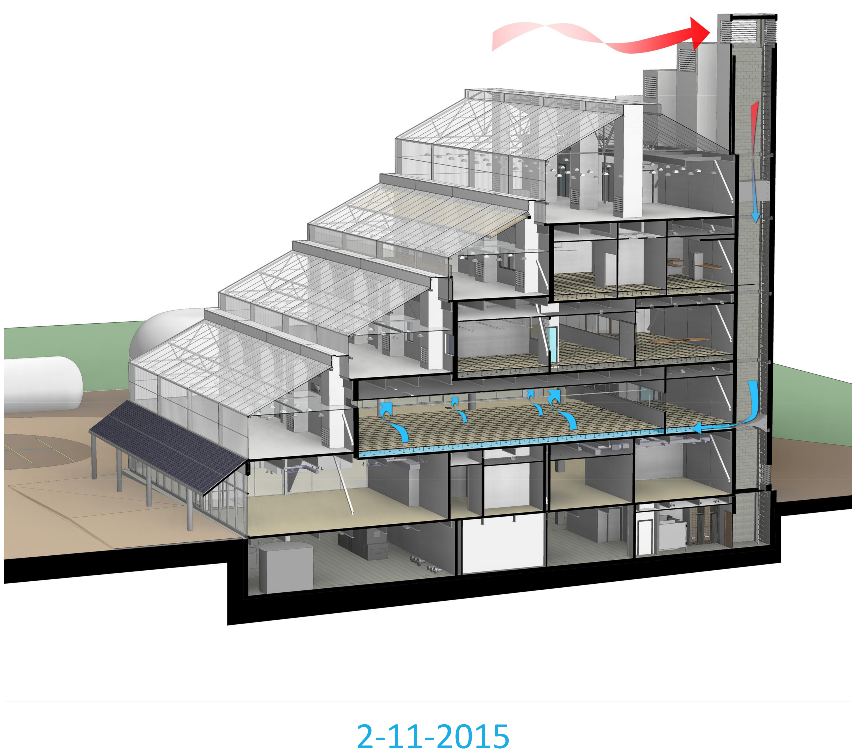
AEI Student Design Competition

Integration Report



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ARCHITECTURAL ENGINEERING INSTITUTE

Contents Table of Contents

Executive Summary

With an overall objective of creating an adaptable educational space capable of producing crops year round, team Synthesis developed three main goals to guide the design and construction process. The goals consisted of:

- Development of an adaptable building design
- Establishing a self-sustaining ecosystem
- Cultivation of a great environment and learning experience through the design and construction of a Vertical Farm

Modular Greenhouse Design

The greenhouses were an interdisciplinary collaboration between all members of the Synthesis team. By designing with the plant in mind, the team chose to focus on how each aspect of the greenhouse would affect the environment being created. The team first chose to implement a closed system greenhouse which would ultimately give Growing Power more control over their facilities and allow them to utilize resources to their full potential. By using this closed system it allowed the team to design for natural cooling and condensation collection within each greenhouse model producing a more efficient facility. In addition to the natural cooling and condensation collection, grow lights have also been implemented in the space to supplement the light the plants receive throughout the year.

In order to create a modular design, the correct materials needed to be chosen and implemented. For the greenhouse, the team chose to use a steel structure with polycarbonate glazing. These materials and modules were arranged in a way that allows the plants to receive the most light possible and for the owner to have as much growing space as can be provided. Each module is approximately 19'-2" by 20' and contains its own source of natural cooling.

Natural HVAC

One of the defining attributes of this building is the use of natural ventilation throughout the building using Raised Access Flooring (RAS) with an Under Floor Air Distribution System (UFAD). With the mechanical constraints that come along with this innovative system, the UFAD is only used on a portion of the 2nd, 3rd and 4rd floors, meaning that those levels needed to be designed for two different slab elevations. It was the job of the entire Synthesis team to develop a comprehensive plan of how the separate elevations could efficiently be tied together and constructed during the project.

Another key characteristic of the natural HVAC system is the use of intake and exhaust towers on the north side of the building to supply outdoor air to each floor and exhaust the stale air. These towers required the team to re-asses the architectural layout and optimize the floor plans to accommodate a working natural HVAC system.

Growing Power as an Ecosystem

By combining the mechanical and electrical systems in the building, the Synthesis team was able to create a building that could produce energy for itself. This building is set to be the prototype for self-sustaining buildings in the future and the team ensured that the bar was set relatively high. The key to this energy production is the idea of Quad-Generation by the Synthesis engineers. This system uses food waste to feed an anaerobic digester which in turn feeds a micro turbine. The micro turbine then provides power to the facilities across the Growing Power site. Not only in this producing energy from the building but it is also removing waste from the local community and keeping it out of local landfills.

Building Enclosure

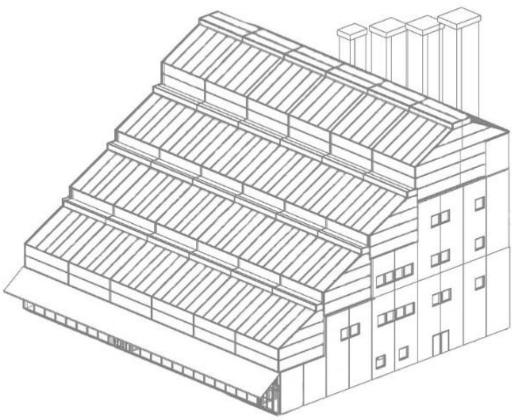
Foundations - The Growing Power building site consists of silty, sandy clay soils which produced a low allowable bearing capacity. The site also features a high water table, with test borings detecting free water at depths ranging from 8'-0" to 12'-0". To accommodate the high water table and low bearing capacity of the soil, the construction engineers, working closely with the structural team, implemented a soil improvement system known as Geopiers, and utilized sheet piling during the excavation process.

Façade - The building façade is split into two factions: architectural precast panels on the north, east and west portions of the building, and a polycarbonate curtain system on the southern façade. Both types of panels were chosen due to the requirements needed for other engineering systems within the building. Polycarbonate was chosen for its light transmittance for the greenhouses and precast panels for its ease in construction and thermal properties to maintain an energy efficient building. Both materials also aid in the reduction of waste on site because of the fact that they are both 'prefabricated' and precut offsite.

In summary, Synthesis is an integrated team dedicated to meeting the client's needs throughout the design and construction of the Vertical Farm.

1.0 Project Introduction

Project description – The 2015 AEI Student Design Competition addresses a five-story vertical farm that is being designed and constructed for a local nonprofit urban farming organization, Growing Power, Inc. The building is located at 5500 W Silver Spring Drive, Milwaukee, Wisconsin. The vertical farm is created using a tiered greenhouse approach on the southern façade of the building. Each floor steps back and utilizes the available southern light in order to house aquaponic systems and grow crops which are used to sell to the surrounding neighborhoods in the retail market on the ground floor. Aside from the year round production of plants and vegetables, the facility houses classrooms, conference spaces, and a demonstration kitchen designed to further Growing Power's expanding mission to become a local and national resource for learning about sustainable urban food production.



The design of the building should address the following challenges proposed in the 2015 AEI Student Design Competition:

1. Design and develop a sustainable building that optimizes construction, design, and lifecycle cost concepts
2. Consider architectural and engineering modifications for a prototype building that will also be built in Miami, FL and other locations across the country
3. Provide a detailed analysis demonstrating the integration of all systems required for operation of the vertical farm

These requests, in conjunction with preliminary information provided regarding Growing Power, Inc. and its needs, led to the development of preliminary goals and design criteria for the entire Synthesis team.

