# *Conservatory Addition for Aldus C. Higgins House Estate*

A Major Qualifying Project Report
Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science

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## Capstone Design Statement

The goal of this Major Qualifying Project is to develop a design concept to revitalize the Aldus C. Higgins House and surrounding gardens. This involved developing a structure that complements the existing estate, designing an appropriate structural system, modeling energy systems for energy efficiency, and providing insight into total costs and benefits for the proposed building.

This capstone experience offers a unique opportunity to immerse oneself in the realm of professional engineering while pursuing an undergraduate degree. Through this project, students have adeptly utilized their diverse coursework backgrounds to showcase competency within their respective curriculum domains:

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As a capstone design experience, this Major Qualifying Project involved structural analysis and design to size steel members used in a unique truss system that complements the design concept created. In addition, the project involved performing multiple energy analyses on the proposed building to reduce the total yearly energy use through the addition of various passive and active strategies. The project also included an approximate cost of the proposed building, including costs of materials, labor, and excavation, as well as an analysis of the different benefits the building could provide to the community.

In order to complete the various parts of the capstone project listed previously, multiple computer-aided design softwares and building codes were used in tandem. For the development of the structural system, the 2015 Edition of the International Building Code as well as the 9th Edition of the Massachusetts State Building Code were referenced for use in the structural software RISA 3-D. Once the structural system was defined, the rest of the proposed building was modeled in Revit and renders were executed in Lumion, and once again the International Building Code was referenced for means of egress as well as maximum building dimensions. Yes, the sentence could be streamlined for clarity and conciseness. For the energy analyses, DesignBuilder was used to analyze energy usage per square foot annually, guiding the selection of optimal windows, HVAC systems, and shading measures to reduce overall building energy consumption. For the cost analysis and cost estimate portion of the project the National Cost

Estimator software was used. A materials list was provided from the Revit model, and then translated into an Excel sheet that showed material lengths and quantities.

As this Major Qualifying Project was interdisciplinary, ample coordination between the architectural design engineers and the project management engineers was key. Architectural design engineers lead the conceptualization and modeling of the proposed building, meticulously incorporating structural systems and energy-efficient features. Subsequently, they provided the project management engineers with essential data, enabling them to conduct a comprehensive cost evaluation based on material schedules and drawing sets. Moreover, project management engineers contributed significantly during the conceptual design phase by compiling detailed benefits lists tailored to various building uses, such as cafes, study spaces, and greenhouses. This collaborative effort facilitated informed decision-making for the architectural design engineers in selecting the most suitable building type to pursue.

## Abstract

This project presents the design and costs of a four-season greenhouse-style conservatory which would be situated on the southwest portion of Higgins Lawn, adjacent to the gardens. The team developed a structural design, a preliminary energy analysis, cost estimates for materials and labor, and detailed renders that conform to building code. The team prioritized architectural and management engineering principles to seamlessly integrate the new structure with the existing landscape, while also strategically highlighting the conservatory's advantages for the university as a whole.

## Executive Summary

The Aldus Chapin Higgins House is a historical, Tudor revival mansion located on the campus of Worcester Polytechnic Institute. Once a home for Aldus Chapin Higgins and his wife Mary Sprague Green, the building was eventually donated to Worcester Polytechnic Institute in 1971. Over the past 50 years, the building has been used to house students, provide office space for multiple groups, as well as host an abundance of events for students, faculty, staff, and alumni. However, there has been a noticeable decline in the use of these various spaces, with many students stating that they have never been to Higgins House. With 29 rooms and expansive garden space, the historic estate boasts ample opportunity for the establishment of a new community-focused space, inviting more people to utilize the estate for local gatherings, events, and cultural activities.

The goal of this project was to revitalize Higgins House through the repurposing of existing spaces, either through renovation or new construction. This goal was met by exploring the benefits of implementing different types of spaces on Worcester Polytechnic Institute campus, surveying the area around and inside the estate, as well as researching various requirements for historical building construction. From this investigation the project team determined that a detached botanical conservatory installed on Higgins House lawn would be most beneficial and feasible, as it provided a new and interesting space that the WPI community could use. This structure meets standards for changes to historical spaces as set by historical preservation organizations, such as the National Parks Service.

To develop the conservatory, the project team surveyed the Higgins House estate and conducted research into supplementary uses of botanical conservatories as well as best choices as to plantings in the conservatory to determine size and height constraints. The next step was to develop conceptual models of potential buildings, which led to a plan for the finalized conservatory. The proposed plan included the following: a fully developed architectural model, a structural system design and analysis, a general energy analysis and subsequent design suggestions, a cost and benefit analysis, as well as a construction schedule timeline.

The proposed building would sit just southwest of Higgins House. It would be almost 100 feet long and 30 feet wide, for a total of just under 2700 square feet. The curved form of the building allows it to be more incorporated with the current gardens—through use of a front patio area—separate from the surrounding areas, although there are entrances and exits on both sides

of the building. Standing 30 feet tall, the building accommodates a wide variety of plants, with the largest including small trees. The building is also designed to mimic the style of Higgins House, with primary materials being stucco, reclaimed stone, and dark metal. The energy model revealed more key design elements for the proposed building, reducing overall energy usage, including operable windows in certain areas to promote natural ventilation. The glazing system is composed of a double-glazed, argon-filled, low-E coated glazing system with smart glass technologies to reduce solar radiation and control thermal comfort.

To meet code requirements for construction in Massachusetts, an arched truss system is recommended. Composition of the truss would be size 6x6x10 square tube steel for the exterior and interior chords with size 4x4x8 square tube steel for the webs is recommended. To support the building laterally, size 6x6x10 square tube steel purlins as well as 1-inch diameter steel cross bracing are recommended at specific locations. The individual trusses would sit 10-feet on center in order to adequately support the building loads. This layout also helped to minimize material costs for the building.

The budget for constructing the conservatory, encompassing materials, labor, and equipment, well surpasses $500,000. This initial estimate accounts for the primary categories yet omits significant expenses related to plumbing, HVAC, and electrical systems. Given these exclusions, the actual costs could significantly overshoot the anticipated budget. However, the benefits of establishing the conservatory extend far beyond its financial outlay, promising to transform the WPI environment profoundly. As a burgeoning educational epicenter for both the campus and external visitors, the conservatory is poised to enrich the student experience greatly. It will not only introduce a serene study space but also imbue the campus atmosphere with a sense of tranquility, thereby enhancing the overall well-being of the student body.

## Authorship

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# 1.0 Introduction

The Aldus Chapin Higgins House is a historic mansion located on the campus of Worcester Polytechnic Institute. Once a home for Aldus Chapin Higgins and his wife Mary Sprague Green, the building was eventually donated to Worcester Polytechnic Institute. Over the past 50 years, Higgins House has been used to house students, provide ample office space for multiple groups, as well as host events for students, faculty, staff, and alumni. Since the building was donated to the school, there has been a noticeable decrease in the use of the various spaces. In addition to that, much of the exterior of the building is in need of desperate repairs. With 29 rooms and expansive gardens, the historic estate boasts ample opportunity for the establishment of a botanical conservatory, giving new life to building and gardens as well as giving a reason to rehabilitate Higgins House.

# 2.0 Background

The following sections give insight into the 100 year history of Higgins House and its gardens, historical preservation and its importance, conservatory design and benefits, as well as cost factors that relate to the previously mentioned. Each section contributes information relevant to designing a conservatory on Higgins House grounds, thus giving new life to the various spaces in and around the building.

## 2.1 From 1923 to now: A History of Higgins House

Aldus Chapin Higgins (1872-1948) was the first son of Milton P. Higgins, the first superintendent of the Washburn Shops and founder of the Norton Company. Growing up in Worcester, Massachusetts, Higgins attended Worcester Polytechnic Institute, graduating 1893. Shortly after, he began his studies at the National University Law School in Washington, D.C.. Upon completing his schooling there and passing the Massachusetts bar, Higgins took a position at his father's company, being put in charge of the various patent and legal matters ("Aldus Chapin Higgins," 2023).

In 1921, Aldus Chapin Higgins commissioned a home alongside his second wife, Mary Sprague Green ("Aldus Chapin Higgins House", 2022). This building, now known as the Aldus Chapin Higgins House, is tucked away near the northwestern half of Worcester Polytechnic Institute's campus. While there is little direct information as to why Higgins chose this location, the proximity to his alma mater and Washburn Shops may have played a role in this decision. Higgins put notable architect of the time Grosvenor Atterbury completely in charge of the design, although it is rumored that Higgins provided many sketches and notes for the design of the building years before Atterbury joined the project ("Aldus Chapin Higgins House", 2022).

The building is a prime example of Revival period architecture in the city of Worcester. A partial replica of the c. 1525 Compton Wynyates in Warwickshire, England (Frongillo, 2023), the 2½ story building is best described as eclectic: the entrance is an octagonal tower, similar to that of a castle, with two roughly rectangular wings stretching out from it at right angles. If the floor plan was not odd enough, the building is adorned with a slew of mismatched, antique leaded casement windows, and many of its interior architectural features were taken from an Italian monastery ("Aldus Chapin Higgins House", 2022).

The gardens around the estate are a crucial element of the site. Atterbury wanted to create a dialogue between the exterior of the space and the interior and did so by the inclusion of various gardens in line with many of the main rooms in the building. Once stretching to where the current Rubin Campus Center resides, the gardens were divided into sections, displaying categories of plants popular in the 1920s and 1930s. There was a general garden section, a section for cuttings, and even one for topiary work: evergreen shrubs and trees that are trained to grow in stylized patterns or shapes (Pennoyer et al., 2009).

After the death of Higgins second wife, Mary Sprague Green, in 1971, the building was donated to Worcester Polytechnic under the conditions that it must be a space for only students, staff, faculty, and alumni to use. Throughout the rest of the 1970s and early 1980s, the space was used to house a plethora of undergraduate students (Frongillo, 2023). Since then, the building has become event space for various campus affairs, including club initiations, national conferences, and even wedding receptions, as well as office space for the Alumni Office, the Foundation Relations Office, and the Government & Community Relations Office. The newest renovation to the building happened in 2017: the Quorum, a café that serves only staff and faculty on campus (Frongillo, 2023).

## 2.2 Historical Preservation

Historical preservation is the act of protecting buildings, landscapes, or other artifacts of historical significance in order to keep the legacy they hold present in modern-day life ("What is Historic Preservation?", 2024). Much of historical preservation is driven by laws and regulations put in place at local, state, and federal levels so that these structures can have an equal chance of surviving for decades and decades to come.

To be considered a historical building, there are three main factors that are assessed: age, significance, and integrity. Age is arguably the easiest factor to evaluate, as to be a historical building the property must be at least 50 years old, although there are some exceptions. Integrity is a bit more subjective, with general assessments revolving around whether or not the structure looks similar to how it did in the past. The final factor, significance, deals with the importance of the structure. More specifically, the structure's past events and activities are examined to determine their impact on the past—the more influential the events and activities are, the more significant the building is ("How to List a Property", 2024).

Once registered as a historical building with the National Parks Service, any renovations or additions to the building must follow a strict set of guidelines. There are four types of these guidelines: preservation, rehabilitation, restoration, and reconstruction. These guidelines address both interior and exterior work on historic buildings and are very general with no discussion on exceptions or unusual conditions. The preservation guidelines include information about the processes necessary to upkeep the current form, materials, and integrity of the current building. The rehabilitation guidelines include information about transforming the building for a compatible use, through additions, repair, and other alterations. The restoration guidelines include information on reinstating the original form or features of the building, bringing it back to its original character by removing features from other periods and/or through reconstruction. The final set reconstruction guidelines includes information about how to properly depict the original forms and features of the building with modern materials through new construction ("The Secretary of the Interior's Standards for the Treatment of Historic Properties", 2023).

The process of adding an addition or even renovating historic buildings can be quite lengthy. In Worcester specifically, there is a process that includes research, reviews and assessments, public hearings, and permit approvals before the construction phase can even begin ("Planning & Regulatory Services", 2024). The research phase can vary in length depending on the complexity of the project, and usually includes researching various historic preservation guidelines both at the local and federal level. Once comprehensive plans are prepared, they are submitted to the Historical Commission, which notifies potentially affected members of the public. A hearing is then held to address any concerns raised by the community. Public notification for the hearing typically takes a month or more, but the hearing itself is usually relatively brief. If no major issues arise, the proposed construction can be approved, initiating the permitting phase.

Just like the public hearings phase, the permitting phase is usually on the longer side. In Worcester, specifically, completed plans for construction must strictly comply with preservation guidelines established by the Worcester Historical Commission ("Historical Commision", 2024) . Subsequently, public approval is required for construction to proceed and to obtain a historic preservation permit. This process can take anywhere from a few weeks to a few months, not to mention that a regular building permit must also be acquired.

### 2.2.1 Historical Preservation Efforts for Higgins House

While Higgins House is a historic building registered with the National Parks Service, there are little to no preservation efforts in regards to Higgins House or the rest of the property around it (the gardens, the Carriage House, etc.). However, in 2009, Worcester Polytechnic Institute contacted Hoffman Architects to discuss the potential of putting a building envelope condition assessment together . The school had noticed significant signs of deterioration throughout the facade as well as in the interior of the building, which included cracking, checking, a dry rot in many timber members in addition to visible efflorescence on many masonry sections. So, in early 2017, Hoffman Architects began their investigation of the building, noting all visible signs of wear in an 158 page document that would cost the school approximately $3,000,000 to fix (Hoffman Architects, 2017).

### 2.2.2 Cost of Historical Preservation

It's hard to provide a general cost estimate for historic preservation as each preservation project is different from the next. However, there are some general estimates for the breakdown of costs as well as for specific materials. For a typical historical preservation project, 60% of the total cost goes towards labor while the other 40% goes into materials. These materials include mostly custom pieces, seeing that many historical buildings didn't have access to mass produced, standardized doors, windows, and so on. Looking at custom windows, for example, prices can range from $400 to $4,000, depending on size, design, and frame materials. This is between 25% and 75% higher than standard windows (Jude, 2024).

Besides custom pieces, there are some rough estimates of structural and envelope repairs. If there's a need for waterproofing of the ground floors, costs range from $5 to $7 per square foot (Janine et al., 2022). If there is a need for removal of hazardous material, that can range from $5 to $20 per square foot of building area, but some historic restorations have been quoted up to $150 per square foot (Banks, 2024) without including preparation, equipment, and labor costs.

Regardless of the price, historical preservation with the goal of readapting the spaces more often than not ends up being slightly less expensive than completing a new build for the same uses. However, as mentioned previously, it is important to note that repurposing historic buildings through additions or renovations is a long and lengthy process due to the regulations put in place both federally and locally.

## 2.3 What is a Botanical Conservatory?

Not to be confused with a college for the study of music and other arts, a botanical conservatory is typically a glass-enclosed room that lets in abundant light, providing a comfortable space for its plants and all its visitors ("Conservatory," n.d.). It differs from a greenhouse as a conservatory is a place for the display of various fauna and flora, while a greenhouse's primary use is to grow these plants. In addition to that, conservatories have primarily been used for general living spaces, except in large scale cases like the Franklin Park Conservatory or Central Massachusetts' own Tower Hill Botanical Garden.

