LDA – 1601
GFS – 1601

Proposed Design for the WPI Foisie Innovation Studio

A MAJOR QUALIFYING PROJECT REPORT SUBMITTED TO THE FACULTY OF WORCESTER POLYTECHNIC INSTITUTE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF SCIENCE IN CIVIL ENGINEERING

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23 March, 2016

Abstract

Worcester Polytechnic Institute has approved plans to construct a new mixed-use academic and residential building on campus, the Foisie Innovation Studio. The goal for the building is to foster the innovative and collaborative skills of WPI students while displaying various project work completed at the school. This project proposes a schematic design for the building emphasizing the structural system as well as cost estimates, schedules and a 5D model visually communicating the building's earned value and feasibility of construction. The project focuses on the utilization of Building Information Modeling as a tool for managing and facilitating construction from the design phase onward.

Authorship

While all team members contributed to the completion of the project and report, the principal responsibilities for each group member are listed by report section.

Abstract - Connor

Capstone Design Statement - Kyle

Professional Licensure Statement - Vinny

1.0 Introduction - Connor

2.0 Background Chapter

3.0 Architectural Model - Ethan

4.0 BIM Structural Model - Ethan and Kyle

5.0 Construction Scheduling - Connor

6.0 Cost-Estimating - Vinny

7.0 Construction Simulation: 5D Model - Connor

8.0 Conclusions - Connor

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Capstone Design Statement

To produce the design for this building, the Foisie Innovation Studio, some primary constraints set forth by ASCE as part of the criteria for a capstone design experience have been considered. These constraints include economic, social, sustainability, constructability and health/safety factors.

The final deliverables for the project have been produced through a standard engineering process, involving iterative analysis and synthesis. This process began with an architectural model for the building used to help visualize the final desired state of the project. Using the architectural model as a point of reference, a structural plan was developed and designed to fit the original layout to the greatest degree possible. At this stage the iteration of analysis and synthesis came into play. If an aspect of the architectural model was discovered to be incompatible with the structural requirements, then the design was refined in order to make the proposed structure completely stable. The structural members were designed through strength analysis utilizing various load combinations (specifically Dead and Live Loads), after which they were analyzed under both wind and seismic loading to ensure the stability of the structure under extreme conditions.

The final portion of the project involves construction scheduling in *Primavera*, cost estimation from the *RS Means* database, and 5D modeling of the project in *Navisworks* in order to analyze the elements of time and cost in the project. Certain aspects of the design were taken under consideration to ensure that they do not pose scheduling or financial burdens on the project. Some steps of this project, such as demolition of Alumni Gymnasium, site preparation for new construction, and interior system design, were included in the schedule and cost, but were not modeled in depth.

The following constraints listed by ASCE have been addressed in the scope of work for this project:

- **Economic**

The design takes into consideration the economic implications of the building and construction process. The financial aspect is not a limitation of the design, but rather a consideration for the quality of the building. Throughout the cost estimation process, methods have been sought to improve upon the cost of the proposed project. One main example of this occurred by minimizing the variation of structural steel beam sizes. By minimizing the variety of beam sizes, those charged with the project are capable of ordering in bulk and saving money by minimizing confusion and waste.

- **Social**

The demolition of Alumni Gym to construct the Foisie Innovation Studio is a significant social conflict that underlies the project. The combination of academic and residential space in one building raises a social constraint for the project. It is important that the residential space provides all the necessary comforts while ensuring an optimal experience for residents and visitors alike. A few steps have been taken to ensure that these constraints are met. To help with the combination of residents and visitors in the same building, work and living spaces for the students have been designed to be located on the 3rd and 4th floors. With all of the "showcase" activity to occur on the 1st and 2nd floors and with additional work and classroom space in the basement, the residents and visitors will be able to coexist without issue.

- **Sustainability**

WPI as an intellectual community has put a large emphasis in sustainability in the last few decades, most evidently in the development of new buildings on the campus. Buildings such as the Recreation Center, East Hall, and Faraday Hall are all either LEED Gold or Silver certified. Thus sustainable practices for design and strategies for whole-building sustainability were considered. One of the first sustainable practices utilized in the design of the proposed Foisie Innovation Studio was selection of materials. Throughout the building structural steel was used as the main structural frame because it required less overall material than a concrete alternative and accordingly less production was necessary. On the architectural side, many materials used for the interior finishes and the exterior enclosures were researched and local manufacturers were used to reduce lengthy transportation.

Though MEP systems were out of the scope of this project, some strategies to aid the building's energy efficiency were considered. Through the use of energy efficient windows and extensive glazing substantial energy can be conserved. Glazing along the south façade of the building had the potential to make it very hot in the atrium; however, the use of motorized curtains will regulate the sun at times of the day when it is very direct and reduce excess heat.

- **Constructability / Manufacturability**

The use of Building Information Modeling (BIM) is an integral part of determining the constructability of the building. By designing the architectural and structural models in the same program (*Autodesk Revit*), inconsistencies were easily identified and the alignment of all elements has been ensured. Manufacturability has also been considered by choosing standard and locally available materials when possible. Clash detection software has been utilized to ensure that the building has been modeled as intended. Additionally, various aspects of the structural design were designed with constructability as a main consideration. For example, the foundation walls that border the basement level were designed as cantilever retaining walls to allow large overturn loads in the vicinity of the building footprint throughout construction. Also in the design of all connections ease of field assembly was a major factor. For all beam-to-girder connections, the angles are to be shop bolted to the girders in advance to save field assembly time and effort.

One of the aspects of manufacturability that was addressed was the use of commonly produced plate sizes. For base plate and footing designs, it was determined that rounding the size to an even 16" x 16" square plate would be beneficial based on the regularity of the size and shape. Also the plate thicknesses were selected in ¼" increments to ensure that the sizes would be readily available from a fabricator.

- **Health/Safety**

The construction of this building in the heart of campus creates a few potential issues. First, the high noise level of the construction site is a threat to disturb the members of the community. Next, there is a safety concern regarding the flow of traffic between Alumni Gym and Higgins Labs. Access to this path has been designed to be restricted in order to ensure the protection of students from site-related hazards. It has also been planned to secure the site when not in use to prevent trespassing and any related injuries. Any inconvenience caused by these restrictions will be mitigated with detours on campus, specifically blocking access to the path between the current Alumni Gym and Higgins Laboratories, commonly referred to on campus as the "wind tunnel". Pedestrians will be encouraged to instead take a path across the front of Higgins Laboratories, passing Beech Tree Circle, and proceeding north past Stratton Hall to access the rest of campus. Access from behind Alumni Gym to the rooftop field and parking garage would be blocked during construction as well. Once this plan had been established, it was determined that trucks and other construction equipment would enter the site via the road between Daniels and Riley Halls, and would exit via a temporary access road to be paved from between Harrington Auditorium and Alumni Gym down to the Higgins House Lot and Salisbury Street.

Building codes are another aspect affecting the health and safety of the project. These codes provide an across-the-board standard for all aspects of the design (mechanical, architectural, structural, and fire safety) which allow for all parties to work in unison during the design process. Ensuring that the codes are followed closely in all aspects of the design has helped guarantee that the structure is sound. Building codes also mitigate the risk of designing a system that is unsafe.

Lastly, due to the mixed-use nature of this building, student safety was a concern. With so many people coming through this building on a regular basis, it was important to make a distinction between public and private space. The proposed design features stair ways in both the front and rear of the building, with the front stairs providing access to the basement, main floor, and loft floor. These floors are all designed for use by the public and visitors. Only the stairways at the rear of the building will reach the residential floors, and the proposed design states that these stair wells will require card-key access, available only to residents. Elevator access to the residential floors will also be restricted from all visitors by requiring card-key access. By separating the lives of residents from other activities occurring in the building, the well-being and safety of students has been improved.

Professional Licensure Statement

Licensure is a way for the government to ensure that qualified professionals are held responsible for the work they perform and that such work is regarded to the highest degree. For engineers, there are many standards and restrictions that must be taken into consideration when performing design work. It is important that licensed engineers act in a professional and ethical manner when producing high quality design work while abiding to specifications.

To obtain a professional engineering license, one must first pass the Fundamentals of Engineering exam that, upon passing, qualifies the person as an engineer in training. The next step is to work as a designer under a licensed engineer for five years. Once a formidable resume is produced detailing the design work, the engineer in training is brought before a board of licensed engineers to make a case for receiving their professional license. If their design work demonstrates high quality and ethical standards, and they pass their Professional Engineering exam, then they will be granted a professional engineering license.

Maintaining this professional license requires holders to continue their design work and education to help adapt to the ever changing specifications, laws, and responsibilities of a professional engineer.

Licensure is exceptionally important both for the individual and for the industry as a whole. For the individual, the license dictates how one should design as well as the ethics and level of professionalism required. The license creates expectations for the engineer and serves as a guide for their careers. In terms of the industry, the license reflects experience and professionalism. Licensed engineers hold more value in their thoughts and designs when performing a project than an unlicensed person. Publically, it is reassuring to have a licensed professional review the design before it is put to use. For example, people may be concerned about driving over a newly completed bridge if it was not approved by a professional engineer. It is in this way that licensure provides a degree of certainty and assurance for society.

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1.0 Introduction:

Located in the northeast corner of the campus quadrangle, Alumni Gym has been a centerpiece of WPI campus life for 100 years. However, for the past four years, due to the construction of the school's new Sports and Recreation Center in 2012, the building has remained vacant in an otherwise bustling area of campus. Despite the current situation, WPI has been making a consistent effort to maintain the building while actively seeking an alternative use for the space. In 2013, the school commissioned a study to convert the gym into an innovation center, but the resulting design was estimated to cost over $18 million and yield only a limited amount of usable space. According to Mr. Alfredo DiMauro, Assistant Vice President of Facilities at WPI, this study led the school to conclude that "modernizing the building (was) impractical" because "it would create a financial hardship and an inefficient use of (the) building" [1]. These findings have led to the school's decision to demolish the gym in favor of designing and constructing a new building. The proposed plan for this new building is a mixed-use academic-residential space named the "Foisie Innovation Studio", which will be designed to highlight the innovative nature that sets WPI apart.

The goal for the Foisie Innovation Studio is to foster the innovative and collaborative skills of WPI students while displaying various project work completed at the school. Gensler Associates, a design and architecture firm based in San Francisco, has been chosen as the architect for the building, while Boston-based Shawmut Design and Construction will serve as the general contractor for the project. According to a campus-wide email from WPI President Laurie Leshin on October 14, 2015 with the subject line *Announcement Regarding the Foisie Innovation Studio*, demolition of Alumni Gym is scheduled to start during the summer of 2016, following the graduation ceremony in May [2].

This MQP proposes a schematic design emphasizing the structural system for the Foisie Innovation Studio as well as cost estimates, schedules and a 5D model simulating the construction sequence and the building's earned value. The construction simulation illustrates the process from site preparation to the conclusion of building construction. The goal for the project's final deliverables remained constant throughout the project and is two-fold, focusing on both structural integrity and project management. In terms of structural integrity of the building, it has been ensured that construction plans respond to all safety requirements by following building codes, ensuring a secure construction site, and limiting access to residential space through building design. In terms of project management, it has been ensured that construction for the proposed design is feasible and clear to all parties involved, by providing cost-estimates and a construction schedule along with a simulation for building construction.

This report proceeds by first providing background on Alumni Gym and mixed-use academic/residential spaces, as well as Building Information Modeling (BIM) and all considerations taken into account during the design process. The background chapter is followed by chapters detailing both the BIM architectural model and BIM structural model. The report continues with information detailing the work performed on construction scheduling and cost estimation, and finally concludes with details on the 5D model and simulation illustrating the construction process.

2.0 Background

Founded in 1865 by two entrepreneurs from Worcester, Massachusetts, WPI has held true to its roots by maintaining a focus on innovation and collaboration. As illustrated by the school's motto "Lehr and Kuntz" (Theory and Practice), WPI students are encouraged to learn not only in the classroom, but by working on real-world projects. Two campus buildings, Boynton Hall and Washburn Labs, have for years served as symbols for the two pillars in the school's philosophy. WPI now seems to be adding a third dimension to its philosophy: Innovation. With its construction following the razing of Alumni Gym, the Foisie Innovation Studio will complement the role of the Boynton Hall and Washburn Labs, while symbolizing the new added educational dimension at WPI.

2.1 History of Alumni Gym

At the time of its construction in 1916, Alumni Gym was the hub of athletics on campus, consisting of three stories above ground and two below. With the necessary $100,000 raised by Arthur D. Butterfield, a WPI professor spearheading the fundraising effort, the building was constructed in time for WPI's 50th anniversary. Due to the immense amount of support from faculty and alumni, WPI had a surplus of funds which it was able to direct towards an indoor pool, currently located in the sub-basement of the gym [1].

Throughout the 20th century, Alumni Gym satisfied the demand for a home for athletics on campus. With the construction of the school's Sports and Recreation Center, it has become clear that this need no longer exists. The Foisie Innovation Studio will aim to serve campus by responding to a different need: the need for a home for innovation and collaboration on campus.

Although no existing features of Alumni Gym will appear in the new “Foisie Innovation Studio”, there remains an element of nostalgia for the history that the gym represents. As noted in the *Worcester Telegram* [3], while WPI is not located within a local historic district, Alumni Gym is listed on the National Register of Historic Places, a list which recognizes properties for a number of reasons, including significant contribution to America’s history and heritage.

The elements that make Alumni Gym unique were important to keep in mind as the design and construction of the Foisie Innovation Studio progressed. One of these elements is something that many students walk by every day, yet perhaps few notice - the “grotesques” located on the side of the gym. These 34 grotesques take a number of different forms: some are athletes and spectators, while others depict singers or musicians [4]. With 6 grotesques on both the east and west walls and 11 on the north and south, the grotesques are a subtle yet charming piece of not only the building, but the school’s character. As of the winter of 2016, the removal and preservation process for the grotesques has begun, with future plans yet to be determined, perhaps incorporating them into the design of the Foisie Innovation Studio. A plaque will also be placed on the site of the new building to honor the importance of Alumni Gym to the WPI community [3].

Figure 1: One of 34 Grotesques on Alumni Gym, Photo by Michael Voorhis

A major focus of the architectural design is paying homage to the nostalgic element of the old building while producing a modern final product responding to the previously noted design goals. The design incorporates the wishes and requirements of WPI’s Board of Trustees as well, who have laid out a number of items to consider for this center of innovation. These plans include housing space for 140 new residents, a necessity for a school accepting an increasing number of students with each passing year, along with new classrooms and workspaces for the Great Problems Seminars, a showcase lobby with digital displays, a robotics engineering lab, maker space, and a center for innovation and entrepreneurship. Additionally, the school aims to include tech suites with flexible configurations in order to encourage collaboration among students looking to share ideas. As the expansive project-based curriculum at WPI continues to develop, it is hoped that these spaces will provide both the resources necessary for students to work to their full potential, and the opportunity for external parties to better appreciate their work.

2.2 Mixed Use Academic/Residential Spaces

By deciding to construct a building which provides both residential and academic spaces, WPI is demonstrating that it understands the trends of today’s education. According to a recent study, students perform roughly 30 percent of their school work while in residence halls [5]. If students have access to tech suites and designated study areas without leaving their building, this time could be spent more productively and would likely increase. WPI isn’t the only school to make an investment into this type of building either - universities such as the University of Colorado, Rutgers University, and the University of Michigan are just three of the many institutions making progress towards blurring the lines between academic and residential spaces [6].

While mixing these two seemingly unrelated aspects of college life appears unconventional, there is emerging research to show that it has its merits. At the University of Michigan, the school’s mixed-use residence hall was designed to help students “address some of the world’s thorniest problems” [6] by increasing their opportunity for collaboration. At WPI, many first-year students participate in the previously mentioned “Great Problems Seminars”, where students tackle real-life problems in teams of 4 to 5, focusing on topics from sustainability to public health. These students will undoubtedly benefit from an increase in space designed for collaboration and the sharing of ideas.

The proposed design for the building comprises a total of roughly 75,000 gross square feet, with 40,000 square feet dedicated to academic space, and 35,000 square feet dedicated to residential space.

There are a number of functions required of the 40,000 square feet of academic space. While this space will hold the previously mentioned tech suites and lecture halls, it will also be used as a display area. There are two types of projects required for upperclassmen at WPI: the IQP (Interdisciplinary Qualitative Project) and MQP (Major Qualifying Project). Selected projects will be placed on display to encourage new students to take on global issues, and they may one day receive the same recognition for their project work. The academic space will also serve as a place for innovation and collaboration, with areas designated for a business incubator as well as a laboratory containing resources for students to perform project work.

For the residential space, the goal is to be able to house 140 students in the Foisie Innovation Studio. Housing will be consistent with other WPI freshman residence halls, consisting of 3 students per room, equipped with 3 beds, desks, and closets. Residential space has also been designed to include additional tech suites and collaboration spaces for the students’ convenience. Since students spend roughly 70 percent of their time in their residence halls [7], it is important to note that the residential floors will also include common rooms for extracurricular activities.

2.3 Building Information Modeling

In recent years, the construction industry has utilized and implemented innovative technologies to improve the quality and efficiency of the construction process. Of these newly emerging and industry driving technologies, the most influential is Building Information Modeling (BIM). BIM is the intelligent process of planning, designing, constructing, and managing projects [8]. BIM allows for better 3D visualization of the project while also facilitating coordination and interoperability amongst the design team, contracting team, and owner, thus promoting collaboration. This “techno-social” trend is expected to propel the construction industry with the aid of a model-based process capable of being easily manipulated and adapted so that all parties involved are provided with a clear and consistent interpretation of the project [8].

2.3.1 BIM and Architectural Functions

Visual displays are one of the most powerful tools available in architectural design. The ability to view a building or structure in a 3D model enables users to see all elements in a clear and realistic manner. This feature aids the architectural design process in terms of design clarity amongst the designer, owner and contractor. Additionally, this clarity and more comprehensive understanding of the design allows all parties to provide input and contribute to solutions.

Some of the principal ways in which BIM is useful in architectural design include dimensioning floor plans, fostering general spatial awareness, visualizing exterior appearance, and assisting in overall placement of a structure within the context of a surrounding area. Floor plans and interior layouts are the cornerstone of architectural design communication and have much to do with the eventual flow of people and activities through a building. The production of these views is a fully coordinated process with the use of BIM software tools. The development of these plans involves finding the appropriate balance between sizing of various rooms and their integration within the footprint of the building - a process which often involves numerous revisions and adjustments. BIM's ability to quickly and consistently alter dimensions and locations of walls simplifies this process, making it more efficient than previously imagined. Additionally, the ability to virtually walk through drafted floor plans offers more spatial awareness in comparison to the traditional 2D layout, making errors and omissions easier to identify than ever before.

2.3.2 BIM and Structural Functions

A key feature of BIM is its structural modeling capability in relation to the architectural design. For example, the relationship between the architectural design of floor plans and interior layouts directly affects the placement of framing columns. The interior layout and intended flow of a building dictate where columns can be placed to minimize interference or to promote improved aesthetics. It is also imperative that the framework agrees with all of the exterior enclosures of the building in order to ensure an accurate design.

Another feature that makes BIM practical and useful is the ability to detect clashes between structural and architectural items during the design phase and even as construction progresses. The application of the clash detection feature allows designers to identify any and all design errors and avoid facing similar issues in the field. This results in reduced construction costs to mitigate as well as fewer requests for information (RFI's) and schedule delays. Clash detection can identify unwanted intersections among beams, walls, and ceilings, as well as between columns and floors. This process of early detection can play a large role in simplifying the task of accurately modeling a structural frame.

One last function of BIM in structural design is the ability to facilitate structural analysis through its interoperability with structural analysis software. Upon completion of numerous hand calculations and analyzing a major structure piece by piece, BIM allows the user to highlight areas of concern. Using structural analysis software, the user can submit the problem areas to various loading conditions and check how the previously selected members respond. Though both manual and computer methods are limited by human input error, the speed and capability of BIM to discover problem areas of a frame is just another example of BIM analysis saving large amounts of time and making the structural design process more efficient.

2.3.3 BIM Planning/Scheduling/Cost Estimating

One of the primary tasks of this project was to create a schedule for the construction of the new Foisie Innovation Studio. This is no simple task, and requires an understanding of building permits, zoning regulations, and the construction activities that must be scheduled while the campus is operating regularly. Utilizing BIM to aid in the development of the schedule saves contractors and designers a significant amount of time and money while also helping them visualize the project. BIM allows users to produce a 5D (cost+time) model, which is advantageous in that it interconnects cost, time, and the 3D building model. This starts construction virtually, which allows for a deeper analysis and evaluation of the project structure before the ground breaks and the project is actually undertaken. For example, if there is a fixed budget for the project, the designer can utilize the program to make sure that the model reflects what is requested.

Using scheduling software, a schedule can quickly be developed to organize the sequence of activities necessary for construction. A widely used program in the industry is *Primavera*, which involves inputting construction activities, linking them together according to their logical dependencies, and producing an effective working schedule. Additionally, a work breakdown structure can be used to organize the construction activities into manageable sections or phases. This simplifies the complex process of coordinating the wide variety of activities done on different sections of the building. This is especially useful given the multi-phase nature of the project.

In addition to the project schedule, cost estimation of procurement and construction must be determined before developing the 5D model. There are many methods used in the industry to forecast the cost of the project. Given the information from the 3D building model and the projected schedule, a quantity takeoff measuring amounts of materials and multiplying them by the unit price provided by data sources, such as *RSMeans 2014,* can be performed. This database provides different cost information that helps to generate a more accurate cost estimate. Depending on the unit to be estimated, a different approach may be taken, such as square feet or unit cost. This creates a hybrid process where certain elements are calculated using square feet or cubic yard and others using the details from the 3D model, such as quantity or type. For example, curtain walls may be priced based on square footage of wall area while the structural beams can be calculated by summing the cost of each individual member used in the model.

Table 1 below lists some relevant BIM software along with their capabilities and applications as used in this project. They are referenced frequently throughout this report.

Table 1: Applicable Software

Software	**Capabilities**	**Application**
Autodesk Revit	3D Modeling	Architectural/Structural design
Primavera	Scheduling	Work breakdown structure, critical path determination
Navisworks	4D/5D Modeling	Full integration of 3D model with cost and schedule for enhanced visualization
Robot	Structural Analysis	Vertical and lateral load analysis for structural design

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2.4 Design Considerations

For projects of this scope and magnitude, there is a wide array of topics which must be considered before and during design production. Examining these potential issues and finding viable solutions is an integral part of the engineering profession. Addressing these issues plays a major role in fulfilling the Capstone Design element included in the project. Specifically, design issues fall into three related yet separate categories: architectural design, structural design, and construction planning. The primary aspects inherent to design decisions include but are not limited to: sustainability, cost, and structural reliability.

2.4.1 Architectural Design

The architectural challenges associated with the design of this building involve not only the aesthetic view of the structure but more importantly its functionality. In terms of aesthetics, the intention of this proposed design is a building that looks sleek and modern, while still staying true to the current theme of the campus which consists primarily of traditional brick buildings. Similar examples include the architecture of other recently constructed buildings on campus such as the Rubin Campus Center, the Bartlett Center, and the Sports and Recreation Center.

In terms of functionality, the layout of the building poses an important architectural challenge. Since it is a multipurpose building, separation of residential and academic space is essential. The new building will contain large lecture halls, residential floors, student collaboration areas, and a showcase atrium for displaying WPI project work (exact specifications and requirements can be found in Section 3.1.1). The placement of these areas is crucial in order to ensure the flow of the building. Additionally, the residential area must be secluded from the more public areas of the building to ensure safety and comfort for students. Although the scope of this project did not cover plans for HVAC, mechanical, electrical, or plumbing systems, it was important for the architectural design to consider the integration of these systems and possible issues they could cause. A few ways these issues were considered was with partition wall thickness, utility shafts spanning the full height of the building, and locating restrooms and showers for vertical alignment of plumbing.

In addition to safety considerations involving the separation of residents and visitors, it is also absolutely necessary for the building to be accessible and safe in the case of an emergency. When developing floor plans, there are a number of major factors to consider to ensure this level of safety. These include the amount of space available per person, means of egress from the building in case of a fire or other emergency, and handicapped accessibility. Engineers and architects have developed professional tools and practices to aid in determining many of these factors. Building codes cover all aspects of structural and architectural design and are in place to ensure that all buildings provide a standard of safety. The most widely accepted and commonly used building code is the *International Building Code (IBC)* [9]. The *IBC* is a model code and provides an industry-accepted baseline of standards for designers to follow for a wide array of topics. However, individual states have specific building codes that account for factors not found in other parts of the country. For example, the *Massachusetts Building Code (MBC)* [10] is the standard building code for the Commonwealth of Massachusetts and has largely adopted the *IBC* with amendments to address exceptions, such as snow loads.

The architectural portion of the code can be broken up into three components: architectural, MEP systems, and fire safety. The architectural provisions set standards for the building layout such as permissible building height and area, hallway widths, and ceiling heights, which partially contribute to egress and other fire safety standards. The MEP standards control the internal operations of the structure such as elevators, HVAC, electrical wiring, and plumbing. Fire safety standards go more in depth to control design aspects including emergency exits and systems for fire prevention and suppression. Although fire safety design fell outside the scope of this project, there are fire safety guidelines which proved valuable during the design process. For example, when modeling the building, it is necessary to ensure that all doors swing outwards instead of inwards, as a means to ensure that egress guidelines have been followed. By having one code which covers all aspects of design, the process becomes much simpler for all parties involved. Structural engineers are able to work seamlessly with architects as a result of this uniform and widely accepted set of codes and standards

2.4.2 Structural Design

There were a number of structural design issues contemplated for the duration of this project. One major aspect of the architectural design that required critical thinking involved the multiple floors of residential space located above a large and predominantly open showcase atrium. On the residential floors, the design aimed to utilize all available space by incorporating living spaces with common rooms, bathrooms, tech suites and laundry rooms. This intention to support so many people and necessities over a long span with minimal intermediate support produced large loads in the center block of the residential floors. These loads are dictated by the usage of the building as outlined in the *IBC*. The extensive spans incorporated in a large, open showcase atrium required the consideration of staggered truss or arch systems to limit the frequency of columns.

Another feature of the building that required special structural consideration is the frequent use of curtain walls in the design. Curtain walls cause loads to be carried by the structure as opposed to bearing loads themselves [11]. Placing brick walls for the residential floors above the curtain walls encompassing the entire lower south façade presented challenges in the design and demanded the consideration of brick facing or veneer instead of full bricks. Additionally, there were requirements of the foundation that called for investigation. The bearing strength of the soil on site needed to be determined to inform whether a shallow foundation system would sufficiently transfer the load from the superstructure to the subsoil, or whether piles would need to be employed [12]. Preliminary plans for the design involved curving exterior walls to give the building a sleek and somewhat modern look. Curved walls introduced multiple design challenges including wind effects and shaping of the framing to follow a smooth curve.

In order to properly analyze the performance of this structure, it was crucial to conduct several types of load analyses. The first and most basic analysis was for gravity loads which the structure will be subjected to on a regular basis. Next, wind loading on the building was considered, ensuring that the building is capable of withstanding lateral loads even in the most extreme weather. Lastly is a seismic analysis, useful for examining the effects of oscillation and vibrations in the event of an earthquake. Some of these tests may seem excessive, especially in New England where there is very limited exposure to hurricanes or earthquakes. However, these code-mandated checks ensured the stability of the structure under the worst circumstances. The *IBC* in conjunction with the *MBC* assisted in determining not only the standard loads for these situations, but also the necessary load factors and load combinations. For the design of structural components, the *IBC* references separate standards and specifications that outline the details of design using certain materials. *The American Institute of Steel Construction* (AISC) [14] manual was used for structural steel design while the published standards by American Concrete Institute (ACI) were referenced for concrete design.

2.4.3 Construction Planning

The existing Alumni Gym is located centrally on the campus of WPI. This could lead to some challenges in terms of accessing the building throughout the construction process and coordinating campus operations. The heavy flow of pedestrian traffic near the Campus Center and Higgins Laboratories (see Figure 2 below) could potentially lead to problems regarding safety. Some phases where this issue could produce a challenge are demolition, site preparation, and construction of the new building. Construction must be done adequately to protect the workers and community from hazardous conditions which could affect their health, safety and overall well-being.

Figure 2: Aerial View of Walkway between Alumni Gym and Higgins Labs, Image by GoogleMaps

The site preparation phase requires the mass movement of ground material as well as its transportation to and from the project. An issue that could arise involves the access to the area given its challenging location in the heart of campus. There are no existing roads that lead directly to this site, so alternative access methods must be proposed and built to address this issue. Additionally, excavating the foundation can be challenging since it requires protecting existing underground utilities. Another issue that arises is establishing enough laydown area for materials and prefabricated elements. The project site may not be large enough to optimize this area while limiting interruption of pedestrian traffic flow.