2.0 Stakeholders

The Synthesis design team considers an integrated design to not only achieve engineering and architecture system integration, but also achieve integration of all project stakeholders and their respective goals.

Growing Power, Inc. – Food production and retail staff, educational tour guides, administrators, volunteers, and other staff related to the operation of the urban farm.

City of Milwaukee, WI. – Local schools, students, local farmers, underprivileged youth, interns, volunteers, local restaurants, local residents and other community members will all be effected by the new Vertical Farm.

Anaerobic digestion on site also creates a reliance on community members, local businesses', and restaurants to provide a continuous supply of food waste for energy production on site.

Synthesis, Engineering for Architecture – Together, the two entities of Engineering and Architecture work as one, delivering an integrated approach to design that takes into account all of the stakeholders and their goals and considerations.

3.0 Project Design Goals

As there are many different stakeholders invested in the project, all with differing agendas, the Synthesis team elected to organize these into three fundamental goals that represent the considerations of everyone involved in project:

Educational

Synthesis is committed to engineering an environment for Growing Power that promotes a meaningful learning experience for everyone who visits the Vertical Farm.

Ecological

All of Synthesis' disciplines must consider their internal impact on other building systems and occupants while also taking into account the external effect they have on the environment.

Adaptable

Strong emphasis has been placed on designing systems that are easily adjustable to changing building conditions, emerging technologies, and geographical environments.

4.0 Design process

Team Roles

In order to enhance collaboration and cultivate an innovative design environment, the Synthesis team decided to complete a personality analysis on each team member and the team as a whole. This effort focused on team members' strengths and passions rather than their disciplines to determine how the team could best collaborate throughout the design process. This method of management allowed for strong interdisciplinary collaboration and enhanced team chemistry. While team members have very different personalities, most of the Synthesis team complement each other personality-wise. A full analysis of all personalities on the team and their relationship to one another can be found in **[Appendix B].**

Communication and Collaboration

Weekly Scheduled Meetings – Every Wednesday at 3:30 pm the Synthesis team met together to discuss each member's progress, and any other issues that had arisen over the past week. Early on in design, the Wednesday meeting was a good platform to present new research, design ideas, and/or results of simulations and preliminary design calculations. An agenda was created for each meeting that listed all of the topics to be discussed. Please visit **[Appendix C]** to see a sample meeting agenda.

GroupMe – This is a smart phone app that allows all of the group members to talk in one message setting where all messages can be seen and responded to by all. Synthesis used GroupMe for many things including: meeting reminders, status updates, design questions, and general logistics discussions. This allowed the team to be able to communicate in any location and at any time so that even if everyone was not in the Thesis Studio (explained on the following page) they could still be reached.

Trello – Trello is an interactive website that allowed the group to create, assign, and categorize tasks on a dashboard that was visible and editable by all. The visibility of this application allowed everyone on the team to be able to know what each person was working on and when it would be done. Each discipline was assigned a color and each team member had full control to make edits within the Trello system. An example portion of the Trello 'board' can be seen in **Figure S1**. Within a card, each member had the ability to make comments, set a due date, add labels, create a checklist, and change the members assigned to the card. Team members communicated and updated each other on progress directly on the card.

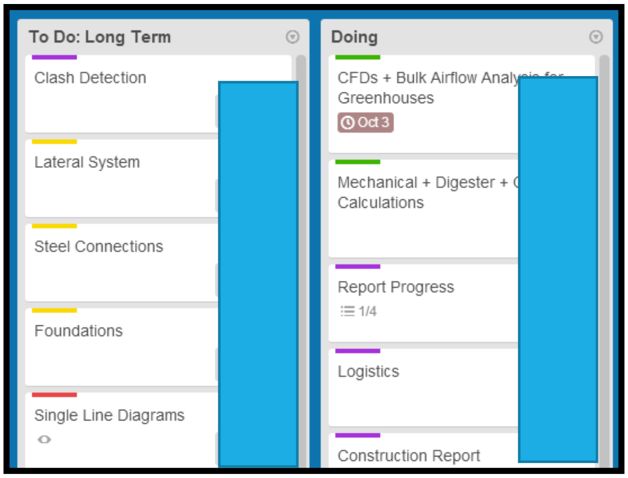


Figure S1: Trello Card

Collaboration Board – As a team, we also created a hard copy sticky note version of Trello in order to compliment the online platform. On the board, there are 3 sections: "I Need", "Questions For", and "I'm Working On." Each option (mechanical, structural, electrical, construction) writes their progress, questions, and needs on their respective card color and places it next to the appropriate section on the board. Other team members can then answer questions and see the needs of others each day when they come in to work. It also provided the team with the self satisfication of being able to throw a card away when the activity was completed.

Bluebeam - The entire Synthesis team utilized Bluebeam as a medium for communicating ideas and solutions. Bluebeam sessions were conducted to be able to collaborate and convey ideas within our team. This tool allowed all members of the team to markup the same PDF either at the same time or during each team members' personal availability. With the use of these markups, an entire discussion could be had through a visual PDF in which each team member can visualize what is being talked about.

File Structure – The Synthesis team shared a folder on the school's network drive. Within this there was a folder structure that allowed each discipline to know where all of their respective information was stored. While the folder was organized by options, the entire Synthesis team had access to the folder and was able to add/edit/rename folders and files.

Work Environment – The Synthesis team was allotted a "Thesis Studio" room which measured about 300ft^2, and housed six computer work stations. The team was given free rein on how to configure and use the space. This room served as the main "office" for the Synthesis team, and served as a place for all eight team members to meet and converse. The small and close-nit atmosphere of the Synthesis office allowed for excellent utilization of knowledge sharing, constant communication between disciplines, and helped resolve minor coordination issues. The layout of the space can be related to that of 'co-location' spaces that are up and coming in the AEC industry. Due to the close quarters and easily adaptable space, team members could complete individual work, work in pairs, or meet and work as an entire team. This space enhanced and fostered a collaborative environment necessary for Synthesis to create the most educational, ecological, and adaptable building possible for Growing Power.

3D & 4D Visualization

This graphic in **[Appendix H]** represents the team's BIM Implementation Plan. This was created in the initial stages of design in order to help organize the software programs each discipline was using and to ensure that ultimately everything would be compatible. The initial design began in Revit where each option then took to their own respective software to analyze each system and make recommendations. Once the design and analysis was done within each software, the information learned was then translated back into Revit. The Revit model was then taken into Tekla BIMSight to run clash detection. Once all the clashes were rectified, the Revit files were used to produce final systems quantities, project drawings, and visuals. During the same time, the Revit file was taken into Synchro where a 4D model of our design was produced. This model was then utilized to produce the final project schedule and sequencing since it revealed things that were not apparent on the 2D drawings. As a team, Synthesis also decided to incorporate the site work into the 4D model in order to get a better picture of the entire site and how all components tie together to make the final product.

Research, Development, & Innovation

In order to meet the shared project goals Synthesis developed, innovative ideas and design solutions were researched, analyzed, and engineered (if they passed the go-no go decision making process). As a team, Synthesis began the design process by initially selecting engineering systems, then assessing and optimizing the architecture to meet these systems. With regards to each system, the process went as follows:

An innovative design solution would be formulated and the concept was then researched and presented back to the entire Synthesis team. Using the knowledge learned through research, the prospective design solution was run through a decision matrix, fostering a Go/No-Go decision. The Go/No-Go decision was determined by the decision matrix results and a team discussion of the idea's effects on the other building systems. If the new design solution passed, it was then handed over to the respective discipline and engineered into the design.