There is no one specific type of plant on display in a conservatory. Looking at the United States Botanical Garden, their conservatory houses tropical plants, like those native to Hawaii, as well as desert plants, such as cacti and succulents ("Gardens & Plants: Conservatory," n.d.). As it is a large-scale conservatory (28,944 square feet of growing space to be exact), the United States Botanical Garden is able to divide and condition the individual space within the conservatory to accommodate plants that thrive in different climates ("Gardens & Plants: Conservatory," n.d.). For a smaller-scale conservatory, you could expect to see plants from different regions, however as they are usually in one room together, these conservatories have only plants that survive in similar climates. Tower Hill Botanical Garden has one of these smaller scale conservatories, with plants such as cycads, date palms, and lemon trees ("The Limonaia," n.d.).

### 2.3.1 Common Design Practices

There are a few general principles of conservatory design. In terms of location, conservatories should avoid shaded environments, especially those with overhead branches, as well as vulnerable foundations. This will help keep the plants healthy as well as prevent the conservatory from sinking into the land early on after construction. In addition to that, research into the local environment and character of the property should be conducted to determine the impact of the conservatory on the space around it. Questions like, “What relationship will it have with the boundary of the property?” and, “How will the construction of the conservatory impact the neighboring buildings/natural environment/people?” are often assessed during this research.

In terms of architecture and structural design, conservatories are primarily made up of a glazing system and metal structural system. In the modern day, most structural systems are made from structural steel, but wood has also been seen in smaller-scale residential conservatories due to easy construction and cheap material cost (“Conservatories”, n.d.). In terms of glazing systems, there are many options for conservatories, but they mostly fall into two categories: glass and rigid plastics. Both groups have their own benefits and drawbacks, as detailed in the Table 2.1 below, depending on the various uses of the conservatory.

*Table 2.1: Glass versus Rigid Plastics*

| | **Glass** | **Rigid Plastics** |
|---|---|---|
| Types[1] | Clear, opaque, frosted, safety, laminated, tempered, heat reflective, smart, single-layer, double-layer, triple-layer, air-filled, argon-filled, etc. | Solid polycarbonate, multiwall polycarbonate, polymethyl methacrylate (PMMA), acrylic, fiber-glass reinforced plastic rigid panel (FRP), etc. |
| Cost[2] | Depends on specific type and dimensions, but generally has higher initial cost | Depends on specific type and dimensions, but generally cost-effective |
| Pros[3] | Broader spectrum of light can penetrate the structure<br><br>Durable: lower maintenance and replacement costs<br><br>Long life span<br><br>Ideal in colder regions due to effective heat retention properties<br><br>Less excessive relative humidity | Effective light transmittance<br><br>Lightweight<br><br>Easy to assemble<br><br>Lower upfront costs<br><br>Can withstand extreme temperatures without distortion, breakage, or absorption of heat |

| | | |
|---|---|---|
| | problems<br><br>Noise reduction | |
| Cons[4] | More expensive upfront<br><br>Higher operating costs<br><br>Potential temperature fluctuations and glare<br><br>Extreme weather events may cause damage = costly | Many have to invest in grow lights to provide full spectrum of light<br><br>Less efficient in heat retention<br>Airtight: can result in excessive humidity<br><br>May lack aesthetic appeal |

[1](Richmond Oak Conservatories Ltd, 2024), (Apex Publishers, 2023)

[2](James, 2024)

[3](James, 2024)

[4](James, 2024), (Apex Publishers, 2023), (Proctor, 2024)

### 2.3.2 Benefits of Conservatories

Conservatories offer many benefits, both for the plants displayed within the structure and those who enter the building. With biodiversity increasing all around the world, new plants brought into conservatories provide valuable insight into new scientific research and conservation practices (Ren et al., 2023). Plants also present educational opportunities for all ages, teaching visitors about ecosystems from all over the world while never having to go far to do so. Having these plants in a confined area also preserves and promotes insect life, which is particularly important for supporting the survival of pollinators, such as bees (“Secrets to Green House Pollination”, n.d.).

Humans also largely benefit from visiting conservatories. With their abundant light and plethora of greenery, immersion into nature has proven to reduce blood pressure, lessened stress levels, and even improves overall mental health. One study, published in the National Library of Medicine, goes on to state that there is evidence between nature exposure and improved cognitive function, brain activity, and even physical activity. The journal goes on to state that there are even longitudinal observational studies occurring to measure the impact of nature engagement on anxiety, depression, and chronic diseases (Chen et al. 2018).

### 2.3.3 Cost Impact of Conservatories

Much discourse exists in terms of the starting cost for a conservatory. While some, prefabricated conservatories that serve as extensions of homes start around \$3,000. Even so, like cars or homes, the bigger and more custom the structure, the more expensive the price becomes. Many 10-foot by 10-foot conservatories range from about \$9,000 to \$15,000. Much larger-scale conservatories start at \$129 per square foot and can get as high as \$400 per square foot (Richardson, 2024). These values don't include professional installation, of which price varies depending on the size, complexity, and location of the conservatory.

# 3.0 Methodology

## 3.1 Building Demands

To legally design and construct a botanical conservatory in Massachusetts, the ninth edition of the *Massachusetts State Building Code* must be used. This code is a combination of international model codes and state specific codes adopted by the Board of Building Regulations and Standards. To be more specific, the *Massachusetts State Building Code* directly references the 2015 versions of various International Codes (*IBC, IRC, IECC, IEBC, IMC, ISPSC,* and portions of the *IFC*) as published by the International Code Council, and has state specific amendments for all chapters of the 2015 *International Book of Codes* (*IBC*). In addition to that, *ASCE 7-10: Minimum Design Loads for Buildings and Other Structures* must be used for more specificity in determining design loads for the building.

It is important to note that when this project started, the tenth edition of the *Massachusetts State Building Code* was not in effect. This code is in effect as of January 1st, 2024 (with a six month concurrency period). Future work on this project should align with the standards set in the tenth edition of the *Massachusetts State Building Code*, which directly amends and references 2021 international codes (*IBC, IRC, IECC, IEBC, IMC, ISPSC,* and portions of the *IFC*).

According to the 2015 *International Building Code*, botanical conservatories fall under "Utility and Miscellaneous Group U" for an occupancy classification. These types of buildings are defined by not being classified in any other occupancy group listed by the *IBC* (Section 312.1, *International Building Code*, 2015), and conservatories do not meet the definitions for any other occupancy group. In addition to that, Group U occupancy classification lists "greenhouses" as an example, which is most similar to a botanical conservatory.

For a Group U occupancy classification, there are a few design constraints that need to be followed. In terms of type of construction, we decided on a Type V construction classification, as it allows for any permitted materials (by code) to be used for structural elements, exterior walls, and interior walls (Section 602.5, *International Building Code*, 2015). From there, a B classification for a Type V construction with no sprinkler system (Section 903.2, *International Building Code*, 2015) was determined to be the best fit due a few different factors; it allows for a maximum building height above the grade plane of 40 feet (Table 504.3, *International Building*

*Code*, 2015), an allowable area of 5,500 square feet (Table 506.2, *International Building Code*, 2015) and 1 story above grade plane (Table 504.4, *International Building Code*, 2015).

Furthermore, we looked at means of egress components for a conservatory to determine maximum occupant load, egress sizing, number of exits, and exit access when designing the proposed building. In terms of building occupancy, the conservatory has a maximum occupant load factor of 300 gross, which will help to determine the maximum occupancy of the building (Table 1004.1.2, *International Building Code*, 2015). The number of exits required is based on the total occupancy load per story: 1 to 500 people requires 2 exits, 501 to 1,000 people requires 3 exits, and more than 1,000 people requires 4 exits (Table 1006.3.1, *International Building Code*, 2015). In addition to that, these exits, in a Group U Type VB construction building, cannot be more than 300 feet away from any point in the building (Table 1017.2, *International Building Code*, 2015).

## 3.2 Building Location and Design

As this project's main focus is to revitalize the area surrounding Higgins House, we needed to determine the best location for a conservatory. The main concern with Higgins House at the moment is that it is tucked away in a non-foot traffic heavy area of campus: the south face of the building faces the backside of Worcester Polytechnic Institute's Campus Center and Harrington Auditorium, and all other faces are hidden behind a plethora of trees. The two main paths that travel by the house are occasionally busy during major transition times, as the parking lot below the school's Rooftop Fields are most accessible by these paths. In looking for the best location for a conservatory, we looked into areas that do not stray too far from the walking paths already commonly used, but also areas that could prove prosperous if a walking path towards the conservatory was developed. In addition to walking path location, proximity to Higgin's House and other academic buildings was also considered. This would create an easier access point from these areas to the proposed conservatory, opening the door for joint events to occur between those buildings.

Fortunately, Higgins House's grounds have ample opportunity for a new building location, as most sides of the building are surrounded by extensive stretches of lawn. The locations we looked at are marked with stars on the site plan below, with the highlighted portions being the most probable locations:

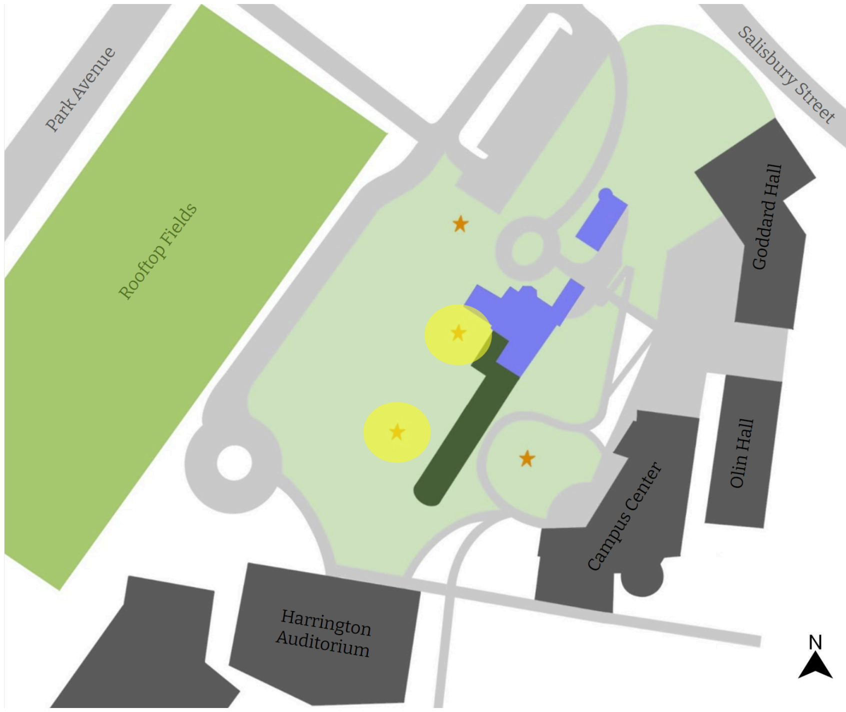


*Figure 3.1: Site Plan of Higgins House (blue) with proposed locations marked*

Additionally, we evaluated how to best design the building to fit the existing space and aesthetic. As Higgins House is a particularly historical part of campus, concerns about constructing a new building that takes away from that history arose. On the other hand, if the building is not particularly eye-catching or interesting, Higgins House may continue to suffer from lack of use and, consequently, neglect-induced decay. For resolution, we researched various styles of greenhouses and conservatories as well as general buildings built around the same time as the house. In addition, we investigated the demands of a growing campus, potential opportunities and uses for the building, and code restrictions to determine the optimal size for the building.

Conservatories, on a very basic level, are typically more modern looking buildings, as the main materials are glass and some combination of steel, aluminum, and wood. As there is very little information on commercial conservatory construction, we looked into common glazing systems for commercial greenhouses and discovered two options: glass and rigid plastics (as discussed in Section 2.3.1).

In deciding which type of system would work best for the proposed building, we looked into code requirements for glazing in conservatories as well as properties of both options. Certain hazardous locations (as defined by the *IBC* in Sections 2406.4.1 through 2406.4.7) require safety glazing (*International Building Code*, 2015). These locations include, but are not limited to, glazing in doors, glazing adjacent to doors, and glazing in windows. If the design of the glazing systems falls into any of these categories, laminated glass, tempered glass, or something similar must be used. In addition to that, if glazing is being used on the roof, it must meet the requirements outlined in Section 2405 of the 2015 *IBC*. In terms of general properties, glass allows for maximum natural light penetration. In addition to that, glass is fade-resistant and much more environmentally conscious. In contrast, rigid plastics offer significant cost savings in bulk, can endure greater impacts from various loads, and are subject to less stringent code regulations, as they pose lower risks in the event of breakage.

## 3.3 Structural Design and Analysis

The following sections detail the methods used to determine the design of the structural systems for the proposed building as well as how RISA 3-D was used to support general calculations.

### 3.3.1 Main Truss System

The structural design for this building used Allowable Stress Design (ASD) load combinations, as the proposed building has less variable loads. In accordance with the 2015 *International Book of Codes*, the load combination analyzed are as follows:

$$D + F \qquad \text{(Equation 16-8)}$$

$$D + H + F + L \qquad \text{(Equation 16-9)}$$

$$D + H + F + (L_r \text{ or } S \text{ or } R) \qquad \text{(Equation 16-10)}$$

$$D + H + F + 0.75L + 0.75(L_r \text{ or } S \text{ or } R) \qquad \text{(Equation 16-11)}$$

$$D + H + F + (0.6W \text{ or } 0.7E) \qquad \text{(Equation 16-12)}$$

$$D + H + F + 0.75(0.6)W + 0.75L + 0.75(L_r \text{ or } S \text{ or } R) \qquad \text{(Equation 16-13)}$$

$$D + H + F + 0.75(0.7)E + 0.75L + 0.75S \qquad \text{(Equation 16-14)}$$

***0.6D + 0.6W + H*** (Equation 16-15)

***0.6(D + F) + 0.7E + H*** (Equation 16-16)

Each variable in the above equations corresponds with a specific type of load. These variables, their definitions, and corresponding values are listed in Table 3.1 and Table 3.2. For more detailed calculations, refer to Appendix A.

*Table 3.1: Summary of loads for Worcester, Massachusetts*

| Loads | | | Units |
|---|---|---|---|
| L | Live load | 0 | psf |
| D | Dead load | 25* | psf |
| $L_r$ | Roof live load | 20 | psf |
| H | Lateral earth pressure | NA | — |
| F | Load due to fluids | NA | — |
| S | Snow load | 22.05 | psf |
| R | Rain load | 0 | psf |
| W | Wind load | **See Table 3.2** | psf |
| E | Earthquake load | NA | — |

*Conservative estimate

*Table 3.2: Summary of leading winds loads for Worcester, Massachusetts*

| Loads | | | Units |
|---|---|---|---|
| $WW_r$ | Windward roof load | 17.8 | psf |
| $WW_{re}$ | Windward roof edge load | 19.2 | psf |
| $WW_w$ | Windward wall load | 26 | psf |
| $WW_{we}$ | Windward wall edge load | 29 | psf |
| $LW_r$ | Leeward roof load | -23 | psf |

| | | | |
|---|---|---|---|
| $LW_{re}$ | Leeward roof edge load | -25.3 | psf |
| $LW_w$ | Leeward wall load | -21.5 | psf |
| $LW_{we}$ | Leeward wall edge load | -24.1 | psf |

Given the loads proposed for a building situated in Worcester, Massachusetts, it was determined that the most critical load combination for all member of the structure was Equation 16-13 from the 2015 *International Book of Codes*: ***D + H + F + 0.75(0.6)W + 0.75L + 0.75($L_r$ or S or R)***. This load combination created the greatest amount of load per square foot of area, so the building must be designed to withstand this calculated maximum.

