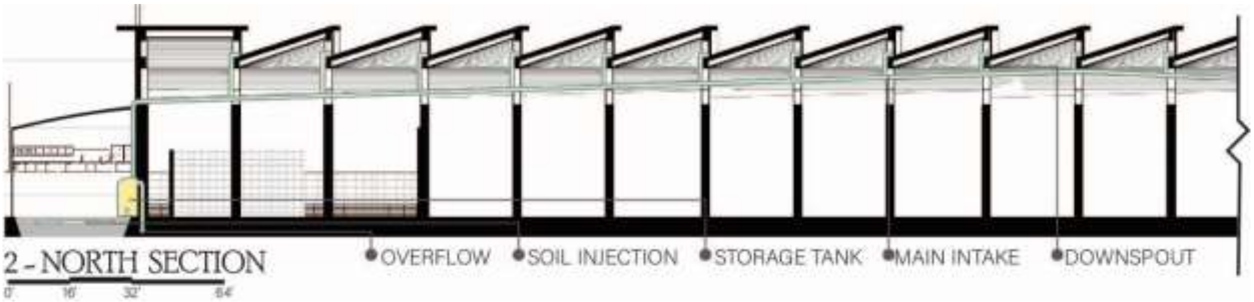


Figure 28 – North Water Collection Section

North Water Collection Section – This image shows, in section view, the water collection and storage systems used in the final design.

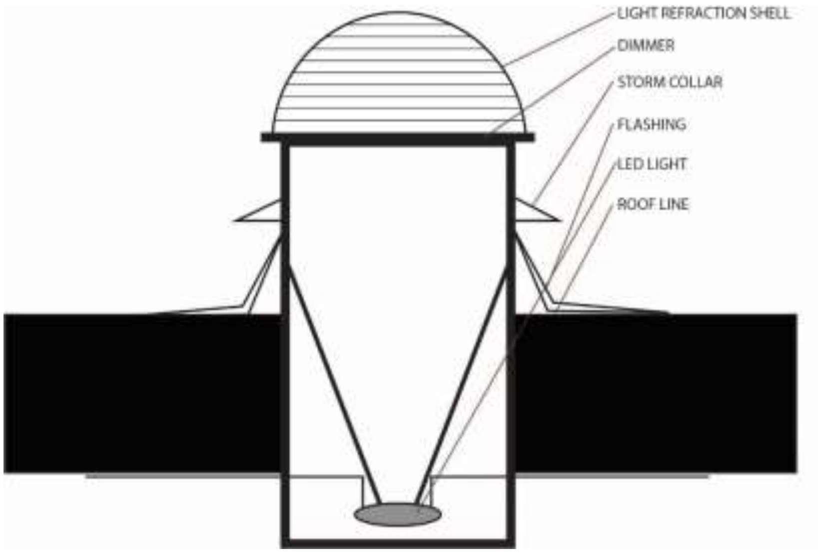


Figure 29 – Tubular Skylight Section

Tubular Skylight Section – This section displays a detail of the tubular skylight that was utilized in the final design to further address lighting goals and needs.