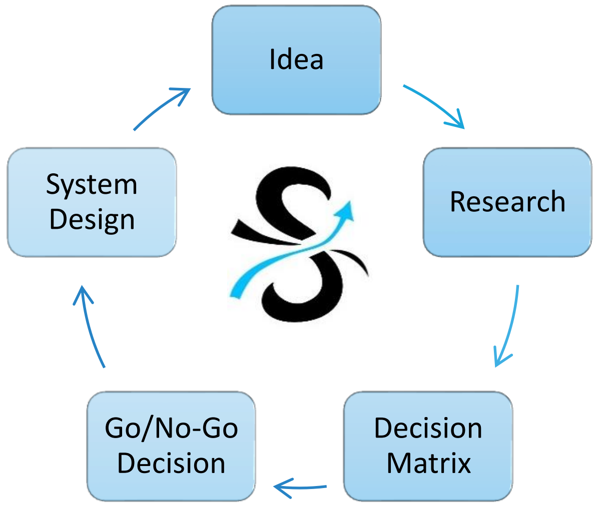


Figure S2: Design Process Diagram

Decision Making

A decision matrix allowed Synthesis to decide which ideas, concepts, and prospective design solutions were fit for the project. The matrix helped remove the "human factor" by utilizing a point system to ensure that every decision kept the Synthesis design goals at the forefront of the discussion.

The matrix utilizes a three point scale and a weighted score assigned to the relative importance of each design criteria. A score of +1 means that the proposed solution helps or improves that category, a score of 0 is neutral, and a score of -1 indicates that the proposed solution negatively effects that design goal or criteria. A weighting of 5 was given to each of the three major project goals (educational, ecological, and adaptable), then the relative importance of the five other goals are weighted accordingly. The total score of the proposed solution was compared to the total score of not implementing that solution or the existing system; the larger total score was deemed the best solution. An example of this matrix is shown in **Figure S3**, detailing the decision behind locating the anaerobic digester inside or outside of the building.

Decision Comparison		Inside	Outside
Criteria	**Wt.**		
Learning Experience/Environment	5.0	-1	+1
Design Adaptability	5.0	+1	0
Self-Sustaining Ecosystem	5.0	0	0
Lifecycle Cost	4.0	0	0
Ease of Constructability	3.0	0	+1
Durability	2.0	+1	0
Maintenance	2.0	-1	+1
LEED Potential	1.0	0	0
Weighted Scores		0.0	**10.0**

Figure S3: Decision Matrix

The decision criteria scores reflect the overall thoughts of the Synthesis team. The group believed that locating the digester outside of the building lends itself to a better learning experience for visitors (thus the score of +1) rather than being inaccessible to students and visitors when located in the basement of the building (score of -1). It takes a specific site layout for the digester to be outside, and not every site will be the same, therefore keeping the digester inside the building actually makes the building design more adaptable. Due to its enormous size, it was decided that placing the digester outside would be much easier to construct than if it were located inside the building. However, placing the digester outside exposes it to the elements of Wisconsin weather and makes it less durable than if it were inside. This being said, it is much easier to access, service, and maintain if it is outside of the building rather than tucked away in the basement. All of these types of factors and decisions were weighed in the Synthesis decision matrix above. The matrix was used in conjunction with practical group discussions to make the final decision to move forward with locating the anaerobic digester outside of the building.

Cost, Budget, & Lifecycle Analysis

With innovative design goals, Synthesis approached each new idea with cost in mind. A balance was established between upfront cost, lifecycle cost, and building efficiency. As ideas were produced by the project team, the construction engineers analyzed how much the different ideas and systems would cost and how they should be considered in the Go-No Go decision. Inherently, by creating an innovative and adaptable design, Synthesis understood that some of the systems that were investigated would cost more than traditional ones. A variety of methods were set in place to effectively evaluate the true cost and value of these systems:

Lifecycle Analysis - Traditional payback analysis over the course of a system or design solution's life span.

Limiting Construction Costs – Utilizing innovative construction methods and techniques to install specific systems and help justify initial upfront costs.

Possible Supplemental Funds - Due to the overall shared project goals and considering the building as a living entity, the Synthesis team felt it was appropriate to consider these impacts and not focus solely on the budget. After realizing these innovative design ideas would place the team over budget, it was decided to research alternative funding methods. One source of funding found by the team was through Focusonenergy.com. Using the online worksheet available, Synthesis has created a spreadsheet to illustrate the amount of funding that can be received for the implementation of the designs on the Vertical Farm project. This spreadsheet can be found in Appendix C of the **[Construction Report]**.

After the initial budget is long gone and the building has been constructed, Growing Power will operate this facility while simultaneously deciding where, when, and how to build similar vertical farms. By performing these analyses, Synthesis has provided the Growing Power organization the means to make informed, big picture decisions as they pioneer the urban and vertical farming industry.

Scheduling, Deadlines, & Documentation

Synthesis not only had to meet competition deadlines but also internal project benchmarks established at the start of the design. By maintaining a schedule and utilizing collaboration tools on a daily basis, the team was able to create a thorough design on a tight schedule. The Synthesis Construction Engineers lead the scheduling front and determined design deadlines by utilizing a pull scheduling technique.

Design Deadlines - By starting at the end of our schedule (submission to AEI), Synthesis worked backwards to determine when each item needed to be complete in order to meet this deadline. From the final deadline date moving backwards, Synthesis first accounted for the final report formatting and visual creation. Time was then allotted for final detailed estimates and sequencing. Before that, the design of all systems had to be complete (which we set to be done by December 1, 2014). From there, deliverables were divided by discipline as each contains different components. All of these preliminary deliverables were driven by when other disciplines needed items. These transferred deliverables were coordinated using the Collaboration Board and Trello along with other communication and coordination methods previously discussed. Setting these dates as goals from the project start aided the Synthesis team to be able to work together to meet both internal and external deadlines crucial to the project's success.

Front Loaded Design Schedule - The Synthesis team understands the importance of controlling cost, not only in construction, but in design and during operation. Traditionally, a building is designed and constructed using the model shown in **Figure S4**, where the most amount of effort is expended during the construction document phase.

This is because architects and engineers usually only have small teams actually "design" the building and systems, and then gain personnel as the process moves into design development and construction documents. By the time the team is in the construction documents phase, the ability to make changes is much more difficult than when in schematic design and design development. As shown by the two cost curves (**Figure S4)**, it is also much more costly to make changes later in design because the entire team is affected and must redesign their respective systems.

Due to the fact that the entire Synthesis integrated design team was on board from the very beginning, the team elected to shift the traditional design process forward, "front loading" the design. In this model, shown in **Figure S5**, a stronger emphasis is placed on early programing, schematic design, and design development in order to make as many big changes to the project as early on as possible.

Along with the cost and time savings associated with not redesigning due to changes later in design, the Synthesis team needed to conduct more initial research and development than in a traditional project. Many of the Synthesis team members had never worked with a greenhouse design before, therefore in the initial stages of design, strong emphasis was placed on learning about how greenhouses were typically designed, constructed, and operated. This upfront effort added to the adoption of a front loaded design process in order for the Synthesis team to successfully deliver a building that meets all of Growing Power's needs.