As the proposed building is a conservatory, the shape of the building would be determined by the dimensions of the truss. Many factors were considered in deciding on these dimensions, such as overall building height and width, roof slope, desired amount of walkable space within the building, and desired types of plants in the conservatory. Keeping these in mind, seven potential truss configurations were developed, as shown in Figure 3.2. For better reference, a 5’9” tall person and a 20’ tree were modeled within the truss system.


*Figure 3.2: Truss system dimension study with heights, depths, and roof slopes*

In addition to the truss configuration, we needed to determine the amount of trusses necessary to support the various loads and the respective cost. For our building, 4 different versions of the main truss system were analyzed, as detailed in Appendix B (It should be noted that this analysis only considered basic factors and didn't include complex wind loading or lateral bracing in order to determine a rough cost estimate efficiently. The chosen system's actual cost was calculated once the system was appropriately designed with all factors included.). Each of these trusses had the same steel configurations, however the actual size of the steel changed due to the change in loading depending on the spacing of the given truss. This was in part to determine aesthetically how the trusses would look inside the space but also to determine the total cost of the steel truss. While a larger space between the trusses means less trusses overall, we also had to think about the price difference between selecting a small steel tube section versus a larger section as well as labor costs associated with such.

Once the configuration of the truss was established, loads (as shown in Table 3.1) were applied along a 2D model of the truss. These loads, as shown in Figure 3.3 and 3.4

below, are spread across the entire exterior of the building. They then are transferred to the individual truss system members, which then transfers each of the resultants into specific locations on the foundation. As the load transfer pathway was relatively simple, sizes of the structural members were calculated as soon as all calculated loads were applied. The structural members were then checked in strength and deflection to make sure they met code. These calculations were completed and checked through a structural analysis software: RISA 3-D.

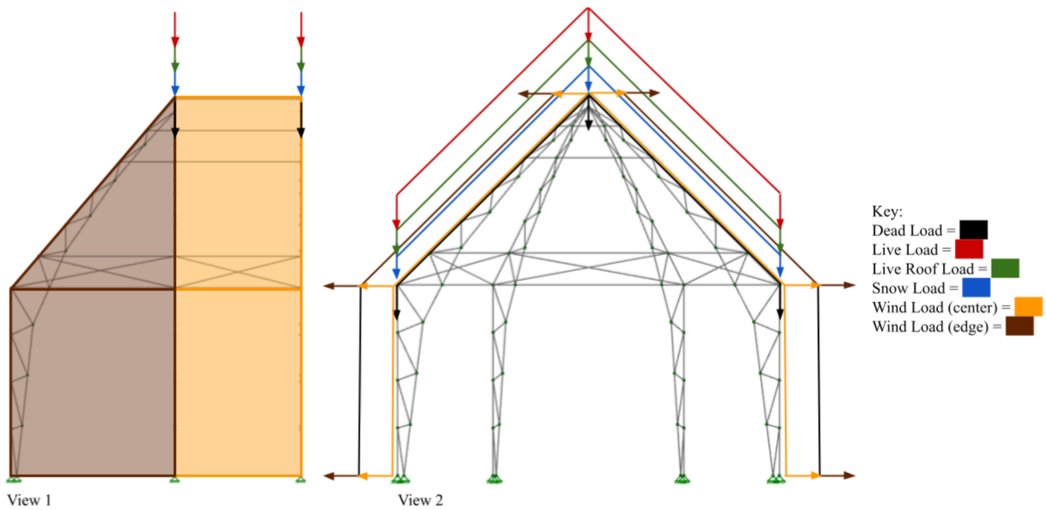


*Figure 3.3: Loads applied on truss for calculations, wind load version 1*

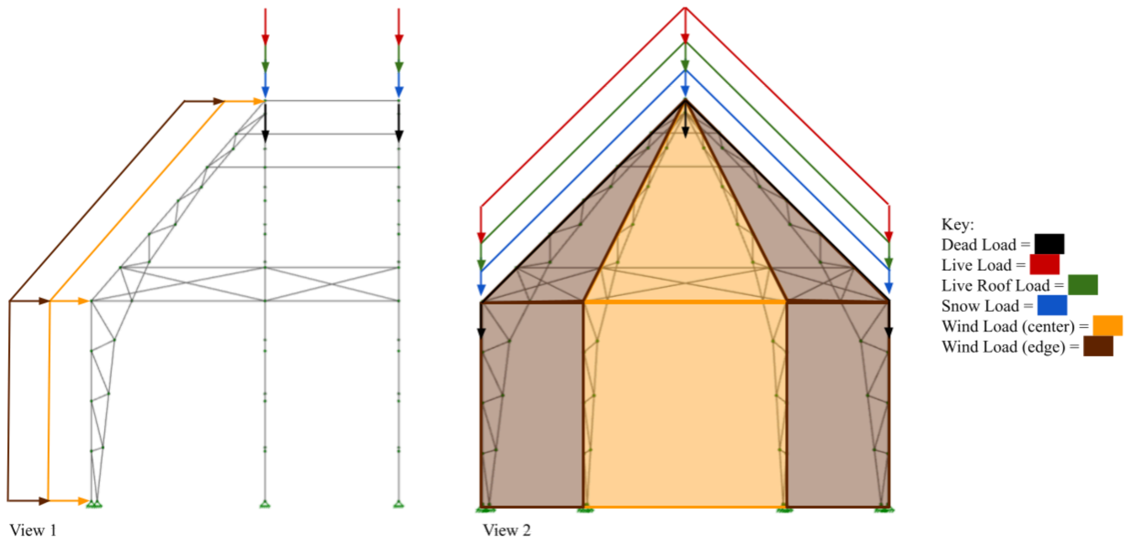


*Figure 3.4: Loads applied on truss for calculations, wind load version 2*

### 3.3.2 Application of RISA 3-D

RISA-3D is a structural analysis software that allows for efficient evaluation of complex structural systems. Knowing that the team wanted the conservatory to reflect a similar style to that of Higgins House, the team determined an arched truss system would suit the building best. Due to the nature of arched trusses, hand calculations are quite tedious, especially when multiple variations of the truss were analyzed in order to determine which version would be most cost-effective. An example of one of the variations of steel truss analyzed is shown below.

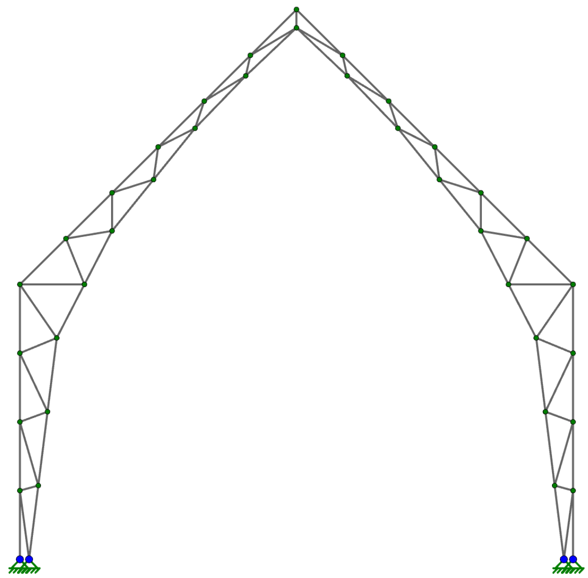

*Figure 3.5: RISA-3D model of truss system*

As the building proposed is symmetrical and faces uniform loading across the entire building, only half of the total building was modeled to maximize the software's calculation efficiency—it can be assumed that loads felt on one side of the building will be the same on the other side of the building. The loads were placed along the RISA-3D model as seen in Figure 3.3 and 3.4, with the only exception being the self-weight of the system, as RISA 3-D calculated this based on the member selected.

## 3.4 Energy Analysis

After determining the design and structural system of the proposed conservatory, the team ran an energy analysis using the energy modeling software DesignBuilder. The focus of the energy analysis was to minimize the total energy usage of the proposed building per year, through the application of both passive and active design strategies. Due to the nature of the proposed building, heavy emphasis was placed on manipulating the windows both in the roof and in the walls to boost energy performance.

### 3.4.1 Application of DesignBuilder

DesignBuilder is an energy modeling software that helps assist in the design of sustainable buildings and structures. This software helped the team to quickly change parameters of the building that have an impact on the overall energy efficiency, such as construction type, lighting systems, HVAC systems, and even electrical generation. Once a complete model was created using Revit, the basic shape of the proposed conservatory was imported into DesignBuilder and edited for simplification. The energy model is detailed in Figure 3.6.

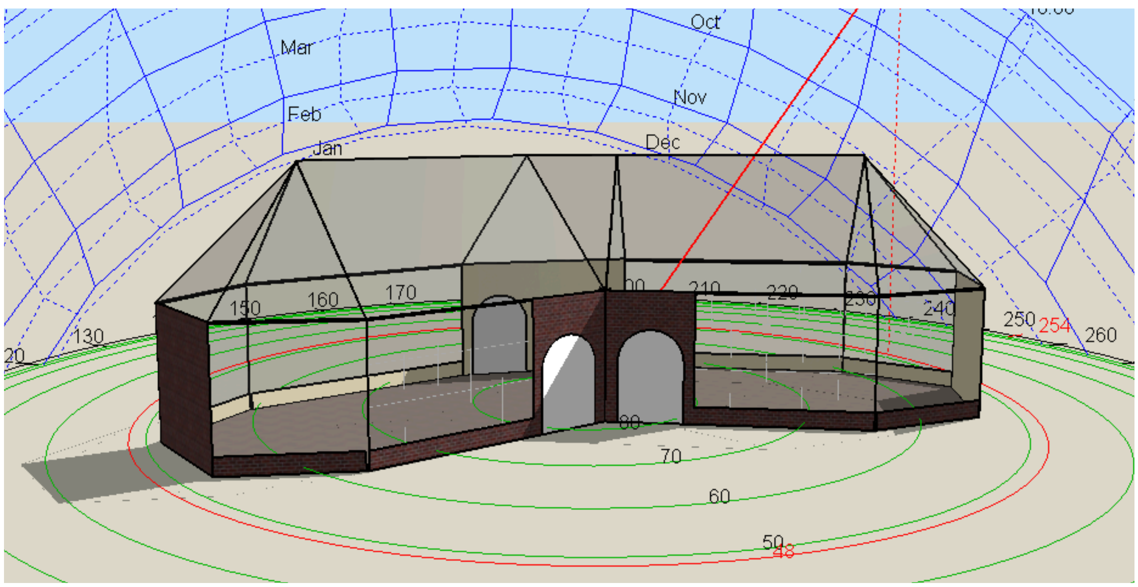


*Figure 3.6: Energy model of building*

Once the building was ready to be analyzed, parameters were specified in order to determine the baseline energy usage for the proposed conservatory. First, the building template was set as a public circulation area where display items are exhibited, as this was the closest template DesignBuilder had to the activity in a botanical conservatory. In addition to that, the construction of the walls, floors, and ceilings as well as the glazing systems were set to the Revit model's defaults. As the design of electrical systems are outside the scope of this project, lightning parameters were turned off. Finally, the HVAC system selected for the baseline test was a fan coil unit with an air cooled chiller, as this is the default HVAC system in DesignBuilder. Once those parameters were set, the energy analysis was run using one full year of weather data from Worcester, Massachusetts. This resulted in a baseline net energy usage of about 212 kBtu per square foot per year.

Following the completion of the baseline energy usage analysis, the parameters were changed once again in order to reduce the baseline values. The team focused mainly on ways to best increase the U-value of the glazing system both in the roof and the walls as well as what HVAC system would most efficiently support the various temperature and natural ventilation needs.

For the glazing system, the team investigated single pane, double-pane, and triple-pane glass. In addition to that, the team explored different types of coatings and smart glass technologies for the previously mentioned glass types in order to find the glazing system combination that best reduces heat transfer through the glass but still provides enough light for various plants to grow. In addition to that, the coatings and smart glass technologies were also investigated for thermal performance and general insulative properties. As botanical conservatories are composed of mostly glass, it was imperative that the glazing system selected could provide proper insulation year-round.

For the HVAC system, DesignBuilder has a plethora of preset templates for common systems and the team looked into three: a fan coil unit, a variable refrigerant flow unit with a dedicated outdoor air handler, and a ground source heat pump unit with heated floors. Each of these systems have different advantages and disadvantages in a conservatory application, as listed in Table 3.3 below. Final selection of the HVAC was based on their impact on the total net energy usage as well as their respective benefits and drawbacks.

*Table 3.3: HVAC System Comparisons*

| | **HVAC System** | | |
|---|---|---|---|
| | **Fan Coil Unit (4-pipe), with District Heating + Cooling** | **VRF (Air Cooled), Heat Recovery, DOAS** | **GSHP Water to Water heat Pump, Heated Floors, Nat. Ventilation** |
| Pros[1] | Cost effective | Increased flexibility for commercial HVAC | Saves money over time |

| | | | |
|---|---|---|---|
| | Easy to install<br><br>Easy to adjust to reconfigured spaces<br><br>Easy maintenance<br><br>Efficient (when maintained properly)<br><br>Compact | retrofit, redesign, or replacement<br><br>Requires less space<br><br>Can meet different heating and cooling demands throughout buildings<br><br>Easy installation<br><br>Can increase energy efficiency by 40% to 50%<br><br>Can operate at different speeds<br><br>Zoned comfort control<br><br>Provides dual heating and cooling<br><br>Long-term savings | Benefits and rebates available for geothermal installations<br><br>If property has adequate ductwork, system can be retrofitted into building<br><br>Environmentally friendly<br><br>Works in most climates |
| Cons[2] | Controls can be affected by other units<br><br>Needs a separate primary system for providing fresh air<br><br>Maintenance can be higher than a central system<br><br>Needs constant access through the ceiling | Higher upfront costs<br><br>Need specialized maintenance knowledge for proper performance | Requires more time and money to install, high upfront costs<br><br>Specific geographic and environmental factors impact total cost of system<br><br>Many require significant landscape alterations<br><br>Open-loop systems may containment groundwater |

[1](Morris, 2023), (Cefaly, 2018), ("VRF System Pros and Cons", n.d.), (EnergySage Staff, 2023)

[2](Morris, 2023), (Cefaly, 2018), ("VRF System Pros and Cons", n.d.), (EnergySage Staff, 2023)

A total breakdown of the selected energy model settings based on the glazing system and HVAC properties can be seen in Appendix C.

## 3.5 Cost Benefit Analysis

### 3.5.1 Application of National Cost Estimator

Once the design of the all-season conservatory to be built was finalized using Rivet and RISA, a thorough cost estimation was made using the National Cost Estimator to ascertain the financial feasibility of the project. This estimation involved an analysis of all materials and resources necessary for the construction. The National Cost Estimator is known for its accurate predictions of construction costs, based on regional data and industry averages. It provided a breakdown of the costs of labor, materials, and equipment. Each element of the design, constructed in Rivet and assessed for structural integrity in RISA, was evaluated individually to ensure the reliability and completeness of our calculations. Additionally, the team entered local market prices for materials and labor into the software to improve the specificity of their estimates. Also, alterations were made based on the unique requirements of the conservatory's design, which includes enhanced sustainability and all-weather functionality.