4.3.4 Elevations

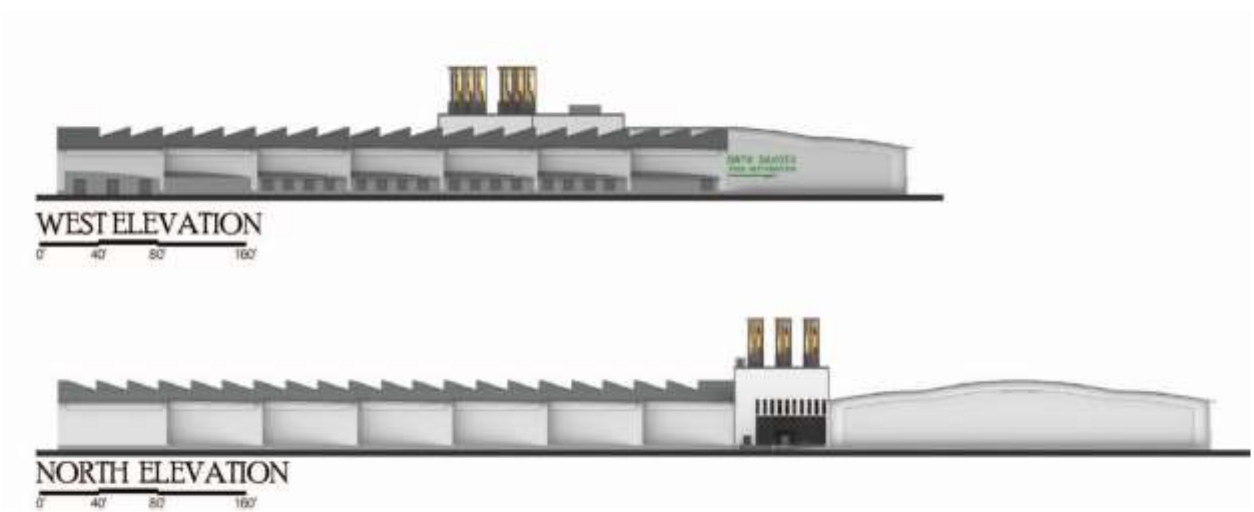


Figure 30 – West and North Elevations

West and North Elevations – This image displays the elevations produced for this project, which showcases the articulation of the roof, as well as the overall look of the warehouse.

4.3.5 Diagrams and Vignettes

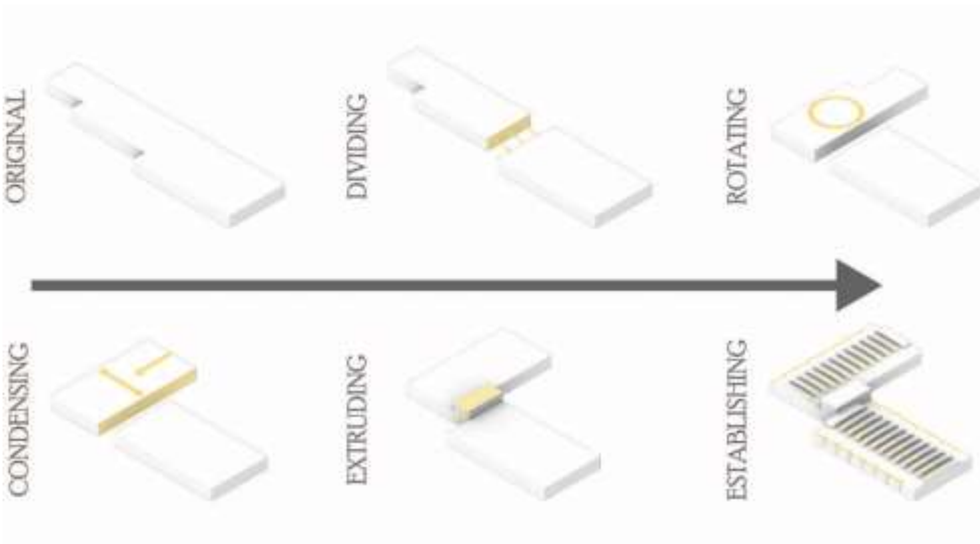


Figure 31 – Form Building Vignette

Form Building Vignette – This image displays the process of form building during schematic design. It shows the different steps taken to convert the original structure into the final design form.