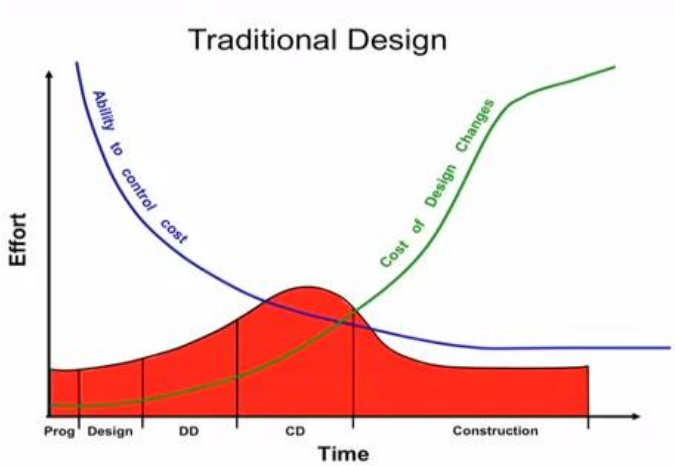


Figure S4: Traditional Design

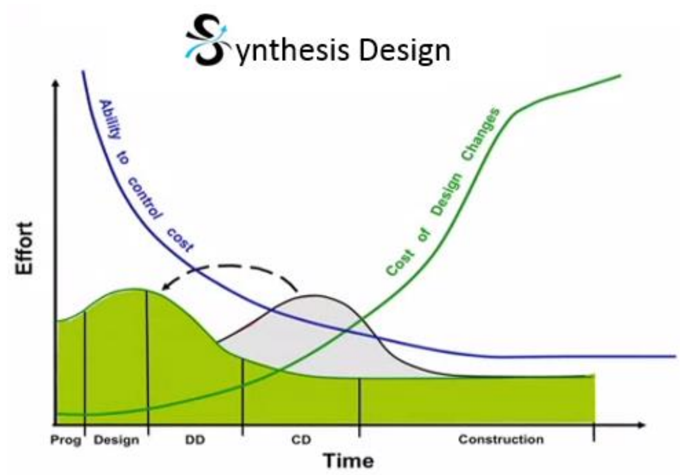


Figure S5: Synthesis Front Loaded Design
https://www.youtube.com/watch?v=9bUlBYc_GI4 Accessed September 15, 2015

5.0 Architectural optimization

Concept & Overview

With a front-loaded design schedule, the Synthesis design team was able to spend more time in the initial stages of design, exploring a variety of big ideas and overall building concepts. Initially, the original architecture of the building provided by TKWA was used as the architecture for the Vertical Farm, and was roughly modeled in Revit exactly as the competition provided plans indicated.

From this point, the construction, structural, mechanical, and electrical engineers began to research and explore their own respective solutions for the Vertical Farm. As a team, ideas and concepts were shared, but for the most part during this initial stage of schematic design, the disciplines were free to explore solutions on their own. It was then discovered that each discipline had an entirely different understanding of what the Vertical Farm was and how it should be designed and constructed.

Each discipline presented their schematic designs to the entire team and decisions were weighed in the decision matrix. It came to a point where there were so many solutions that aligned with the shared project goals that they began to contradict one another as they applied to the existing architecture. There was a unified belief throughout the entire Synthesis team that these innovative engineering solutions were a stronger representation of the overall project goals than the existing physical architecture of the Vertical Farm. These ideas manifested in the form of four major engineering components:

Modular Greenhouse Design

Natural HVAC System

Growing Power as an Ecosystem

Building Enclosure

Synthesis realized the best way to meet the overall project goals was not only for the engineering components to enhance the architecture, but for the architecture to enhance the engineering components. The entire Synthesis team helped redesign the architecture of the Vertical Farm while still preserving the general special layouts and floor to floor functions. Throughout this process the team developed a full understanding of how Growing Power planned to use the building and how each engineering system complimented one other. The redesigned building maintained the same program spaces as well as their original square footages. Visit **[Drawing A100-A105]** to see the updated architectural floor plans.

6.0 Greenhouse Design

In order to create a greenhouse which optimizes plant growth, Synthesis first gained an understanding of photosynthesis and plant physiology down to the cell level. Knowledge of how plants grow and develop allowed Synthesis to critically examine the complex and changeable relationship between plants and their environment. This research allowed the team to compile an interdisciplinary matrix of design criteria for optimal growing conditions.

The team studied successful greenhouse concepts used in various regions of the world. Combining these solutions, synthesis developed a single greenhouse design capable of functioning efficiently and effectively in multiple climates. The final design is shown **in Figure S6.** A detailed explanation of the transition from the original greenhouses to the Synthesis greenhouses can be found in **[Appendix J]**

Each tiered greenhouse is comprised of six identical greenhouse “modules” that connect side to side to create the overall greenhouse for that floor. A modular greenhouse design was designed for constructability purposes as well as enabling entire building adaptability to other site locations.

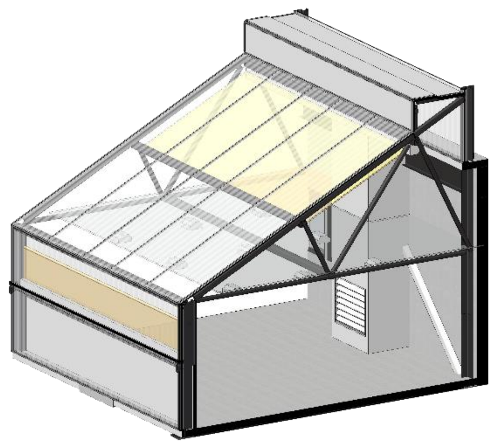


Figure S6: Rendering of one Greenhouse Module

These modules will be constructed on site, but each piece of the greenhouse module will be delivered to site prefabricated for the size/shape necessary. This eliminates construction waste for the greenhouses in terms of exterior enclosure. The steel inside each greenhouse is erected level by level along with the rest of the building. After steel erection is complete, the façade system (precast concrete and polycarbonate) will be erected. Once the polycarbonate is complete and the building is weather-tight the CMU walls within the greenhouse will then be constructed. After the CMU walls, the horizontal polycarbonate and all interior pieces will be completed for the greenhouse portion of the building.

Closed System - Unlike typical greenhouses, the module system is designed as a “closed system” – meaning there is no outside air that enters the greenhouse. This closed system gives four main advantages to Growing Power:

1. *Reduced water usage* – Plants continually transpire and lose water greenhouse design prevents water from escaping and allows for the collection of all condensation produced.
2. *Increased CO_2 concentration* - Enriched CO_2 concentrations produced are controlled and preserved in a closed greenhouse.
3. *Pest control* – Pests are major sources of plant diseases in greenhouses. The closed greenhouse prevents them from entering, thus eliminating the need for pesticides.
4. *Temperature and humidity control* – Greenhouses are normally cooled through ventilation and evaporation. This presents a problem for hot and humid climates, such as Miami where there is minimal potential for evaporative cooling. A closed greenhouse allows temperature and humidity set points to be maintained in any climate.

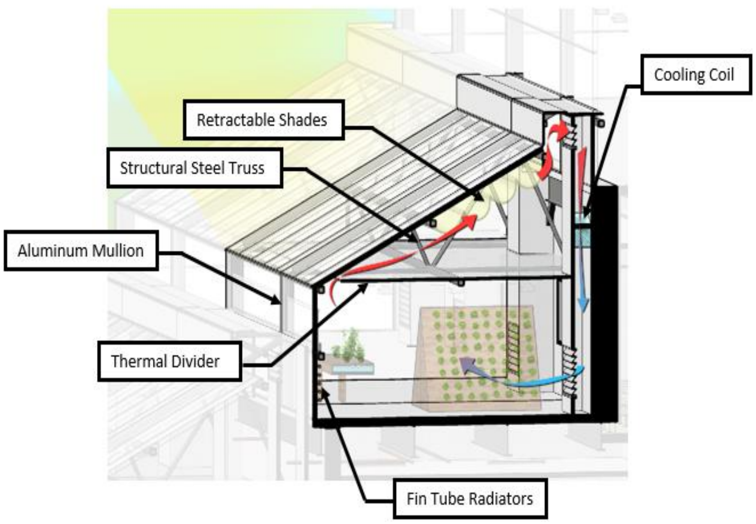


Figure S7: Greenhouse Module Cooling

Natural Cooling - In order to cool, condition, and create adequate air flow inside the closed module, a natural convection system was designed. The system works by creating two separate thermal zones in each module: a supply zone and a return zone. They are separated by a clear plastic thermal separator, otherwise known as a continuous clear polycarbonate panel. A mechanical shaft in the rear (North wall) of each module houses a cold water heat exchanger that is responsible for cooling and conditioning the air from the return zone back to the desired temperature inside the supply zone. The suns energy heats the return zone throughout the day which causes natural convection of rising hot air and falling cool air to drive the closed system inside each module. **[Figure S7]** illustrates this process. Each heat exchanger shaft covers the area of one module. It should be noted that each module is constructed side to side without a physical wall separating them, except for the two modules on either end of each greenhouse. Please also reference the **[Mechanical Report, Section: 5.0]** for further explanation of the natural cooling inside the greenhouse.