### 3.5.2 Benefits Analysis

Concurrently with the cost estimation phase, a thorough benefits analysis was carried out to determine the numerous advantages that the all-season conservatory would offer to the WPI campus. The main areas of benefits identified included educational, environmental, and revenue generating enhancements.

# 4.0 Recommendations

The following sections explains the numerous considerations for the proposed conservatory, including the general architectural design, the finalized structural system, architectural and HVAC elements to consider to reduce energy usage, costs of the previous listed, and an extensive benefits list.

## 4.1 Final Design

Figure 4.1 below is a Lumion render of the final design. Additional renders from the model can be seen in Appendix D.

*Figure 4.1: Render of the proposed conservatory*

The proposed building is 30 wide by just under 100 feet long, for a total area of about 2700 square feet. The building stands 30 feet tall, coming from a combination of 15-foot tall walls and a 45° pitched roof. The conservatory is one large room, allowing for more organic movement throughout the building, as depicted in Figure 4.2. Additionally, there are dual sets of doors flanking each side of the building, facilitating entry and exit from separate directions. Elevations better detailing the structure can be seen in Appendix E.

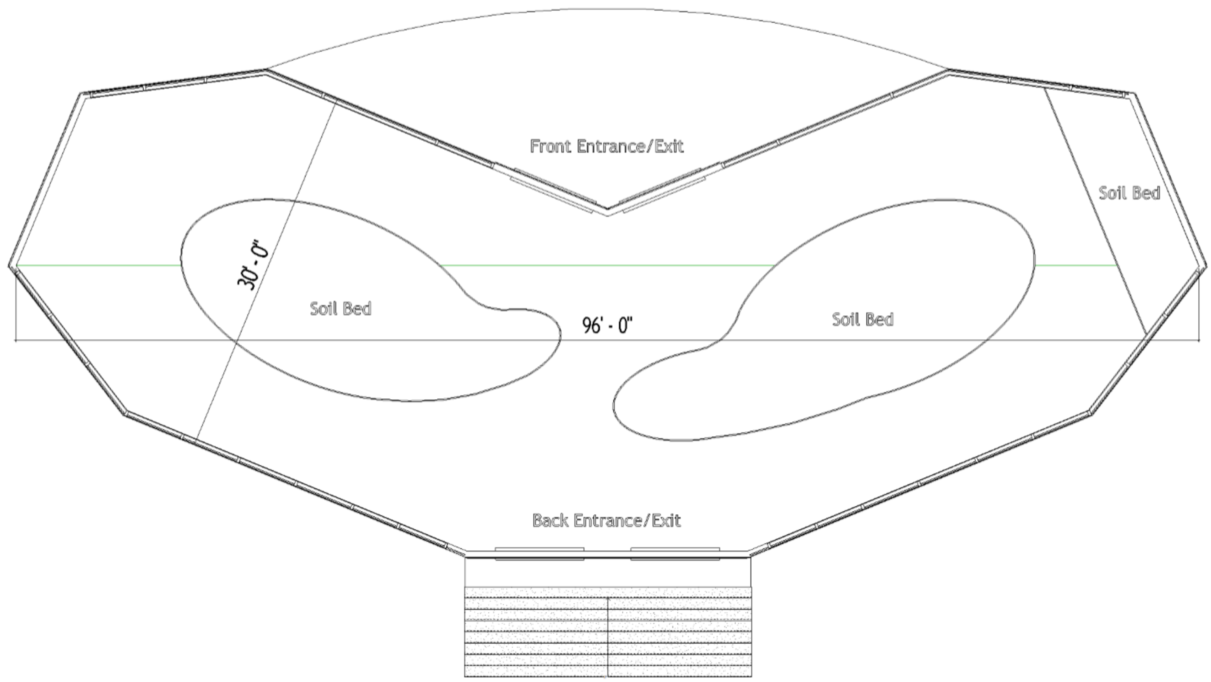


*Figure 4.2: Plan view of conservatory*

In terms of materials, the proposed building uses a combination of stone, metal shakes, large glass panels, and concrete, to best reflect the aesthetic of Higgins House. In addition to that, the steel frames of the various glass panels on the roof and walls were organized in a way to not only structurally support the glass, but also to simulate the wood and stucco façade of a traditional Tudor Revival home.

In terms of location, the conservatory best fits in the southwest part of the estate, tucked in between the edge of the current hedges and a small patio garden that extends from Higgins House, as seen in Figure 4.3. The proposed building not only defines a new, intimate space in combination with the current gardens but also maximizes the retention of general lawn space, particularly to the northwest of the structure. In doing so, the location minimizes disruptions for events held on the Higgins House lawns while offering an updated space within the gardens to make use of. Moreover, the location provides improved sightlines to Higgins Estate from the Park Avenue Garage as well as from the Rubin Campus Center, potentially increasing visibility of the estate to individuals utilizing these areas.

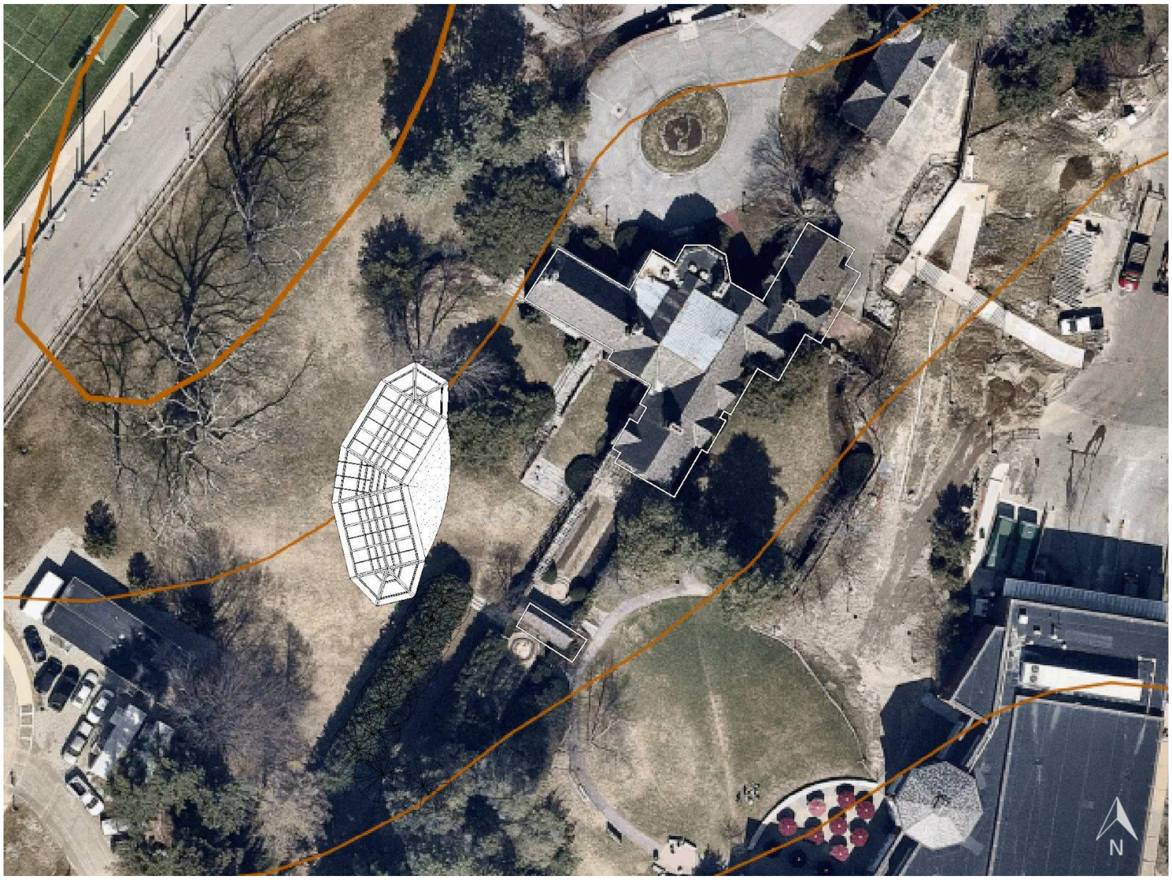


*Figure 4.3: Site plan of conservatory, to scale*

On another note, it should be stated that this location is on a slight hill, so excavation and grading will be necessary for proper construction. However those stipulations are outside the scope of this project, so a licensed geotechnical engineer should be consulted for more detailed site work.

Finally, the proposed conservatory will house plants that are typically found in the New England region. The decision to house native plants in the conservatory stems from a combination of educational and conservational benefits. By prioritizing these types of plants, the conservatory will not only serve as a display of the region's natural greenery but also will actively contribute to the preservation of local ecosystems. Moreover, showcasing native plants provides invaluable educational opportunities, fostering a deeper understanding of local ecology and potentially promoting conservation awareness among visitors. By connecting people to the natural world within their own community, the conservatory can inspire a sense of pride and responsibility towards local biodiversity, ultimately fostering a more sustainable relationship between the general population and the local environment. More about the environmental and societal impacts of these types of plants in the conservatory is detailed in Section 4.5, and a full list of potential plants is cataloged in Appendix F.

## 4.2 Structural System

The main structural system for the final design is a set of 10 custom arched steel trusses, each consisting of two main parts: the exterior chords and the interior webs. The arches span 30 feet across and 30 feet high and are made up of hollow tube and solid round A36 Gr.36 steel. Each truss will sit 10 feet apart except for two half-truss systems on either end of the building, positioned as detailed in Figure 4.4.

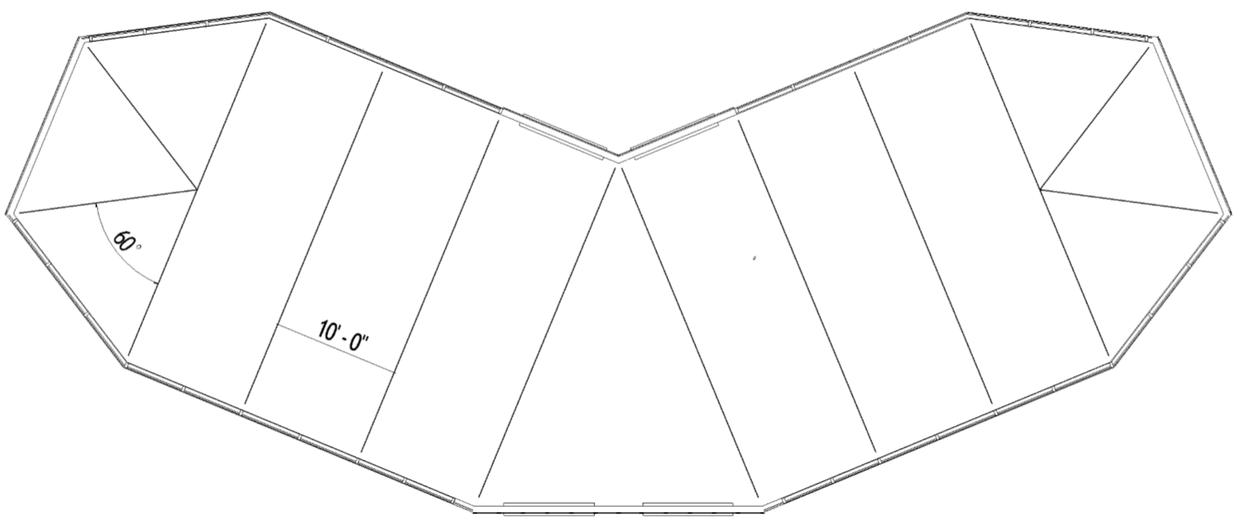


*Figure 4.4: Position and spacing of structural system*

The exterior chords will be size HSS6x6x10 and the interior will be size HSS4x4x8. To support the system laterally, purlins connecting the individual trusses together at specific locations will be size HSS6x6x10, and cross-bracing between certain purlins will be 1” diameter solid tube steel, laid out in an “X” shaped pattern. The individual members of the truss system will be welded together, while lateral connections will be either bolted or welded by recommendation of a licensed structural engineer. The individual trusses will be constructed off-site, with the rest of the system being assembled on site.

## 4.3 Elements for Energy Conservation

In order to reduce the overall net site energy of the proposed building, a specific glazing HVAC system with specific parameters were selected. These systems were selected based on an ideal indoor temperature range of 68℉ to 75℉, as this temperature range best fit the environment that native New England plants grow best in. In addition to that, the systems were selected on their ability to efficiently maintain a relative humidity of around 60% to 70%.

For the glazing system for both the roof and the walls, the system will be double-pane and have a low-E coating. Each pane will be 6 millimeter thick, with a 13 millimeter argon-filled gap and a switchable, electrochromatic reflective shading system. Both on the roof and on the walls there will be operable windows located at the top 20% of the panels, in order to promote natural ventilation at two different levels. Finally, there will be a 1 meter overhang located at the top of the wall glazing system.

From the three HVAC systems investigated, the proposed conservatory will benefit most from a variable refrigerant flow unit with a dedicated outdoor air handler. As discussed in Section 3.4.1, the VRF system's modular design allows for precise temperature and humidity control, crucial for maintaining the delicate balance required by diverse plant species. The VRF system's ability to simultaneously heat and cool different zones ensures optimal conditions throughout the conservatory, accommodating various plant habitats under one roof. Additionally, the DOAS component ensures a constant supply of fresh, filtered air, promoting plant health and minimizing the risk of airborne pathogens. Furthermore, the energy efficiency of VRF technology translates into cost savings and reduced environmental impact, making it an ideal choice for sustainable botanical environments.

After these considerations were input into the energy model, the proposed total site energy was reduced by 65.5%, for a final value of about 73 kBtu/sq. ft./year. This puts the proposed conservatory at a similar site energy usage intensity (EUI) to the median site EUI in the United States for a library ("What is Energy Usage Intensity (EUI)?", n.d.). Despite its relatively high energy usage, it's important to acknowledge that the building's mostly glass composition poses challenges to overall energy efficiency. Glass, while offering aesthetic benefits and natural light, typically has low insulation properties—even with the previous suggestions made—leading to increased energy consumption for heating, cooling, and lighting. Final values from the energy model can be seen in Table 4.1 below.

*Table 4.1: DesignBuilder Energy Analysis Results*

| **Final Energy Analysis Values** | | |
|---|---|---|
| Source | Value | Units |
| Original Total Site Energy | 212.16 | kBtu/sq. ft./year |
| **Proposed Total Site Energy** | **72.92** | **kBtu/sq. ft./year** |
| Proposed Total Source Energy | 214.27 | kBtu/sq. ft./year |
| Proposed Heating | 139858.57 | kBtu/year |
| Proposed Cooling | 50553.06 | kBtu/year |
| Proposed Water Systems | 1123.59 | kBtu/year |

## 4.4 Cost Breakdown

The total cost estimate for the designed structural system, indoor landscaping, and other furnishings amounts to $576,139, which equates to $213 per square foot. This estimate, considered conservative, comprehensively covers various aspects of the project, as outlined in Appendix G. The breakdown is as follows: $118,951 for labor, $8,468 for equipment, $213,923 for materials, $54,690 for subcontracted work, and $104,958 for stationary equipment, furnishings, and landscaping. Importantly, this estimate includes a 15% contingency fee to address any unforeseen expenses related to the design and construction of the conservatory. To ensure accuracy in our cost estimate, the project utilized the National Cost Estimator software. By entering the zip code for Worcester Polytechnic Institute (01609), we automatically adjusted our estimates to reflect local pricing conditions through the city cost index. This methodology not only enhances the reliability of our estimates but also adjusts for regional cost variances in materials and services, aligning our budget with current market rates in Worcester.