Naturally, the physical construction of the building poses the greatest challenge in terms of disturbing the environment of the campus. Similar to other phases, accessing the centralized building site may be difficult when transporting steel, concrete, and other larger elements of the final product. Even positioning cranes and other large equipment while protecting pedestrians is difficult. In addition, there are disconcerting impacts such as the loud noise created. Noise is a sensitive subject since many of the freshmen residential halls are located across the quad near the construction site. Construction noise could affect student's sleeping and studying habits, therefore preventing the project management team from utilizing overnight shifts to meet deadlines. Lastly, there is the issue of controlling dust created on the job site as to limit harm to members of the community. To limit the negative effects of these constraints, the team analyzed alternatives for site access from different hot spots around the campus. One potential option is from the circle located by the parking garage up behind Harrington Auditorium. Additionally, laydown area was determined for utilization throughout the project. A suitable area is the existing parking lot currently located between Alumni Gym and the Bartlett Center. Lastly, the schedule only permits work between the hours of 8:00am and 5:00pm. This caters to the daily activities of the campus.

3.0 BIM Architectural Model

The scope of work for this project involved an architectural design, structural design, and construction plan for the Foisie Innovation Studio. The architectural design was developed as a 3D computer model that displays the end state of the building, taking into consideration the aesthetics, floor plans, zoning regulations, fire safety in terms of egress, and MEP spacing requirements for the structure.

3.1 Building Intent/Architect Programming

The start of the project was based on a simple statement of intent of the actual project that was distributed to the student body by the Board of Trustees, outlining basic requirements for the design of the Foisie Innovation Studio. These requirements were:

- 76,000 GSF building
- 41,000 GSF dedicated to Academic space
- Residential space for approximately 140 undergraduate students
- Placement on current site of Alumni Gymnasium
- Enhancement of current building visibility and pedestrian accessibility

Although these details provided some valuable information, the goal was to make this design as close to the real intent of the new building as possible. Unfortunately, determining more of the school's intent proved difficult because detailed plans for the building had yet to be fully developed. After several conversations with Professors Leonard Albano and Guillermo Salazar, as well as with the Vice President of Facilities for WPI, Mr. Alfredo DiMauro, a number of additional requirements for the building were established:

- Two lecture halls to house Great Problem Seminars (approx. 70 students each)
- Area dedicated to robotics engineering program
- Tech Suites in residential space
- Additional areas dedicated to classes and offices
- Area dedicated to showcasing WPI student project work
- Maker space to foster and enable student creativity

These requirements reflect the overall goal for the building, as defined by WPI and the Board of Trustees, to highlight the innovative and collaborative skills of WPI students. With these requirements and some idea of the school's general goals for the building, an architectural vision of the building was formed. Using the vision and spatial requirements, a design was developed with defined spaces for each aspect of the architectural program. The classification of usable space for the building as designed is shown in Figure 3 below.

Residential Space				**Academic Space**			
3rd & 4th Floor	**SF**	**Basement**	**SF**	**1st Floor**	**SF**	**Mezzanine**	**SF**
Dorms	13242	Toilet Rooms	438	Toilet Rooms	540	Entrepreneurial Small Office	850
Bathrooms	2776	Hallways	3358	Robotics Lab	1968	Entrepreneurial Large Offices	1323
Common Rooms	2784	GPS Tech Suites (5)	790	Global Impact Showcase Atrium	6891	Entrepreneurial Conference Room	723
Collaborative Work Area	2362	Lecture Halls	5265	Exhibition Area	3025	Loft Viewing Area	3614
Laundry	792	Collaborative Workspace	4759	Collaborative Project Display Area	2187	Toilet Rooms	434
Janitor Closets	792	Robotics Lab	1873	Closets	424		
Hallways	9842	Maker Space Labs	1425	Maker Space	2252		
Subtotal	32590	*Subtotal*	17908	*Subtotal*	17287	*Subtotal*	6944
Residential Space Total	**32590**			**Academic Space Total**	**42139**		
						Total Usable Space	
						74729	

Figure 3: Breakdown of Usable Space

3.2 Architectural Design

Based on the outlined requirements for the project, an Architectural BIM model for the building was produced in *Autodesk Revit*. The purpose of this architectural model was to develop an intended appearance for the building, develop a plan for the interior and exterior layouts of the building, and provide an outline to allow the structural design to proceed. As the structural design progressed through various stages, the working architectural model was revised to be conducive to the placement of structural members. However, careful consideration was taken to ensure that the architectural layouts were consistent with the original spirit of the design. Continuous iterations of both models ensured cohesion between both architectural and structural layouts.

A key concept desired in the architectural design was the idea of a showcase with maximum visibility and openness. One way this idea was addressed was by designing an atrium on the main floor with a 25' ceiling. Bordered by a mezzanine level for visitors to look out over project displays (Figure 4), this atrium will be the first impression for guests entering the building. In addition to the atrium, open staircases and wide door-less entryways were included. These elements will allow visitors to flow from one area to the next with minimum interruption and maximum visibility.

Figure 4: Proposed Showcase Atrium, Rendering from Autodesk Revit

Another way the subject of visibility and showcasing student work was addressed was by including interior windows into lab spaces and a curtain wall for a glass elevator. Curtain walls along the lower levels of the south facade also allow visibility into the main academic floors of the building from the quad and provide large amounts of natural light for the interior. The curtain walls on the south facade and on each of the corners also serve as a visual link to some of the other more modern buildings located on the quad. Additionally, curved north and south facades were incorporated to create an original and innovative building outline. By curving these facades and squaring off at the corners, the building forms the shape of an I for “innovation” (Figure 5), much like Kaven Hall is shaped somewhat like a C for “civil engineering” and Atwater Kent used to resemble an E for “electrical engineering”.

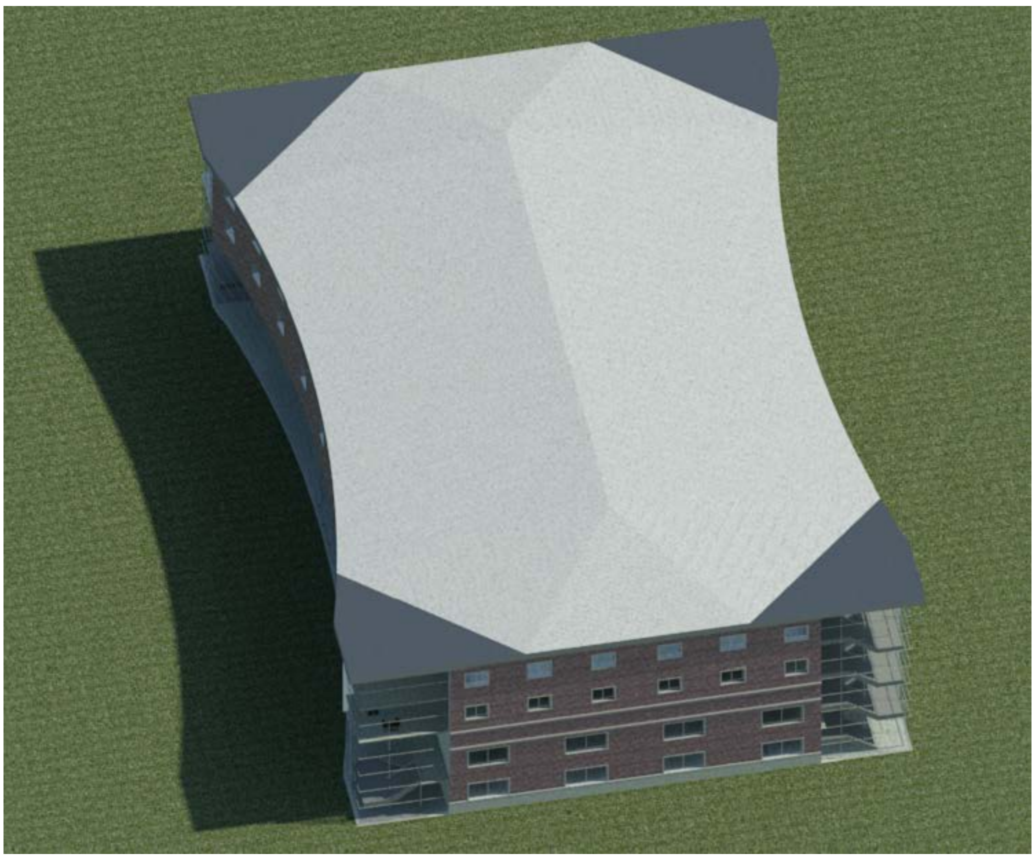

Figure 5: Proposed I-Shaped Design, Rendering from Autodesk Revit

Some more practical aspects of the architectural design include the standardized location of bathrooms on each of the lower three floors to consolidate plumbing and simplify pipe work. On the 3rd and 4th floors, the bathrooms were situated in the center block of the building so as not to waste perimeter space where dorm rooms could be located. With these bathrooms located directly above the atrium, it was determined that it would be efficient to create a pair of MEP shafts adjacent to the elevator to seamlessly link to all floors of the building. Another space requirement of MEP involves the interior partition walls. To allow for all services to travel through common partitions wherever necessary, typical partition walls have been designed for a thickness of one foot. These and other aspects of the layouts can be seen in Figure 6.

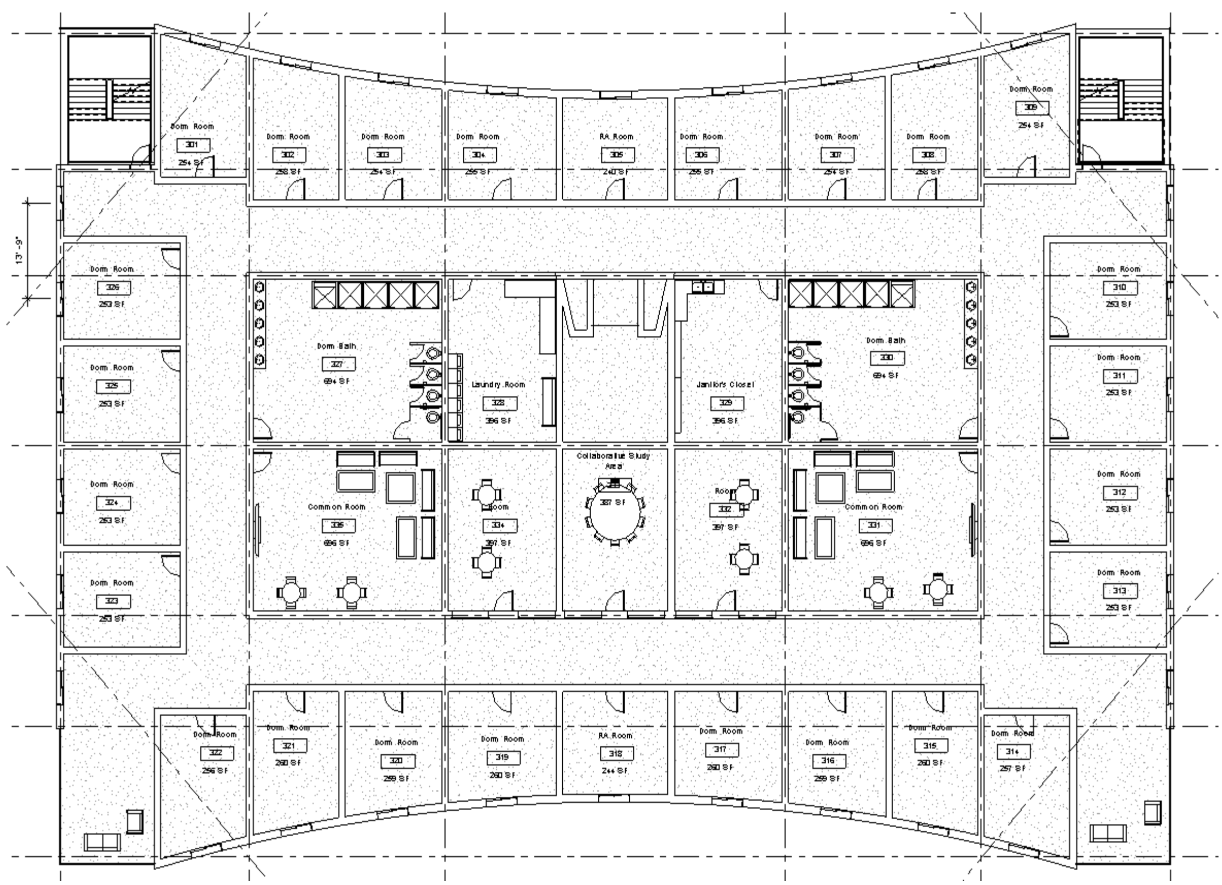

Figure 6: Proposed Residential Floor Layout, Image from Autodesk Revit

Considerations of functionality were also prevalent within the architectural design. Using dimensions of existing triples on the campus, each dorm room on the residential third and fourth floors was designed with sufficient square footage for three students. Additionally, every dorm room was designed with a window as they were placed on the perimeter of the layout. To make certain of this, common rooms, bathrooms, laundry rooms, and collaborative work areas were located in the center block of the building. The social aspect of residence halls was also considered. Since the hallways of residential floors are commonly used as gathering places for students, the design contains hallways that are 9.5' wide.

When considering functionality on the academic floors, it was determined that offices would have windows as well. On the other hand, since windows were deemed less necessary for lecture halls, tech suites, and lab spaces, these rooms were placed in the basement level. Additional floor layouts and images or the architectural design can be found in Appendix B.

3.3 Building Codes

The *International Building Code (IBC)*, and *Mass Building Code (MBC)* were used in the design of the structure to ensure that the building meets the standards set forth by the governing authorities. The building codes were referred to when designing architectural aspects such as building height and area, hallway widths, egress, handicapped accessibility, and other safety features. Some of the key factors that were followed are listed below, compared to the actual design dimensions.

Table 2: Design Specification vs. State Building Code

Factor	Mass Building Code Requirement	Proposed Design
Building height (Stories)	4	4
Floor area per story (Avg. SQFT)	25667 (Avg. between occupancies)	16506 (Avg. by floors)
Minimum stairway width (in)	44	72
Minimum corridor width (in)	44	81
Minimum dormitory room area (SQFT)	120	301

4.0 BIM Structural Model

The structural design of the building encompasses the skeletal structure including floor systems, roof systems, and vertical supports. The completed design contains plans for all supporting members, joints, and foundations in the structure. Additionally, there is an in-depth analysis of the strength and serviceability performance of the design with calculations for the gravity loads, wind loads, and seismic loads. To display these plans, a 3D *Autodesk Revit* structural model was developed to coordinate seamlessly with the architectural model. This model displays locations and sizes of the primary structural members as well as typical connections. The *Autodesk Revit* model has other purposes that are discussed later in this section.

4.1 Building Codes

The structural design of the building adheres to the 8th edition of the *MBC*. This document acts as the governing code for Massachusetts and as an amending document to the 2009 version of the *IBC*. Chapters 16 (Structural Design) and 17 (Structural Tests and Special Inspections) of the *MBC/IBC* were the primary sections used for the structural design process. Chapter 16 explains requirements of structural design and contains tables that list the live load factors for all occupancy types (defined in *IBC* Chapter 3: Use and Occupancy Classification). These factors determined the necessary strength of the framing in each part of the building. Chapter 17 outlines the necessary tests performed on the structure to ensure construction and material quality and proper execution of the design. Additionally, this chapter explains the requirements for testing in areas such as basic load resistance, wind load resistance, and seismic load resistance. Although these standards are set forth through the *IBC,* other specifications are also referenced. The common source for structural design loads is *ASCE 7-05: Minimum Design Loads for Buildings and Other Structures* [13].

While Chapters 16 and 17 of the *IBC* outline general structural design requirements, Chapters 18 through 26 provide guidance in the use of various materials in design and construction. The most important sections to note in this project were Chapters 18 (Soils and Foundations), 19 (Concrete), 21(Masonry), 22 (Steel), and 24 (Glass and Glazing). Although these chapters have some information on the requirements of the design of these materials, they primarily reference other standards and specifications. For example, the chapter on steel refers to sections of the American Institute of Steel Construction (AISC) specification that was used in the design of steel members. Therefore, these external standards were essential in the design of all components of the building.

4.2 Loads

The loading conditions for this building were determined using the *IBC* and the standards set forth by *ASCE 7-05, Minimum Design Loads for Buildings and Other Structures* [13] as well as snow, wind, and seismic loads for Worcester from the *MBC*. The minimum standards were followed in every case, but some areas were over-designed for constructability purposes. In these circumstances the members and components were initially sized to accommodate the minimum standard loads. However, final sizes were increased to make beam sizes more consistent which will, in turn, make construction easier. The live loads used for calculations are displayed in Table 2 below.

Table 3: Live Loads for Calculations, based on ASCE 7-05 Minimum Design Loads for Buildings and Other Structures

Occupancy/Use	Uniform (psf)	Concentrated (lb)
Offices	50	2,000
Classrooms	40	1,000
First Floor Corridors (others same as surrounding occupancy)	80	1,000
Roofs (flat ordinary)	20	-
Roofs (gardens or assembly)	60	-
Lobbies	100	-
Stairs and exit ways	100	-
Walkways and elevated platforms	60	-
Elevator machine room grating	-	300
Manufacturing (light)	125	2,000
Manufacturing (heavy)	250	3,000
Dormitories (Hotels and multifamily houses Private rooms and corridors)	50	-

The load conditions were defined according to LRFD standards, using 1.6L + 1.2D as the load combination for all loads within the floors of the building, and 1.2D + 1.6 (L_r or R or S) as the load combination for roof loads. For columns extending to the roof level 1.2D + 1.6L + 0.5S was the governing load combination.

4.3 Structural Grid

The geometries and dimensions of the functional spaces in the architectural model were critical in determining the structural grid of the frame. As stated earlier, through an iterative process the architectural layout was formed in a manner conducive to the placement of the vertical members in the structural grid. Using the architectural model, appropriate column locations were determined within the framework of the layout that would be non-intrusive. Establishing reasonable span lengths between these vertical members was integral to sizing members and defining spacing of floor joists. In addition, to limit superfluous material and construction time, members were spaced efficiently while still observing architectural floor thicknesses. Span lengths between columns were limited to no more than 35' in locations where common floor systems would be used. The structural grid is displayed below in Figure 7.

A primary area where columns were avoided was the showcase atrium. This created a necessity for trusses to span these larger openings. Upon placement of the columns and determination of each individual span length, the beam and girder systems were orientated with the beams spanning the shorter distances wherever possible. However, since all beam and girder systems were orientated in the same direction, beams span the longer dimension in a few instances. Utilizing the loads classified earlier, these columns, beams, and girders were sized appropriately as shown in section 4.5.

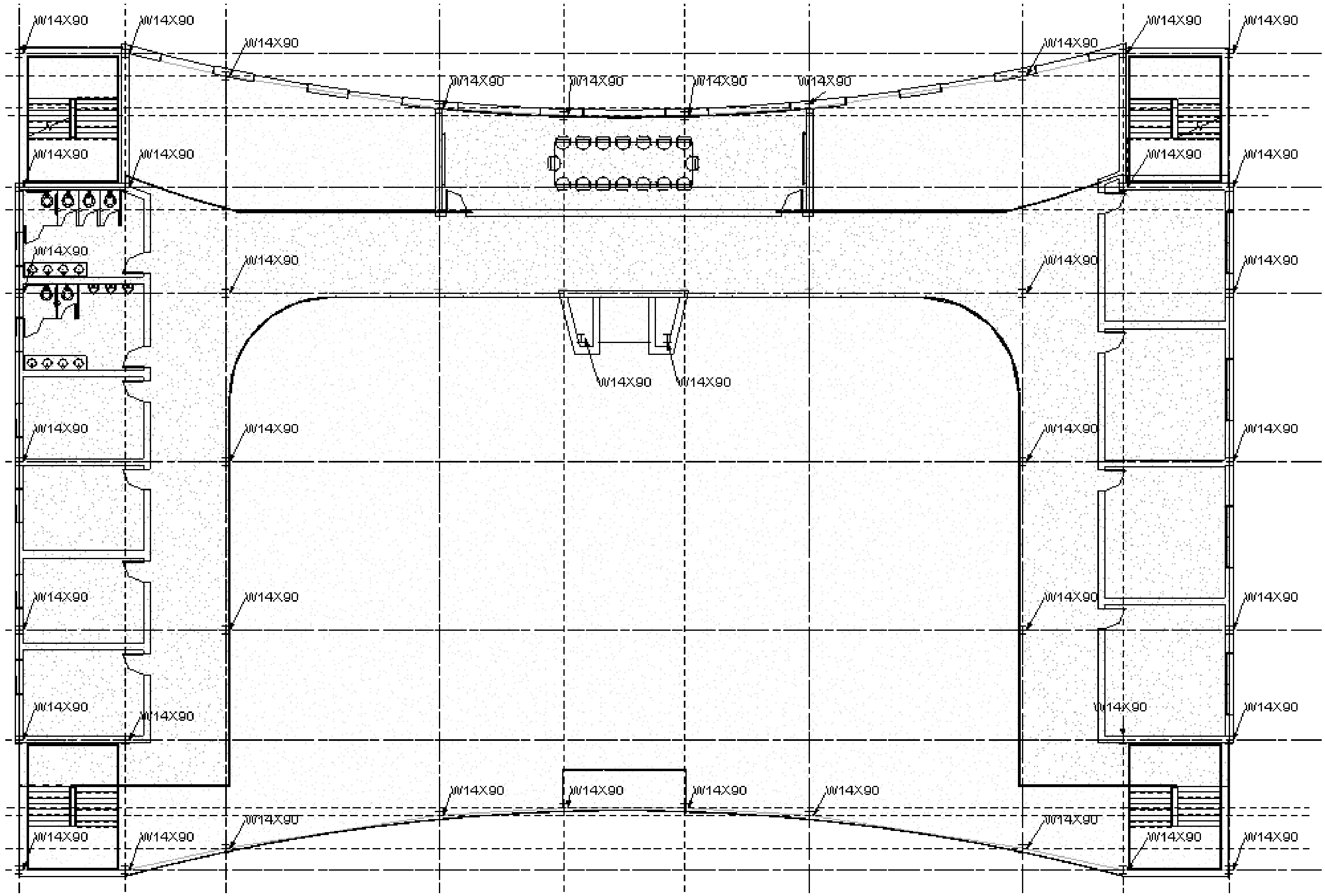

Figure 7: Structural Grid with Overlaid 2nd Floor Mezzanine

4.4 Floor Systems

Floor systems are a primary part of the structural design, and the mixed use of the building and open architectural design created challenges and opportunities in the design. The natural divide of the residential third and fourth floors from the academic lower levels led to the utilization of two different flooring systems. On the lower levels as well as the east and west sections of the residential floors where spans are shorter and columns are more frequent, a three-inch concrete slab on three-inch metal decking floor was used over a traditional steel beam and girder system. This system allowed ceiling heights to be preserved while also giving more shape flexibility. The second type of flooring system used was concrete hollow core planks supported by a staggered truss system. Both of these floor systems allowed for off-site manufacturability and provided advantages regarding flexibility in scheduling. In addition to these final floor systems a reinforced concrete alternative for the academic sections of the design was considered. Using reinforced concrete in the high foot traffic areas of the lower levels of the Foisie Innovation Studio would allow for better vibration resistance than the structural steel design, however due to the established structural grid the reinforced alternative proved to be far less efficient both in cost and

4.4.1 Joist & Girder Sizing

Member sizing on different floors demanded various considerations depending on intended use of the area below as well as story heights. For example, selecting shallow members was necessary for the mezzanine level due to a story height of 10’ with lab spaces intended for below. However, on the first and third levels, depth of the structural framing was not a critical concern because each had a 15’ story height below as seen in Figure 8.

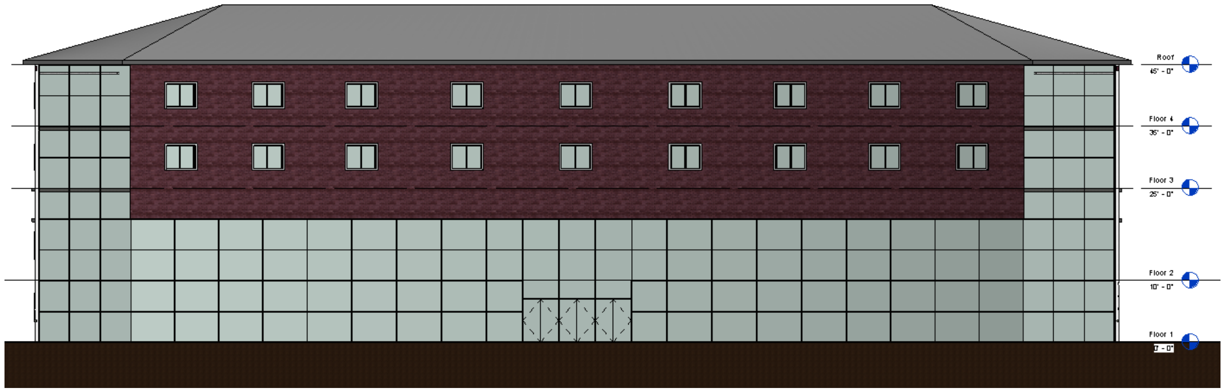

Figure 8: South Elevation of Proposed Foisie Innovation Studio, Image from Autodesk Revit

Another consideration for the framing of various floors was the number of joists and girders necessary to ensure serviceability. On every floor, there will be a significant amount of foot traffic, and it is important that the floor systems are stiff enough to not deflect noticeably. Therefore, the spacing of the beams was limited within each system, and members were designed to deflect minimally while also meeting the bending and shear requirements of the loads. One last consideration when sizing exterior supporting members was that exterior finishes, such as curtain walls and brick veneer, have differing loads. So, in certain locations throughout the building, an exterior beam could be tasked with supporting one finish below and another finish above.

The structural members of the building were designed in many phases, beginning with joists, then sizing exterior beams, then progressing to girders. Each member system was designed for bending using the designed spans from the column placement, the loads for each span and occupancy, and a determined tributary spacing. Once the member was sized based on required bending moment capacity, the *AISC Steel Construction Manual* [14] was consulted to check that the size met compact section criteria and calculated the deflection of the beam under dead and 50% live loads using the equation:

Equation 1: Deflection

$$\Delta = \frac{5wL^4}{384EI}$$

This calculated deflection was then compared to the serviceability limit of deflection using span length (L)/ 360 with a max allowable deflection of 1 inch. If the calculated deflection eclipsed the serviceability deflection, a larger beam size was selected. This process was iterated until the joist had acceptable deflection. Due to the earlier determined spacing of joists, the loads on each joist were relatively small and thus the deflection criteria often governed the member size. Upon completion of the deflection check, a check of the beam's shear capacity was conducted to complete safety. Using the following LRFD relationships for shear capacity and maximum shear formulas, it was verified that the each member satisfied the *AISC Specification* for shear:

Equation 2: Shear Force

$$V_u = w_u \ * \frac{L}{2}$$

Equation 3: Shear Capacity

$$\phi V_n = \ \phi A_w C_v (.6F_y)$$

Samples of these calculations can be found in Appendix D. Once the beams were sized appropriately, the next step was to standardize the sizes to aid constructability and manufacturability of the design. Thus sizes that were infrequent were increased to the next frequently used size. The sizes used on each floor can be seen in Table 4 below:

Table 4: Joist Sizes Used Per Floor

Floor	Joist Sizes Used
1st	W12x26, W18x35, W18x40
Mezzanine (2nd)	W12x26, W12x53, W12x106
3rd	W12x16, W16x31
4th	W12x16, W12x50

Following the finalization of joist sizes, the girders were sized using the same process while keeping in mind that for the practicality and ease of connection, each girder had to be at least as deep as the beams that would be connected to it. Also, in the case of the girders, the weight of the beams that bear on them was included in the load combination equation. The member sizes used for the girders can be seen in Figure 9. The framing plans of the second floor mezzanine and third floor can be seen below in Figures 10 and 11.