Dimensions – Much of the module's physical design derived from the capabilities/limitations of the mechanical shaft. The module depth (North – South direction) is 19'-2" and was determined by how "far" the 2' deep x 4' wide mechanical shaft could throw the air into the space. The width of the module (East-West direction) is 19'-2", which corresponds to exactly one half of a structural bay (38'-4") for the entire building. This is significant if, in the future, Growing Power selects a site for an additional Vertical Farm with more southern facing real estate than in Milwaukee. Instead of spending time and money to redesign the building to include longer southern facing greenhouses, the adaptable Synthesis design can be used again. The Vertical Farm (and south facing greenhouses) can be easily extended by simply adding one structural bay and two greenhouse modules to the building. This modification would increase the greenhouse areas by 33% (2 modules have been added, there were 6 to start). This process can be repeated a number of times depending upon the existing site conditions of the next Vertical Farm. The Synthesis mechanical team collaborated with the structural team to ensure that the conditioned air from the central shaft would cover the width of each module.

Structure – Each module consists of two structural steel truss supports on either side of the module (spaced 19'-2"). A decision was made during design to use slightly larger members and only include two trusses per module rather than using 4 small membered trusses. The lighting team worked closely with structure to ensure that the trusses would not create significant shading issues for the plants.

Polycarbonate Panels - The greenhouse glazing was determined by the Synthesis structural and lighting team, however all disciplines played a role in the implementation of the panels and mullion system for each module. A light weight material was desired when considering wind loads for the next Vertical Farm possibly located in Miami, FL, a region traditionally known for high hurricane winds and loads. The exact material and properties was determined by the lighting group who conducted an in depth study on the glazing system.

Plants use a different spectral distribution of light than humans see. The useful light that plants absorb is known as photosynthetically active radiation (PAR) while the useful region of light that humans see is known as the visual spectrum. Manufacturers of glazing materials only give transmittance values (how much light gets through) in terms of visual transmittance because that is what people see. This is not the case for plants, therefore Synthesis' lighting/electrical team developed a method to calculate the PAR transmittance of materials in order to select the most efficient polycarbonate panel. Please see the **[Lighting/Electrical Report: Section 5.0]** for a more detailed explanation of PAR transmittance and optimizing the glazing.

Panel Layout – The Synthesis team worked with a local Milwaukee distributor of the *Makrolon multi UV 5M/25-20* polycarbonate panels manufactured by *Bayer MaterialScience* in order to determine the best way to layout the panels on each greenhouse module. It was important for Synthesis to design the panel layout for each greenhouse module opposed to designing for each entire greenhouse in order to preserve the adaptable design capabilities; therefore nothing, including the panel layouts, would need to change if more modules were added to the next Vertical Farm. Because the panels are 25mm thick the panels can span up to 24' x 4'. Working with the distributor, Synthesis recognized that there was no charge for cutting the panel in the 24' direction; meaning the contractor would be charged for the exact length. However, in the 4' direction, there is a fixed charge and panel sizes of less than 4' wide would generate waste (which was factored into the detailed estimate and budget). The construction team helped generate the constraints of the panel layout while the entire team helped to lay out the panel system in order to minimize waste and also minimizing steel mullions that support the panels. Please see **[Drawing A108]** for a detailed description of the panel layouts for the greenhouse modules.

Condensation Collection – As plants live and grow, they transpire water to their surroundings. Because the Vertical Farm plants live in a closed greenhouse environment, their transpiration will compound throughout the day, ultimately causing the humidity to rise. In a normal greenhouse, that humidity is dealt with by ventilating the space with outdoor air. However, in the closed environment, the humidity will rise and condensation will occur first on the coldest surface in the greenhouse module. In the summer that surface will be the heat exchanger shaft in the rear of the module. A drip tray is located at the bottom of the mechanical shaft in order to control and collect this condensation to reuse as graywater in the rest of building. In the winter the same issue arises, however the mechanical shaft is no longer the coldest surface in the space - the south facing vertical glazing is because it is exposed to the cool temperatures of the Milwaukee winter. This causes a problem because there is a larger surface area that collects condensation, thus making it more difficult to control and collect. In order to combat this, a special cold bridge mullion has been designed that utilizes a steel structural gasket that is exposed to both the outside and inside of the greenhouse. Because steel is a better conductor than polycarbonate, the steel cold bridge mullion will be the coldest surface in the winter, thus creating a more controlled approach to collecting condensation in the greenhouse. There will be one allocated cold bridge mullion per module, while the rest of the steel mullions will be using the flush glazing technique and will only occur on the inside of the polycarbonate. See **[Mechanical Report: Section: 5.0]** to read more about gray water collection.

Supplemental Grow Lighting – Grow lighting is used to supplement daylight delivered to the crops being grown in the greenhouses. There are nine 325 watt *Lumigrow* fixtures per greenhouse module that are spaced 6' apart on center. The grow lights hang

7.0 Natural HVAC System

Concept and Overview

Synthesis determined early on that Growing Power would be a truly special client to work with. Synthesis adopted Growing Power's dedication to the community and sustainable practices when idealizing potential engineering solutions. Synthesis determined that strict indoor temperature set points do not necessarily need to be met exactly, and that slight variations in indoor comfort conditions would be acceptable (+ or – 2°F). This design philosophy allowed Synthesis to explore creative, passive mechanical solutions.

Synthesis defines Natural HVAC as a mechanical system in which airflow is driven by the wind, sun, and thermal buoyancy as opposed to electric fans. The system is designed to supply conditioned 100% outdoor air to floors two through four, 365 days a year. This is accomplished through the use of passive downdraft cooling, and passive updraft heating. These systems funnel air into an underfloor utility plenum from which it is distributed to occupied zones. Implementing these systems proved to be a challenging multidisciplinary effort, with wide-ranging implications.

Architectural Optimization

Since the entire roof area of the building is fitted with greenhouses, supply shafts and the solar chimney are required to be attached to the façade. They must also extend above the roof in order to catch the wind without being blocked by the building. The ideal location for the shafts is the northern façade, to avoid shading the upper greenhouses; however, a key component of the Natural HVAC system is to minimize the distance between the supply shafts and the solar chimney. The proportions of the original building would require the air to travel a total of 246 feet if the supply shafts and solar chimney were attached to the northern façade.

Reducing this air travel distance was a major consideration for Synthesis when optimizing the architecture. The building was widened in the East-West direction, and shortened in the North-South Direction. This change allowed for less greenhouse shading, more usable space receiving daylight, and reduced the Natural HVAC air travel distance by 44%. The mixed-use nature of the Vertical Farm renders certain spaces on each floor ill-suited for underfloor air distribution. Floors two through four contain restrooms, greenhouses, and mechanical/electrical rooms which require a raised slab. During the architectural optimization phase, great care was taken to group rooms to be served by the natural HVAC system together, creating a clean separation between the differing slab heights for each floor.