## 4.5 Benefits of the Proposed Conservatory

**Educational Benefits**: The conservatory is designed as a living laboratory where students from disciplines such as biology, environmental science, and architecture can engage in practical learning experiences. It will provide unique opportunities for academic research and experimentation, enriching the curriculum and demonstrating practical applications of theoretical knowledge.

**Community Engagement**: The conservatory will host public events, workshops, and exhibitions, acting as a hub for community interaction and attracting visitors from beyond the college. This will strengthen community ties and enhance the college's reputation as a leader in community-oriented initiatives.

**Revenue Generation**: The conservatory is designed not only as an educational and community resource but also as a significant source of revenue for the college. Two key revenue streams have been identified: event hosting and a visitor ticketing program.

- **Event Hosting**: With its aesthetic appeal and functional design, the conservatory is an ideal venue for external events such as weddings, conferences, and corporate gatherings. Renting out the space for these events can generate substantial income. During the analysis, we researched market rates for venue rentals in the region to establish competitive yet profitable pricing. The design of the conservatory incorporates versatile spaces that can be quickly and economically adapted to host a variety of events, maximizing its rental potential throughout the year.

- **Visitor Ticketing Program**: A ticketing program for visitors provides another viable revenue stream. This program allows the general public, including both local residents and tourists, to purchase passes for admission to the conservatory. The ticketing options can vary, including everything from a single-day pass to annual memberships that offer additional benefits such as special event invitations and discounts on workshops. This strategy not only generates consistent income but also promotes ongoing engagement with the wider community.

Additionally, the conservatory, if built, would be expected to contribute to the physical and mental well-being of students and staff by providing a serene environment conducive to relaxation and to study. The presence of a diverse plant collection will also promote biodiversity and serve as a sanctuary for local wildlife, further contributing to the campus's ecological goals.

# 5.0 Conclusion and Further Development

The history of Higgins House at Worcester Polytechnic Institute spans decades, reflecting its significance as a campus and community landmark. However, since being donated to the school in 1971, the estate saw a decline in usage by the campus population, prompting a revitalization of its grounds. Recognizing the benefits of conservatories, which extend beyond their botanical beauty to serve as educational resources and peaceful sanctuaries, our team developed a comprehensive plan to repurpose Higgins House and its surrounding gardens. By reclaiming a section of the southwest lawn for a botanical conservatory, Worcester Polytechnic Institute would not only be able to enrich academic pursuits across various disciplines but also provide a calm space for students, staff, and faculty to utilize. Moreover, the conservatory would offer new sources of revenue through ticketing programs and event hosting, further enhancing its value to the campus community.

The plan included an architectural concept, a design for a structural system and a complementary analysis, an energy usage analysis, as well as a cost and benefits analysis. The plan did not cover structural design of the slab-on-grade concrete floor and footings, specific building envelope connection details, the installation logistics of the selected HVAC system, the design of electrical systems, and a further developed cost analysis with the previously mentioned considerations. In addition to that, continued research into revenue sources and when the proposed conservatory could reach net-zero cost could be investigated.

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# Appendix A: Load Calculations for Structural Analysis

| Loads | | | Units | Notes |
|---|---|---|---|---|
| L | Live load | 0 | psf | One story building, live load not applicable |
| D | Dead load | 25 | psf | Conservative sum of all materials on structure |
| $L_r$ | Roof live load | 20 | psf | Roof live load for unoccupied, ordinary pitched roof (Table 1607.1 *IBC,* 2015) |
| H | Lateral earth pressure | N/A | — | Not applicable for given structural design |
| F | Load due to fluids | N/A | — | Not applicable for given structural design |
| S | Snow load | 22.05 | psf | **See calculations below** |
| R | Rain load | 0 | psf | Not applicable for structural design |
| W | Wind load | **See below** | psf | **See calculations below** |
| E | Earthquake load | N/A | — | Greenhouses are exempt from earthquake loads |

| Snow Load Calculations | | | |
|---|---|---|---|
| **Variable** | | **Value** | **Source** |
| Minimum flat roof snow load | $p_f$ | 35 psf | *780 CMR,* Table 1604.11 |
| Slope Factor | $C_s$ | .63 | *ASCE 7-10*, Figure 7-2a (Solid line) |
| Snow Load | $p_s$ | 22.05 psf | *ASCE 7-10*, Section 7.4 |

| Wind Load Calculations | | | | |
|---|---|---|---|---|
| **Wind Loads** | | | **Units** | **Notes** |
| $WW_r$ | Windward roof load | 17.8 | psf | **See calculations below** |
| $WW_{re}$ | Windward roof edge load | 19.2 | psf | **See calculations below** |
| $WW_w$ | Windward wall load | 26 | psf | **See calculations below** |

| | | | | |
|---|---|---|---|---|
| $WW_{we}$ | Windward wall edge load | 29 | psf | **See calculations below** |
| $LW_r$ | Leeward roof load | -23 | psf | **See calculations below** |
| $LW_{re}$ | Leeward roof edge load | -25.3 | psf | **See calculations below** |
| $LW_w$ | Leeward wall load | -21.5 | psf | **See calculations below** |
| $LW_{we}$ | Leeward wall edge load | -24.1 | psf | **See calculations below** |

| **Wind Parameters** | | | |
|---|---|---|---|
| **Parameter** | | **Value** | **Source** |
| Risk Category | | II | *ASCE 7-10*, Table 1.4-1 |
| Basic Wind Speed | V | 124 mph | *780 CMR*, Table 1604.11 |
| Wind Directionality Factor | $K_d$ | 0.85 | *ASCE 7-10*, Section 26.6, Table 26.6-1 |
| Exposure Category | | B | *ASCE 7-10*, Section 26.7 |
| Topographic Factor | $K_{zt}$ | 1 | *ASCE 7-10*, Section 26.8, Table 26.8-1 |
| Gust Effect Factor | G | 0.85 | *ASCE 7-10*, Section 26.9 |
| Enclosure Classification | | Partially Enclosed | *ASCE 7-10*, Section 26.10 |
| Internal Pressure Coefficient | $GC_{pi}$ | +0.55, -0.55 | *ASCE 7-10*, Section 26.11, Table 26.11-1 |
| Velocity Pressure Exposure Coefficient | $K_z$, $K_h$ | 0.7 | *ASCE 7-10*, Table 27.3-1 |
| Velocity Pressure | $q_z$ | 23.42 psf | *ASCE 7-10*, Equation 27.3-1 |
| External Pressure Coefficient | $GC_{pf}$ | **See below** | **See calculations below** |
| Mean roof height | | 22.5 ft | From building geometry |
| Roof slope angle | | 45° | From building geometry |
| Windward wall width | B | 50 ft | From building geometry |
| Side wall width | L | 30 ft | From building geometry |

| | | | |
|---|---|---|---|
| Wind Pressure | p | **See below** | **See calculations below** |

| **Wind Pressures for Load Case A (*ASCE 7-10*, Figure 28.4-1)** | | | | |
|---|---|---|---|---|
| **Surface*** | **$GC_{pf}$** | **p, +0.55** | **p, -0.55** | **Notes** |
| 1 | 0.56 | .234 | 26.0 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 2 | 0.21 | -7.96 | 17.8 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 3 | -0.43 | -23.0 | 2.81 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 4 | -0.37 | -21.5 | 4.22 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 1E | 0.69 | 3.28 | 29.0 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 2E | 0.27 | -6.56 | 19.2 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 3E | -0.53 | -25.3 | 0.47 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 4E | -0.48 | -24.1 | 1.64 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |

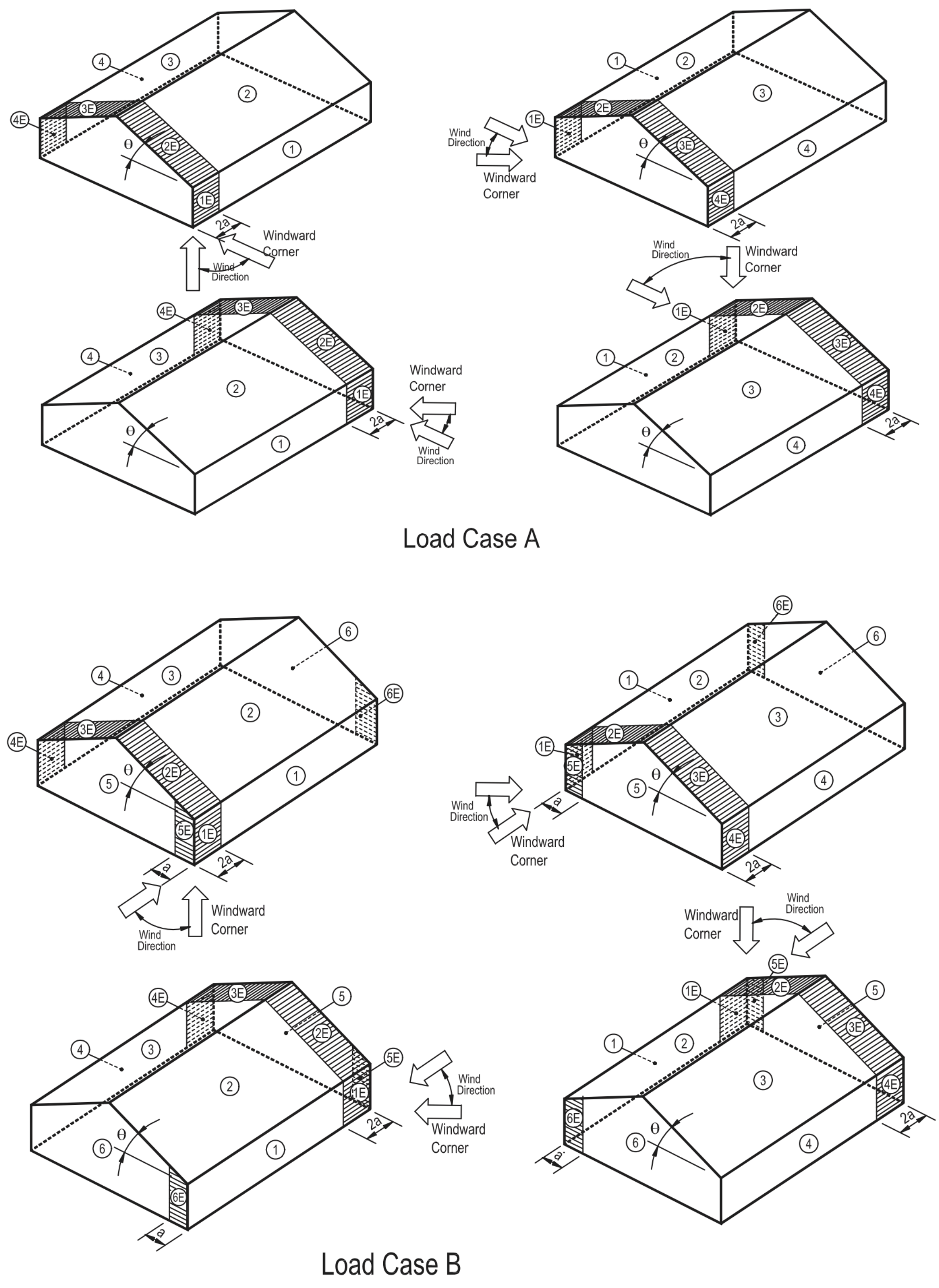
*See "Surface Locations" table for context

| **Wind Pressures for Load Case B (*ASCE 7-10*, Figure 28.4-1)** | | | | |
|---|---|---|---|---|
| **Surface*** | **$GC_{pf}$** | **p, +0.55** | **p, -0.55** | **Notes** |
| 1 | -0.45 | -23.42 | 2.342 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 2 | -0.69 | -29.04 | -3.279 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 3 | -0.37 | -21.55 | 4.216 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 4 | -0.45 | -23.42 | 2.342 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 5 | 0.4 | -3.51 | 22.25 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 6 | -0.29 | -19.67 | 6.089 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 1E | -0.48 | -24.12 | 1.639 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 2E | -1.07 | -37.94 | -12.18 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 3E | -0.53 | -25.30 | 0.468 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 4E | -0.48 | -24.12 | 1.639 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |
| 5E | 0.61 | 1.410 | 27.17 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |

| | | | | |
|---|---|---|---|---|
| 6E | -0.43 | -22.95 | 2.810 | *ASCE 7-10*, Figure 28.4-1 (cont.), Equation 28.4-1 |

*See “Surface Locations” table for context

| **Surface Locations, from *ASCE 7-10* Figure 28.4-1** |
|---|



## Appendix B: Basic Truss Configuration Analysis

Four truss configurations were studied in order to determine the most cost effective structural system. These trusses were the same in terms of overall shape, however their member size and location in the building changed as deemed appropriate. The systems analyzed were spaced 4 feet on center, 6 feet on center, 8 feet on center, and 10 feet on center. With the loads (as detailed in Appendix X) applied to each system, the following tables describe each truss system's respective member sizes and total amount of that type of truss needed to meet code requirements in the proposed building. In addition to that, the tables include material and labor costs for each configuration.  This study was completed using RISA 3-D for efficiency purposes.