<Structural Usage>

A	B	C
Structural Usage	Family and Type	Count
Chord	W-Wide Flange: TRUSS PH	58
Girder	W-Wide Flange: TRUSS PH	4
Girder	W-Wide Flange: W12X16	69
Girder	W-Wide Flange: W12X26	57
Girder	W-Wide Flange: W12X50	10
Girder	W-Wide Flange: W12X53	8
Girder	W-Wide Flange: W12X79	6
Girder	W-Wide Flange: W12X106	12
Girder	W-Wide Flange: W12X170	2
Girder	W-Wide Flange: W14X30	16
Girder	W-Wide Flange: W16X31	20
Girder	W-Wide Flange: W18X35	10
Girder	W-Wide Flange: W18X40	14
Girder	W-Wide Flange: W21X44	12
Girder	W-Wide Flange: W24X68	12
Girder	W-Wide Flange: W24X84	8
Girder	W-Wide Flange: W30X99	2

Figure 9: Girder Schedule with Sizes and Counts, Image from Autodesk Revit

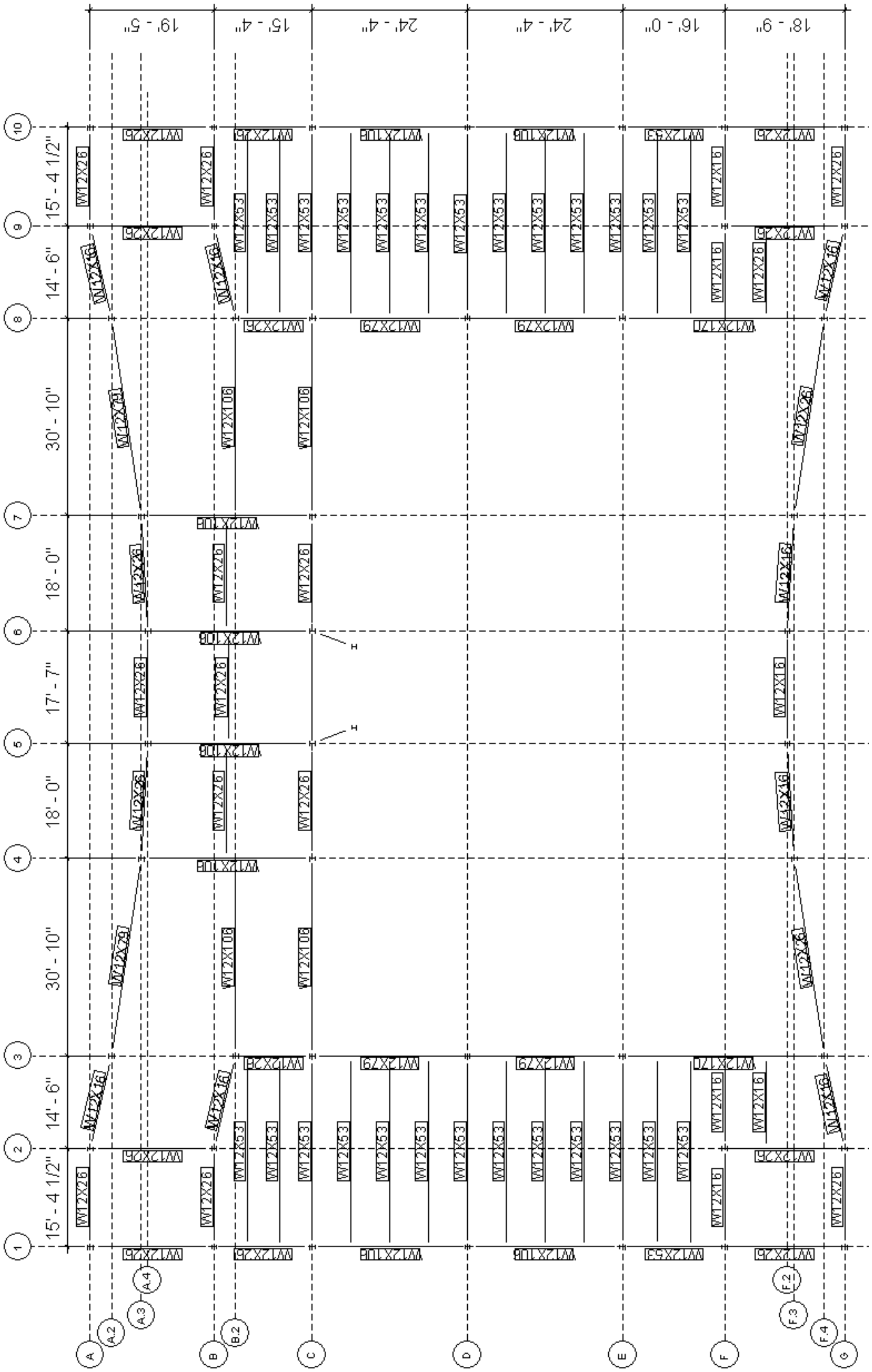

Figure 10: 2nd Floor Mezzanine Framing Plan, Image from Autodesk Revit

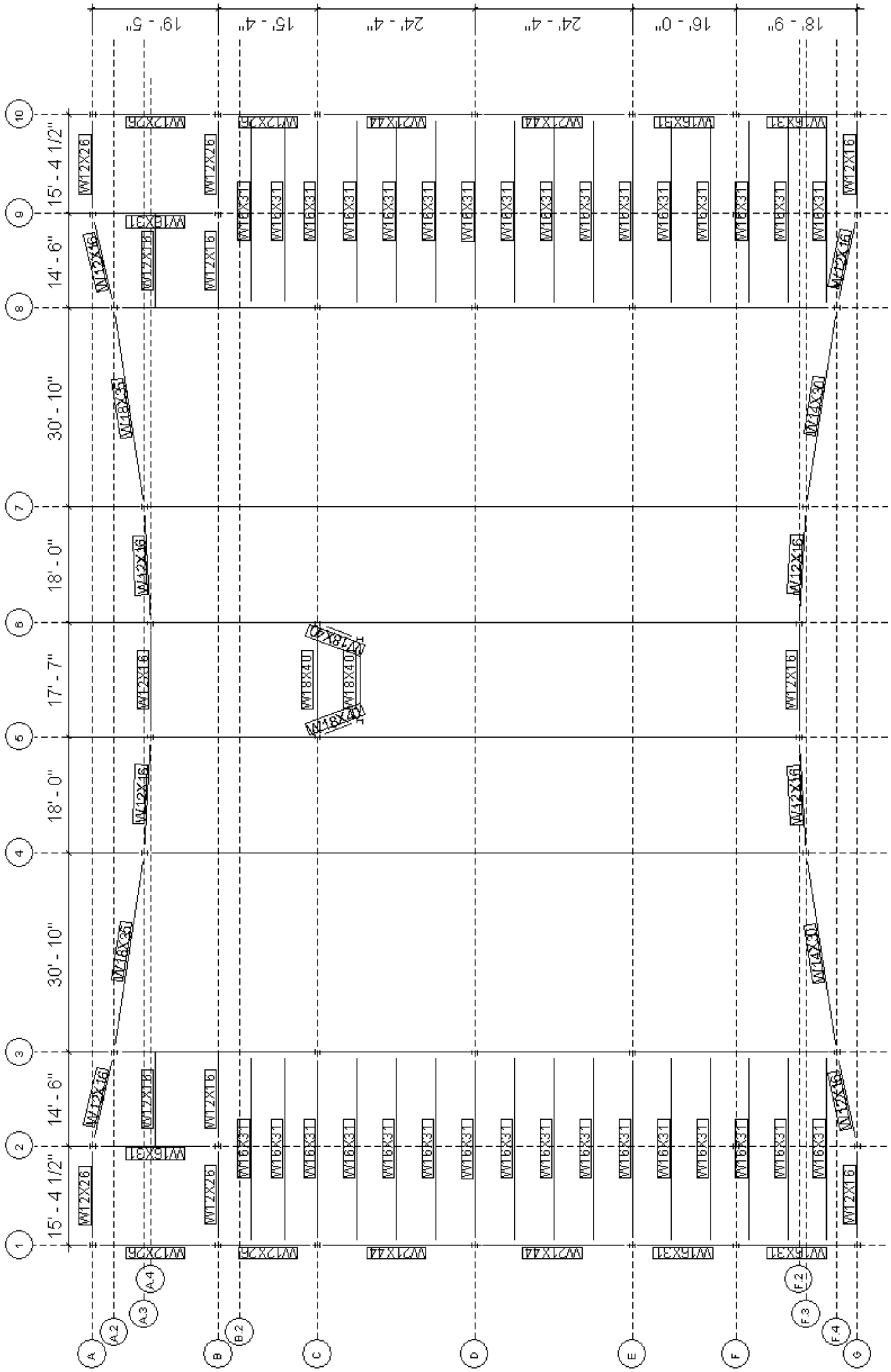

Figure 11: 3rd Floor Structural Framing Plan, Image from Autodesk Revit

Additional structural framing plans and images can be found in Appendix C.

4.4.2 Staggered Truss System

The use of a staggered truss system allows several advantages over a classic beam and girder set up. Staggered trusses allow for large open spaces and flexibility which is ideal for the architectural layout of this design. The constructability of these systems has proven to be much more effective due to their simple nature and ability to be assembled off site. Therefore, this system seemed to be a great option to use within the center portion of the proposed design.

The system works by using Pratt trusses in a staggered position in order to minimize the amount of supports needed. The geometry of a Pratt truss was selected because it is able to effectively sustain loads on both its top and bottom chords and the diagonal members are in tension, leaving the shorter vertical members in compression. This allowed for a lighter distribution of steel members, as steel members offer greater strength in tension. The truss carries loads in both the top and bottom chords from the floor at the level of the truss and the floor at the next level above (as can be seen in Figures 12 and 13).

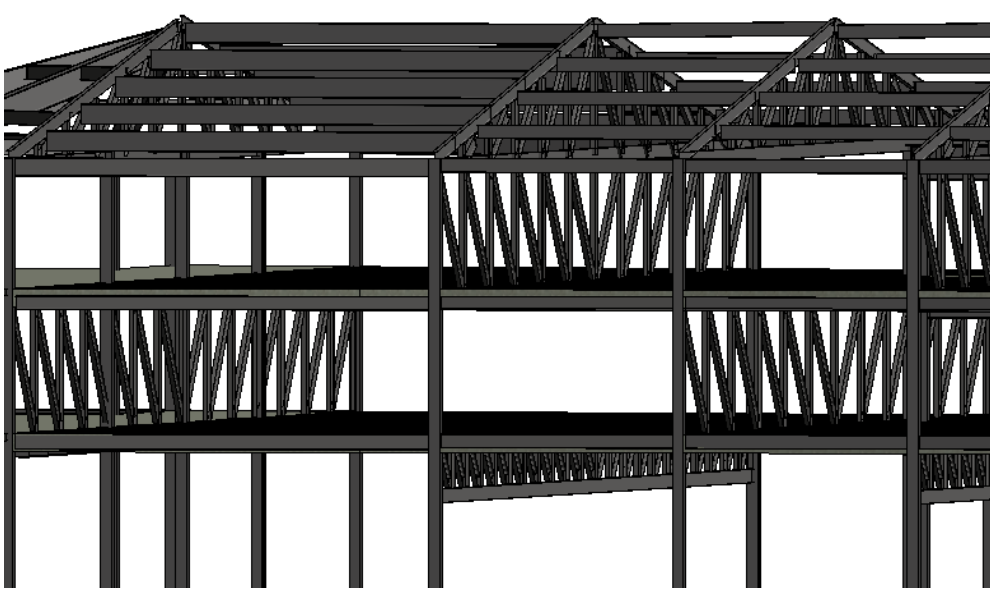

Figure 12: Staggered Truss System, Image from Autodesk Revit

Due to the layout of the building, the hallways run through portions of the trusses because the trusses are hidden in the walls, therefore a solution had to be developed so that the trusses could meet these constraints. A mixture between a Pratt truss and a Vierendeel truss was developed in order to allow space for the hallways to pass unhindered (as can be viewed in Figure 13). The only significant difference with this design was that the connections for the members in the Vierendeel panels had to be designed with moment-resisting joints in order to maintain a stable truss system.

The spans between trusses are supported by a concrete system known as hollow core plank. The plank is precast in the factory and comes in a variety of sizes to hold a wide range of loads over different spans. These floor systems can be used for spans of up to 60’ between trusses. This system is also very effective because many of the components can be assembled in steel mills and concrete factories which allow for quick erection on the construction site. Most parts of the system can be delivered and installed in a short amount of time. Manufacturers claim that up to 3500 square feet of hollow core plank can be installed in one day [15].

The use of a staggered system instead of traditional methods was an easy decision. The design of this system was not much different than that of any other truss systems. The biggest difference was that loads for two floors were carried by each truss. Some loads being carried were very significant and required large members, which proved to be a challenge to design the truss so that it could fit within the walls of the building. There were eight different truss designs developed for varying lengths and depths depending on the location of the truss.

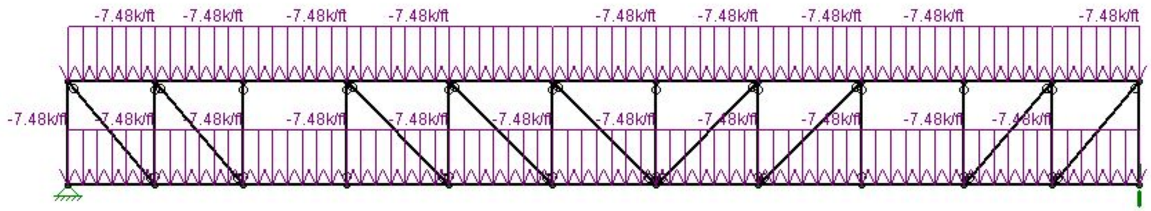

Figure 13: Proposed Vierendeel Truss, Image from Risa-2D

The trusses were modeled in *RISA 2D Software* in order to perform an analysis of the internal forces in each member. The model was made as simply supported with pinned fixtures for the connections, with the exception of the Vierendeel panels which required moment-resisting connections. Once the internal forces for each member were determined, they were designed to standard based on if they were in tension or compression. Members were sized using *AISC Steel Construction Manual,* Parts 4 & 5 for design of compression members and design of tension members. Vierendeel sections were designed using Part 6 of the manual for combined flexural and axial forces [14].

The hollow core plank was designed based on the sizing chart provided by the manufacturer for the thickness needed to support the loading conditions and span of the design [15]. It was determined that 10” thick plank would be needed to support the loading conditions across the span between trusses. The manufacturers advertise that the sizing tables are accurate but the actual size of the planking would be designed by their engineers. The dimensions and loading conditions for the trusses are as follows:

Table 5: Dimensions and Loading Conditions for Trusses

Length (ft)	Height (ft)	Tributary Width (ft)	Loading* (K/ft)
24	10	30	5.31
31	10	30	5.32
100	10	18	3.62
104	10	18	3.62
112 (Gable)	9	30	2.23
104 (Gable)	9	24	3.14
100 (Gable)	9	24	3.14
24	5	30	5.36
31	5	30	5.32
50	5	18	4.81
100	5	42.5	3.16

(*Loading uses the load conditions for the corresponding floors of the building with LRFD combination 1.6L+1.2D, 1.6 (L, R, or S) + 1.2D for gabled roof trusses)

The biggest concern in the design for compression is buckling due to the slenderness of a member. Therefore, the most important parameter for selecting members (using AISC Table 4-1 [14]) is the KL factor, K being an effective length factor and L being the length of the member. K is the coefficient that converts a given column and boundary conditions into an equivalent Euler Column, (*K Factors found in AISC Specification Appendix 7*). The K factors used for the selection of members for these truss systems was 1.0 for all members as outlined in Chapter 4 of the *AISC Steel Construction Manual* [14]. The design strength of each member ($\phi_c P_n$) was calculated by dividing all forces found in the *RISA* analysis by 0.9 (ϕ_c).

The design of tension members was performed using AISC Table 5-1 [14]. All members were demonstrated to satisfy conditions for both yield and rupture strength to negate any failures in the system. The design strength of each member ($\phi_t P_n$) was calculated by dividing all forces found in the *RISA* analysis by 0.9 for yield strength and .75 for rupture strength (ϕ_t).

For constructability purposes, members were grouped based on their strength requirements and two series of members were chosen that satisfied the needs of the design, one set of sizes for tension members and another for compression members. A range of design strengths were assigned to each size W shape beam that would be used in the design. W14 shapes were chosen for consistency. Moreover, W14 sections seemed to offer the lightest members for the required strength required when performing a preliminary member selection. The selected member sizes used and their available strength values are displayed in the tables below.

Table 6: Compression Members in Trusses

Member Sizes	Available Strength (Kips)
W14x48	475
W14x82	910
W14x109	1340
W14x132	1620
W14x159	1970
W14x176	2180
W14x193	2560
W14x211	2680
W14x233	2960

Table 7: Tension Members in Trusses

Member Size	Available Strength (Kips)
W14x38	410
W14x61	650
W14x99	1060
W14x120	1290
W14x145	1560
W14x159	1710
W14x176	1900
W14x233	233

The practice of categorizing member sizes rather than fitting sizes to each individual member greatly enhances the constructability and design process of the system. Although it may cost more in materials, the truss assembly becomes much simpler when each truss follows a similar pattern in member sizes, and all the sizes are similar in geometry. It also sped up the design process because rather than referring to the tables on every member there was already a predetermined size for each load condition. It also saved a lot of time with checking designs, because many of the members were designed to withstand much more load than is required, and not much time was spent redesigning members that fail checks.

4.4.3 Reinforced Concrete Alternative

Using reinforced concrete in the high foot traffic areas of the lower levels of the Foisie Innovation Studio would allow for better vibration resistance than the structural steel design; however, due to the established structural grid the reinforced alternative proved to be far less efficient both in cost and floor depth. The structural grid required the consistent use of a beam-slab system with the slabs acting as one-way slabs based on the long rectangular bays. As a result of the bay sizes, the beam sizes were rather large and the slabs were far thicker than the three-inch slab on three-inch decking of final floor design. With the thicker slabs and large beam sizes, it was determined that reinforced concrete was not an appropriate alternative to fit the architectural design and the established structural grid. The preliminary design work for the reinforced concrete alternative can be found in Appendix E.

4.5 Roof Design

The roof was designed as a system of gabled trusses in conjunction with connecting beams to support loads that the top of the building may encounter. These gabled trusses were designed in the same process as the staggered truss system, with the exception of the use of Vierendeel panels for the latter. The basic loading combination used when analyzing member forces was 1.2D + 1.6 (L_r, R, or S). Due to the high annual accumulation of snow in the city of Worcester, snow was the dictating load in design which was 55 PSF, as set forth by the *MBC*. Other considerations that were used in the calculation of dead loads were shingles, MEP, metal decking, ceiling, and sheathing. The roof was designed to have a 10.2° pitch, where the trusses rise 9 feet in the center; this would provide adequate runoff for rain water or accumulated ice and snow.

Most of the design for this system was very standard, however distributing the loads to the corners of each building proved difficult at first because of the span from the top of the last truss in the series to the corner of the building.

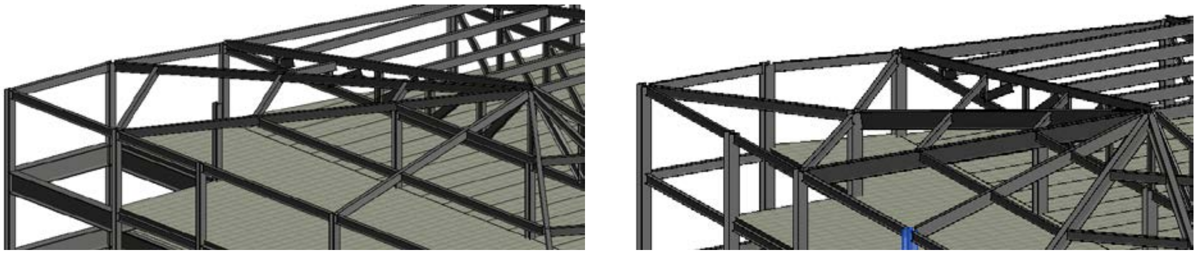

Figure 14: Roof Hip Alternative to Shorten Span, Image from Autodesk Revit

After several alternatives were reviewed it was determined that placing columns at the corners of the stairwell sufficiently shortened the span of the hip support (Figure 14). This span reduction greatly reduced the required size of the hip supports. The four corners of the building were designed to have no pitch, this was for design and constructability purposes. Where the north and south facing walls are curved, it proved more efficient to eliminate part of the pitched portion of the roof in order to keep the majority of the system square rather than designing a curved system for the roof as well. Rather than having excess water and snow runoff at the corners, a drain system will lead to the gutters along the sides of the building.

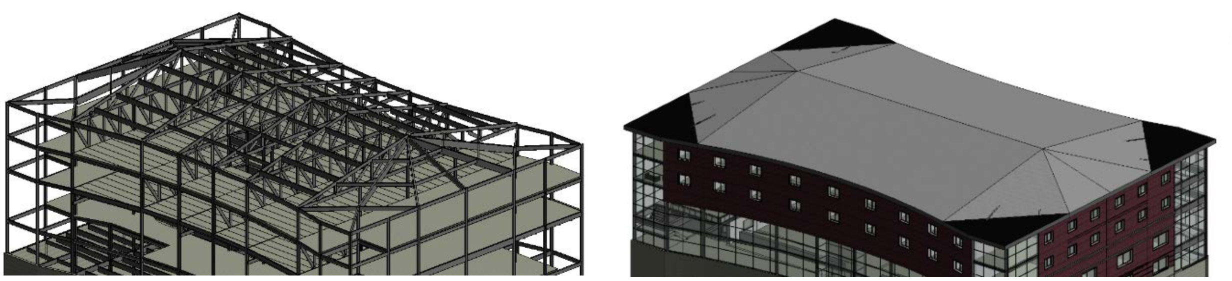

Figure 15: Structural and Architectural Representation of the Roof, Image from Autodesk Revit

4.6 Lateral Load Analysis

Upon completion of the BIM structural model, a structural analysis was performed using *Autodesk Robot*. This program allowed for testing of seismic and wind loads to be performed on a model of the building's frame. The frame was designed to be a rigid structure to avoid the need for additional support for the building. The frames for the building are made up of the exterior walls, two frames for lateral stability in each direction (North/South and East/West). The frames running from North to South are comprised of 7 columns, while the East to West frames are made up of 10 columns. Each frame was modeled separately rather than a model of the entire lateral-load resisting system. This is because it is much simpler to model and analyze one frame at a time. In order to analyze the lateral loading effects in both the North/South and East/West directions, separate models were made of the frames that span those directions. Due to the varying load paths of the wind analysis, both models had to be constructed in 3D.

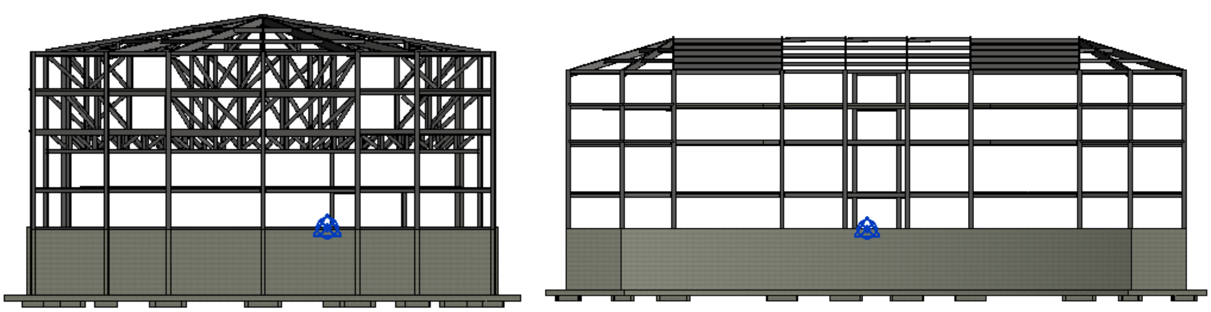

Figure 16: Structural Representation of East & South Wall Framing Systems, Image from Autodesk Revit

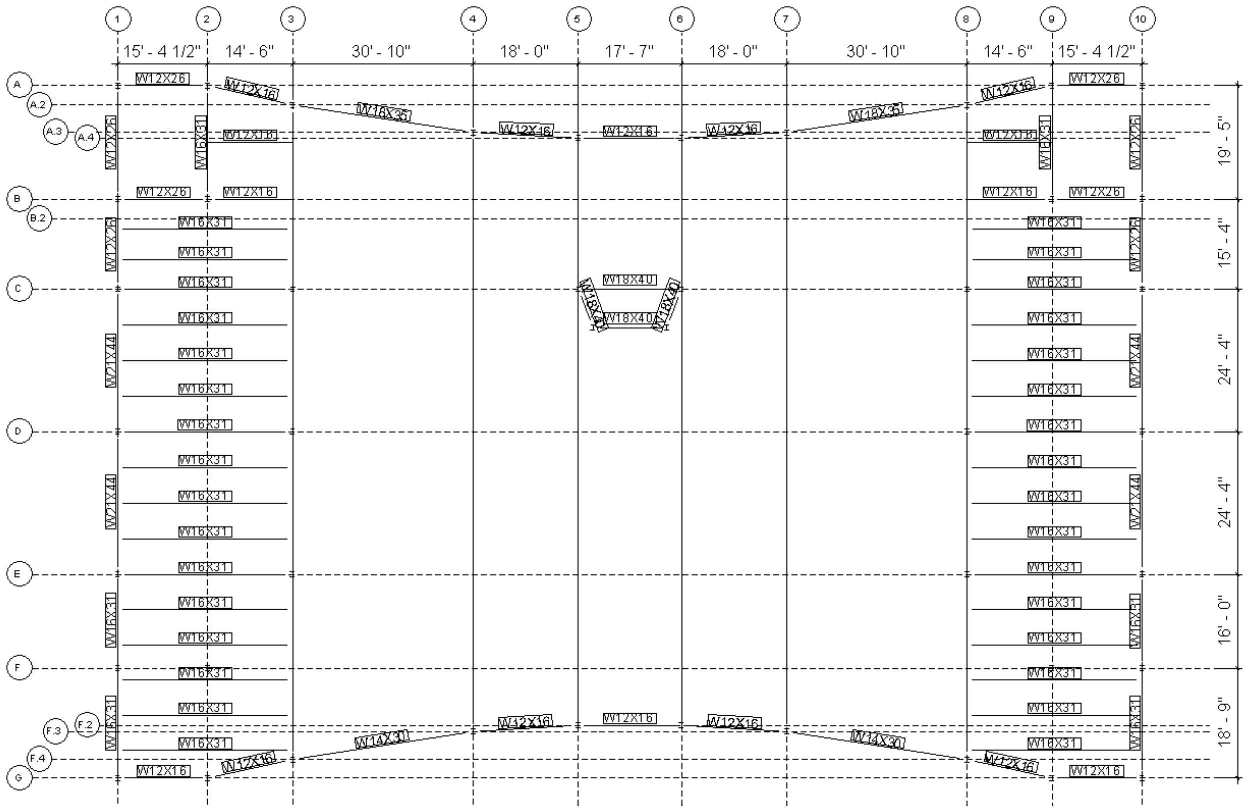

Figure 17: Plan View of Framing System, Image from Autodesk Revit

The wind analysis was conducted for the Main Wind Force Resisting System, using the method for buildings of any height as outlined in *ASCE 7-05* [13] in accordance with the *MBC*. This method essentially examines the effects of external pressures produced by wind loads on the frame in four different "cases". Case 1 examines the forces perpendicular to the face of the frame being examined. Case 2 applies both a perpendicular force to the frame coupled with translational moment around the corners. The third case involves applying forces in both the X and Y directions. The fourth case examines the effects of all three forces acting on the building at the same time. The wind forces were based on building dimensions, roof type, surrounding conditions, and wind speed (found in *MBC,* identified by city).

The Seismic analysis was similar to the wind analysis; however, it was much simpler because it did not involve varying cases and conditions. The shear force for each story of the building was calculated based on the dimensions and total weight of the building, as well as the spectral response acceleration values for the city of Worcester (found in the *MBC*). This produced a shear force that could be applied to the base of the building in order to simulate the effects of an earthquake on the frame. The results of both the seismic and wind analyses were used to perform a second-order analysis in order to check the stability of the columns for excessive lateral translation due to either lateral forces or moments.

Autodesk Robot is capable of performing P-Delta Analyses in order to observe the effects of combined lateral and gravity loads. This was used to draw conclusions on the frame's design and determine any flaws. The software was used to identify the columns in the frame that would accumulate the most stress due to lateral forces. Since all the columns were designed to be the same size (more detail to follow in *4.7 Column Design*), only the global extreme values from the model were examined. The member subjected to the highest translational moment and axial force was selected for further analysis to confirm sufficient stability.