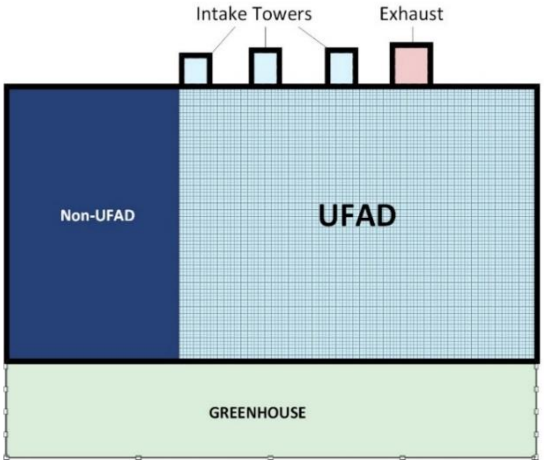


Figure S8: UFAD Separation Diagram

Utility Plenum Coordination

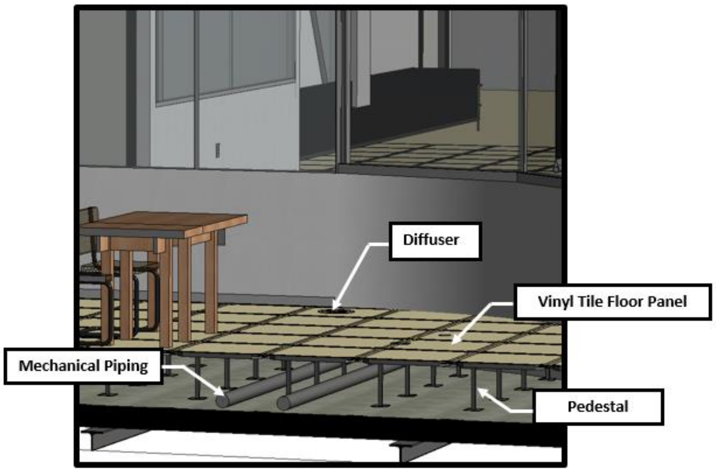


Figure S9: UFAD Breakdown

A major concern with underfloor air distribution is the potential for any leakage and entrainment of particles in the utility plenum. This is important for the construction engineers to ensure that construction of the plenum is tight and done correctly. Besides tight construction, another way Synthesis is combatting these possible issues is by utilizing linoleum tiles that will be placed on top of the Utility Plenums (depiction shown below). Due to the fact that these tiles are staggered on the grid, it helps to prevent air leakage and the possibility of particles falling into the under floor plenum. This system also allows for the tiles to be replaced easily providing easy maintenance and repair for Growing Power throughout the building's life.

Synthesis determined that certain program spaces within the building such the greenhouses, restrooms, mechanical spaces, and corridors between the elevator and greenhouses would not be conducive to a raised floor system due to concerns about dirt, spills, and heavy loads. When optimizing the architecture, Synthesis grouped together all rooms served by the underfloor utility plenum, and all rooms not served in order to best utilize the underfloor plenum without hurting the building's performance requirements.

In order to ensure uniform floor heights throughout the building, two slabs, poured at different heights were used for the floors that contain utility plenums. The termination of the utility plenum was coordinated to end in line with the structural grid, allowing for deep beam to girder connections to account for the elevation change.

The challenge with the two different floor elevations was obtaining a uniform diaphragm action across the entire floor. Many disciplines were explored to overcome this challenge,

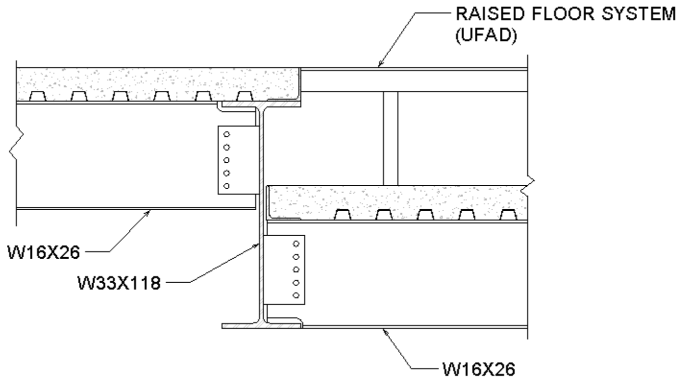


Figure S9: UFAD Floor Transition

such as double beams at the step, offsetting one beam, and placing kickers to tie the two diaphragms together, as illustrated in **Figure S9**. Ultimately it was decided to proceed with a deep beam which allowed us to obtain full diaphragm action, as well as being the most cost effective solution.

The inclusion of the underfloor plenum reduced the space requirements for the Ceiling Plenum, leading to opportunities to reduce floor-to-floor heights. Reducing the floor to floor heights allowed us to reduce the total steel required in the building (by decreasing the total loads) and to have an easier building to construct. The lower floor to floor height reduced the ladder size that would have originally be needed to install any items run under the slab of the floor above.

Reducing the floor-to-floor heights required significant coordination between the Mechanical and Structural Engineers. The natural HVAC system designed by the Mechanical team requires low air velocities and low pressure drops throughout.

8.0 Growing Power Ecosystem

Many urban areas face a problem with the absence of available fresh produce and healthy, affordable food choices in local neighborhoods. Growing Power is taking action to revolutionize local communities within these food deserts by providing high-quality, healthy, and affordable food for residents.

When designing a building that produces food for the community, it is important to understand naturally occurring agricultural ecosystems. Traditionally, plants live and grow in soil, bearing fruits and vegetables each season. Once these plants die, their remains break down and fertilize the very soil in which they once thrived. The fertile soil serves as an excellent ground for new seedlings to sprout and begin the cycle over again, thus creating a prosperous self-sustaining ecosystem.

Figure S10: Ecosystem Diagram

Growing Power is an ecosystem within the community. They currently import local food waste for composting soil and fertilizer. In the Patterns developed by TKWA (architects who provided the competition approved drawings) it was expressed that Growing Power wanted to mimic the natural cycle of food production, using food waste as a fuel source for onsite energy production. Tipping fees that are assessed and charged by Growing Power will be less than the local landfill in order to provide a financial incentive for local businesses to participate. This energy is directly used to power the Vertical Farm, ultimately providing the community with food. This establishes Growing Power an integral part of the local ecosystem

Food waste is delivered to a plug-flow mesophilic anaerobic digester resulting in the production of usable biogas that is combusted in a 200 kW microturbine. Liquid and solid fertilizer is also produced and is harvested for composting nutrient rich soil at existing Growing Power sites to be sold to the local community.

Quad-Generation

The biogas produced from anaerobic digestion is pretreated then combusted in a 200 kW microturbine resulting in the co-production of:

1. Electricity
2. Heating
3. Cooling
4. Carbon Dioxide

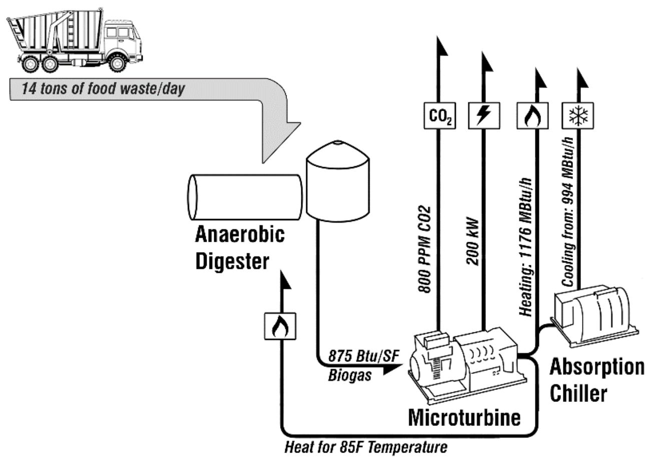


Figure S11: Quad-Generation Scheme

Electricity

The maximum power produced from the microturbine is 200kW. This is able to meet the peak electrical demand on any given day of the year. Excess electricity that is produced is sold back to the power grid or can be used to power the existing greenhouses at the building site.