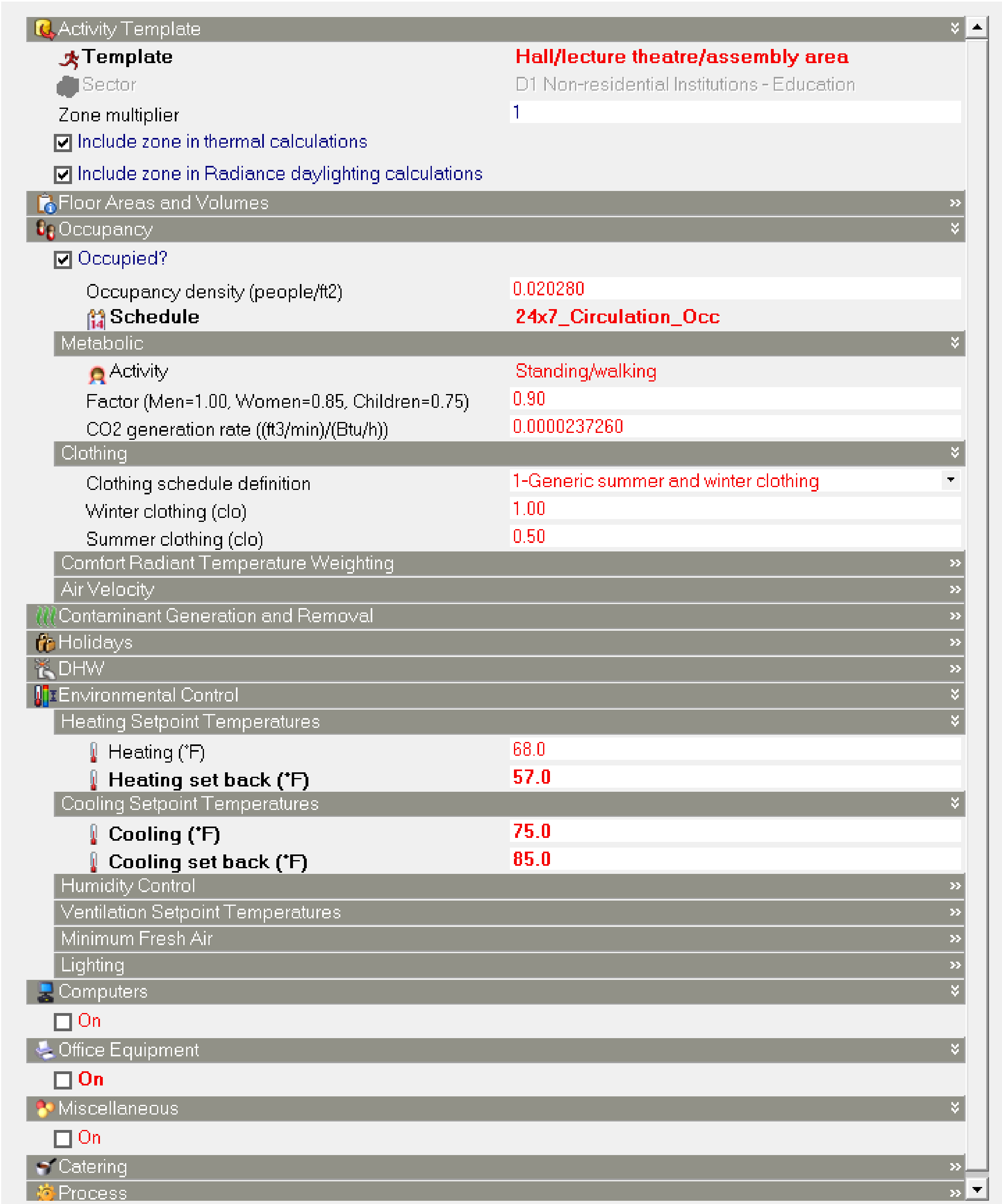
| **Truss Configuration: 4 feet o.c.** | | | | |
|---|---|---|---|---|
| | **Size/Shape** | **Material (l.f.)** | **Weight (in tons)** | **Cost (Total of Chords)** |
| **Outer Chords** | HSS2.5x2.5x.174 | 140.43 | 0.3659 | $1,729.94 |
| **Interior Webs** | HSS2x1x.116 | 90.49 | 0.0931 | $452.41 |
| **Total (for one truss)** | | 230.92 | | $2,182.35 |
| **Total (for req. amount)** | 24 trusses = | 5542.13 | | $52,376.40 ft |

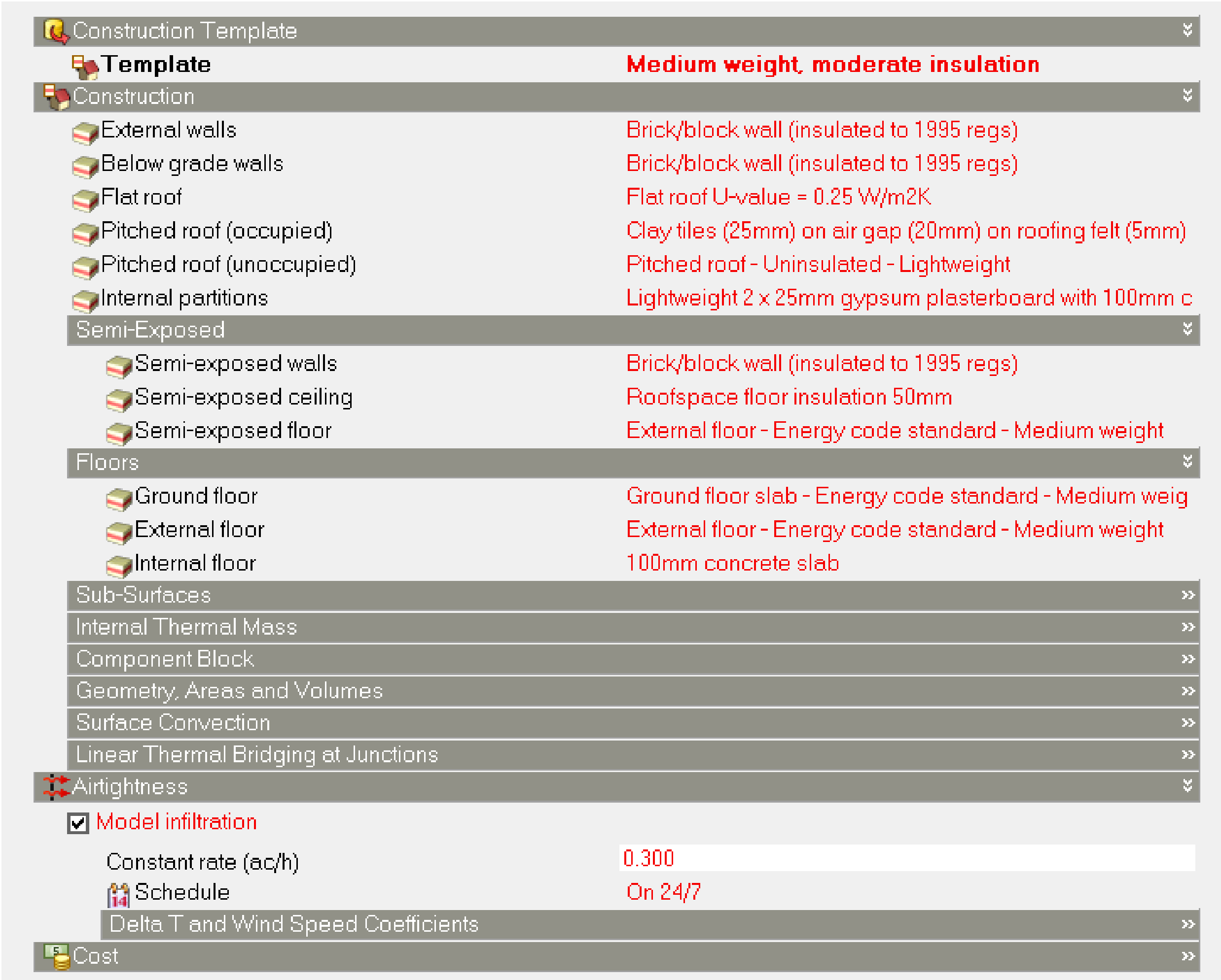
| **Truss Configuration: 6 feet o.c.** | | | | |
|---|---|---|---|---|
| | **Size/Shape** | **Material (l.f.)** | **Weight (in tons)** | **Cost (Total of Chords)** |
| **Outer Chords** | HSS2.5x2.5x.291 | 140.43 | 0.5583 | $2,639.92 |
| **Interior Webs** | HSS2x1x.116 | 90.49 | 0.0931 | $452.41 |
| **Total (for one truss)** | | 230.92 | | $3,092.33 |
| **Total (for req. amount)** | 18 trusses = | 4156.6 | | $55,661.94 |

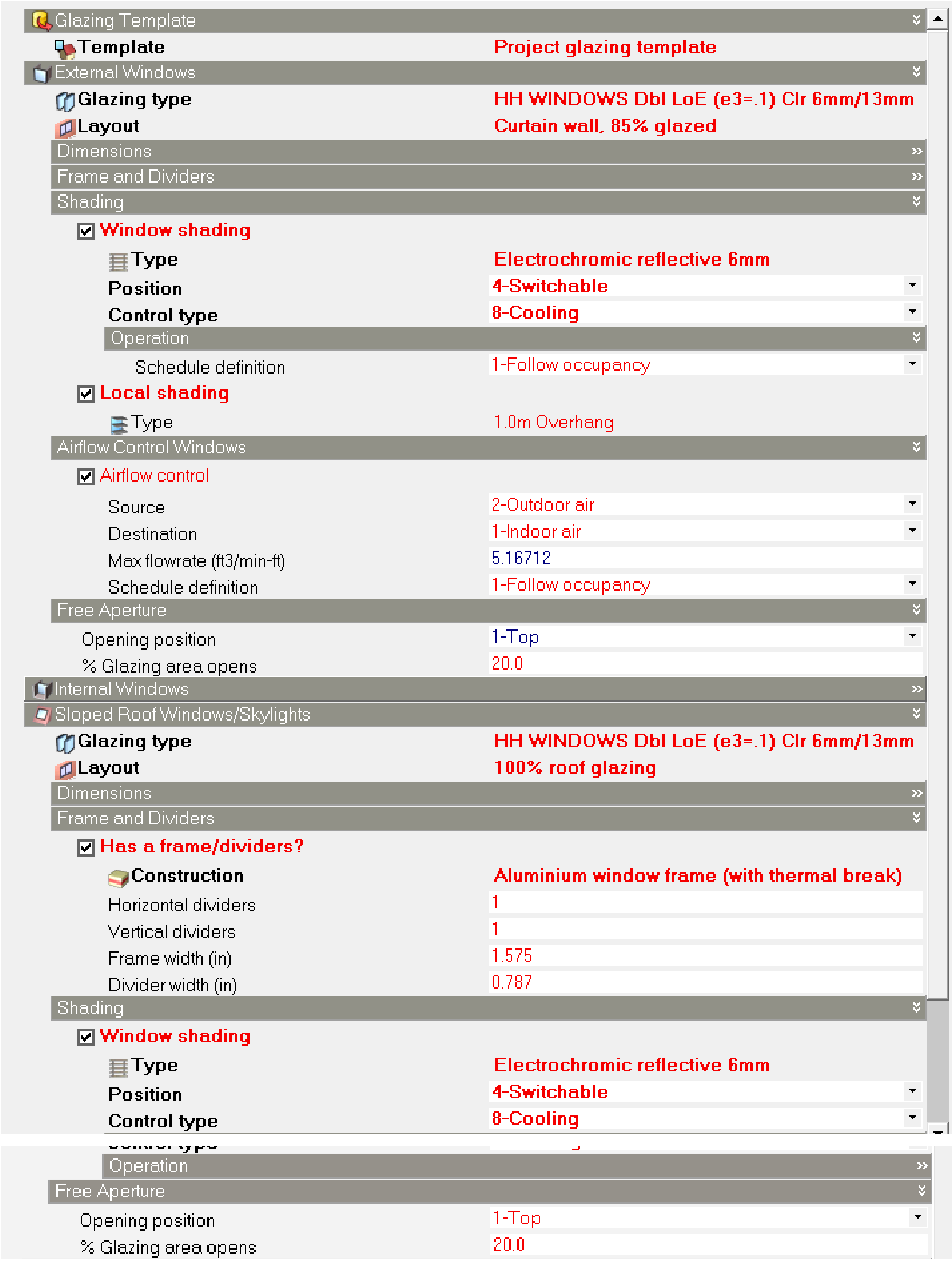
| Truss Configuration: 8 feet o.c. | | | | |
|---|---|---|---|---|
| | **Size/Shape** | **Material (l.f.)** | **Weight (in tons)** | **Cost (Total of Chords)** |
| **Outer Chords** | HSS3x3x.174 | 140.43 | 0.5488 | $2,494.91 |
| **Interior Webs** | HSS2x1x.116 | 90.49 | 0.0931 | $452.41 |
| **Total (for one truss)** | | 230.92 | | $3,047.32 |
| **Total (for req. amount)** | 14 trusses = | 3232.9 | | $42,662.48 |

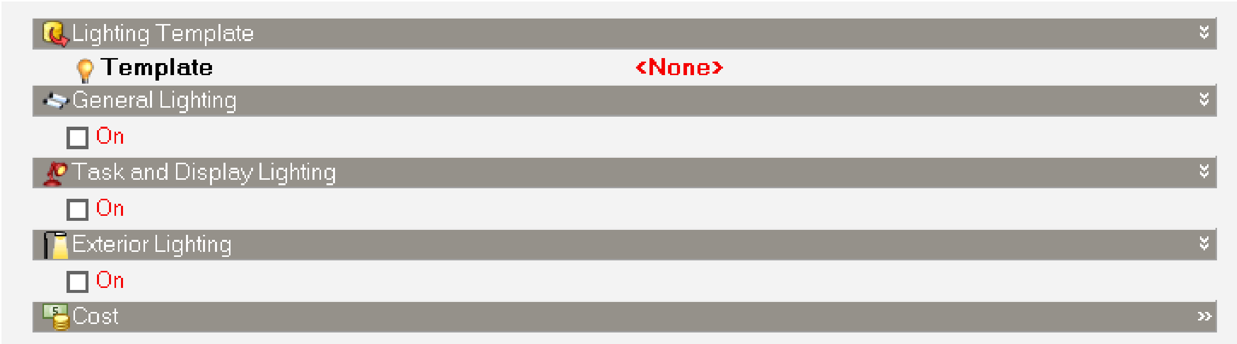
| Truss Configuration: 10 feet o.c. | | | | |
|---|---|---|---|---|
| | **Size/Shape** | **Material (l.f.)** | **Weight (in tons)** | **Cost (Total of Chords)** |
| **Outer Chords** | HSS6x6x10 | 140.43 | 0.6130 | $2,898.05 |
| **Interior Webs** | HSS4x4x8 | 90.49 | 0.2664 | $1,259.45 |
| **Total (for one truss)** | | 230.92 | | $4,157.50 |
| **Total (for req. amount)** | 10 trusses = | 2309.2 | | $41,575.00 |