4.7 Column Design

Finally, upon completion of all horizontal spanning members, column sizes were calculated, first using axial compressive strength and then by investigating their capacity for combined bending and axial forces using interaction equations in chapter H of the *AISC Specification*. The columns were analyzed as part of a rigid frame, and a few key assumptions were made to determine the effective length factor K:

- Behavior is purely elastic
- All members are prismatic
- All Joints are moment resisting
- Joint resistance is proportional to I/L for members
- All columns buckle simultaneously

A preliminary size for each column was calculated using the available strength in axial compression found in Table 4-1 of *The AISC Steel Construction Manual* [14] compared to the Pu value calculated from totaling the loads from the girders acting on each column. A top-to-bottom approach was employed when sizing the columns to account for loads throughout the structure. Once the axial load was calculated and a few sufficient column sizes were identified, the column with the lowest r_x/r_y ratio was selected for stability in both axes. Then to standardize the sizes a W14x90 was selected for each column. Following a structural analysis of combined gravity and lateral forces based on the preliminary W14x90 size, the columns were checked for combined bending and axial force using the following interaction equations:

Equation 4: Interaction Equation H1-1a

$$\frac{P_r}{P_c} \geq 0.2 : \frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0$$

Equation 5: Interaction Equation H1-1b

$$\frac{P_r}{P_c} < 0.2 : \frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0$$

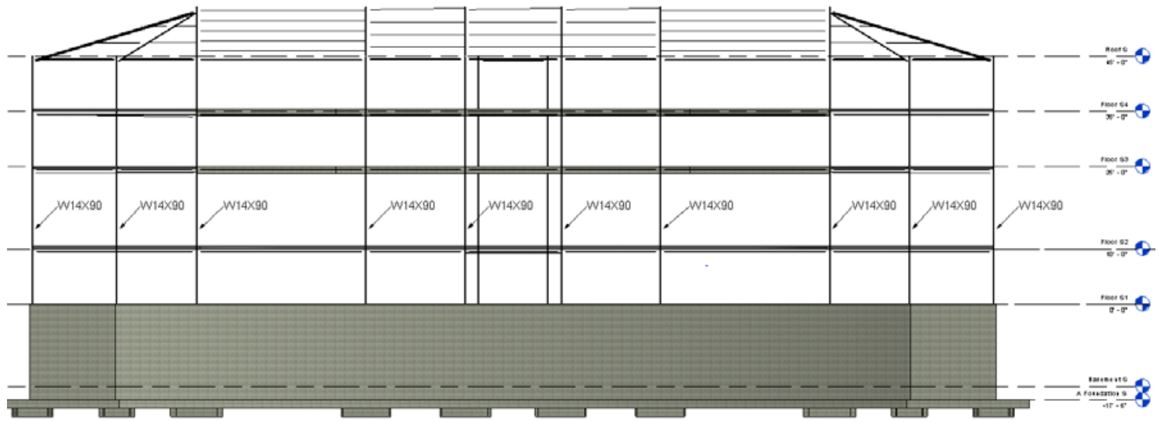

Figure 18: South Elevation of Steel Framing, Image from Autodesk Revit

4.8 Connections

In both the steel truss systems and the overall superstructure, bolted connections were used to connect members within the truss, beams to girders, and girders to columns. For practicality, one typical beam-to-girder connection and one typical girder-to-column connection were designed based on a range of loading conditions. The number of rows, plate sizes, and bolt sizes necessary to account for the forces acting on the girders and columns were determined using techniques outlined in *Structural Steel Design* [16]. Connections for the Vierendeel truss panels were determined to be full penetration welds which would be fabricated by the manufacturer prior to truss assembly.

For the beam-to-girder connections a single angle shear connection was used. The single angle allows for easy field assembly as the angle will be bolted to the girder off-site and then the beam will be attached in place. Using A325-N, ¾" diameter bolts, the following processes and checks were used to determine the number of bolts and angle thickness of a sufficient connection:

- Required # of bolts based on Bolt shear capacity
- Connection Stability
- Bolt Bearing on Angle (Tear out vs. Bearing):
- Angle Shear Rupture
- Angle Shear Yield
- Block Shear Rupture of Beam (for coped flanges)
- Tension Rupture of Beam (for coped flanges)
- Shear Yield of Beam
- Bolt Bearing on Beam Web
- Bearing on the Girder Web

For an example of these calculations refer to Appendix D. The beam-to-girder connections typically did not need to withstand large forces and were often governed by connection stability equation:

Equation 6: Connection Stability

$$T \geq L_A \geq \frac{T}{2}$$

Where L_A is the length of the single angle and T is a detailing property of the supported beam found in Table 1-1 of *The AISC Steel Construction Manual* [14].

To ensure the connections were stable an additional bolt was added and the angle was lengthened. This was even more critical for deeper beam sizes such as W16x31. The following table shows the beam size (nominal depth), the required number of bolts, and the thickness of the angle.

Table 8: Beam-to-Girder Connection Requirements by Beam Size

Beam Size (nominal depth)	# of Bolts Required	Angle Thickness
W12x	2	3/8”
W16x	3	1/4”
W18x	3	1/4"

An additional concideration was that some beams would require coped flanges in order to reach the web of the girders. This was the case when the beam and the girder were the same depth as shown in Figure 19. To aid in field constructability the plates will be shop bolted to the girders as denoted by the red through lines in Figure 19.

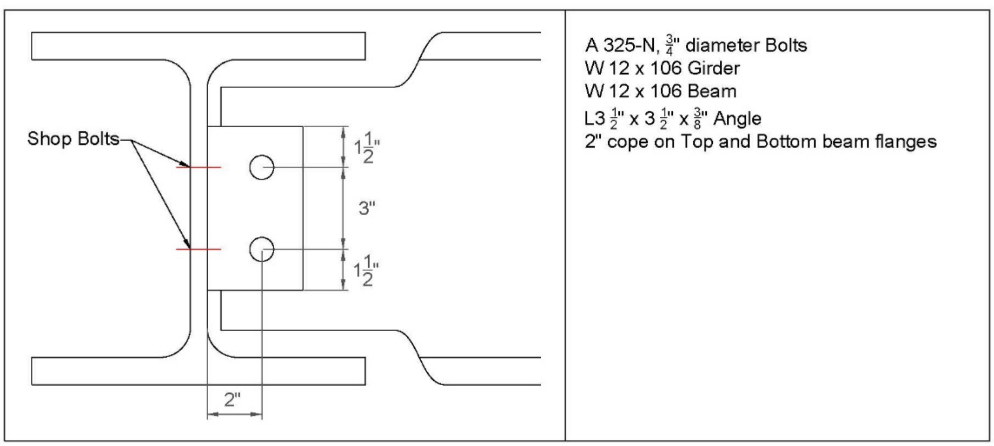

Figure 19: Typical Beam-to-Girder Connection with Coped Flanges

The girder-to-column connections utilized double-angle shear connections with bolted flange plates to resist moment. Although a double-angle connection typically would utilize coped flanges for ease of field assembly, the moment resisting aspects of the connection require the flanges to remain un-coped. The same processes and checks were performed for these connections as for the beam-to-girder connections, only substituting the girder for the beam and the column flange for the girder web. Due to the larger loads carried by the girders these connection were not typically governed by the stability equation, and thus the number of bolts is more related to the shear forces. Table 9 displays the required number of bolts and angle thickness for ranges of shear force.

Table 9: Girder-to-Column Connection Requirements by Shear Force

Shear Force	# of Bolts Required	Angle Thickness
0 – 71.56 *[kips]*	2	1/4”
71.56 – 107.34 *[kips]*	3	5/16”
107.34 – 143.12 *[kips]*	4	5/16”

Though it is important to note that in a few specific cases the girders were still governed by the length of the angle and thus the same process of adding a bolt was used. This is the case in Figure 20. This sample calculation can be referenced in Appendix D.

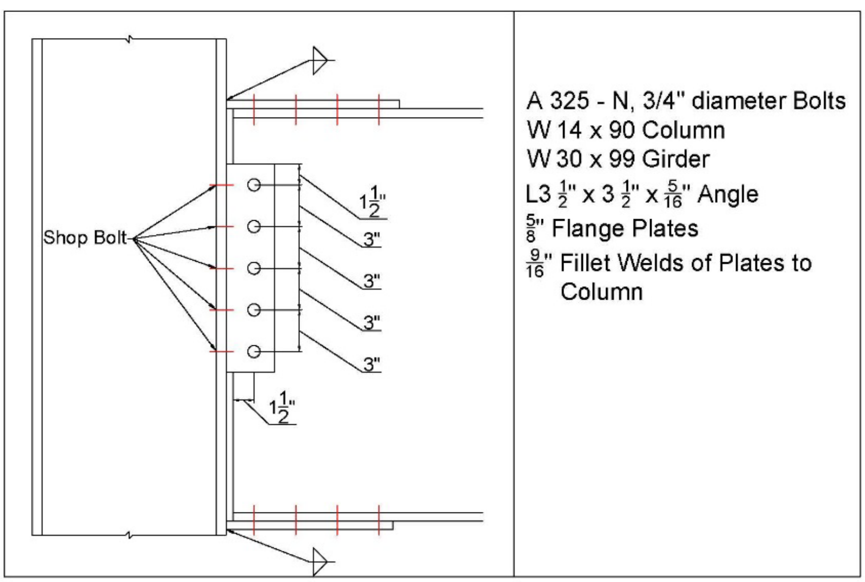

Figure 20: Typical Girder-to-Column Connection with Coped Top Flange

4.9 Base Plates & Footings

The substructure, also referred to as the foundation, was included in the structural design through the design of base plates and spread footings for the columns. The purpose of a foundation is to transfer the loads of the building to the subsoil below. The subsoil was determined to have a bearing strength of 8 ksf by a geotechnical study [12] which the foundation has to match in order to prevent excessive total and differential settlement. In the case of this project, the WPI campus has glacial till, which is a strong soil and doesn't require a deep foundation system. To match the bearing strength of the subsoil below, strip footings on the foundation walls and spread footings on the columns were used. Additionally cantilever retaining foundation walls were utilized to benefit constructability in the early stages of construction. This wall detail permits heavy construction equipment and construction materials to be placed in the vicinity of the foundation wall prior to the framing of the first floor level. Accommodating these large overburdens adjacent to the foundation walls will conserve space in areas where strict site restrictions exist.

The base plates for the columns were established by first calculating a minimum area A_1 based on both the bearing strength of the concrete footing and the column factored load P_u. Next, using the higher of the column property db_f and dA_1, the minimum dimensions of the plate N and B were calculated. These dimensions were then used to calculate the actual A_1 value. Then the corresponding bearing stress in the concrete footing was used to determine the thickness of the plate *t.* Due to all of the columns being W14x90 and for the sake of practicality, the base plates were a consistent 16" x 16" with varying thicknesses. By selecting square plates and using a square arrangement of anchor bolts, field and shop work were simplified. Table 10 displays the thickness based on ranges of the factored column load P_u. Sample calculations can be found in Appendix D.

Table 10: Base Plate Thickness by Factored Column Load

Factored Column Load P_u	Plate Thickness
81.7 – 183.9 *[kips]*	3/4”
183.9 – 326.9 *[kips]*	1”
326.9 – 510.7 *[kips]*	1 1/4”
510.7 – 735.5 *[kips]*	1 1/2"
735.5 – 1001.0 *[kips]*	1 3/4"

The concrete footing sizes were obtained by calculating the allowable soil pressure and the maximum service load P. The allowable soil pressure (S) was calculated to be 7.255 ksf for a footing 36 in thick. Then using the footing area equation a minimum was calculated. Finally, the dimensions of the footing were determined from the minimum footing area. Table 11 displays selected footing sizes based on the maximum service load. Additionally, an engineering sketch of the smallest footing case can be seen in Figure 21.

Table 11: Concrete Column Footing Sizes by Range of Maximum Service Loads

Maximum Service Load P	Footing Sizes
0 – 261.2 *[kips]*	6’ x 6’ x 3’
261.2 – 464.3 *[kips]*	8’ x 8’ x 3’
464.3 – 725.5 *[kips]*	10’ x 10’ x 3’

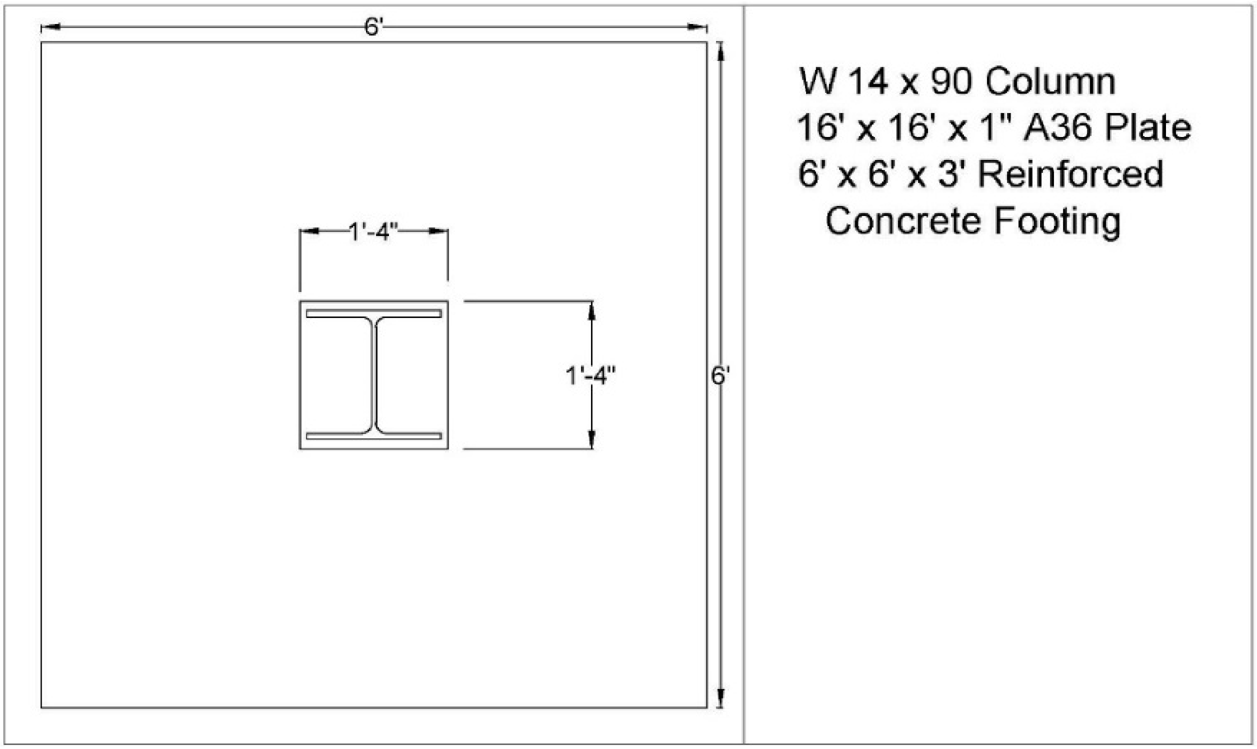

Figure 21: Engineering Sketch of Typical Column Base Plate

5.0 Construction Scheduling

In order to verify the feasibility of this proposal within the constraints set by WPI President Laurie Leshin in a campus-wide email on October 14th 2015, the team set forth to create a schedule for the construction of the building. With the start and end dates for construction defined, the activities necessary to complete the building were identified and arranged in a logical sequence, which was presented as a network diagram. The Critical Path Method, which is a network-based scheduling approach, was then used to assemble this information and to determine the critical activities for the execution of the project. .

5.1 Identification of Activities

A number of web sources were consulted to acquire foundational knowledge about the construction process and the range of activities that are involved in erecting a building of this nature. This information was organized using the Construction Specifications Institute (CSI) classification system for design (Uniformat) and construction (Masterformat) work. Having first consulted the Masterformat standard, Uniformat was ultimately settled upon as a means to organize activities. While Masterformat organizes activities based on materials and trades, Uniformat arranges construction information based on functional elements or parts of a facility without regard to the materials and methods used to accomplish them. Uniformat's approach to organizing data is also important to the continued development of Building Information Modeling (BIM) software, as its system organization allows objects to be placed before their properties have been further defined.

As shown in Figure 22 on the next page, the ASTM Uniformat II Classification for Building

Elements organizes by three different levels. The levels are Major Group Elements (Level 1), Group Elements (Level 2), and Individual Elements (Level3).

ASTM Uniformat II Classification for Building Elements (E1557-97)

Level 1 Major Group Elements	Level 2 Group Elements	Level 3 Individual Elements
A SUBSTRUCTURE	A10 Foundations	A1010 Standard Foundations A1020 Special Foundations A1030 Slab on Grade
	A20 Basement Construction	A2010 Basement Excavation A2020 Basement Walls
B SHELL	B10 Superstructure	B1010 Floor Construction B1020 Roof Construction
	B20 Exterior Enclosure	B2010 Exterior Walls B2020 Exterior Windows B2030 Exterior Doors
	B30 Roofing	B3010 Roof Coverings B3020 Roof Openings
C INTERIORS	C10 Interior Construction	C1010 Partitions C1020 Interior Doors C1030 Fittings
	C20 Stairs	C2010 Stair Construction C2020 Stair Finishes
	C30 Interior Finishes	C3010 Wall Finishes C3020 Floor Finishes C3030 Ceiling Finishes
D SERVICES	D10 Conveying	D1010 Elevators & Lifts D1020 Escalators & Moving Walks D1090 Other Conveying Systems
	D20 Plumbing	D2010 Plumbing Fixtures D2020 Domestic Water Distribution D2030 Sanitary Waste D2040 Rain Water Drainage D2090 Other Plumbing Systems
	D30 HVAC	D3010 Energy Supply D3020 Heat Generating Systems D3030 Cooling Generating Systems D3040 Distribution Systems D3050 Terminal & Package Units D3060 Controls & Instrumentation D3070 Systems Testing & Balancing D3090 Other HVAC Systems & Equipment
	D40 Fire Protection	D4010 Sprinklers D4020 Standpipes D4030 Fire Protection Specialties D4090 Other Fire Protection Systems
	D50 Electrical	D5010 Electrical Service & Distribution D5020 Lighting and Branch Wiring D5030 Communications & Security D5090 Other Electrical Systems
E EQUIPMENT & FURNISHINGS	E10 Equipment	E1010 Commercial Equipment E1020 Institutional Equipment E1030 Vehicular Equipment E1090 Other Equipment
	E20 Furnishings	E2010 Fixed Furnishings E2020 Movable Furnishings
F SPECIAL CONSTRUCTION & DEMOLITION	F10 Special Construction	F1010 Special Structures F1020 Integrated Construction F1030 Special Construction Systems F1040 Special Facilities F1050 Special Controls and Instrumentation
	F20 Selective Building Demolition	F2010 Building Elements Demolition F2020 Hazardous Components Abatement

Figure 22: ASTM Uniformat Classification, Image from National Institute of Standards and Technology [17]

There are eight Major Group Elements: General Conditions, Site Work, Substructure, Shell, Interiors, Services, Equipment and Furnishings, and Special Construction and Demolition. Considering these eight Major Group Elements created an umbrella under which any necessary activities for the project could be organized. These Major Group Elements are divided into smaller Group Elements (Level 2). For example, the Shell Major Group is divided into Superstructure, Exterior Enclosure, and Roofing. By carefully examining the Level 2 elements and considering the proposed building design and plan for construction, a base of activities to start was established.

With this activity breakdown to work from, similar construction projects from both the past and present were examined in order to identify Level 3 elements applicable to the construction of the Foisie Innovation Studio. Some of the first sources consulted were Major Qualifying Projects from previous years. One of the more relevant projects, titled “Design of the New WPI Residence Hall” [18] focused on the construction of East Hall; one of WPI’s more recently constructed residential buildings. Constructed in 2008, East Hall “provides apartment-style housing and an eco-friendly environment for about 230 upperclassmen” and showcases WPI’s movement toward sustainable design [18]. While the Foisie Innovation Studio is not designed solely for the purpose of housing students, many construction activities were determined that would overlap for the two projects. In addition to these overlapping elements, it was important to consider activities that would only apply for the academic component of the building, such as the installation of equipment for the robotics engineering lab, or lecture hall furnishings.

Included in the 2008 MQP is the construction schedule for East Hall which provides a list of activities [18] as well as durations for a multitude of elements. This schedule proved extremely helpful as parallels could often be drawn between the Foisie Innovation Studio and East Hall, despite differences regarding the specific layout and usages of the two buildings.

5.2 Determination of Durations

In addition to examining the aforementioned East Hall construction schedule, other sources were utilized to determine durations for the already identified activities. One of these sources was a construction simulation video [19] for a new 50-million dollar wellness center at Worcester State University. The video shows the entire completion of the building from start to finish, and timestamps allowed for a better understanding of how long common activities would take for a building of this scale.

For activities with the highest level of design detail, such as the erection of structural steel, it was possible to perform a calculation to obtain a more specific estimate for the activity's duration. For example, according to RS Means, a crew of 8 people working 56 labor hours per day, one linear foot of steel can be erected in 0.072 labor hours [20]. This calculation for a segment of steel in the proposed design for the Foisie Innovation Studio is shown below.

- 1 Linear Foot / 0.072 hours = 13.89 Linear Feet per crew per labor hour
- 13.89 Linear Feet / labor hour * 56 labor hours = 777 Linear Feet per day
- Among the 12 segments of structural steel in the design (4 Eastern, 4 Central, 4 Western) are roughly 19,000 linear feet of structural steel (average 1600/segment)
- 1600 LF / 777 LF per day = 2.06 days per segment
- A rate of 3 days per segment was defined for the schedule to account for the steel being erected in the winter in Worcester, MA

Using these productivity rates, it became possible to acquire a specific duration for each section of steel to be erected. Table below illustrates how durations were determined by type of activity.

Table 12: Duration Estimation Breakdown

Type of Activity	Duration Estimation Source
Site Prep / Foundation	Worcester State Simulation
Structural Steel Erection	RS Means Calculation
Enclosure, Services, Furnishings	East Hall Schedule

More than any other phase of the scheduling process, common sense and careful judgement was relied upon in order to determine durations for the nearly 200 activities comprising the Foisie Innovation Studio construction schedule. While references served to provide a reasonable first estimate, each individual construction project is different and therefore presents different challenges. The ultimate goal was to provide realistic estimates that would also respond to the fast pace and deadline communicated by President Leshin.

5.3 Determination of Precedence and Order

The construction simulation video [19] for the Worcester State Wellness Center also proved most advantageous for determining the precedence and order of activities for construction scheduling. The time-lapse video provided by W.T Rich Company starts with site preparation, continues with foundations, and concludes with the enclosure of the building. Beyond watching this time-lapse video, a visit was made to a construction site in Worcester, where Skanska was constructing a new building for the Worcester Regional Transit Authority. Listening to those charged with the project and observing their progress provided insight into which tasks would be complete at a certain stage of the project, and also shed light on some techniques for scheduling real-world projects.

5.4 Input of Information into Primavera

In order to organize the construction schedule in the most concise and visually appealing manner, Oracle's *Primavera* software was utilized. *Primavera* was chosen from a group of scheduling software available at WPI due to its ease of use and its industry-wide popularity. The first step in the process was to create a new project for the Foisie Innovation Studio. After the project had been established, all of the individual activities which had been identified were added to the schedule, along with their respective durations. The next step in *Primavera* was to establish the precedence of activities, or the network diagram. The network diagram could be formed through a couple of strategies. First, by clicking on an activity, the user is able to choose activities from a list and identify if they proceed or follow the chosen activity. Perhaps the simpler option is to draw arrows from one activity to the next, showing precedence in the network diagram provided by *Primavera*. After listing all precedence in the project and giving each individual activity its place in the network diagram, the "Schedule" button can be used. This button first determines the critical path, which identifies the "critical" activities. Critical activities are those with no "float", which means that any delay in their completion will cause a delay in the completion of the overall project. Activities which have a float of greater than zero can be delayed for a certain amount of time without impacting the project's completion. The "schedule" function also served to provide start and end dates for each activity and the project as a whole**.** This process was completed multiple times over the course of the project in order to incorporate new knowledge about the construction process and refine the schedule as much as possible

5.5 Final Critical Path and Key Portions of Diagram

The figure below displays the final network diagram for the project. This network diagram shows the overall sequencing for all 200-plus project activities and demonstrates how sections of the project flow together. Activities along the critical path are shown in red.

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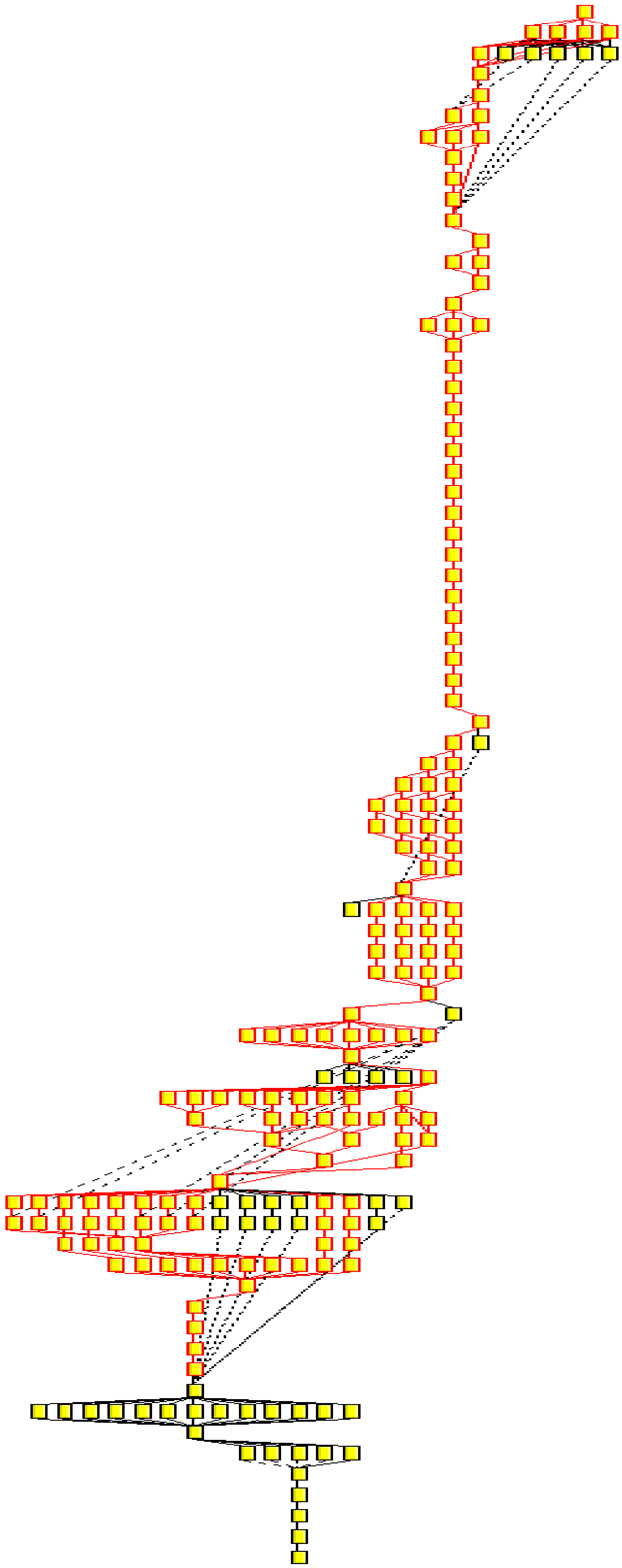

Figure 23: Final Critical Path, Image from Primavera

The below figures are included to display sequencing for some key areas in the building's construction. Many of these areas are located on the critical path, and thus timely completion of these activities will be crucial to the project's success.