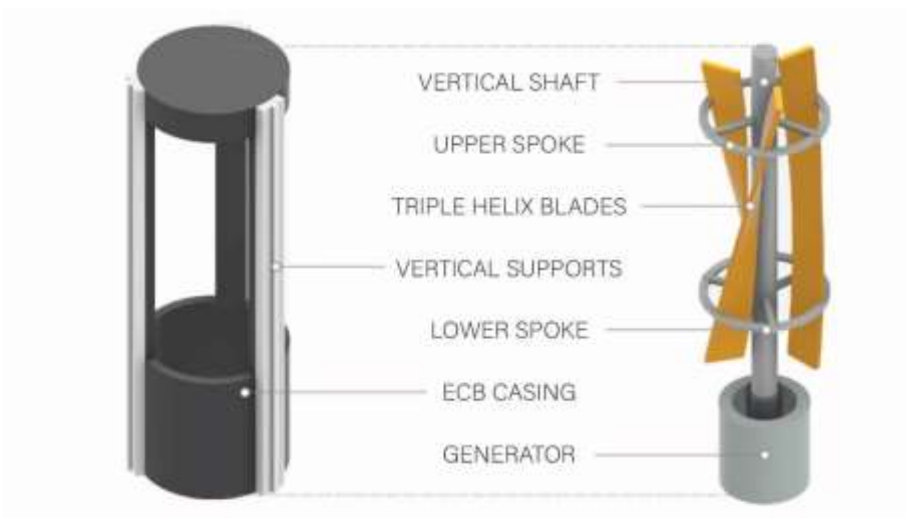


Figure 32 – Vertical Wind Harvester Diagram

Vertical Wind Harvester Diagram – This image displays the vertical wind harvesters utilized in the final design to realize the goal of 50% renewable energy usage.

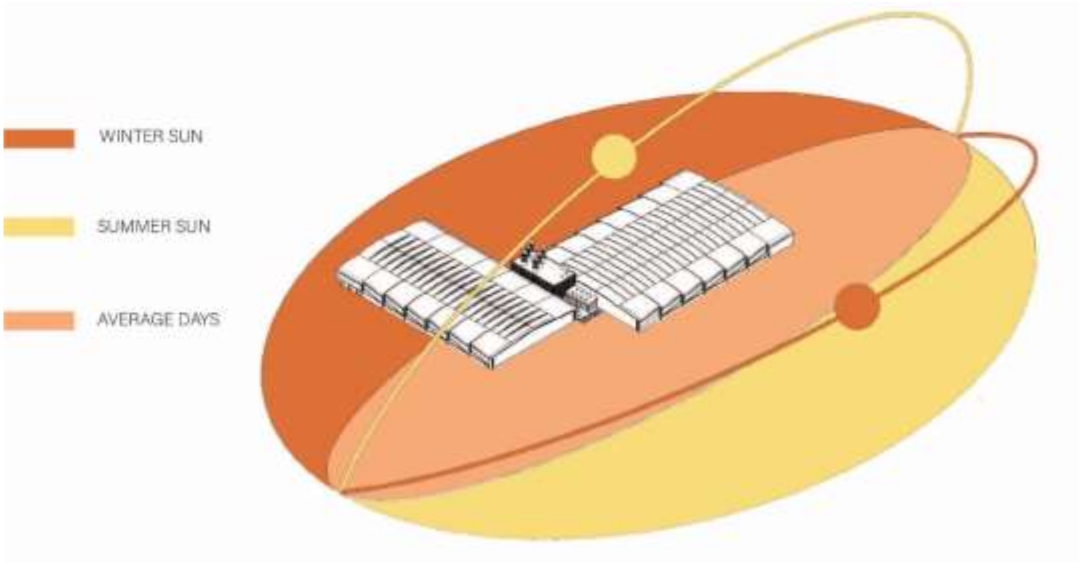


Figure 33 – Sun Path Diagram

Sun Path Diagram – This image displays the sun path diagram that was produced for this project that assisted in ensuring lighting constraints, as well as observing the different in illumination at different times of the year.