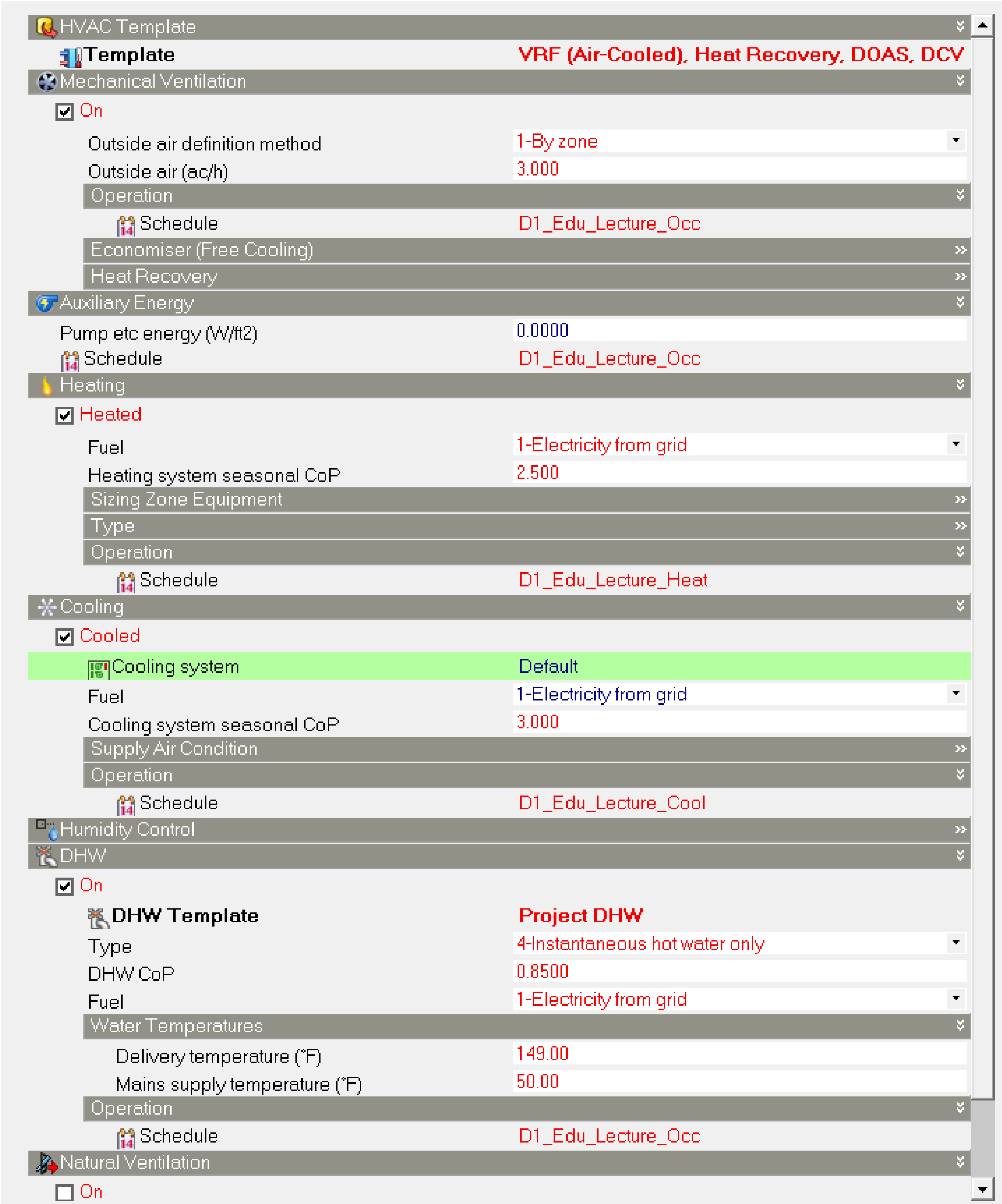
# Appendix C: DesignBuilder Selected Parameters




Construction Template
Template
Medium weight, moderate insulation
Construction
External walls
Brick/block wall (insulated to 1995 regs)
Below grade walls
Brick/block wall (insulated to 1995 regs)
Flat roof
Flat roof U-value = 0.25 W/m2K
Pitched roof (occupied)
Clay tiles (25mm) on air gap (20mm) on roofing felt (5mm)
Pitched roof (unoccupied)
Pitched roof - Uninsulated - Lightweight
Internal partitions
Lightweight 2 x 25mm gypsum plasterboard with 100mm c
Semi-Exposed
Semi-exposed walls
Brick/block wall (insulated to 1995 regs)
Semi-exposed ceiling
Roofspace floor insulation 50mm
Semi-exposed floor
External floor - Energy code standard - Medium weight
Floors
Ground floor
Ground floor slab - Energy code standard - Medium weig
External floor
External floor - Energy code standard - Medium weight
Internal floor
100mm concrete slab
Sub-Surfaces
Internal Thermal Mass
Component Block
Geometry, Areas and Volumes
Surface Convection
Linear Thermal Bridging at Junctions
Airtightness
Model infiltration
Constant rate (ac/h)
0.300
Schedule
On 24/7
Delta T and Wind Speed Coefficients
Cost


Glazing Template
Template
Project glazing template
External Windows
Glazing type
HH WINDOWS Dbl LoE (e3=.1) Clr 6mm/13mm
Layout
Curtain wall, 85% glazed
Dimensions
Frame and Dividers
Shading
Window shading
Type
Electrochromic reflective 6mm
Position
4-Switchable
Control type
8-Cooling
Operation
Schedule definition
1-Follow occupancy
Local shading
Type
1.0m Overhang
Airflow Control Windows
Airflow control
Source
2-Outdoor air
Destination
1-Indoor air
Max flowrate (ft3/min-ft)
5.16712
Schedule definition
1-Follow occupancy
Free Aperture
Opening position
1-Top
% Glazing area opens
20.0
Internal Windows
Sloped Roof Windows/Skylights
Glazing type
HH WINDOWS Dbl LoE (e3=.1) Clr 6mm/13mm
Layout
100% roof glazing
Dimensions
Frame and Dividers
Has a frame/dividers?
Construction
Aluminium window frame (with thermal break)
Horizontal dividers
1
Vertical dividers
1
Frame width (in)
1.575
Divider width (in)
0.787
Shading
Window shading
Type
Electrochromic reflective 6mm
Position
4-Switchable
Control type
8-Cooling
Operation
Free Aperture
Opening position
1-Top
% Glazing area opens
20.0

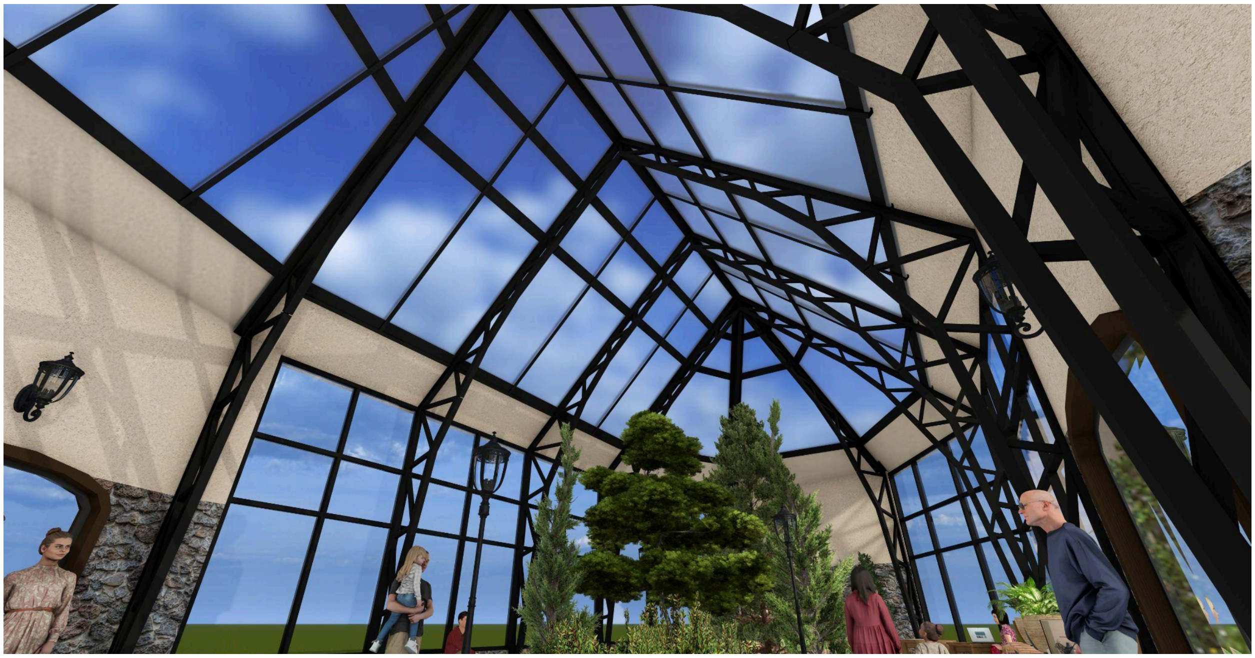

Lighting Template
Template
<None>
General Lighting
On
Task and Display Lighting
On
Exterior Lighting
On
Cost


HVAC Template
Template VRF (Air-Cooled), Heat Recovery, DOAS, DCV
Mechanical Ventilation
On
Outside air definition method 1-By zone
Outside air (ac/h) 3.000
Operation
Schedule D1_Edu_Lecture_Occ
Economiser (Free Cooling)
Heat Recovery
Auxiliary Energy
Pump etc energy (W/ft2) 0.0000
Schedule D1_Edu_Lecture_Occ
Heating
Heated
Fuel 1-Electricity from grid
Heating system seasonal CoP 2.500
Sizing Zone Equipment
Type
Operation
Schedule D1_Edu_Lecture_Heat
Cooling
Cooled
Cooling system Default
Fuel 1-Electricity from grid
Cooling system seasonal CoP 3.000
Supply Air Condition
Operation
Schedule D1_Edu_Lecture_Cool
Humidity Control
DHW
On
DHW Template Project DHW
Type 4-Instantaneous hot water only
DHW CoP 0.8500
Fuel 1-Electricity from grid
Water Temperatures
Delivery temperature (°F) 149.00
Mains supply temperature (°F) 50.00
Operation
Schedule D1_Edu_Lecture_Occ
Natural Ventilation
On

# Appendix D: Lumion Renders of Proposed Conservatory

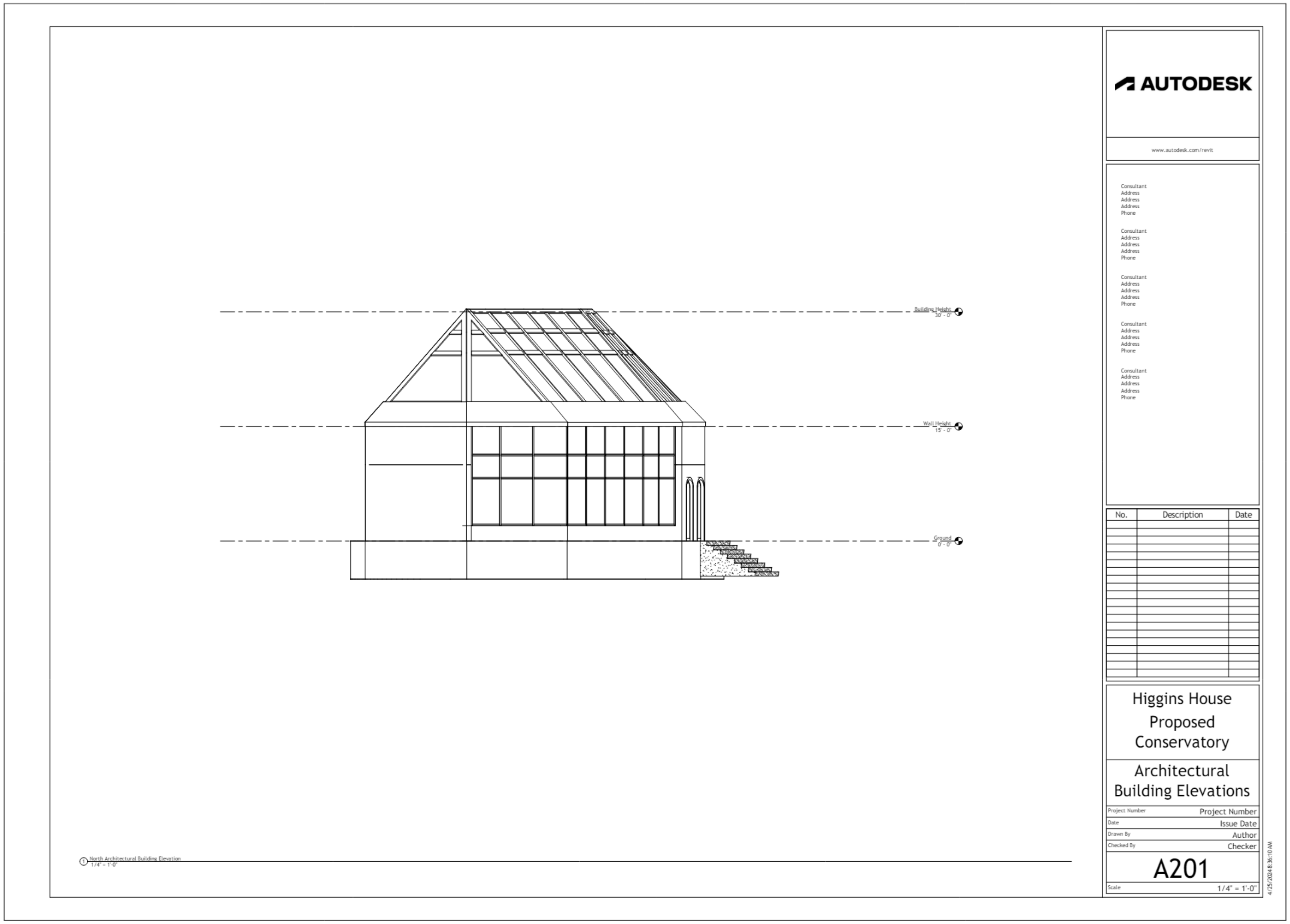
Exterior Renders:

Interior Renders:

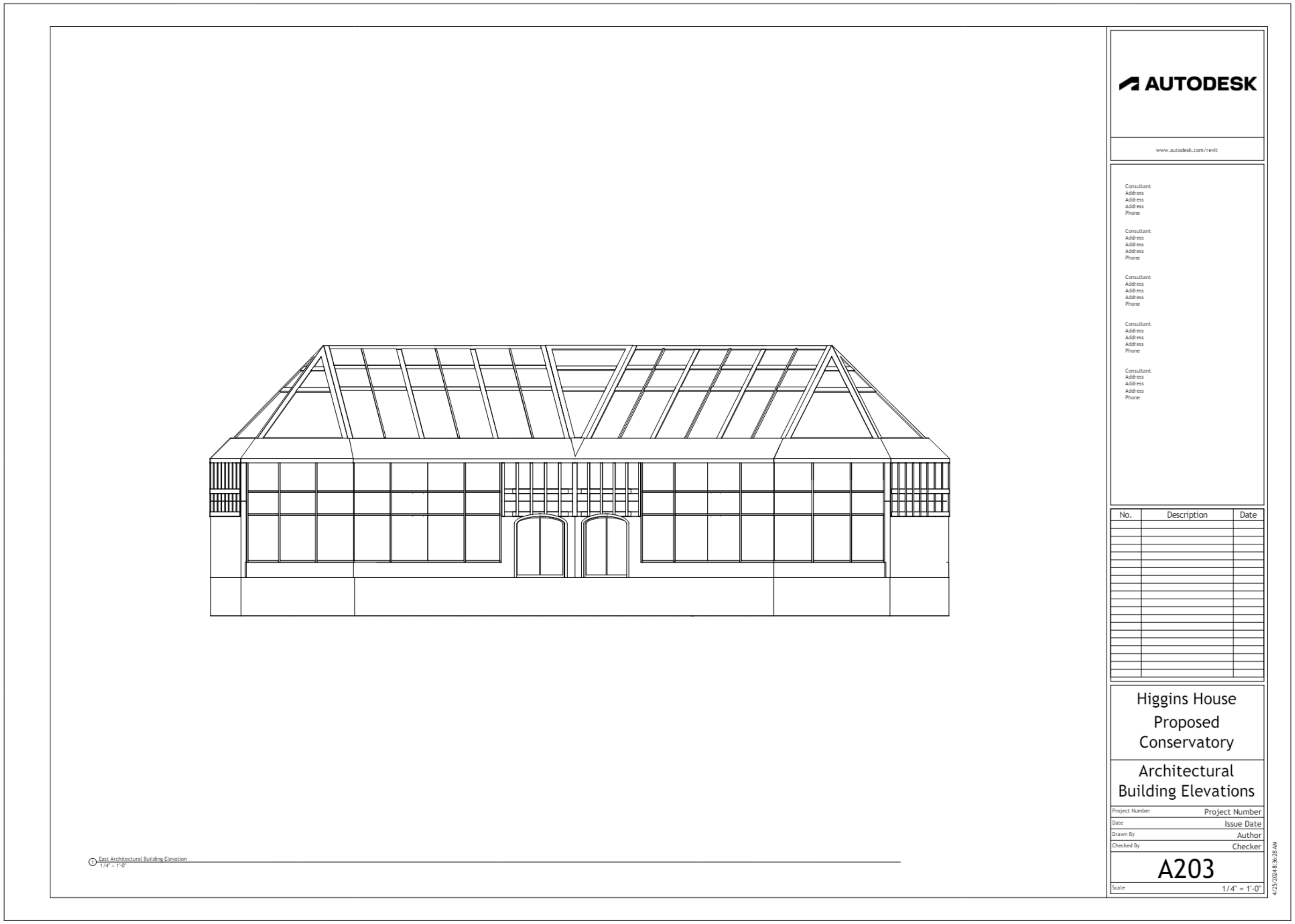


# Appendix E: Elevation Drawings

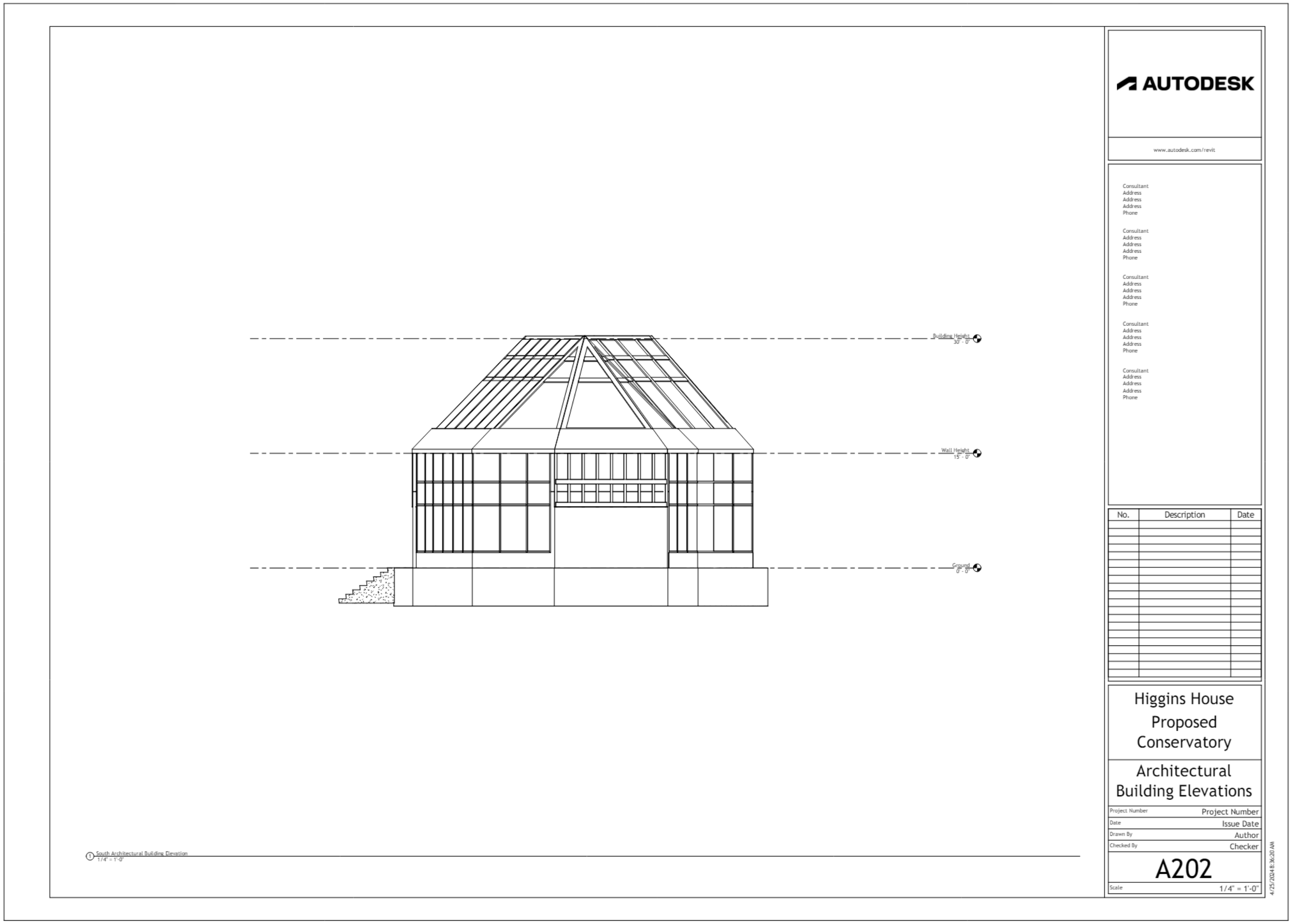
North Elevation:



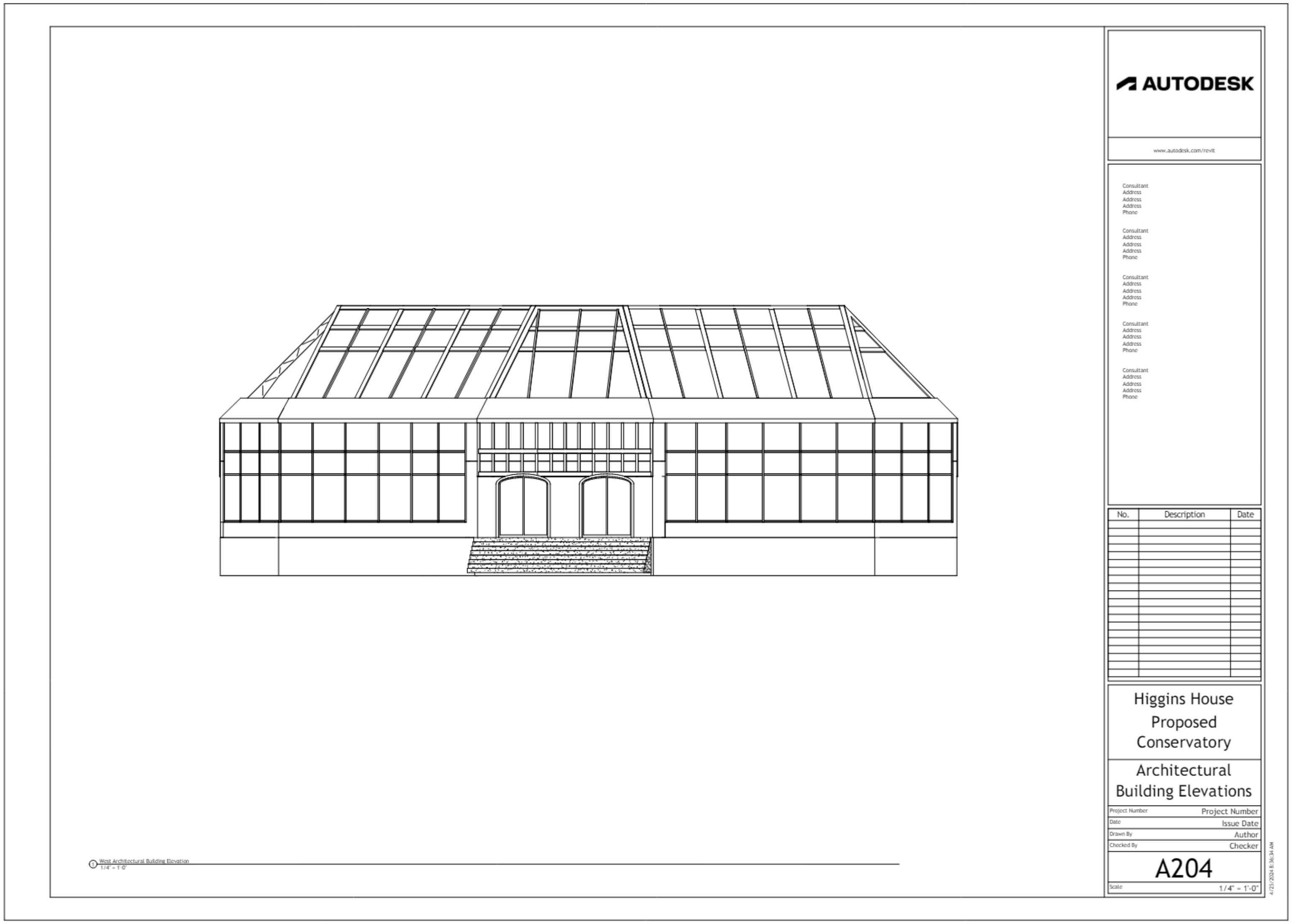
East Elevation:



South Elevation:



West Elevation:



# Appendix F: Potential Plants to be Displayed

| Categories of Plants | | | |
|---|---|---|---|
| **Flowers** | **Climbers** | **Shrubs** | **Trees (10-20 ft.)** |
| Cypripedium acaule | Parthenocissus quinquefolia | Arctostaphylis uva-ursi | Alnus serrulata |
| Spiranthes cernua | Vitis labrusca | Comptonia peregrina | Aralia spinosa |
| Pogonia ophioglossoides | Campsis radicans f. flava | Juniperus communis | Salix discolor |
| Platanthera ciliaris | Lonicera sempervirens | Kalmia angustifolia f. rubra | Zanthoxlyum americanum |
| Allium schoenoprasum | Clematis virginiana | Rubus occidentalis | Prunus maritima |
| Ipomoea purpurea | Vitis labrusca | Sambucus racemosa | Benthamidia florida |
| Aquilegia canadensis | | Vaccinium corymbosum | Amelanchier |
| Actaea pachypoda | | | |
| Caltha palustris | | | |
| Campanula rotundifolia | | | |

# Appendix G: Cost Breakdown Tables

| Cost Estimate | | |
|---|---|---|
| **Material Type** | **Cost (with Labor, Materials and Equipment included)** | **Labor Cost Code** |
| **Earthwork** | | |
| Site Clearing | | |
| Clear wooded area, pull stumps; Using a 460 HP D-9 dozer | $6,543.00 | C2 |
| Building Layout | | |
| Site rough grading, set lath | $1,040.00 | - |
| Building corners, location and grade | $1,150.00 | - |
| Dozer Excavation | | |
| Loam or soft clay; 460 HP D-9 dozer with “U” blade, (185 CY per hour) | $120.00 | TO |
| **Metals** | | |
| Square Tube Columns (6”x6”) | $28,981.00 | H7 |
| Square Tube Columns (4”x4”) | $12,946.00 | H7 |
| Prepare Metals for Painting SSPC; brush, scrape, sand by hand | $4,049.00 | PA |
| Structural Metals, Paint on coat; spray heavy coat | $825.00 | PA |
| Steel Fabrications | | |
| Steel support fabrication | $91,001.00 | IW |
| **Openings** | | |

| | | |
|---|---|---|
| Glazing | | |
| Double insulated smart glazing | $102,247.00 | G1 |
| Window Tint Film | | |
| Solar control, 45% to 70% light transmission | $9,173.00 | G1 |
| Motorized Window Fixtures | | |
| 30’ high | $13,048.00 | C8 |
| Glass Doors | | |
| Aluminum framed with fixtures | $198.00 | CC |
| **Thermal and Moisture Protection** | | |
| **100% Silicone Caulk** | | |
| ½” x 1”, 44 LF/gallon, 45 LF per hour | $308.00 | RF |
| **Concrete** | | |
| Excavation for Concrete Work | | |
| Trenching with a ½ CY utility backhoe/loader, small jobs, good soil conditions | $4,329.00 | S1 |
| Column Forms for square or rectangle columns | | |
| Up to 12”x 12”, using nails, snap ties, oil and column clamps | $25.00 | F5 |
| Reinforcing for Cast-in-Place Concrete | | |
| ⅞” diameter, #7 rebar | $629.00 | RB |
| Cast-in-Place Concrete, Subcontract | | |
| Structural slabs, including shoring, 6”, 2 way beams | $52,500.00 | - |

| | | |
|---|---|---|
| Concrete Slab Finishes | | |
| Scoring concrete surface, hand work | $24.00 | CM |
| **Masonry** | | |
| Stonework | | |
| Rough stone veneer, 4” place over stud wall | $51,794.00 | M4 |
| Walls | | |
| Stucco Wall 8” | $5,911.00 | B1 |
| **Roof Work** | | |
| Steel Panel Roofing | | |
| Roof panels, 26 gauge, 0.019” thick | $2,777.00 | R1 |
| Shake eave trim | $109.00 | R1 |
| Exterior Stucco | | |
| Stucco exterior facing wall with gypsum wall board interior | $6,305.00 | B1 |

| Equipment, Furnishing, and Landscaping Costs | | |
|---|---|---|
| Item | Quantity | Cost |
| Equipment | | |
| Tables | 11 | $5,943.00 |
| Chairs | 17 | $3,283.00 |
| Garden Lamps | 6 | $6,000.00 |
| Wall Lighting Fixtures | 4 | $4,000.00 |
| Furnishings | | |

| | | |
|---|---|---|
| Cast Aluminum Benches with Pine Wood Slats | 2 | $732.00 |
| Plants and Landscaping | | |
| Exotic Plants | - | $50,000.00 |
| Native Plant Species | - | $20,000.00 |
| General Landscaping | - | $15,000.00 |

| Craft Codes, Hourly Costs and Crew Compositions | | |
|---|---|---|
| Craft Code | Cost per Man Hour | Crew Composition |
| B1 | $34.11 | 1 laborer and 1 carpenter |
| CC | $53.53 | 1 carpenter |
| CM | $51.84 | 1 cement mason |
| C2 | $50.12 | 1 laborer, 2 truck drivers, and 2 tractor operators |
| C8 | $47.60 | 1 laborer and 1 carpenter |
| F5 | $48.78 | 3 carpenters and 2 laborers |
| G1 | $48.86 | 1 glazer and 1 laborer |
| H7 | $63.76 | 1 crane operator and 2 iron workers (structural) |
| IW | $66.64 | 1 ironworker (structural) |
| M4 | $48.19 | 1 laborer and 1 marble setter |
| PA | $53.78 | 1 painter |
| RB | $65.75 | 1 reinforcing ironworker |
| RF | $49.93 | 1 roofer |
| R1 | $36.22 | 1 roofer and 1 laborer |
| S1 | $49.73 | 1 laborer and 1 tractor |

| | | |
|---|---|---|
| | | operator |
| TO | $57.79 | 1 tractor operator |

| Cost Estimate Summary Table | |
|---|---|
| Total Man Hours | 2396.8 hours |
| Total Material Cost(s) | $213,923.00 |
| Total Labor Cost | $118,951.00 |
| Total Equipment Cost | $8,468.00 |
| Total Subcontract Cost | $54,690.00 |
| Total Equipment, Furnishing, and Landscaping | $104,958.00 |
| Total before Contingency Fee | $500,990.00 |
| 15% Contingency Fee | $75,149.00 |
| **Total Including Contingency Fee** | **$576,139.00** |