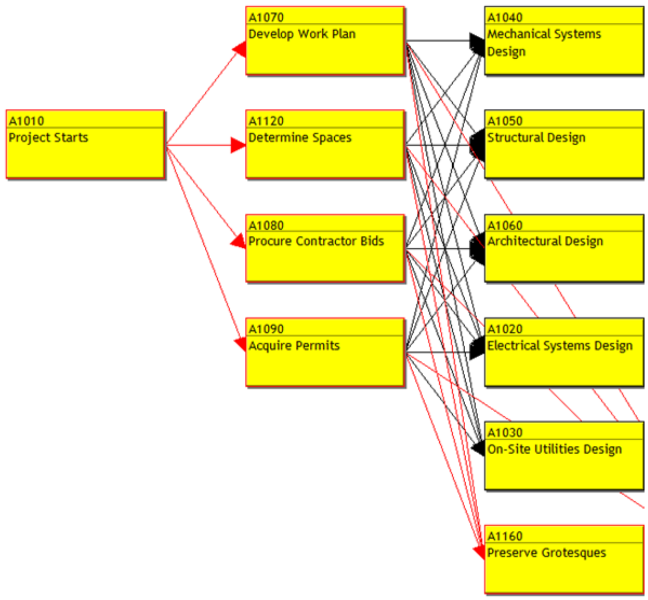

Figure 24: Project Management and Design Activities after Project Start, Image from Primavera

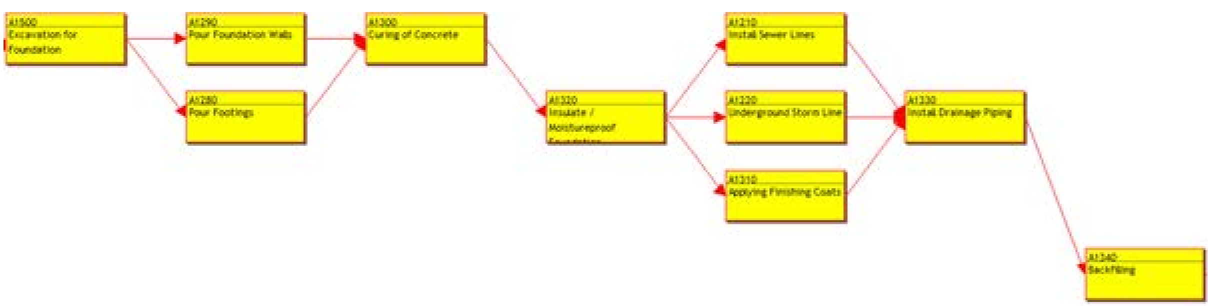

Figure 25: Foundation Construction, Image from Primavera

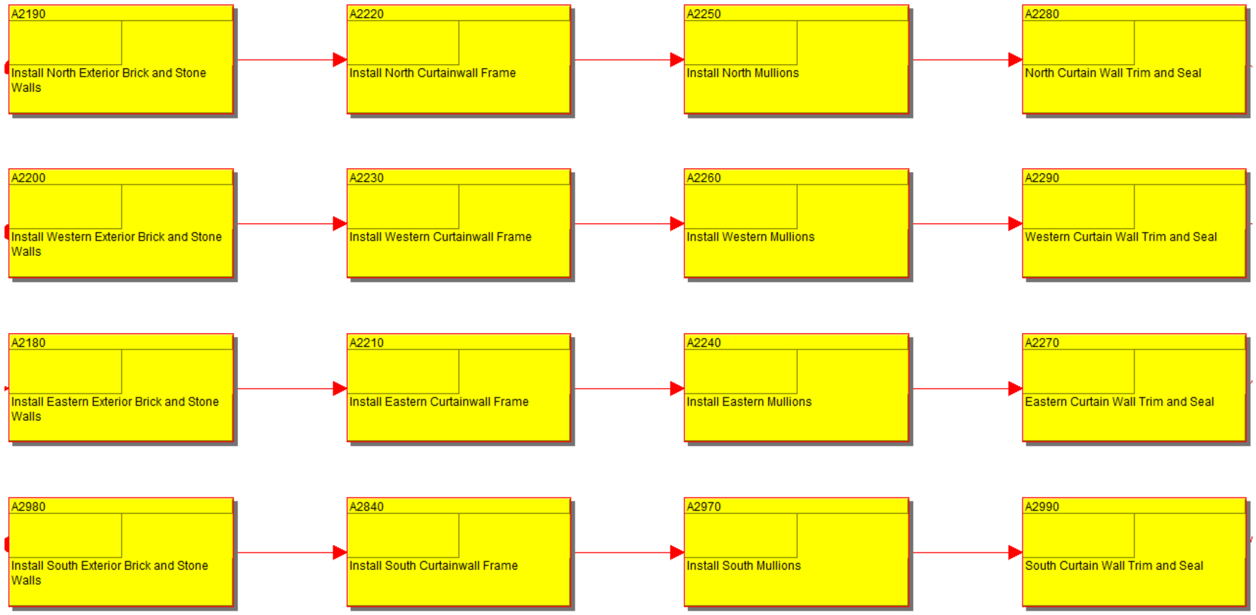

Figure 26: Construction of Exterior Walls, Image from Primavera

6.0 Cost Estimating

While the architectural model, structural model, and schedule were being completed, estimating the cost of construction began. As previously discussed, a hybrid approach was used to determine the total cost based on the type of unit installation to be estimated. This involved a level of detail analysis that determined the accuracy of the estimate. There are three classes of cost estimating with progressively less detail that were used: Class A, B, and C. Class A uses a detailed breakdown of labor, materials, and equipment with exact unit prices. This was utilized for the structural model takeoff. Class B uses building component format with composite unit pricing. This was used for the architectural model takeoff. Class C is solely a cost per square foot summarizing building components based on historical data. This was used for demolition, site work, and building services.

To aid in calculating cost estimation information, a Microsoft Excel spreadsheet was developed that organized each element based on how the cost was determined and displayed values for the appropriate units of measure, such as quantity, weight, or volume. This was beneficial when performing the cost estimating calculations and determining the cost of the construction activities. The spreadsheet helped organize the unit prices of each element so they could be assigned to construction activities in the schedule. Table 13 below illustrates the approach to estimating the different types of building systems.

Table 13: Cost Estimating Approaches

Building System	**Approach**	**Comments**
Earthwork	Cost ($)/square foot of site area	For excavation and site prep
Foundation	Cost ($)/cubic foot of concrete	Footings, foundation wall, basement floors
Structural Steel	Cost ($)/member	Based on member size and weight
Flooring	Cost ($)/square foot of floor	Based on floor type
Exterior Walls	Cost ($)/square foot of exterior wall	Brick wall, curtain wall
Interior Walls	Cost ($)/square foot of interior wall	Double sided, steel stud drywall
Ceilings	Cost ($)/square foot of ceiling	Matrix and foam tiles
Roofing	Cost ($)/square foot of roofing	Shingles and EPDM
Fixtures	Cost ($)/unit	Toilets, elevator, furniture
Windows	Cost ($)/window	Depending on size and type
Doors	Cost ($)/door	Depending on size and type

6.1 Unit Cost Method

For the majority of building features, quantity takeoffs were used to retrieve the design information from the Revit model. The quantity was then multiplied by the unit price from the *RSMeans 2014* database to establish cost. This process involved using the schedules created by the BIM model to ascertain information such as unit quantity and size. For structural features, such as steel beams, concrete, or curtain wall, the exact size of the elements was known, so the quantity and unit price were used to calculate the cost per linear foot.

6.2 Square Foot Method

For activities and features associated with demolition, site work, and building services, the square foot costs provided by *RSMeans 2011* was utilized and multiplied by the square footage of the building. Since design work in these fields was not performed, the square foot method proved to be the most efficient means of estimating the cost. While the level of detail may be lower, given the scope of the project, estimating these features using square footage was more suitable.

6.3 Cost Analysis Alternatives

In an effort to “double-check” the total cost estimate, three separate calculations with different levels of detail were developed. First, the total footprint of the building was utilized and multiplied by a cost factor in *RSMeans 2011* based on the type of exterior wall and framing used. Figure 27 below illustrates the calculation to determine the construction cost.

RSMeans 2011 sheet is a preliminary double check for the cost estimate of the building. It is based on the RSMeans 2011 Square Foot Cost book and uses the total square foot cost of typical buildings based on the structural framing and exterior wall type. The square footage of each building type was multiplied by its respective cost per square foot to calculate the cost estimate. This is an example of a Level C cost estimate.

RSMeans 2011				
		SF	Cost/SF	Cost
p. 102	College Classrooms (2-3 stories)	31687	$194.00	$6,147,278.00
p. 104	College Dorm (2-3 stories)	35466	$190.60	$6,759,819.60
p. 108	College Lab	6293	$295.70	$1,860,840.10
p. 158	Laundromat	1584	$300.00	$475,200.00
p. 174	1 Story Office	7500	$225.00	$1,687,500.00
		82530		**$16,930,637.70**

Figure 27: Total Square Foot Method, Image from Microsoft Excel

Next, the cost was quantified for each division by square foot, increasing the level of detail. For example, cost per square foot to install HVAC systems in a college classroom is $19 [20].

Figure 28 below illustrates how building components were subdivided and priced. The total cost includes a time factor to escalate the price to 2016.

Square Foot sheet is a preliminary double check for the cost estimate of the building. It is based on the RSMeans 2011 Square Foot Cost book and uses the square foot cost of typical building components. The square footage of each building type was multiplied by its respective cost per square foot to calculate the cost estimate. This is a more detailed Level C cost estimate.

College Classrooms	SF **31687**			**Office**	**7500**			**College Dorms**	SF **35466**		
		Cost/SF	Total Cost			Cost/SF	Total Cost			Cost/SF	Total Cost
Substructure	Standard Foundation	$0.63	$19,962.81	Substructure	Standard Foundation		$0.00	Substructure	Standard Foundation	$1.95	$69,158.70
	Slab on Grade	$2.49	$78,900.63		Slab on Grade		$0.00		Slab on Grade	$1.65	$58,518.90
	Basement Excavation	$0.14	$4,436.18		Basement Excavation		$0.00		Basement Excavation	$0.06	$2,127.96
	Basement Walls	$1.47	$46,579.89		Basement Walls		$0.00		Basement Walls	$1.21	$42,913.86
TOTAL	$10,909,348.46										
	$2,727,337.12										
	$1,090,934.85										
	$14,727,620.42										

Figure 28: Square Foot Method, Image from Microsoft Excel

Finally, to most accurately estimate the cost of construction, a hybrid approach of unit cost for features designed either architecturally or structurally and square foot cost for demolition, site work, and building services was completed, as outlined above in sections 6.1 and 6.2. This allowed for an estimate of internally designed work.

6.4 Calculating Total Cost

The construction cost includes the cost of transportation, installation, and completion of each building feature. After totaling those costs, to scale the project properly, a location and time index was used to account for the geographic and inflation factors. Figure 29 below illustrates a summary of the construction cost estimate. This cost is consistent with the value displayed in Figure 27, demonstrating a high level of accuracy succeeding the double check.

Level 1: Major Group Elements	Level 2: Group Elements	Cost
A. Substructure	A10 Foundations	$327,227.25
	A20 Basement Construction	$719,348.00
B. Shell	B10 Superstructure	$2,268,007.27
	B20 Exterior Enclosure	$1,365,397.95
	B30 Roofing	$40,555.20
C. Interiors	C10 Interior Construction/Finishes	$1,009,695.75
	C20 Stairs	$300,595.00
D. Services	D10 Conveying	$65,000.00
	D20 Plumbing	$1,725,028.45
	D30 HVAC	$1,279,996.80
	D40 Fire Protection	$290,455.91
	D50 Electrical	$1,800,338.35
E. Equipment & Furnishings	E10 Equipment	$213,044.00
	E20 Furnishings	$759,986.00
F. Special Construction & Demolition	F10 Special Construction/Site Work	$1,227,717.59
	F20 Selective Building Demolition	$112,500.00
01 21 61-Cost Indexes	Total	$13,504,893.52
Location	1.107	
Inflation	1.132	
	CONSTRUCTION COST	**$16,923,306.19**

Figure 29: Summary of Construction Cost, Image from Microsoft Excel

To calculate the total project cost, costs associated with designing, permitting, contracting, and managing, or soft costs, were added. Based on *RSMeans 2014*, this required adding 33% of the construction cost; 25% for general contractor fees and 8% for architect fees. This produced the final total project cost of $25 Million. Given the total square footage of the building is roughly 82,500 SF, the total cost per square foot is $300/SF, comparing consistently to standard academic-residential projects of this type and size.

7.0 Construction Simulation - 5D Model

After completion of the schedule and cost estimates along with architectural and structural models, the 5D model was prepared. While a CPM network and Excel documents do a fine job of documenting schedules and cost estimates, they do not illustrate this information in a visual and comprehensive manner. A 5D model allows both the owner and all parties working on the project to visualize how the building will come together and the earned value of each element or phase as construction progresses. In this project, the 5D model is a simulation that starts from a fully prepared site and concludes with the finished building.

With the first three dimensions of the process having been established (length, width, and height of the building from the 3D BIM model), the next dimension to be incorporated was time. Autodesk's *Navisworks Manage* was utilized to create a model simulating the construction process over time, starting with a structural shell of the building, and gradually adding all other structural and architectural elements. As these elements accumulate in the simulation, the software also displays a number representing the earned value for the building based on its actual progress as it compares to actual progress; that is to say, it illustrates how each additional element adds to the cost and value of the building. This simulation has been made as thorough and in-depth as possible, and it allows the user to easily visualize how each phase contributes to the overall completion of the process.

7.1 Phasing of Revit Models

The first step before creating the 5D model in *Navisworks* was to organize elements from the architectural and structural BIM models into phases of construction. By completing this task, the selection of individual elements would be much simpler when it came time to finalize the simulation. Phasing elements in *Revit* is a fairly straightforward process, as one simply needs to select a building element and assign it to the corresponding phase in which the element is built. *Revit* also allows the user to select all similar elements in the project, so it is often not necessary to select and assign elements too many times for an individual phase. Phases for the architectural model include Demolition, Site Work, Foundation, Concrete Slabs, Stairs, Exterior Walls, Utilities, Partitions, Doors and Windows, Interior Finishes, and Furnishings. As shown below in Figure 30, the structural model is broken into phases including Eastern Pod Steel, Central Pod Steel, Western Pod Steel, and Roofing. Once these phases have been created in *Revit*, the models can be exported to *Navisworks* for the creation of the 5D model.

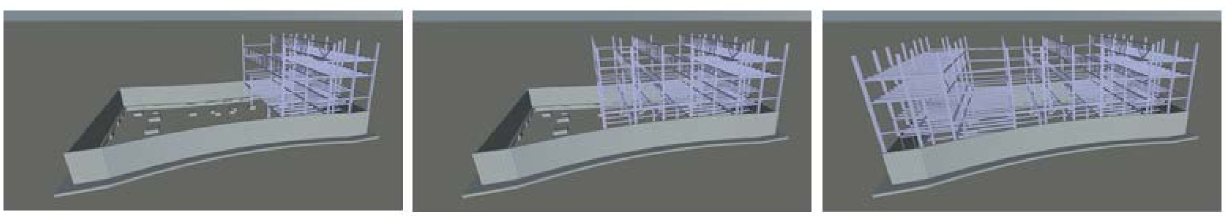

Figure 30: Breakdown of Structural Steel Pods, Image from AutodeskNavisworks

7.2 Importing Models into *Navisworks*

When phasing for both the structural and architectural models had been completed, the models were imported separately into a shared *Navisworks* file. The files were already linked in *Revit* to make work easier, but had to be imported separately for the purpose of the *Navisworks* simulation. This task was accomplished by opening one of the models in the file, and then appending the other file onto it. Since the BIM models were created on the same footprint, all elements lined up correctly and with no clashing. After importing the models, the user can visualize how the building will look with structural and architectural elements in the same view (shown below).

Figure 31: Foisie Innovation Studio Rendering of the Integrated Structural and Architectural Models, Image from Autodesk Navisworks

As shown in Figure 32 below, a clash-detection can be performed in *Navisworks* in order to identify any problems of compatibility between the elements contained in the two *Revit* models. While many clashes were found between the two models, they were caused by discrepancies between the comprehension levels of *Revit* and *Navisworks*, and not by spacing issues.

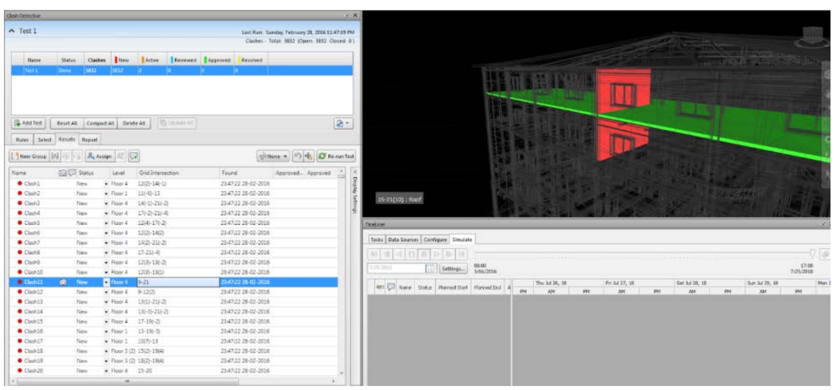

Figure 32: Clash Detection test, Image from Autodesk Navisworks

7.3 Importing Schedule and Cost-Estimates

With the 3D spatial and object representations added into the *Navisworks* model, it was necessary to add the fourth and fifth elements of cost and time. Both of these dimensions were added by linking the *Primavera* schedule to the *Navisworks* model. For reasons of compatibility, it was first necessary to convert the *Primavera* file to an MPX (*Microsoft Project*) file before importing. After this step was completed, the MPX file was imported, complete with scheduling and cost data, into the *Navisworks* file. Cost data can also be added directly into the *Navisworks* model, if preferred. When this was completed, the schedule appeared in the timeline section of the model as illustrated in Figure 33.

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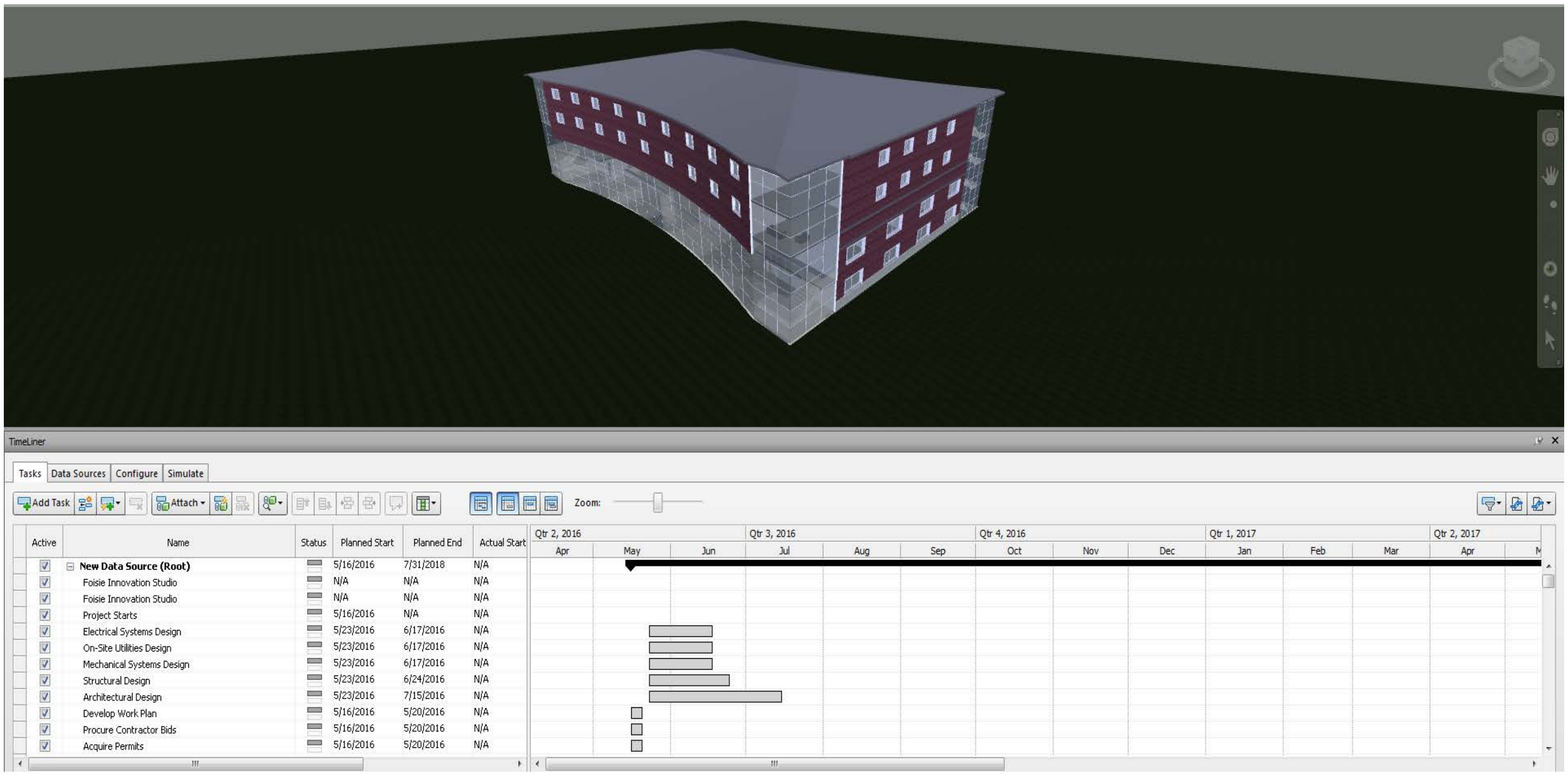

Figure 33: Navisworks Schedule and Timeline, Image from Autodesk Navisworks

7.4 Linking Building Elements & Corresponding Schedule Tasks

When all elements for the *Navisworks* model were in place, the final step was to link activities with their respective schedule and cost elements. The most important tool for this task is *Navisworks'* “selection tree”. The selection tree allows users to select elements existing in the model without having to click on the model itself. There are three ways to use the selection tree, either utilizing the “Standard”, “Compact”, or “Properties” setting. Standard selection, which is illustrated in Figure 34, displays elements by floor and breaks elements up by category where they can be selected individually. The next option, Compact selection was not used as it only serves to help users select a whole floor. Properties selection allows the user to choose elements by phase created, material, or any other property characteristic of an individual element. This option allowed the phases identified earlier in the process to be selected with ease. The combination of the Standard and Properties options for the selection tree ensured that any desired element or group of elements in the 3D model could be selected without difficulty before linking the elements to a schedule activity.

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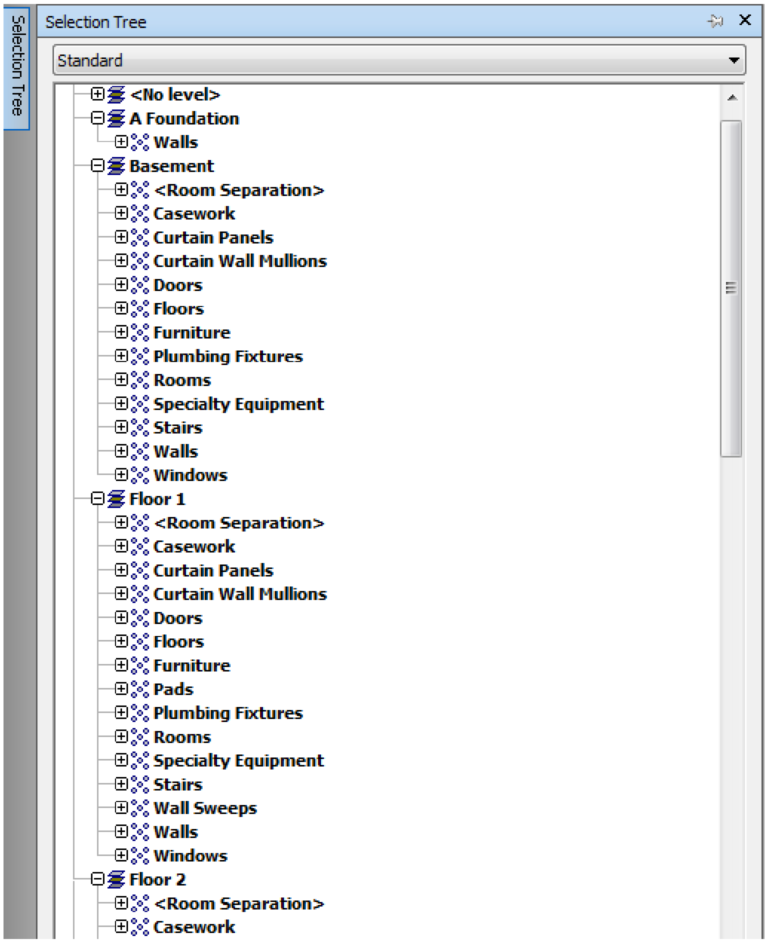

Figure 34: Standard Selection Tree, Image from Autodesk Navisworks

After an element or group of elements had been selected, the only remaining task was to create a link with the appropriate schedule activity. When the 3D elements were selected, it was simply necessary to right-click on the relevant schedule activity or activities and select “Attach Current Selection”. When this has been completed, the task type must be chosen as “Construct”. When this process has been completed for all desired 3D elements, the simulation is ready to be executed, demonstrating how both the building and its cost or earned value progress over time. A plot illustrating the buildings earned value over the course of the project is shown below.

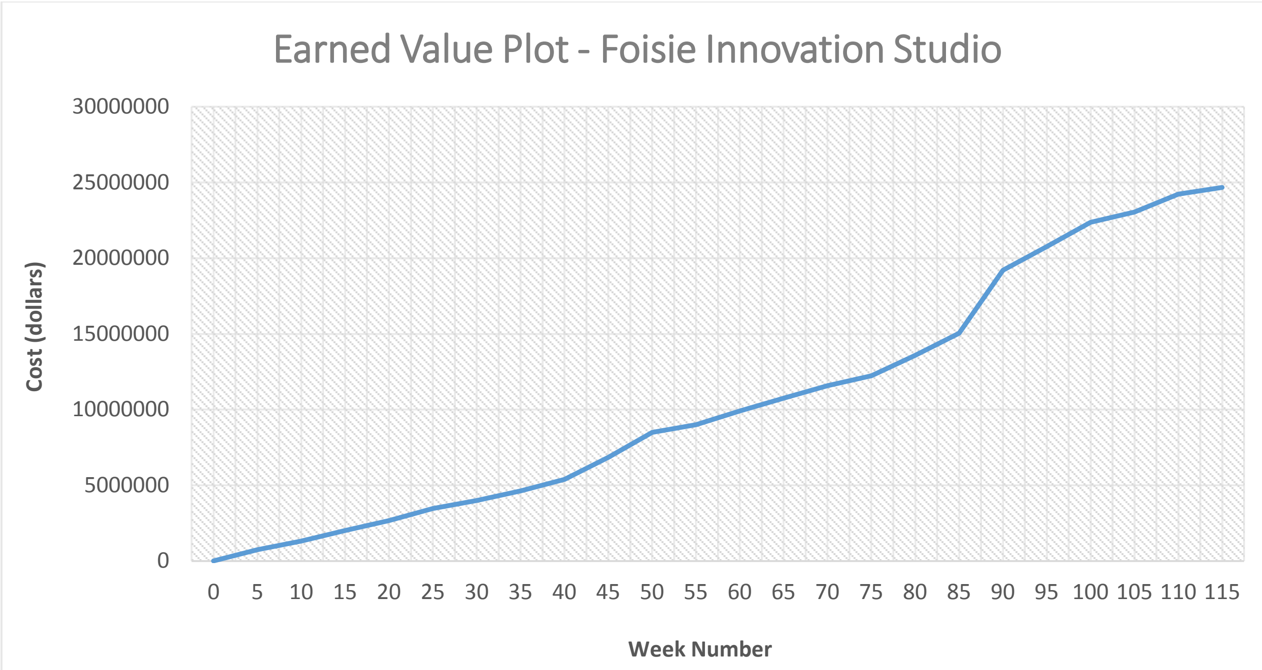

Figure 35: Foisie Innovation Studio Earned Value Plot, Image from Microsoft Excel

As demonstrated by the above figure, the cost, or earned value, of the building increases at a relatively low rate at the beginning and end of the project, and somewhat steeper at certain points in the middle of the project. This curve can be referred to as a “lazy-s” curve, and is characteristic of the typical earned value of a building during construction. As shown in the figure, there are two main areas where the cost seems to spike, reaching a higher slope than other parts of the graph. These points of inflexion are located between weeks 50 and 60 and weeks 85 and 90 respectively. While the erection of structural steel is taking place during the first period, utilities and the conveying system are being finalized between weeks 85 and 90. The areas of lesser slope, located at the beginning and end of construction, are times when site preparation and finalization tasks are being completed, which do not add greatly to the cost of the project.

7.5 Creating a Simulation

After completing the previously detailed steps, the 5D simulation was nearly finalized, the only remaining task being to manage the settings for the simulation. The settings tab allows the user to choose the interval time, playback duration, and any text to be overlaid in the video. For example, the video for the Foisie Innovation Studio includes the percent completion for the project, the week number, and cost (shown in green). When the Foisie Innovation Studio simulation was completed it was exported as a Windows AVI file where it could be saved and uploaded wherever desired. The simulation proceeds as shown by the highlights below.