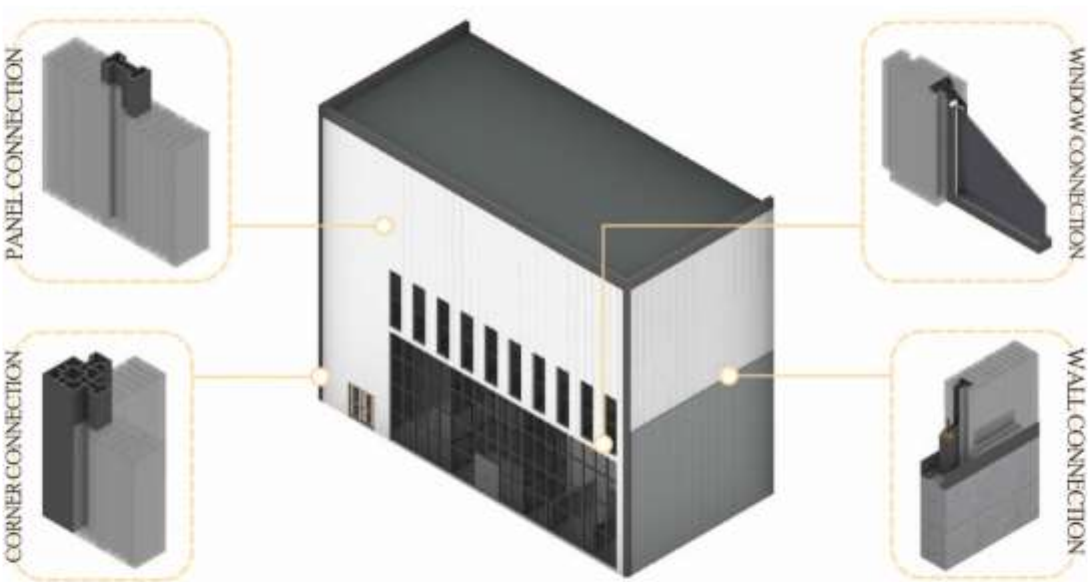


Figure 34 – Paneling Diagram

Paneling Diagram – This image displays the details made to break down the structure and modularity of the translucent paneling that was utilized in the final design to realize the natural lighting goals.