It is important to the Quad-Generation scheme that the microturbine stays up and running at all times. Therefore, the emergency power for the building will be in the form of natural gas. If biogas ever becomes unavailable the fuel source for the microturbine will switch from biogas to utility natural gas. This is a deemed a reliable emergency fuel source by the local jurisdiction because pipeline interruption is highly unlikely. The microturbine is designed specifically for this application and has two fuel source inputs.

Heating

The microturbine produces 1350 MBH of exhaust heat which is transferred to a hot water loop by an exhaust gas heat exchanger. The hot water loop is heated to 180°F to be used for comfort heating, domestic hot water, and as a heat source for an absorption chiller.

Cooling

The hot water loop will provide the heat source for a 60 ton single effect absorption chiller. This absorption chiller will produce a lower than typical supply temperature of 40°F chilled water in order to reduce airside pressure drops for the natural HVAC system. Heat is rejected from the absorption chiller to an open loop geothermal system.

Carbon Dioxide

Carbon dioxide is vital for plant growth and production in the photosynthesis process. Plants require carbon dioxide as humans require oxygen. The carbon dioxide concentration in the atmosphere ranges from 350-400 ppm.[1] By artificially raising the CO_2 concentration around plants to 1000 ppm, crop outputs increase by 40%. This concept was applied to the Vertical Farm greenhouses by utilizing the carbon dioxide produced from the microturbine.

4.2 Site Layout

The Growing Power, Milwaukee site is pictured in **Figure S4** above. The footprint of the Vertical Farm, along with all other site logistics was coordinated with the entire Synthesis team. The following considerations applied:

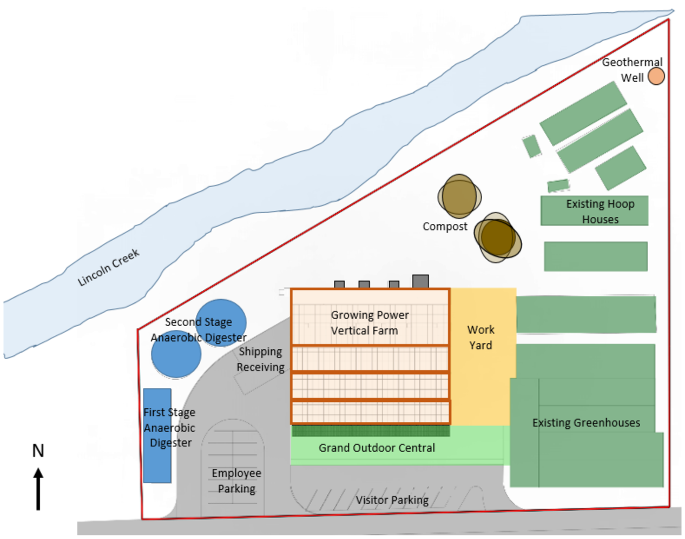


Figure S11: Site Plan

Building Location – The building has been located to the west of the Growing Power existing facilities. The location works well with respect to the existing greenhouses on site because it is set as far back (north) on the site as possible and eliminates shading.

Grand Outdoor Central – Located directly in front of the Vertical Farm sits the Grand Outdoor Central. This area was important for Growing Power to have a green grass gathering space for large groups like field trips and tours in the summer.

It also serves as an area for Growing Power to communicate new ideas and concepts to the community.

Work Yard - The work yard lies between the existing facilities and the new Vertical Farm. This area is a concrete work space for growing worms and other messy operations. The concrete topping and placement of the work yard creates a good buffer for anticipated high traffic between the new farm and the existing facilities.

Loading Dock, Parking , Digester, Wells - The Geothermal Well delivers constant cold water to the chilled water loop in the system. The water is used to help cool the absorption chiller and other mechanical applications. The warmer water is then rejected into Lincoln Creek. Per the building code that Milwaukee has adopted (IBC 2009) the digester needs to be 250 feet from the underground wells to prevent any chance of water contamination. In order to meet this code requirement, it was clear that the two items needed to be on opposite ends of the site. Due to this requirement, the team placed the underground wells in the northeast corner of the site and preliminarily placed the digester on the west side of the site. The next item was the loading dock and truck turnaround required for delivery movement along the site. Once those turnaround angles were drawn, the team developed the parking area to fit within the space provided along the building's front and west facades. This left the team with the space in the northwestern corner (along the site line) to place the digester. It is also important to note that the digester was placed in the configuration shown to allow for dump trucks to be able to deposit the waste into the digester without interrupting traffic flow.

60/40 Request - The Synthesis team composed the Growing Power site while maintaining the principal of 60/40 requested by the owner. This means that 60% of the site is utilized for growing while 40% can be paved. Ultimately, the Synthesis proposal for the Growing Power site is composed of 73% growing and 27% pavement, without taking the growth within the building into account.

9.0 Building Enclosure

To meet the goals of Synthesis and the owner of Growing Power, the main focus of the structural team was developing an adaptable structural system that was capable of being implemented throughout the United States with minimal changes. With this goal in mind, a composite steel super-structure with moment and eccentrically braced frames for lateral resistance was chosen after considering the implications on all of the other design disciplines at Synthesis.

By using a steel super-structure, the building's architecture was allowed more freedom, with the reduction of columns and imposing structure within the interior space. The larger bay sizes allowed the structural team to eliminate the original column line that ran directly through the gathering space. The EBFs were closely coordinated with the architecture to appear within existing walls when available. When braced frames were not able to be used in areas such as the gathering space, moment frames were implemented to eliminate any obstructions.

With a steel superstructure, the schedule of construction was expedited. The structural design of the building was optimized to created uniform bay sizes with similar member sizes and connections for many of the beams, creating a more constructible building. The building could be constructed faster due to the elimination of curing time of the concrete members.

In the greenhouses, a steel structure limited the size of the members to smaller shapes. By doing this, less natural sunlight would be blocked from the crops below, allowing increased production within these spaces.

A composite steel superstructure also, was beneficial for the mechanical team at Synthesis due to the reduced member sizes within the building. By restricting the structural beam depth to 16 inches in the UFAD section of the building, the ceiling plenum sizes were optimized, leaving ample space for the return air to travel under the beams and out of the building.

On top of the benefits for the other design teams at Synthesis, steel created a building that is adaptable to move throughout the country. Due to steel being a relatively light weight structural system compared to other systems, the buildings seismic loads in high seismic regions would be reduced due to a lower weight. Also, to deal with the building being moved seismic controlled regions, eccentrically braced frames were used due to their high response modification factor. The lightweight structure also reduced the sizes of the footings needed for areas like the Milwaukee site where the bearing soil is poor.

5.1 Foundation

One of the main concerns when designing the foundation system for the building was coming up with an innovative solution for the low bearing capacity of the soil, and the high water table. The provided geotechnical report for the site recommended spread and strip footings for the foundation system. After a preliminary analysis of the foundation loads on the building, it was determined that the spread footing system would not be sufficient to support the building.

Wanting to produce an efficient and cost effective solution to the foundation issue, the structural team consulted with the construction team on the best approach. Two methods were selected as solutions to the problem: a mat slab foundation, or a ground improvement system.