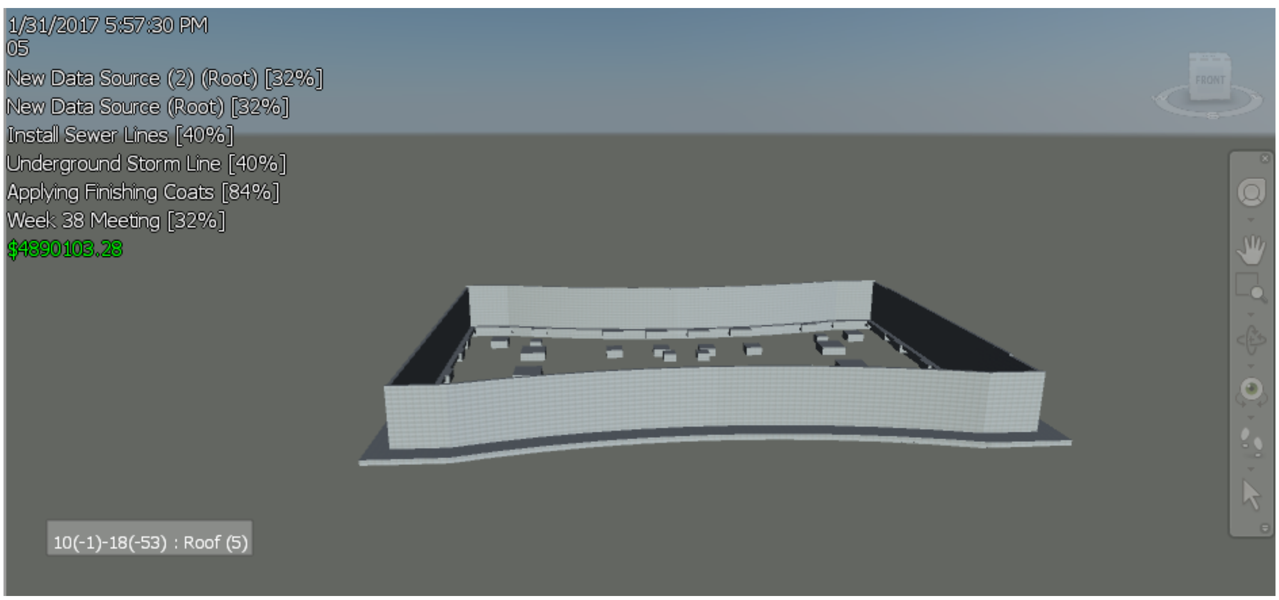

Figure 36: 5D Simulation, Foundation Completed, Week 38, $4,890,103.28, Image from Autodesk Navisworks

After demolition and site preparation are completed, the footings and foundation walls are the first parts of the building to be constructed. This stage is followed by the erection of structural steel, shown in Figure 37.

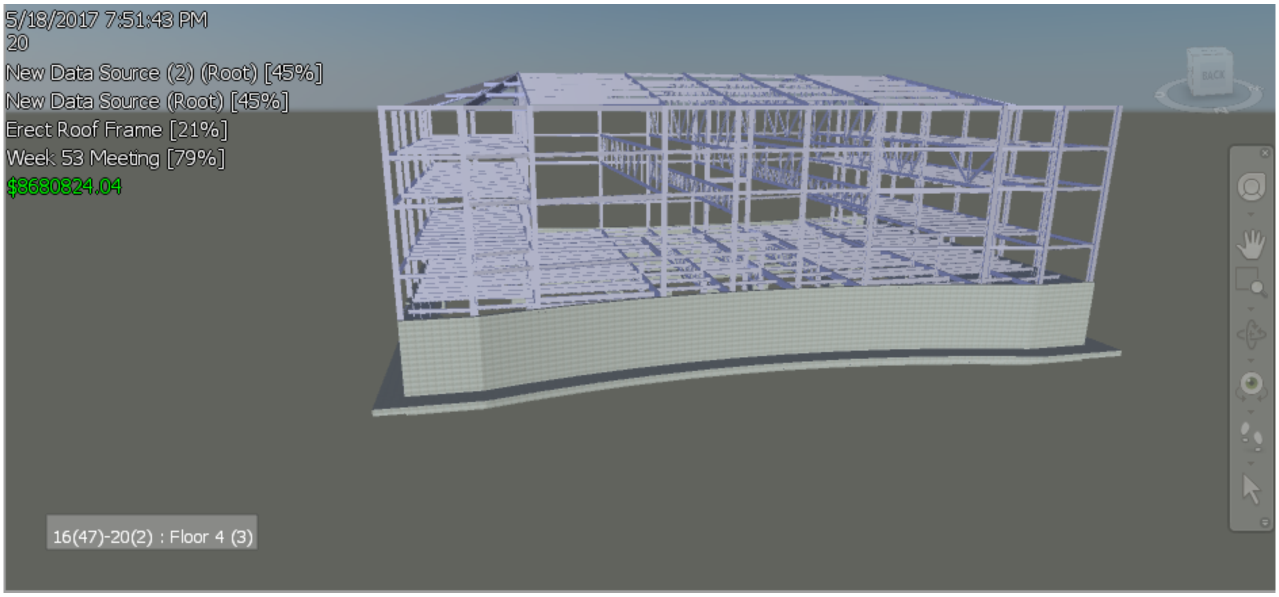

Figure 37: 5D Model, Structural Steel Completed, Week 53, $8,680,824.04, Image from Autodesk Navisworks

As illustrated by the earned value plot, the erection of structural steel represents a substantial portion of the total cost of the project. As shown in the figure, the cost is already nearly $9 million after this stage.

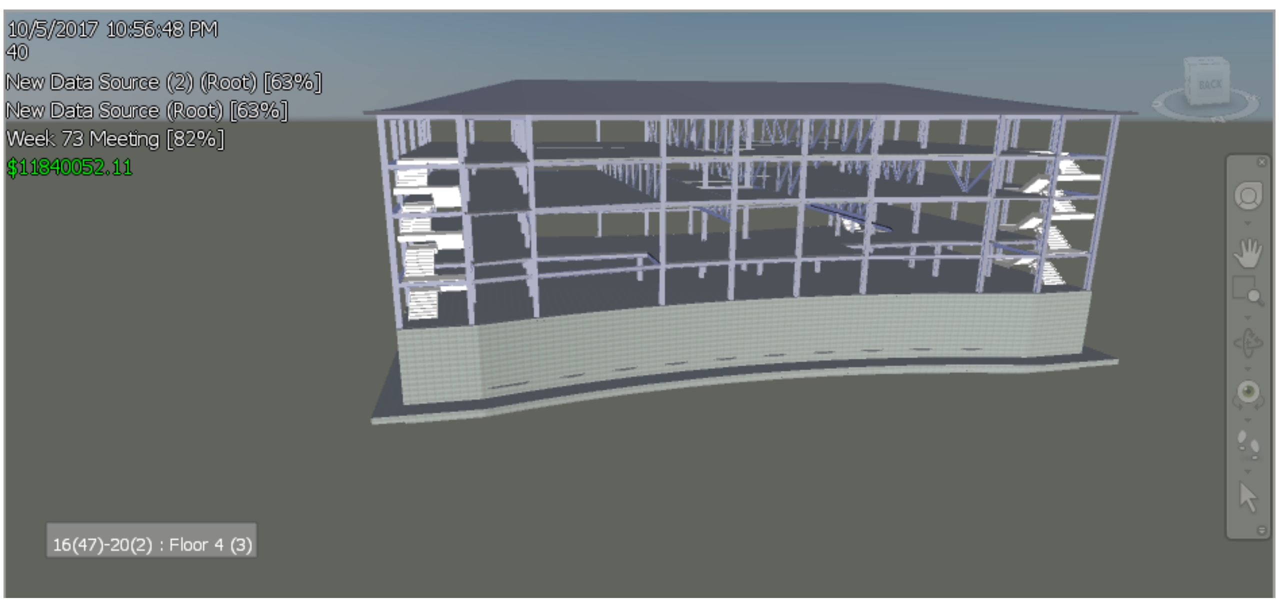

Figure 38: 5D Model, Floors and Roofing Completed, Week 73, $11,840,052.11, Image from Autodesk Navisworks

Figure 39: 5D Model, Exterior Enclosure Completed, Week 87, $15,254,407.40, Image from Autodesk Navisworks

Following erection of structural steel, concrete floors were placed as well as stairs. This process was designed to be completed from the ground up, starting at the basement floors and continuing to the upper residential floors. Next, brick and stone walls are added followed by all glazing for the building, including curtain walls and windows.

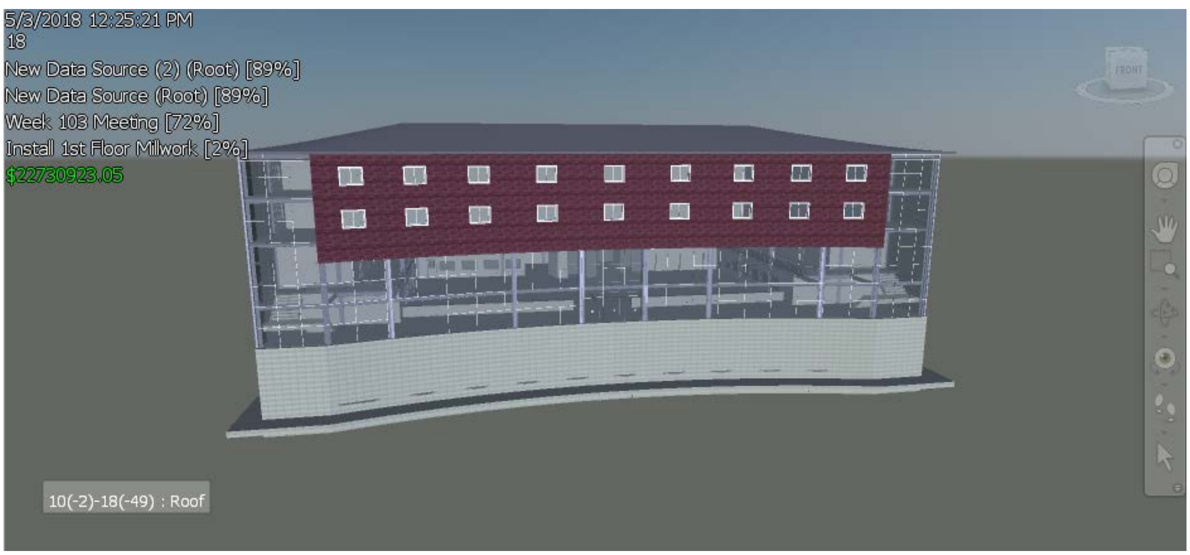

Figure 40: 5D Model, Partitions & Utilities Completed, Week 103, $22,730,923.05, Image from Autodesk Navisworks

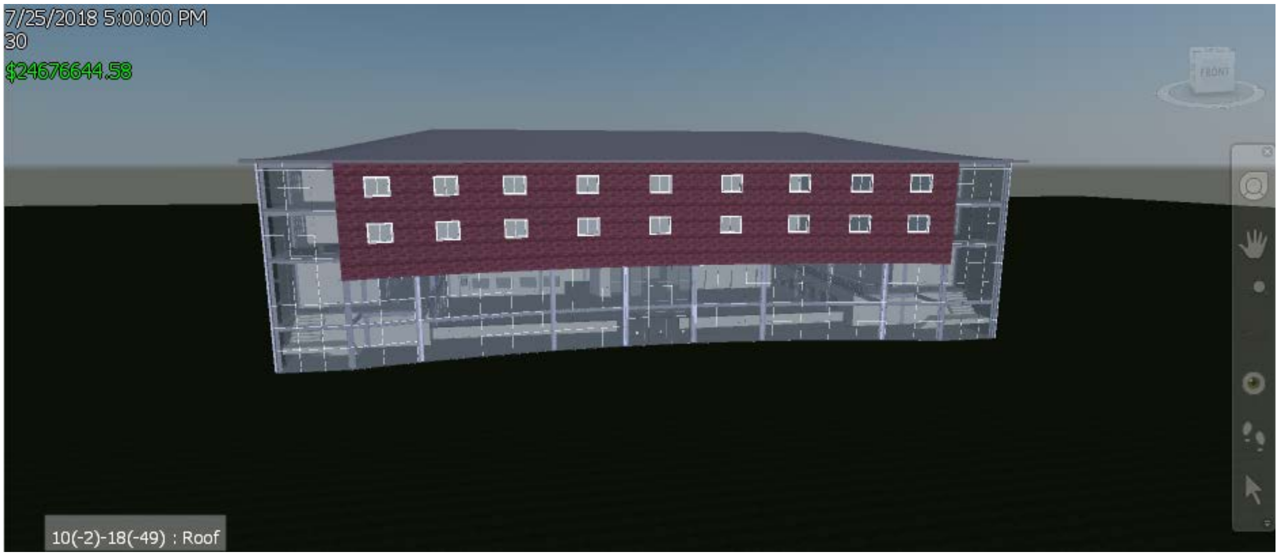

Figure 41: 5D Model, Project Completed, Week 115, $24,676,644.58, Image from Autodesk Navisworks

Once the exterior enclosure is finalized, the only remaining phases are the addition of partitions and utilities, and then the finalization of the building site. These two stages are illustrated in Figures 40 and 41.

Link to current simulation: https://www.youtube.com/watch?v=dGwUXYA23gs

Link to walkthrough video: https://www.youtube.com/watch?v=GLzmuD22c8Y

8.0 Conclusions

After much consideration, WPI and its Board of Trustees decided to demolish Alumni Gym in favor of constructing a new, mixed-use academic-residential space named the “Foisie Innovation Studio”. There were a number of objectives set forth by WPI related to the usage of this new building. These objectives included but were not limited to: giving students a home to foster their collaborative and innovative pursuits, allowing for a space to showcase the work done by all WPI students, and creating more living space for the growing student population.

With these objectives for the project in mind, the goal became to carry out an alternative design for this building, including architectural, structural, and project management components.

In terms of architectural design, this alternative design in the form of an architectural BIM model responds to the wishes of WPI and its Board of Trustees. Creating a very open and free-flowing environment was pivotal to ensure that a large amount of students’ accomplishments and ideas could be put on display. Collaborative spaces and a multitude of labs have also been included to make sure that this type of work can continue to be produced by WPI students.

Structural design and analysis also comprise a large component of the work accomplished in this report. A structural BIM model was created, illustrating the layout of all structural components. All necessary calculations were performed in order to size members and ensure that the building is structurally sound.

For the project management component, a schedule with a high level of detail was created to show the proposed timeline for this alternative design. Cost estimates were also produced in order to gain an understanding of the final cost and cost drivers for a project of this nature and to benchmark the proposed design against comparable projects.

These architectural, structural, and project management components were combined to produce a 5D model and simulation illustrating the construction process. This simulation has been included in order to provide a clear visual for how the proposed building would be constructed.

These project components have provided a great deal of insight into a wide range of subjects, predominantly an improved sense of the feasibility of different projects, whether it be architectural and structural feasibility, or determining if a project's schedule or budget is both feasible and reasonable. The results of this project have shown that this particular plan for the building is feasible, but required an iterative process to meet all final requirements. This MQP has also shown the links between different areas of a project. While different group members focused and specialized in different domains for the project, it was necessary for all members to spend a great deal of time working together, due to the nature of this type of project and building construction in general.

All the aforementioned components combine to form an insightful MQP relating to the construction of a new, mixed-use academic and residential building on campus. Future MQP groups will be able to benefit from this report by finding a depth of information on how to perform work related to Building Information Modeling and its architectural and structural components, as well as cost-estimation, construction scheduling and 5D simulations.

The project could serve as a reference for WPI when it is looking to construct a new residence hall or showcase building. In terms of future MQP projects, groups could look at this design and attempt to incorporate more specific design for mechanical, electrical, and plumbing equipment, or fire safety equipment. While these elements were considered, a team with specialties in these domains would gain experience by learning how to incorporate this type of equipment into a design where their inclusion was not a top priority.

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Appendix A: Project Proposal

2.0 Background

Founded in 1865 by two entrepreneurs from Worcester, Massachusetts, WPI has held true to its roots by maintaining a focus on innovation and collaboration. As illustrated by the school's motto "Theory and Practice", WPI students are encouraged to learn not only in the classroom, but by working on real-world projects. In order to provide a workspace for these projects and also display previous work, WPI has chosen to construct the Foisie Innovation Studio following the razing of Alumni Gym.

2.1 History of Alumni Gym

At the time of its construction in 1916, Alumni Gym was the hub of athletics on campus, consisting of three stories above ground and two below. With the necessary $100,000 raised by Arthur D. Butterfield, a WPI professor spearheading the fundraising effort, the building was constructed in time for WPI's 50th anniversary. Due to the immense amount of support from faculty and alumni, WPI had a surplus of funds which it was able to direct towards an indoor pool, currently located in the sub-basement of the gym.

Throughout the 20th century, Alumni Gym satisfied the demand for a home for athletics on campus. With the construction of the school's Sports and Recreation Center, it has become clear that this need no longer exists. The Foisie Innovation Studio will aim to serve campus by responding to a different need; the need for a home for innovation and collaboration on campus.

Although none of the existing features of Alumni Gym will appear in the new "Foisie Innovation Studio", there remains an element of nostalgia for the history that the gym represents.

As noted in the *Worcester Telegram* [10], while WPI is not located within a local historic district, Alumni Gym is listed on the National Register of Historic Places, a list which recognizes properties for a number of reasons, including significant contribution to America's history and heritage.

The elements that make Alumni Gym unique are important to keep in mind as the design and construction of the Foisie Innovation Studio progress. One of these elements is something that many students walk by every day and never notice - the gargoyles located on the side of the gym. These 34 gargoyles take a number of different forms: some are athletes and spectators, while others depict singers or musicians [4]. With 6 gargoyles on both the east and west walls and 11 on the north and south, the gargoyles are a subtle yet charming piece of not only the building, but the school's character. A plaque will also be placed on the site of the new building to honor the importance of Alumni Gym to the WPI community [10].

Figure 1: One of 34 Gargoyles on Alumni Gym, Photo by Michael Voorhis

A major focus of the architectural design is paying homage to the nostalgic element of the old building while producing a modern final product responding to the previously noted design goals. The design will incorporate the wishes and requirements of WPI's Board of Trustees as well, who have laid out a number of items to consider for this center of innovation. These plans include housing space for 140 new residents, a necessity for a school accepting an increasing number of students with each passing year, along with new classrooms and workspaces for the Great Problems Seminars, a showcase lobby with digital displays, and a center for innovation and entrepreneurship. Additionally, the school aims to include tech suites with flexible configurations in order to encourage collaboration among students looking to share ideas. As the expansive project-based curriculum at WPI continues to develop, these spaces will provide students with the resources necessary to work to their full potential.

2.2 Mixed Use Academic/Residential Spaces

By deciding to construct a building which provides both residential and academic space, WPI is demonstrating that it understands the trends of today's education. According to a recent study, students perform roughly 30 percent of their school work while in residence halls [1]. If students have access to tech suites and designated study areas without leaving their building, this time could be spent more productively and would likely increase. WPI isn't the only school to investigate this type of building either - universities such as the University of Colorado, Rutgers University, and the University of Michigan are just three of the many institutions making progress towards blurring the lines between academic and residential spaces [11].

While mixing these two seemingly unrelated aspects of college life may seem unconventional, there is emerging research to show that it has its merits. At the University of Michigan, the school's mixed-use residence hall was designed to help students "address some of the world's thorniest problems" [9] by increasing their opportunity for collaboration. At WPI, many first-year students participate in the previously mentioned "Great Problems Seminars", where students tackle real-life problems in teams of 4 to 5, focusing on topics from sustainability to public health. These students will undoubtedly benefit from an increase in space designed for collaboration and the sharing of ideas.

The proposed design for the building will comprise a total of roughly 75,000 gross square feet, with 40,000 square feet dedicated to academic space, and 35,000 square feet dedicated to residential space.

There will be a number of functions required of the 40,000 square feet of academic space. While this space will hold the previously mentioned tech suites and lecture halls, it will also be used as a display area. There are two types of projects required for upperclassmen at WPI: the IQP (Interdisciplinary Qualitative Project) and MQP (Major Qualifying Project). Selected projects will be placed on display to encourage new students to take on global issues and receive the same recognition for their project work one day. The academic space will also serve as a place for innovation and collaboration, with areas designated for a business incubator as well as a laboratory containing resources for students to perform project work.

For the residential space, the goal is to be able to house 140 students in the Foisie Innovation Studio. Housing will be consistent with other WPI freshman residence halls, consisting of 3 students per room equipped with 3 beds, desks, and closets. Residential space will also include additional tech suite and collaboration space for the student’s convenience. Since students spend roughly 70 percent of their time in their residence halls [6], it is important to note that the residential floors will include common rooms for extracurricular activities.

2.3 Building Information Modeling

In recent years, the construction industry has utilized and implemented innovative technologies to improve the quality and efficiency of the construction process. Of these newly emerging and industry driving technologies, the most influential is Building Information Modeling

(BIM). BIM is the intelligent process of planning, designing, constructing, and managing projects [13]. BIM allows for better 3D visualization of the project while also facilitating coordination and interoperability amongst the design team, contracting team, and owner, thus promoting collaboration. This techno-social trend is expected to propel the construction industry with the aid of a model-based process capable of being easily manipulated and adapted so that all parties involved are provided with a clear and consistent interpretation of the project [13].

2.3.1 BIM and Architectural Functions

Visual displays are one of the most powerful tools available in architectural design. The ability to view a building or structure in a 3D model enables users to see all elements in a clear and realistic manner. This feature is beneficial because it facilitates the architectural design process in terms of communication between the owner, designer, and contractor.

Some of the principal ways in which BIM is useful in architectural design include the dimensioning of floor plans, general spatial awareness, visualization of exterior appearance, and overall placement of a structure within the context of a surrounding area. Floor plans and interior layouts are the cornerstone of architectural design communication and have much to do with the eventual flow of traffic through a building. The development of these plans involves finding the appropriate balance between sizing of various rooms and their integration within the footprint of the building - a process which often involves numerous revisions and adjustments. BIM's ability to quickly and consistently alter dimensions and locations of walls simplifies this process, making it more efficient than previously imagined. Additionally, the ability to virtually walk through drafted floor plans offers more spatial awareness in comparison to the traditional 2D layout, making errors and omissions easier to identify than ever before.

2.3.2 BIM and Structural Functions

Another key feature of BIM is the structural modeling capability in relation to the architectural design. For example, the relationship between the architectural design of floor plans and interior layouts directly affects the placement of framing columns. The interior layout and intended flow of a building dictate where columns can be placed to minimize interference or poor aesthetics. It is also imperative that the framework agrees with all of the exterior enclosures of the building in order to ensure an accurate design.

Another feature that makes BIM practical and useful is the ability to detect clashes between structural and architectural items in the design. The application of the clash detection feature allows designers to identify any and all design errors and avoid facing similar issues in the field. Clash detection can identify unwanted intersections among beams, walls, and ceilings, as well as between columns and floors. This process of early detection can play a large role in simplifying the task of accurately modeling a structural frame.

One last function of BIM in structural design is the ability to perform structural analysis of a building frame and determine areas of weakness or inefficiency within the model. Upon completion of numerous hand calculations and analyzing a major structure piece by piece, BIM allows the user to highlight areas of renewed concern. The use of structural analysis software to check member sizes and their response to various loading conditions will catch errors and omissions. Discovering problem areas of a frame is just another example of BIM analysis saving large amounts of time and making the structural design process more efficient.

2.3.3 BIM Planning/Scheduling/Cost Estimating

One of the premier aspects of our project is to design the schedule for the construction of the new Foisie Innovation Studio. This is no easy task, and requires an understanding of building permits, zoning regulations, and the construction activities that must be scheduled while the campus is operating regularly. Utilizing BIM to aid in the development of the schedule saves contractors and designers a significant amount of time and money while also helping them visualize the project. BIM allows users to produce a 5D (cost+time) model, which is advantageous in that it interconnects the cost, time, and architectural and structural model. This allows for a deeper analysis and evaluation of the project structure before the ground breaks as we undertake the project virtually. For example, if there is a fixed budget for the project, the designer can utilize the program to make sure that the model reflects what is requested.

Using scheduling software, a schedule can be developed to organize the sequence of activities necessary for construction. A widely used program in the industry is *Primavera*, which involves inputting construction activities, linking them together, and producing an effective working schedule. Additionally, a work breakdown structure can be used to organize the construction activities into manageable sections or phases. This simplifies the complex process of coordinating the wide variety of activities done on different sections of the building. This is especially useful given the multi-phase nature of the project.

In addition to the project schedule, cost estimation of the construction must be determined before developing the 5D model. There are many methods used in the industry to forecast the cost of the project. Given the information from the 3D model layout and the projected schedule, a quantity takeoff measuring amounts of materials and multiplying them by the unit price provided by data sources such as *RSMeans* can be performed. This database provides different cost information that helps to generate a more accurate cost estimate. Depending on the unit to be estimated, a different approach may be taken, such as square feet or number of units. This creates a hybrid process where certain units are calculated using square feet or pounds and others using the details from the 3D model such as quantity or type. For example, curtain walls will be priced based on square footage while the structural beams can be calculated by the cost of each individual member used in the model.

Table 14 below lists some relevant BIM software and highlights their capabilities and applications for this project. They will be referenced frequently throughout this paper.

Table 14: Applicable Software

Software	**Capabilities**	**Application**
Autodesk Revit	3D Modeling	Architectural/Structural design
Primavera	Scheduling	Work breakdown structure, critical path determination
Navisworks	4D/5D Modeling	Full integration of 3D model with cost and schedule for enhanced visualization
Robot	Structural Analysis	Vertical and lateral load analysis for structural design

2.4 Design Considerations

For projects of this type in scope and magnitude, there is a wide array of topics which must be considered before and while producing a design. Looking at these potential issues and finding viable solutions is an integral part of the profession of engineering. Addressing these issues will play a major role in fulfilling the Capstone Design element included in the project.

Specifically, design issues will fall into three related yet separate categories: architectural design, structural design, and construction planning. Other aspects which will require the group's consideration include but are not limited to: sustainability, cost, and innovation in design.

2.4.1 Architectural Design

The architectural challenges associated with the design of this building involve not only the aesthetic view of the structure but more importantly its functionality. In terms of aesthetics, our intention is for the building is to look sleek and modern, while still staying true to the current theme of campus which consists primarily of traditional brick buildings. Similar examples include the architecture of other recently constructed buildings on campus such as the Rubin Campus Center and the Sports and Recreation Center.

In terms of functionality, the layout of the building poses an important architectural challenge. Since it is a multipurpose building, separation of residential and academic space is essential. The new building will contain large lecture halls, residential floors, student collaboration areas, and a showcase lobby for displaying WPI project work (exact specifications and requirements can be found in Section 3.1.1). The placement of these areas is crucial in order to ensure the flow of the building. Additionally, the residential area must be secluded from the rest of the building to ensure safety and comfort for students. Although the scope of this project will not cover plans for HVAC, mechanical, electrical, or plumbing systems, it is important for the architectural design to consider the integration of these systems and possible issues they could cause.

In addition to safety considerations involving the separation of residents and visitors, it is also absolutely necessary that the building is designed to be accessible and safe in the case of an emergency. When developing floor plans, there are a number of major factors to consider to ensure this level of safety. These include the amount of space available per person, egress from the building in case of a fire or other emergency, and handicapped accessibility. Engineers and architects have developed professional tools and practices to aid in determining many of these factors. Building codes cover all aspects of structural and architectural design and are in place to ensure that all buildings provide a standard of safety. The most widely accepted and commonly used building code is the *International Building Code (IBC)*. The *IBC* provides an industry-accepted baseline of standards for designers to follow for a vast array of topics. In addition to the *IBC*, each state has its own unique list of guidelines to be followed. For example, the *Massachusetts Building Code (MBC)* accounts for factors not found in other parts of the country, such as snow loads.

The architectural portion of the code can be broken up into three components: architectural, MEP systems, and fire safety. The architectural codes set standards for the building layout such as building height, hallway widths, and ceiling heights, which partially contribute to egress and other fire safety standards. The MEP standards control the internal operations of the structure such as elevators, HVAC, electrical wiring, and plumbing. Fire safety standards go more in depth to control design aspects including emergency exits and systems for fire prevention and suppression. Although fire safety is another entire design process in itself which falls outside the scope of this project, there are fire safety guidelines which will prove valuable during the design process. By having one code which covers all aspects of design, the process becomes much simpler for all parties involved. Structural engineers are able to work seamlessly with architects as a result of this uniform and widely accepted set of codes and standards

2.4.2 Structural Design

There will be a number of structural design issues to keep in mind for the duration of this project. One major aspect of the architectural design that could require critical thinking involves the multiple floors of residential space located above a large and predominantly open display hall. On the residential floors, the design will look to utilize all available space by incorporating living spaces with common rooms, bathrooms, tech suites and laundry rooms. This intention to support so many people and necessities in a relatively small area will produce large dead and live loads from the two residential floors. These loads are dictated by the usage of the building as outlined in the *IBC*. The extensive spans incorporated in a large open display hall will likely involve truss or joist systems to limit the frequency of columns. Another feature of the building that will produce a structural challenge is the frequent use of curtain walls in the design. Curtain walls cause loads to be carried by the structure as opposed to bearing loads themselves. Placing large brick walls for the residential floors above the curtain walls encompassing the entire lower south façade could present challenges in the design. Additionally, there are requirements of the foundation that will need to be investigated. Determining the bearing strength of the soil on site will inform whether a shallow foundation system will sufficiently transfer the load from the superstructure to the subsoil, or whether piles will need to be employed. Preliminary plans for the design involve curving exterior walls to give the building a sleek and somewhat modern look. This creates the challenge of determining how to support these curved walls.