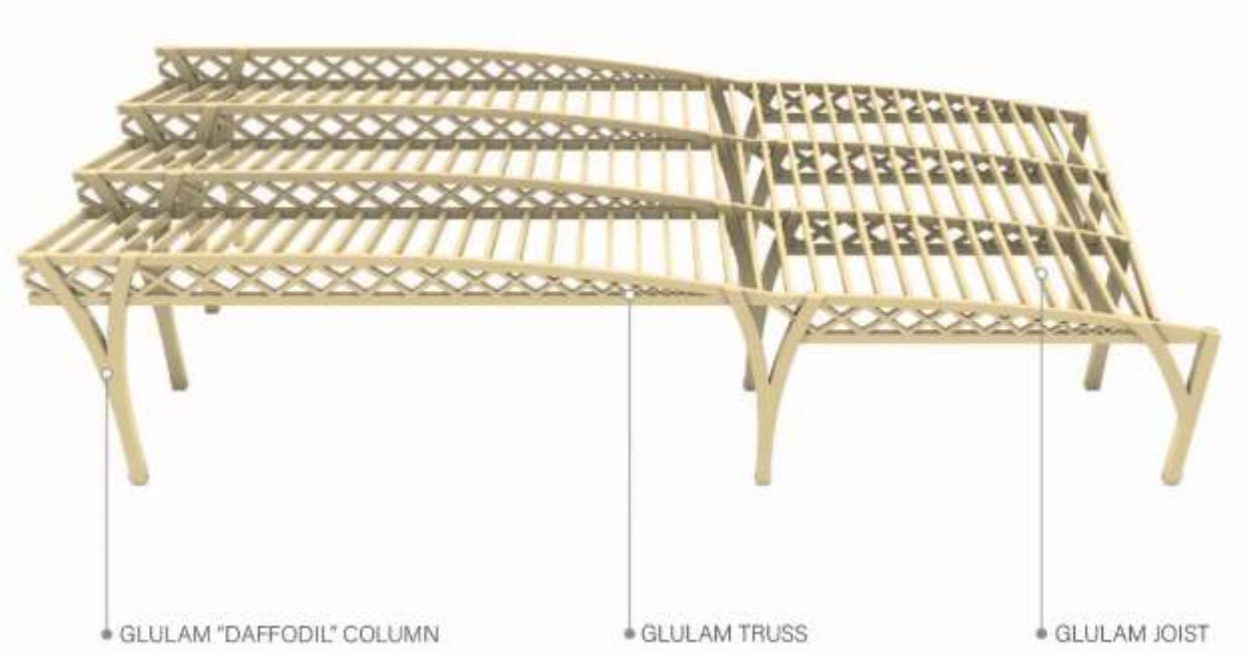


Figure 35 – Structural Diagram

Structural Diagram – This image displays a section of the glulam timber construction that was used in this project. It shows the different components that were used to create the custom structure needed to make the saw tooth roof design.

4.3.6 Physical Model

Figure 36 – ¼" Scale Model

1/4" = 1' Scale Model – This image shows the model that was produced at the end of the design. It was made to showcase the intricacies of structure, and how the trusses and columns slot together.

Figure 37 – 1/16'' Scale Model 1

Figure 38 – 1/16" Scale Model 2

1/16” = 1’ Scale Model – This model was produced to show how a section of the structure is fitted together, as well as the implications it could have for prefabricated production of the glulam structural members.

4.4 Conclusions

While this design has been brought to a conclusion, there is still much work that could be done. Further research and design are a must to bring this project to its full potential. With the complicated goals and objectives, a truly thoughtful and aesthetically provocative design would take years more to flush out the best design.

The first area of design that could be further developed is the utilization of sustainable energy implementation. Though this design met the goals at the beginning, this idea could be pushed further. Moving forward, I could set the goal for a net-zero design. In order to accomplish this, I would further investigate renewable energy sources, opting to utilize geothermal energy as a means of heating. Solar panels could be installed onto the roof of the structure, providing more solar energy harvesting. The large amount of greenspace on the site provides opportunities for wind harvester installation or solar fields. Pushing renewable energy usage further would greatly improve this design.

The second aspect of the design that I would like to further develop is its natural lighting exposure. The design met my goals, as per the lumens per square foot that was developed early in the project. However, this could have been pushed more, maybe by looking into more translucent paneling integration, or perhaps investigating other, cheaper alternatives to glazing. In addition, I would like to look further into another orientation of the building, finding ways to get more south-facing glazing, as well as other iterations of design to find more ways to improve daylighting by the placement and amount of glazing.

Finally, I believe it could be highly useful to find ways to quantify and collect data in the realm of natural lighting and the relation to worker productivity and health. I completed a very rough ROI for this project, which I believe is highly useful in presenting my project's feasibility and credibility. I would like to look into ways to provide more data and mathematical equations to produce further credibility to my design within the reach of *my* design.

Previous Project Appendix

2nd Year

Fall 2020:

Professor – Jennifer Brandel

Project 1 Name: Land Artist Studio

Project 1 Typology: Livable Art Studio

Project 2 Name: Boat House

Project 2 Typology: Training Facility

Spring 2021:

Professor – Milton Yergens

Project 1 Name: Unconventional Dwelling

Project 1 Typology: Housing/Residential

Project 2 Name: 7th Street Cooperative

Project 2 Typology: Mixed-Use Residential

3rd Year

Fall 2021:

Professor – Emily Guo

Project 1 Name: Island Park Community Arts Center

Project 1 Typology: Heavy Timber Art Center

Project 2 Name: Dakota Village

Project 2 Typology: Masonry Renovation

Spring 2022:

Professor – Regin Schwaen

Project 1 Name: First Nation Conclave

Project 1 Typology: Concrete Cultural Center

Project 2 Name: Fargo National Military Cemetary

Project 2 Typology: Memorial Center

4th Year

Fall 2022:

Professor – Bakr Aly Ahmed

Project 1 Name: The Tiers

Project 1 Typology: Mixed Use Residential

Spring 2023:

Professor – Chris Hawley

Project 1 Name: Marvin Windows Competition

Project 1 Typology: Custom Residential

Project 2 Name: The Rise

Project 2 Typology: City Block Masterplanning

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