A mat slab system employed with a foundation wall perimeter would act as a “bathtub” and accommodate the high foundation loads, as well as the hydrostatic pressures on the building. While solving the issue structurally, the mat slab system would be costly, and delay the schedule.

A ground improvement system would allow the designers to increase the allowable bearing capacity of the soil, while increasing the schedule, and reducing costs. To account for the high water table, a French drain perimeter system used in addition to a duplex sump pump, would alleviate the high water table issues on site.

Consulting with the entire Synthesis team about the possible solutions, the mechanical team noted that they could use the ground water being pumped in through the pump in the basement for their grey water system, reducing potable water usage [**See Mechanical Report]**.

The design engineers conducted more research into Ground Improvement in order to ensure that soil modification was plausible. Through further analysis It was determined that that the GeoPier Rammed Aggregate Pier System would work to increase the bearing capacity of the site soil up to four times its original capacity **[Structural Report: Section 12.3]**.

By implementing this GeoPier system, the cost of the foundation was able to decrease greatly and efficiently support the building loads. The cost for soil improvement was relatively low for the amount of money that could be saved by decreasing the footing sizes by a significant amount.

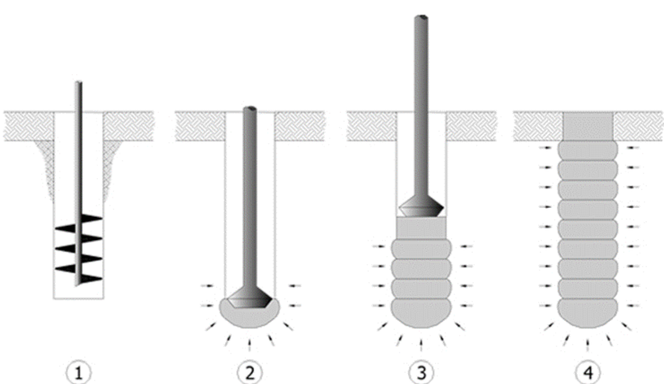


Figure S12: Construction Process of Geopiers

Geopiers use natural, local aggregate and often reclaimed aggregates such as glass of concrete, providing a sustainable and environmentally friendly solution.

5.2 Building Facade

Requirements – The first step in selecting a façade system for the east, west, and north faces of the building consisted of Synthesis outlining the requirements desired to assist in the efficiency of the Milwaukee building and the building as a prototype. These requirements are as follows:

- Durability characteristics
- Thermal resistance properties
- Aesthetic appeal
- Prevention Through Design opportunities

Solution Process – The design teams wanted to maintain the original precast façade, but required a higher thermal resistance. The result was a precast sandwich panel system consisting of three inches of structural concrete on the interior face, three inches of rigid insulation in the middle, and three inches of architectural concrete on the exterior face as shown in **Figure S13 below.**

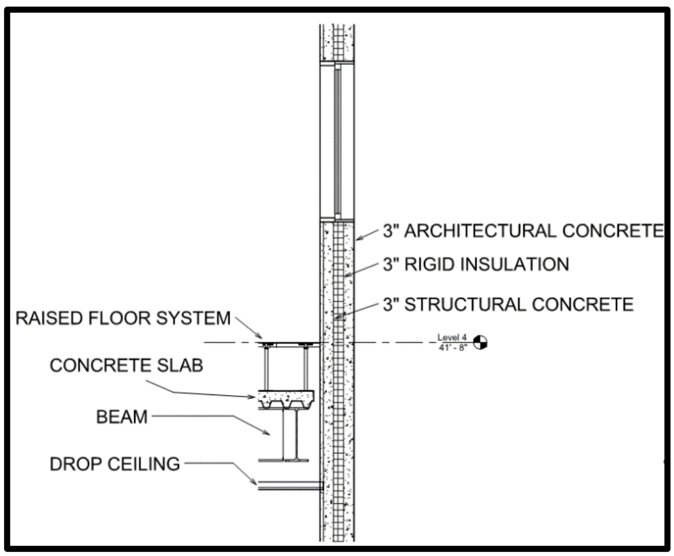


Figure S13: Facade Panel Detail

The panel system utilizes an overall U-value of 0.052. The city of Milwaukee, WI is located in ASHRAE climate zone 6. Table XX below describes the different components and recommendations associated with each item of the building envelope. One way to help minimize cooling and heating loads in the Growing Power Vertical Farm is to increase the Resistance value (R-value) of the building envelope.

Table S1: Recommended R Values for Climate Zone 6

Item	R-Value
Roofs	30
Walls	19
Floors	38

Through consultation with a precast plant in the area, the designers developed an original layout using panels of 12 feet wide and spanning floor-to-floor (14'-4"). The Construction Engineers saw the opportunity to use Prevention through Design by using the panels as Fall Protection during the construction process. This was found to be more beneficial than having the structural system prefabricated for the installation of temporary railings.

After further discussion between the Structural and Construction Engineers, it was determined that using 12-foot wide panels required transportation difficulties that could be avoided by using a smaller panel width. As a result, the panels were developed based on the structural connections required for each panel to be able to resist loading until the building enclosure was completed; therefore, they are 10 feet wide and span two floors (28 feet) – as seen in Figure X.

The Construction Engineers determined the panels could be formed in a nearby precast plant and shipments could be sequenced to maximize the installation process. The panels also provided the opportunity for the Prevention Through Design concept to be implemented. To save time and money, the panels will become the fall protection during the construction process. The schedule has been sequenced to allow for the panels to be installed after the superstructure; therefore, the only workers that will have to be tied off will be those installing the panels and the steel workers. The main concerns for the layout of the panels included window and door placement and the structural grid. The more repetitive the panels are, the lower the cost of forming them is; therefore, the team has produced a layout that optimizes the use of only a few varying panel form dimensions (see Appendix X).

Ultimately, Synthesis was able to integrate the façade system to cater all of the systems used in the Vertical Farm

The Synthesis lighting/electrical team needed to comply with the following codes to meet the guidelines of the project, and deliver a truly adaptable building:

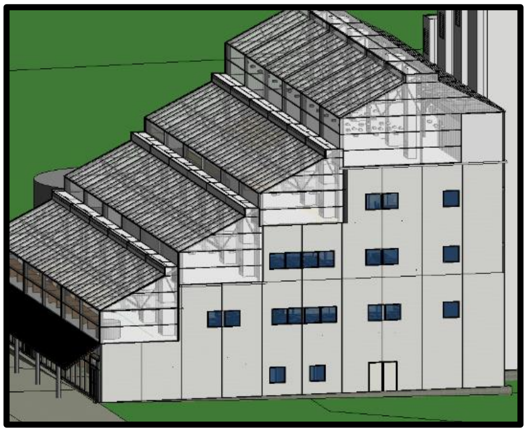


Figure S14: East Facade Panel Layout

10.0 Conclusion

Growing Power, Inc. and the entire Milwaukee local community will benefit from the implementation of the new Vertical Farm. From volunteers and employees working at the farm to community members receiving food, Growing Power's new Vertical Farm will touch everyone in the community.

Educational

Synthesis delievered an integrated design that not only educates Growing Power, but the community as well.

Ecological

The energy efficient Vertical Farm produces 108% more power than it actually uses, making it net zero and giving power back to the existing site and the grid. Without the entire team being on board with major building concepts from the beginning, this would not have been a possibility.

Adaptable

Through the use of Greenhouse Modules and a reversible Natural HVAC system, the Vertical Farm can function well in any environment.

Growing Power, Inc. will now have a Vertical Farm that will shape the future of Urban Farming as a whole.