In order to properly analyze the performance of this structure, it will be crucial to conduct several types of load analyses. The first and most basic analysis will be for gravity loads which the structure will be subjected to on a regular basis. Next, wind loading on the building shall be considered, ensuring that the building is capable of withstanding lateral loads even in the most extreme weather. Lastly is a seismic analysis, useful for examining the effects of oscillation and vibrations in the event of an earthquake. Some of these tests may seem excessive, especially in New England where there is very limited exposure to hurricanes or earthquakes. However, they ensure the stability of the structure even under the worst circumstances. The *IBC* in conjunction with the *MBC* will assist in determining not only the standard loads for these situations, but also the necessary factors of safety. For the design of structural components, the *IBC* references separate standards and specifications that outline the details of design using certain materials. The American Institute of Steel Construction (AISC) manual is used for steel design while the published standards by American Concrete Institute (ACI) are to be referenced for concrete design.

2.4.3 LEED Certification

Leadership in Energy and Environmental Design (LEED) is a program which accredits people and certifies buildings for developing sustainable design and promoting community wellness. There are several categories for LEED certification including: Building Design and Construction, Building Operations and Maintenance, Interior Design and Construction, Homes, and Neighborhood Development [12]. Each different type of project has its own evaluation criteria to determine if the project meets the certification requirements. Projects are evaluated in many different areas pertaining to their operation and design. The criteria can range from the use of recycled materials during construction of a building to the use of low energy light bulbs during operations. When applying for certification, a design team member will evaluate the project and determine how many points should be awarded in all aspects of the design using a LEED scorecard noted in Appendix A [12]. A portfolio for the project is then compiled and submitted to LEED for evaluation. This portfolio is reviewed by the LEED Council and a composite score is generated to determine whether or not the project meets the requirements for certification. Based upon the number of points earned by the project, it is awarded one of the four certifications (in order of increasing quality): LEED Certified, LEED Silver, LEED Gold, and LEED Platinum [12].

It is important that the Foisie Innovation Studio consider LEED because in the last few years, WPI has implemented a policy that all new buildings will be LEED Certified. While a large portion of the points needed for certification do not fall under the scope of this project, it is still crucial to examine the aspects that could be utilized such as recycling construction materials.

2.4.4 Construction Coordination

The existing Alumni Gym is located centrally on the campus of WPI. This will lead to some challenges in terms of accessing the building throughout the construction process and coordinating campus operations. The heavy flow of traffic near the Campus Center and Higgins Laboratories (see Figure 2 below) may lead to problems regarding safety. The major phases where this issue will produce a challenge are site preparation and construction of the new building. Construction must be done adequately to protect the workers and community from hazardous conditions which could affect their health, safety and overall well-being (OSHA).

Figure 2: Aerial View of Walkway between Alumni and Higgins, Photo by GoogleMaps

The site preparation phase requires the mass movement of ground material as well as its transportation to and from the project. An issue that could arise involves the access to the area given its challenging location in the heart of campus. There are no existing roads that lead directly to this site, so alternative access methods must be designed to address this issue. Additionally, excavating the existing foundation can be challenging since it requires special machinery to dig up or blast. Another issue that arises is establishing enough laydown area for materials and prefabricated elements. The project site may not be large enough to optimize this area while limiting interruption of pedestrian traffic flow.

Naturally, the physical construction of the building will pose the greatest challenge in terms of disturbing the environment of the campus. Similar to other phases, accessing the centralized building site will be difficult when transporting steel, concrete, and other larger elements of the final product. Even positioning cranes and other large equipment while protecting pedestrians will be difficult. In addition, there are disconcerting impacts such as the loud noise created. Noise is a sensitive subject since many of the freshmen residential halls are located near the construction site. Construction noise could affect student’s sleeping and studying habits, therefore preventing the project management team from utilizing overnight shifts to meet deadlines. Lastly, there is the issue of controlling dust created on the job site as to limit harm to members of the community.

3.0 Methodology

The scope of work for this project involves an architectural design, structural design, and construction plan for the Foisie Innovation Studio. The architectural design will be a 3D computer model that displays the end state of the building, taking into consideration the aesthetics, floor plans, zoning regulations, and MEP spacing requirements for the structure. The architectural model will lead into the structural design of the building which involves the design of the skeletal structure. The completed design will have plans for all supporting members, joints, and foundations in the structure. There will also be an in-depth analysis of the strength and serviceability performance of the design with calculations for the normal loads, wind loads, and seismic loads on the building.

While the designs of the physical structure are being completed, the plans for construction will be conducted. First, the schedule for the project will be laid out showing the planned duration of each phase of the project in real time. After completion of the architectural and structural models, the 5D model can be prepared. Upon completion, cost estimates and an approximate schedule will show the progress of the building's construction. Once these deliverables have been completed, they will be compiled into a professional proposal as if these were designs from a professional design firm.

3.1 Architectural Model

3.1.1 Building Intent/Architect Programming

To start the project, we were given a simple statement of intent that outlined basic requirements for the design of this building. These requirements are:

- 75,000 GSF building
- 40,000 GSF dedicated to Academic space
- Residential space for approximately 140 undergraduate students
- Placement on current site of Alumni Gymnasium
- Enhancement of current building visibility and pedestrian accessibility

Although these are informative initial directions, we want to make this design as close to the real intent of the new building as possible. However, this is difficult because detailed plans for the building have yet to be developed. After several conversations with our advisors, Professors Albano and Salazar, as well as the Vice President of Facilities for WPI, Alfredo DiMauro, we have been able to realize the following requirements for the building:

- Two lecture halls to house Great Problem Seminars (approx. 70 students each)
- Area dedicated to robotics department
- Tech Suites in residential space
- Additional areas dedicated to classes and offices
- Area dedicated to showcasing WPI student project work

These requirements will highlight outstanding research and innovation conducted by students which helps to show the caliber of work that the WPI community is capable of producing on a regular basis.

3.1.2 Architectural BIM

Based on the outlined requirements for the project, a 3D computer model of the building will be produced in *Autodesk Revit* as an architectural reference. This model will include general concepts of how the internal and external layout of the building will look. The purpose of this preliminary model is to develop a sense of what we want the building to look like from the site, develop a plan for the layout of the building, and give us an idea to work with to create the structural design. The architectural model will display the concept as closely as possible to what the final building should look like. However, as the design progresses through various stages, it may need to be revised. Should we discover components that create obstacles in the structural design or constructability of the building itself, we will resolve these early on in the process.

3.1.3 Building Codes

The *International Building Code (IBC)*, and *Mass Building Code (MBC)* will be used in the design of our structure to ensure that the building meets the standards set forth by the governing authorities. The building codes will be referred to when designing architectural aspects such as building height, hallway widths, egress, handicapped accessibility, and other safety features.

3.1.4 Zoning

In addition to the *IBC* and *MBC,* there are zoning ordinances specific to the city of Worcester. They provide specifications for zoning building height, setbacks, allowable space buildings, and the amount of usable space in a lot.

3.2 BIM Structural Model

There are three main aspects of this project, each with a primary BIM deliverable. For the structural portion of the project, the main deliverable is a 3D *Autodesk Revit* structural model that coordinates seamlessly with the architectural model. This model will clearly display locations and sizes of the primary structural members as well as typical connections. Additionally, *Autodesk Revit* will be used in various ways throughout the design process to be discussed further in this section.

3.2.1 Building Codes

The structural design of the building will refer to the 8th edition of the *MBC*. This document acts as the governing code for the location of the project and as an amending document to the 2009 printing of the *IBC*. Chapters 16 (Structural Design) and 17 (Structural Tests and Special Inspections) of the *MBC/IBC* are the primary chapters used for the structural design process. Chapter 16 explains the requirements for structural design, specifically the classification of loads. There are different loads that will be used in the structural design based upon the occupancy type of the building (found in *IBC* Chapter 3: Use and Occupancy Classification). Chapter 16 contains tables that list the live load factors for all occupancy types. These factors will determine the necessary strength of the structure in each part of the building. Chapter 17 refers to tests on the structure to ensure its stability. This chapter explains the requirements for testing in areas such as basic load resistance, wind load resistance, and seismic load resistance. Although these standards are set forth through the *IBC,* there are portions that reference other specifications. The common source for general structural design is *ASCE 7-05 (American Society of Civil Engineers)* [13].

While chapters 16 and 17 of the *IBC* outline general structural design requirements, chapters 18-26 provide guidance in the use of various materials in design and construction. The requirements for a variety are given in these chapters. The most important sections to note in this project will be chapters 18 (Soils and Foundations), 19 (Concrete), 21(Masonry), 22 (Steel), and

24 (Glass and Glazing). Although these chapters have some information on the requirements of the design of these materials, they primarily reference other standards and specifications. For example, the chapter on steel refers to sections of the American Institute of Steel Construction (AISC) code that should be used in the design of steel members. Therefore, these external standards will be used when designing the portions of the building made from these materials.

3.2.2 Loads

Throughout the process of designing the structural support for the Foisie Innovation Studio, we will need to determine whether concrete or steel is best suited for the loading cases faced by our building. However, we must determine the governing design loads for different areas of the building. Using our architectural model and the building codes, we will designate the corresponding occupancy and live loads for the functions of different rooms.

The vertical or gravity loads that will be considered in the structural design process are dead, live, and snow. Dead loads will be calculated based on the thickness of the floor slabs, the weight of structural members, and the permanent contents of the floor plan. Live loads will be determined by referencing the *MBC* and *IBC* for occupancy loads and typical live loads based on intended use. Additionally, in circumstances where there may be multiple functions over one span, we will select the application with the highest typical live load for our calculations. Also using the *MBC* and *IBC,* we will determine the necessary snow loads for the Worcester area to ensure the safety of our design. The horizontal loads that will be considered in the structural design process are wind and seismic. These loads will be found in the *MBC* and will be tested in our structural analysis software.

3.2.3 Superstructure

The superstructure is a primary part of the structural design. The superstructure will be comprised mostly of steel, but may also contain concrete components when spanning larger distances such as the display hall. Based on the loading cases outlined above, both concrete and steel solutions will be evaluated and the most efficient, aesthetically pleasing, and constructible solution will be selected. Though steel boasts advantages such as higher tensile strength and off-site manufacturability, there are cases in which concrete may be preferred. For example, if the trusses are too large to be aesthetically pleasing, concrete arches could be favored. Upon selection of the most appropriate material, we will create an *Autodesk Revit* structural model through which we can do further analysis and ensure agreement with the *Autodesk Revit* architectural model.

3.2.4 Frame Shape

The shape of the superstructure and its general placement are critical in determining the span lengths. This is crucial when sizing members and making decisions regarding the use of concrete or steel. Using the architectural model that we have developed, we will be able to determine the most appropriate column locations within the framework of the anticipated design. We will choose column locations that will cooperate with the model but are also as frequent as possible in order to limit span lengths when feasible. With the columns placed in the structural *Autodesk Revit* model, we will determine the span lengths that either girder-beam systems or girder-truss systems will need to span. Then, we will define simple beam and girder systems to cover the resultant spans. These column, beam, and girder systems will then be sized appropriately using the following processes.

3.2.5 Member Sizing

Using the resultant spans from the placement of columns in the initial frame shape and the loads for each span, we will use techniques outlined in *Structural Steel Design* or *Design of Reinforced Concrete* to size the beams, girders and columns. While sizing each beam and girder, we will run checks for bending, shear, and deflection to ensure that the members won't fail or deflect excessively. Additionally, while sizing the columns, we will run checks for buckling and shear. We will also employ a top to bottom approach when sizing the members in order to carry loads down through the structure properly.

3.2.6 Trusses

Trusses will be considered for the largest spans in our design such as the first floor display hall. In order to design the truss system, we will start by selecting a sample configuration and then solve for the member forces both manually using the Method of Joints and the Method of Sections, as well as electronically using *Risa 2D.* Manually obtaining the member forces will allow us to find the members that are subjected to the highest forces and thus select appropriately sized members. Then, we could use those selected sizes in the *Risa 2D* analysis to ensure deflection limits are satisfied.

3.2.7 Structural Analysis

Upon completion of the *Autodesk Revit* structural model, we will be perform structural analysis using the plugin for *Autodesk Revit* called *Robot*. We will use *Robot* to further check member sizing to ensure adequate stiffness of the frame. Also, we will be able to identify members both under the most stress and deflecting excessively. When we identify these problematic members, we will resize and reconfigure the frame to increase support. Furthermore, we will be doing seismic and wind analyses using the *Robot* program.

3.2.8 Connections

In both the steel truss systems and the overall superstructure, we will be using bolted connections to connect members within the truss, beams to girders, and girders to columns. For practicality, we will be designing one typical beam to girder connection and one typical girder to column connection based on the most intense loading conditions. We will determine the number of rows, plate sizes, fillet weld sizes, and bolt sizes necessary to account for the forces acting on the girders and columns using techniques outlined in *Structural Steel Design*. Additionally, using bolted connections for the truss members will ensure that they do not resist moment as they would if a weld connection was used.

3.2.9 Substructure

The substructure, also referred to as the foundation, is the next aspect of structural design. The purpose of a foundation is to transfer the loads of the building to the subsoil below. All subsoil has an associated bearing strength which the foundation has to match in order to prevent excessive total and differential settlement. To match the bearing strength of the subsoil below, foundations can be of different depth and footing styles. In the case of this project, the WPI campus typically has glacial till, which is a strong soil and thus doesn’t require a deep foundation system. We will design a shallow foundation system which will include retaining foundation walls and footings. However, the necessary retaining strength of the foundation walls is limited due to the minimal risk of overturning or horizontal sliding.

The size of the footings in the foundation will be determined using a Load and Resistance Factor Design (LRFD) method to sum the load acting through the columns. Based on the total axial load and the amount of area covered by the footings, we will decide which footing type to use. If the total area of the footings is less than 50% of the building's floor area, then spread footings will be appropriate. If the total area is more than 50%, then a mat foundation is appropriate.

3.3 Scheduling / Planning:

While advancing with the architectural and structural models, we will also conduct work on the planning and scheduling for the project. Planning represents a large part of the project's scope and is an integral step in both major and minor construction projects. Good planning allows the owner to limit site disturbance and develop the most cost and time efficient means for construction. The first stage of the planning process involves breaking down the construction into phases; in our case, site preparation and new construction.

3.3.1 Phasing and Durations

With the project phases defined, we will generate the required activities included in each phase, along with their individual durations. These durations will be determined by consulting different sources such as *RSMeans.* We'll also examine the durations of similar projects by consulting experts and researching the construction of other mixed-use buildings with a similar scale. Next, we will determine the work breakdown structure and establish the order of activities based on precedence. By determining these relationships, we are able to create a schedule for the project, including the identification of a critical path. Although the schedule and its critical path(s) may continue to be refined throughout the project, they will provide the owner with a strong idea of the project's direction and total duration.

3.3.2 Schedule Calculation

In order to effectively calculate a construction schedule, it is useful to utilize a form of available project management software. In the case of this project, Oracle's *Primavera* will be relied upon heavily in order to perform these otherwise tedious tasks. *Primavera* was chosen due to its user-friendly design and wide range of functions and capabilities. These tools make *Primavera* fully capable of supporting the completion of the three main tasks for planning: first, to define tasks and the logic network for the construction process, then to determine the critical path, and finally to organize and illustrate all data in order to provide a comprehensive and clear model.

3.4 Cost Estimating

While the architectural model, structural model, and schedule are being completed, we will begin to estimate the cost of construction. As previously discussed, we will be using a hybrid approach to determine the total cost based on the type of unit installation we are trying to estimate. This involves a level of detail (LOD) analysis that determines how precise the estimation will be. Since we know the exact details of the structural model, those elements will be estimated with a higher LOD.

3.4.1 Square Foot and Unit Cost Methods

For any non-structural features, such as fixtures, flooring, windows, or ceilings, we will retrieve the unit price from the *RSMeans* database and multiply it by the number of designated units to determine the cost, whether they be square feet, size, or quantity. For structural features, such as steel beams, concrete, or curtain wall, we will know the exact size of the elements and can use the quantity and unit price to determine the cost. Gathering this information involves performing quantity takeoffs, where we will use the schedules created by the BIM model to ascertain information such as square footage or number of units. In addition, we will incorporate the time of installation of each element to determine the total cost of fabrication, transportation, and erection/installation.

3.4.2 Software

To aid us in calculating cost estimation information, we will develop a Microsoft Excel spreadsheet that will organize each element based on how it was determined and display its quantity and size provided by the *RSMeans* cost database. This will be beneficial when performing the cost estimating calculations. The significant component of the cost estimation is determining the cost of the construction activities. The spreadsheet will help us organize the unit prices of each element so we may divide them into construction activities in the schedule. We will also utilize *DProfiler*, a computer program that allows for automatic cost estimation as a 3D model is created. The table below outlines the building systems and our anticipated approach to determine their cost estimations.

Table 15: Cost Estimating Strategy

Building System	**Approach**	**Comments**
Earthwork	Cost ($)/cubic foot	For excavation and site prep
Foundation	Cost ($)/cubic foot	Footings, foundation wall
Structural Steel	Cost ($)/member	Based on member size and weight
Steel Trusses	Cost ($)/	Based on size and type

Structural Concrete	Cost ($)/cubic foot	Beams, walls, floors
Flooring	Cost ($)/square foot	Assuming generic flooring
Exterior Walls	Cost ($)/square foot	Assuming universal thickness
Interior Walls	Cost ($)/square foot	Assuming universal thickness
Ceilings	Cost ($)/square foot	Assuming universal thickness
Roofing	Cost ($)/square foot	Given uniform thickness
Fixtures	Cost ($)/unit	Toilets, elevator, railings
Windows	Cost ($)/unit	Depending on size and type
Doors	Cost ($)/unit	Depending on size and type

3.5 Construction Simulation - 5D model

While a CPM network and Excel documents do a fine job of documenting schedules and cost estimates, they do not illustrate this information in a clear and comprehensive manner. It is for this reason that the group will create a 5D model for the construction process of the new building. This simulation will start from a fully prepared site and conclude with the finished building.

After the first three dimensions of the process have been established (length, width, and height of the building from the 3D BIM model), the next dimension to be incorporated is time. We will utilize *Navisworks* to create a model simulating the construction process over time starting with a structural shell of the building, and gradually adding all other structural and architectural elements. This simulation will be made as thorough and in-depth as possible. The software does a great job of illustrating the establishment of each phase, and allows the user to easily visualize how each phase contributes to the overall completion of the process.

To complete our 5D model, we will incorporate the cost estimate in *Navisworks*. This allows us to see how the cost correlates with project schedule throughout the construction phases. To create this feature, we must use the assigned costs associated with the construction activities so they appear in the simulation of the construction process.

4.0 Deliverables

Our deliverables will be a 3D BIM architectural and structural model, a corresponding construction schedule and cost estimation, and a 5D model simulating the construction sequence while incorporating time and money. The current version of the architectural model is displayed in the screenshots below. This model will continue to be adapted in order to respond to the demands of the structural model.

4.1 BIM Model

Exterior:

Figure 3: South View of Building

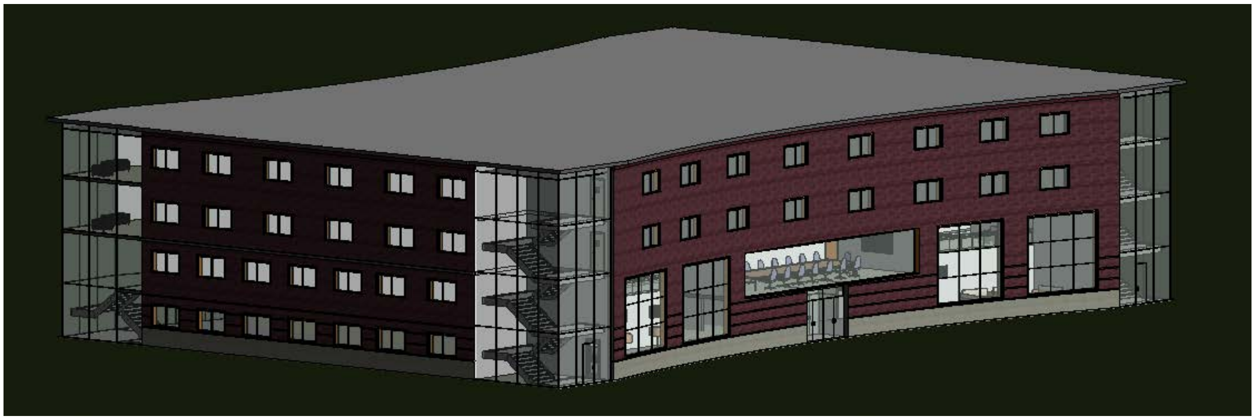


Figure 4: Northeast View of Building

Basement Floor:

Figure 5: Conference Room

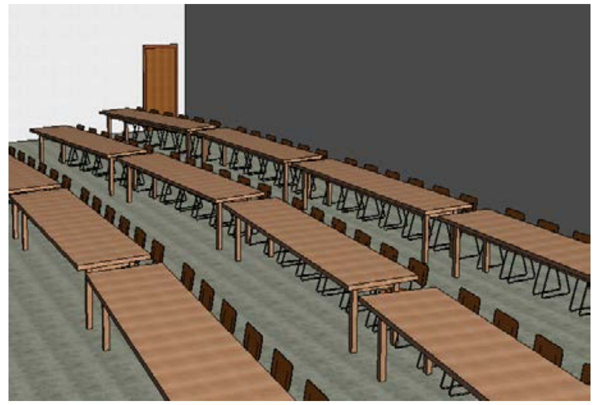


Figure 6: Lecture Hall

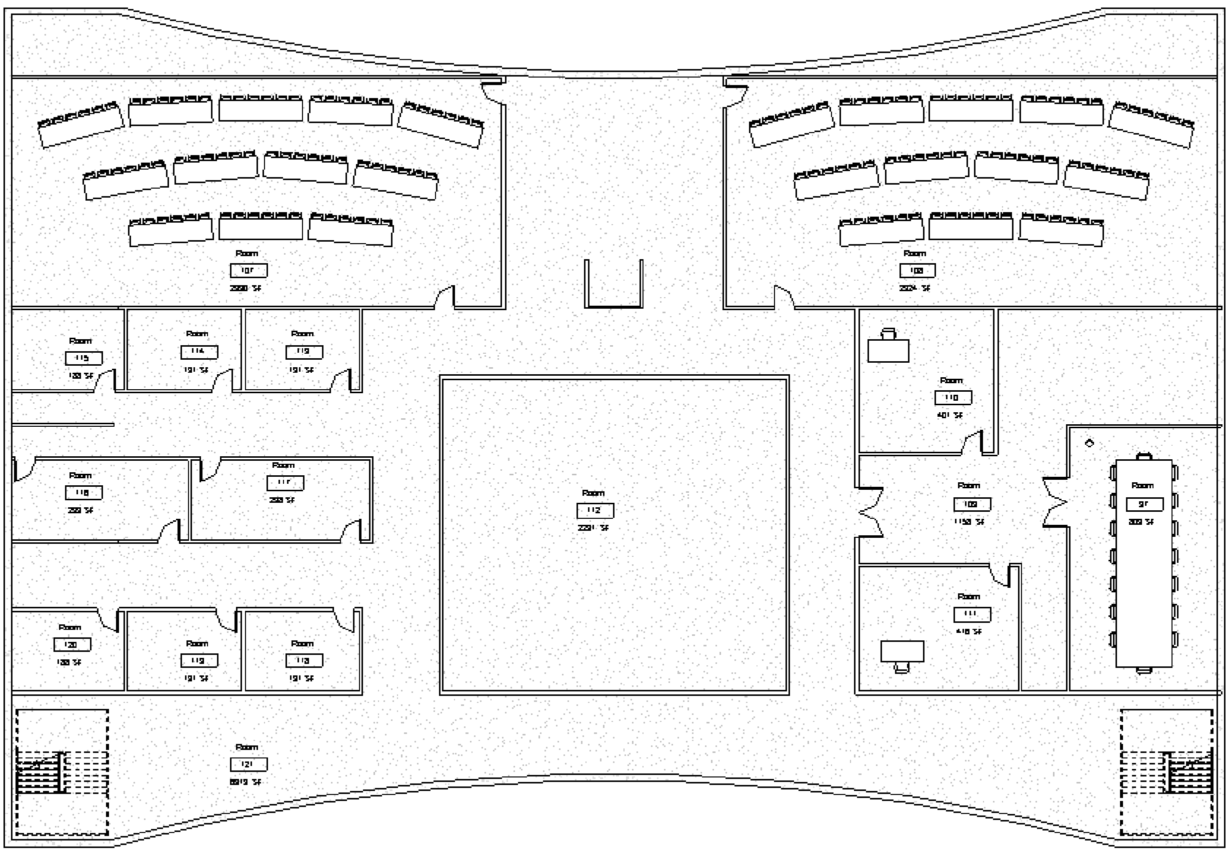


Figure 7: Basement Floor Plan

1st Floor:

Figure 8: Rear Lobby/Exhibition Area

Figure 9: Welcome Desk

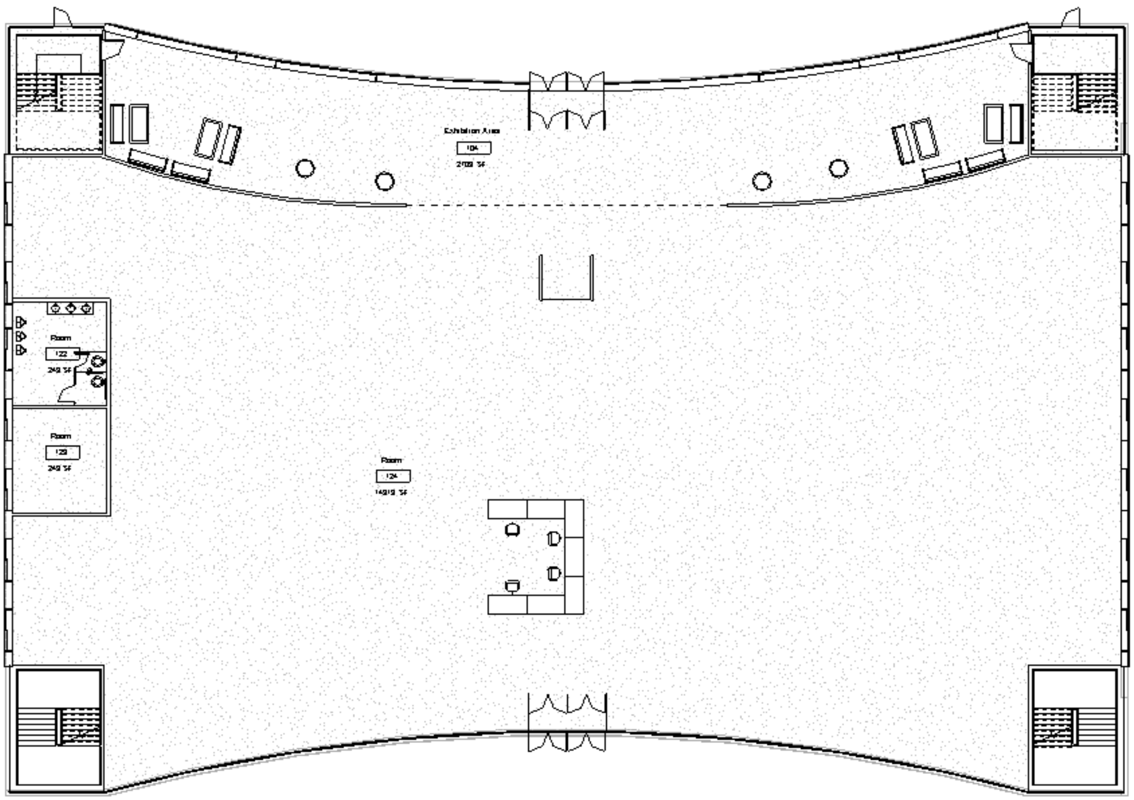


Figure 10: 1st Floor Plan

2nd (Loft) Floor:

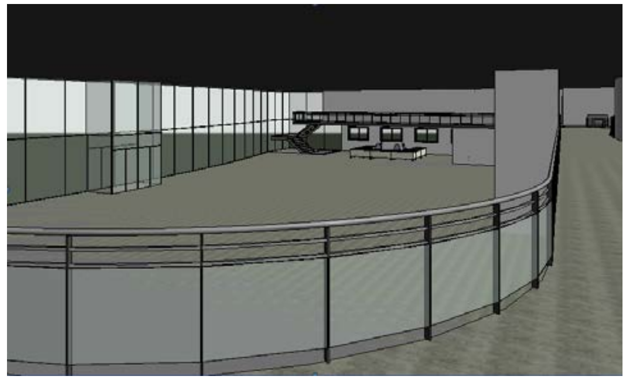


Figure 1142: Loft Conference Room

Figure 12: Loft Area

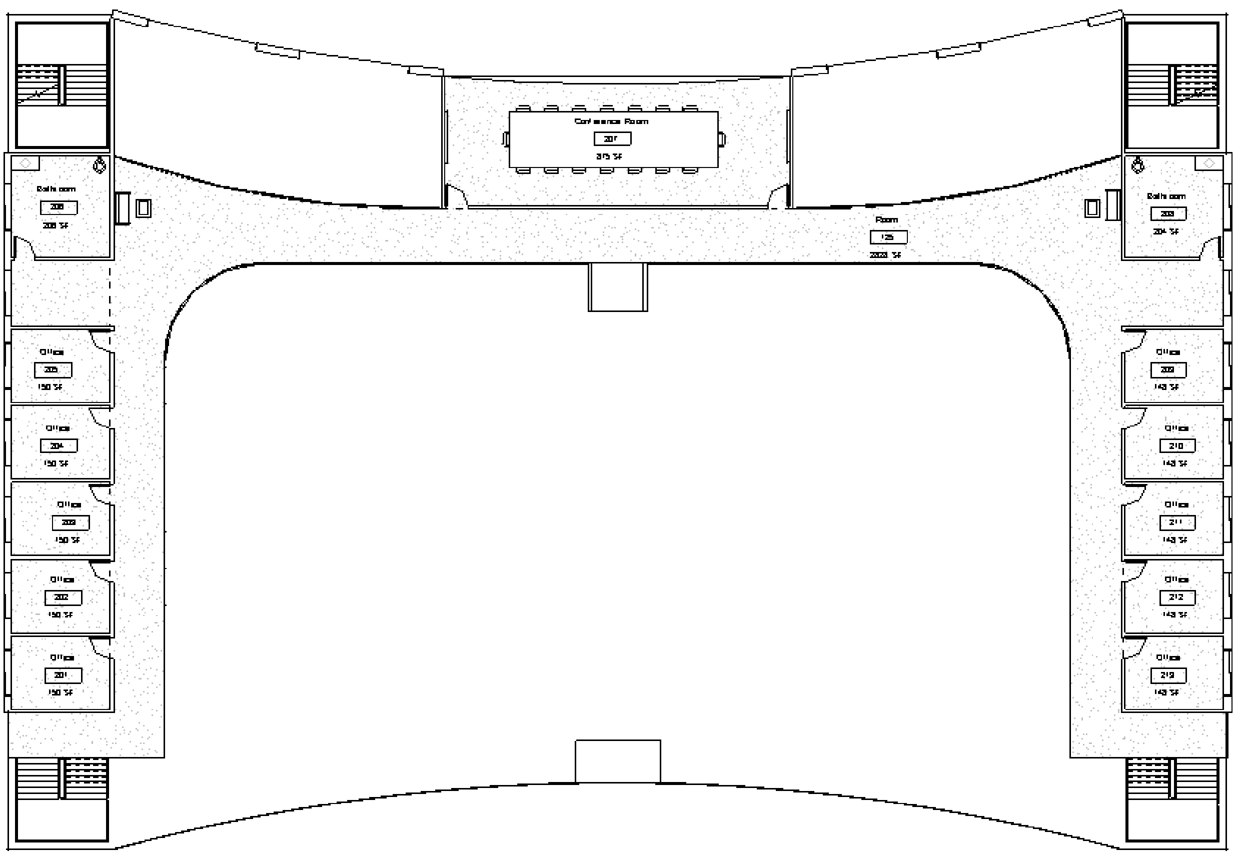


Figure 13: 2nd Floor Plan

3rd and 4th Floors:

Figure 14: Collaborative Work Area

Figure 15: Dorm Room

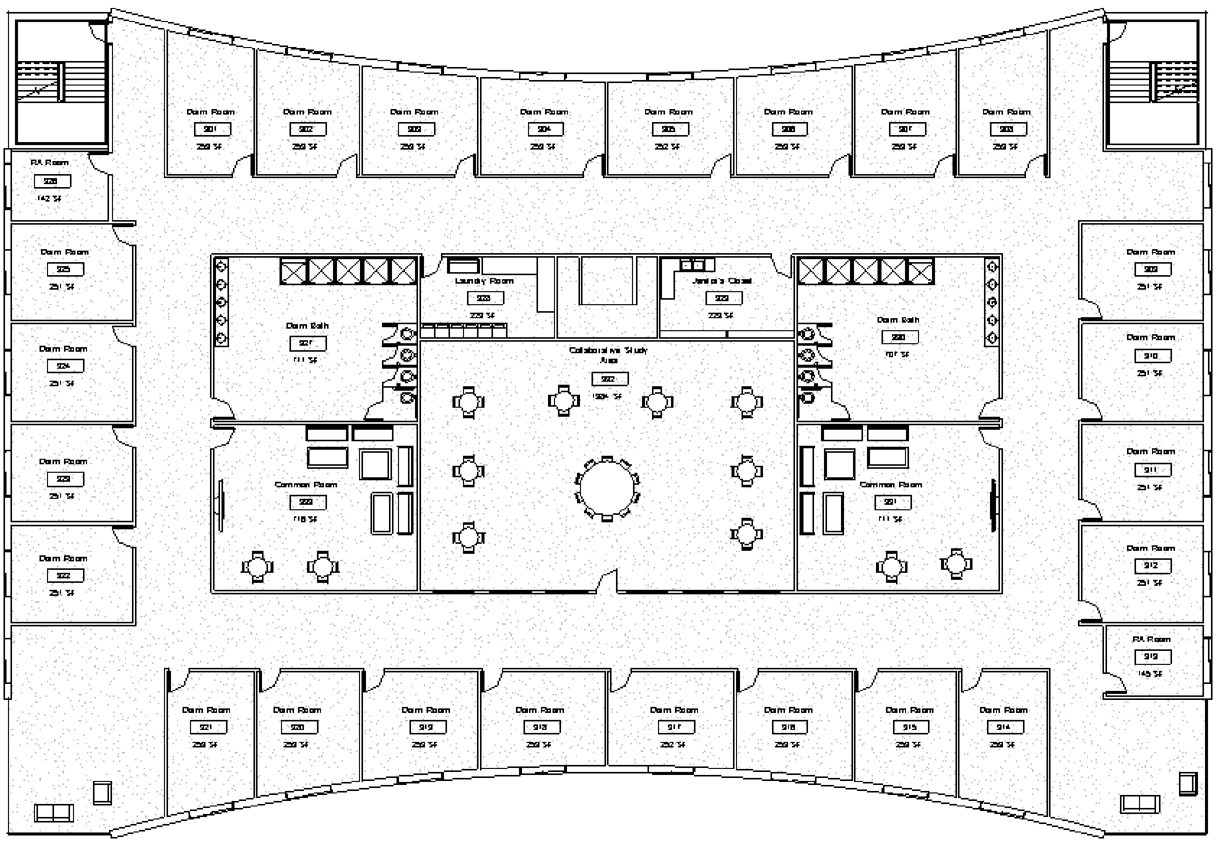
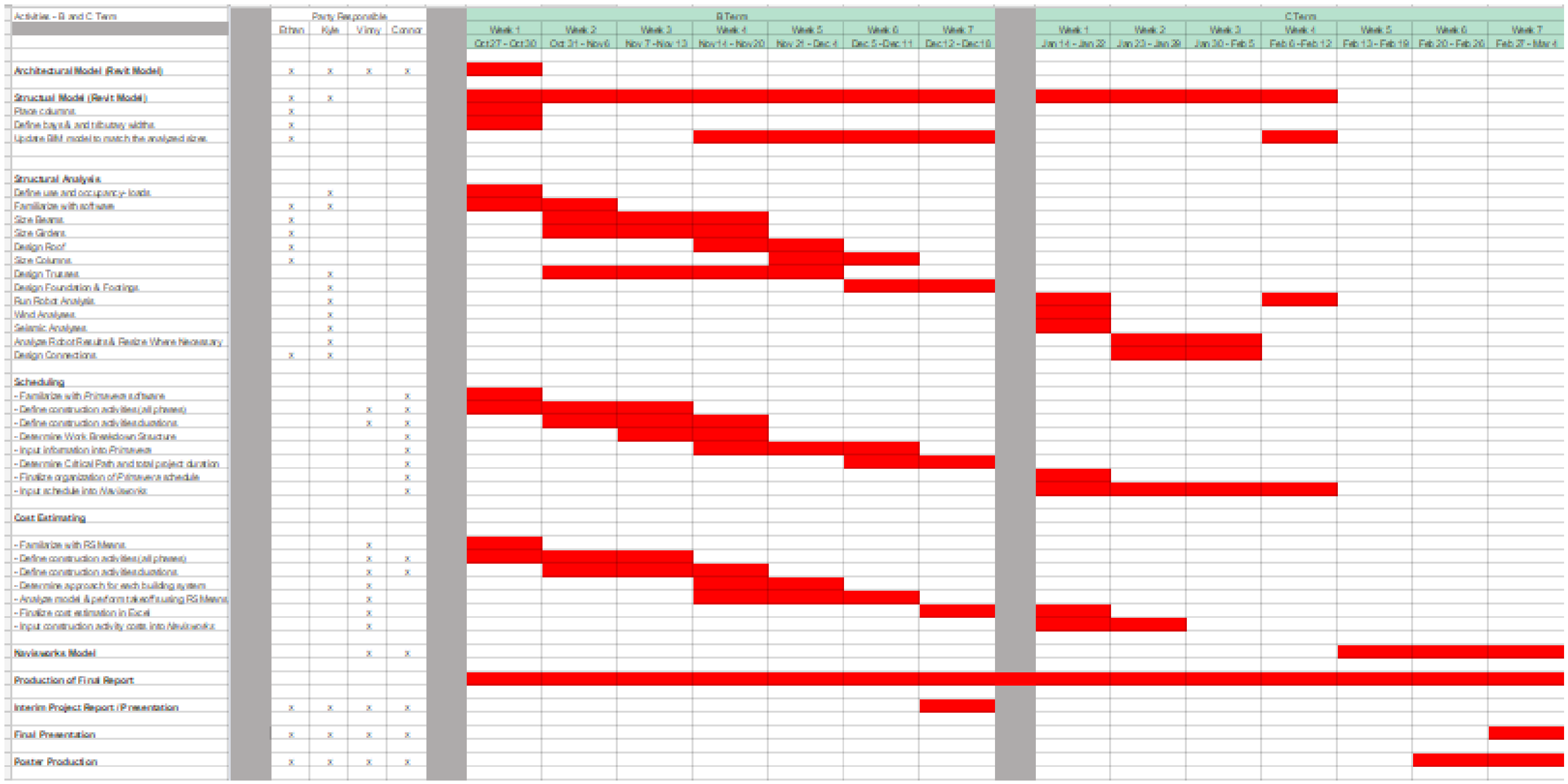


Figure 16: Residential Floor Plan

4.2 Current Plan for Usage of Space:

Residential Space		
Dorm Rooms	(28) 253 sq. ft dorm rooms	12730 sq. ft total of dorm rooms housing 144 Freshmen and 4 Resident Advisors
	(16) 251 sq. ft dorm rooms	
	(4) 252 sq. ft dorm rooms	
	(2) 145 sq. ft dorm room	
	(2) 142 sq. ft dorm room	
Bathrooms	2836 sq. ft	
Common Rooms	2854 sq. ft	
Collaborative Work Area	3968 sq. ft	
Laundry	458 sq. ft	
Janitor Closets	458 sq. ft	
Hallways	11650 sq. ft	
Total:	34954 sq. ft	
Academically-Driven Innovation Studio		
Basement		
Business Incubator	2784 sq. ft	
Collaboration Lab	2231 sq. ft	
Tech Suites	1140 sq. ft	
Lecture Halls	4654 sq. ft	
Bathrooms	591 sq. ft	
Hallways	6313 sq. ft	
First Floor		
Rear Entrance Lobby / Exhibition Area	2709 sq. fr	
Showcase Atrium	14919 sq. ft	
Bathrooms	486 sq. ft	
Loft		
Conference Room	875 sq. ft	
Offices	1490 sq. ft	
Bathrooms	410 sq. ft	
Loft Viewing Area	2828 sq. ft	
Total:	41520 sq. ft	
Grand Total:	76474 sq. ft	

5.0 B/C-Term Project Schedule


Activities - B and C Term
Party Responsible
Ethan
Kyle
Vinny
Connor
B Term
C Term
Week 1
Week 2
Week 3
Week 4
Week 5
Week 6
Week 7
Oct27 - Oct30
Oct 31 - Nov 6
Nov 7 - Nov 13
Nov 14 - Nov 20
Nov 21 - Dec 4
Dec 5 - Dec 11
Dec 12 - Dec 18
Jan 14 - Jan 22
Jan 23 - Jan 29
Jan 30 - Feb 5
Feb 6 - Feb 12
Feb 13 - Feb 19
Feb 20 - Feb 26
Feb 27 - Mar 4
Architectural Model (Revit Model) x x x x
Structural Model (Revit Model) x x
Place columns x
Define bays & and tributary widths x
Update BIM model to match the analyzed sizes x
Structural Analysis
Define use and occupancy loads x
Familiarize with software x x
Size Beams x
Size Girders x
Design Roof x
Size Columns x
Design Trusses x
Design Foundation & Footings x
Run Robot Analysis x
Wind Analyses x
Seismic Analyses x
Analyze Robot Results & Resize Where Necessary x
Design Connections x x
Scheduling
- Familiarize with Primavera software x
- Define construction activities (all phases) x x
- Define construction activities durations x x
- Determine Work Breakdown Structure x
- Input information into Primavera x
- Determine Critical Path and total project duration x
- Finalize organization of Primavera schedule x
- Input schedule into Navisworks x
Cost Estimating
- Familiarize with RS Means x
- Define construction activities (all phases) x x
- Define construction activities durations x x
- Determine approach for each building system x
- Analyze model & perform takeoffs using RS Means x
- Finalize cost estimation in Excel x
- Input construction activity costs into Navisworks x
Navisworks Model x x
Production of Final Report
Interim Project Report / Presentation x x x x
Final Presentation x x x x
Poster Production x x x x

6.0 Assignment of Responsibilities

- Architectural and Structural Design: Ethan
- Structural Analysis: Kyle
- Construction Scheduling: Connor
- Cost-Estimating: Vincent
- Construction Simulation: Vincent, Connor

7.0 Documentation of A-Term Work

7.1 A-Term Gantt chart

Week					0	1	2	3	4	5	6	7
Day	Ethan	Vinny	Kyle	Connor				Friday	Friday	Friday	Friday	Friday
Date								18-Sep	25-Sep	2-Oct	9-Oct	16-Oct
First team meeting	x	x	x	x								
First meeting with advisors	x	x	x	x								
Walkthrough of Alumni Gym	x	x		x								
Establish methods of communication	x	x	x	x								
Alias												
Blackboard page												
Google Drive for students												
Refine Scope	x	x	x	x								
Define research topics												
Set project goals												
Definition of roles/mindset												
Deliver problem statement	x		x									
Literature Review / Gather Data												
Building Codes			x									
Zoning Regulations		x										
Similar MQPs	x											
Academic-Residential Buildings				x								
Building Software				x								
MEP Fundamentals	x											
Basic Architectural Design		x										
Duration of Activities				x								
History of Alumni Gym				x								
Survey of Residents			x									
Background Chapter Planning												
Outline	x	x	x	x								
Annotated Bibliography	x	x	x	x								
Background Chapter Draft	x	x	x	x								
Background Chapter Revision	x	x		x								
Methodology Chapter Planning		x	x									
Outline												
Revit Model Outline Complete	x	x		x								
Methodology Chapter Draft	x	x	x	x								
Presentation of Proposal	x	x	x	x								
Methodology Chapter Revision	x	x	x	x								
Finalize Plan for Revit Model	x	x	x	x								
Proposal Revision	x	x	x	x								
Submission of Proposal	x	x	x	x								

7.2 Proposal Authorship

Abstract - Connor

Capstone Design Statement - Kyle

Professional Licensure Statement - Vinny

1.0 Introduction - Connor

2.0 Background Chapter

- 2.1 History of Alumni Gym - Connor
- 2.2 Mixed-Use Residential and Academic Buildings - Connor
- 2.3 Building Information Modeling - Ethan, Vinny
- 2.4 Design Considerations - Ethan, Vinny, Kyle

3.0 Methodology Chapter

- 3.1 Architectural Model - Kyle
- 3.2 Structural Model - Ethan, Kyle
- 3.3 Scheduling / Planning - Connor
- 3.4 Cost Estimating - Vinny
- 3.5 Construction Simulation - 4D and 5D Models - Vinny, Connor

4.0 Deliverables

- 4.1 Revit Architectural Model - All

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Appendix A

LEED v4 for BD+C: New Construction and Major Renovation
Project Checklist

Project Name:
Date:

Y	?	N			
			Credit	Integrative Process	1

Y	?	N			
0	0	0		**Location and Transportation**	**16**
			Credit	LEED for Neighborhood Development Location	16
			Credit	Sensitive Land Protection	1
			Credit	High Priority Site	2
			Credit	Surrounding Density and Diverse Uses	5
			Credit	Access to Quality Transit	5
			Credit	Bicycle Facilities	1
			Credit	Reduced Parking Footprint	1
			Credit	Green Vehicles	1

Y	?	N			
0	0	0		**Sustainable Sites**	**10**
Y			Prereq	Construction Activity Pollution Prevention	Required
			Credit	Site Assessment	1
			Credit	Site Development - Protect or Restore Habitat	2
			Credit	Open Space	1
			Credit	Rainwater Management	3
			Credit	Heat Island Reduction	2
			Credit	Light Pollution Reduction	1

Y	?	N			
0	0	0		**Water Efficiency**	**11**
Y			Prereq	Outdoor Water Use Reduction	Required
Y			Prereq	Indoor Water Use Reduction	Required
Y			Prereq	Building-Level Water Metering	Required
			Credit	Outdoor Water Use Reduction	2
			Credit	Indoor Water Use Reduction	6
			Credit	Cooling Tower Water Use	2
			Credit	Water Metering	1

Y	?	N			
0	0	0		**Energy and Atmosphere**	**33**
Y			Prereq	Fundamental Commissioning and Verification	Required
Y			Prereq	Minimum Energy Performance	Required
Y			Prereq	Building-Level Energy Metering	Required
Y			Prereq	Fundamental Refrigerant Management	Required
			Credit	Enhanced Commissioning	6
			Credit	Optimize Energy Performance	18
			Credit	Advanced Energy Metering	1
			Credit	Demand Response	2
			Credit	Renewable Energy Production	3
			Credit	Enhanced Refrigerant Management	1
			Credit	Green Power and Carbon Offsets	2

Y	?	N			
0	0	0		**Materials and Resources**	**13**
Y			Prereq	Storage and Collection of Recyclables	Required
Y			Prereq	Construction and Demolition Waste Management Planning	Required
			Credit	Building Life-Cycle Impact Reduction	5
			Credit	Building Product Disclosure and Optimization - Environmental Product Declarations	2
			Credit	Building Product Disclosure and Optimization - Sourcing of Raw Materials	2
			Credit	Building Product Disclosure and Optimization - Material Ingredients	2
			Credit	Construction and Demolition Waste Management	2

Y	?	N			
0	0	0		**Indoor Environmental Quality**	**16**
Y			Prereq	Minimum Indoor Air Quality Performance	Required
Y			Prereq	Environmental Tobacco Smoke Control	Required
			Credit	Enhanced Indoor Air Quality Strategies	2
			Credit	Low-Emitting Materials	3
			Credit	Construction Indoor Air Quality Management Plan	1
			Credit	Indoor Air Quality Assessment	2
			Credit	Thermal Comfort	1
			Credit	Interior Lighting	2
			Credit	Daylight	3
			Credit	Quality Views	1
			Credit	Acoustic Performance	1

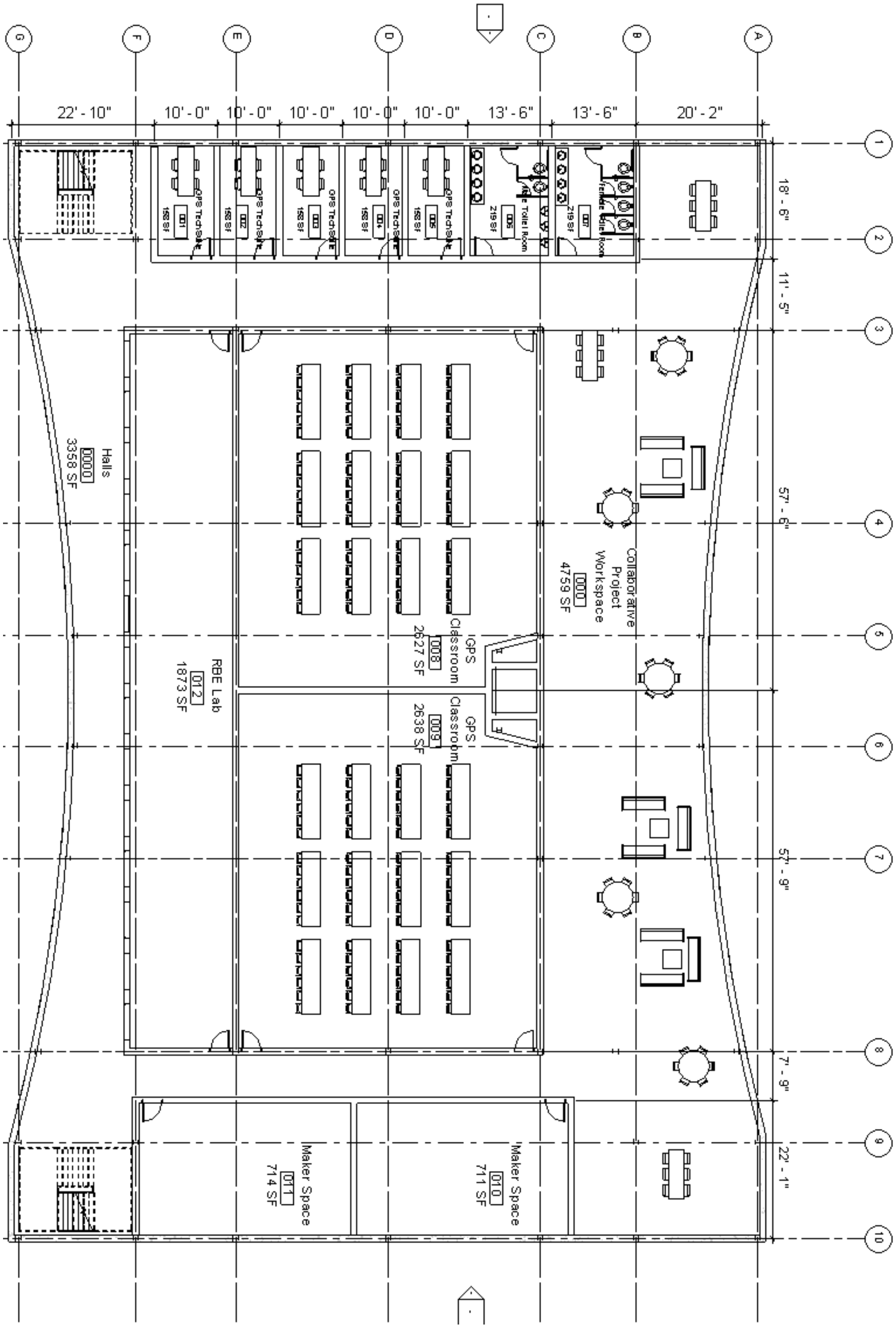
Y	?	N			
0	0	0		**Innovation**	**6**
			Credit	Innovation	5
			Credit	LEED Accredited Professional	1

Y	?	N			
0	0	0		**Regional Priority**	**4**
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1

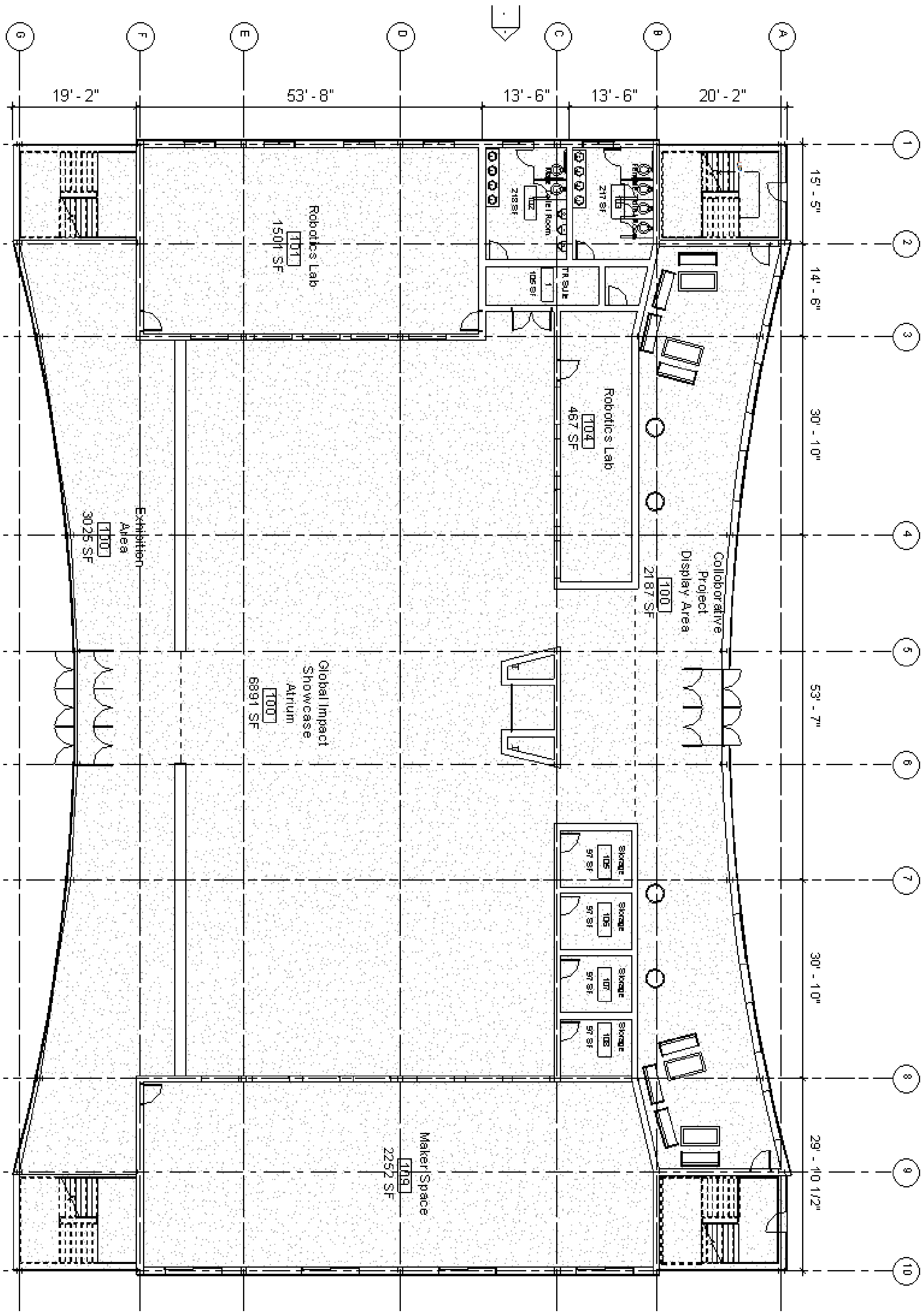
Y	?	N			
0	0	0	**TOTALS**	**Possible Points:**	**110**

Certified: 40 to 49 points, **Silver:** 50 to 59 points, **Gold:** 60 to 79 points, **Platinum:** 80 to 110

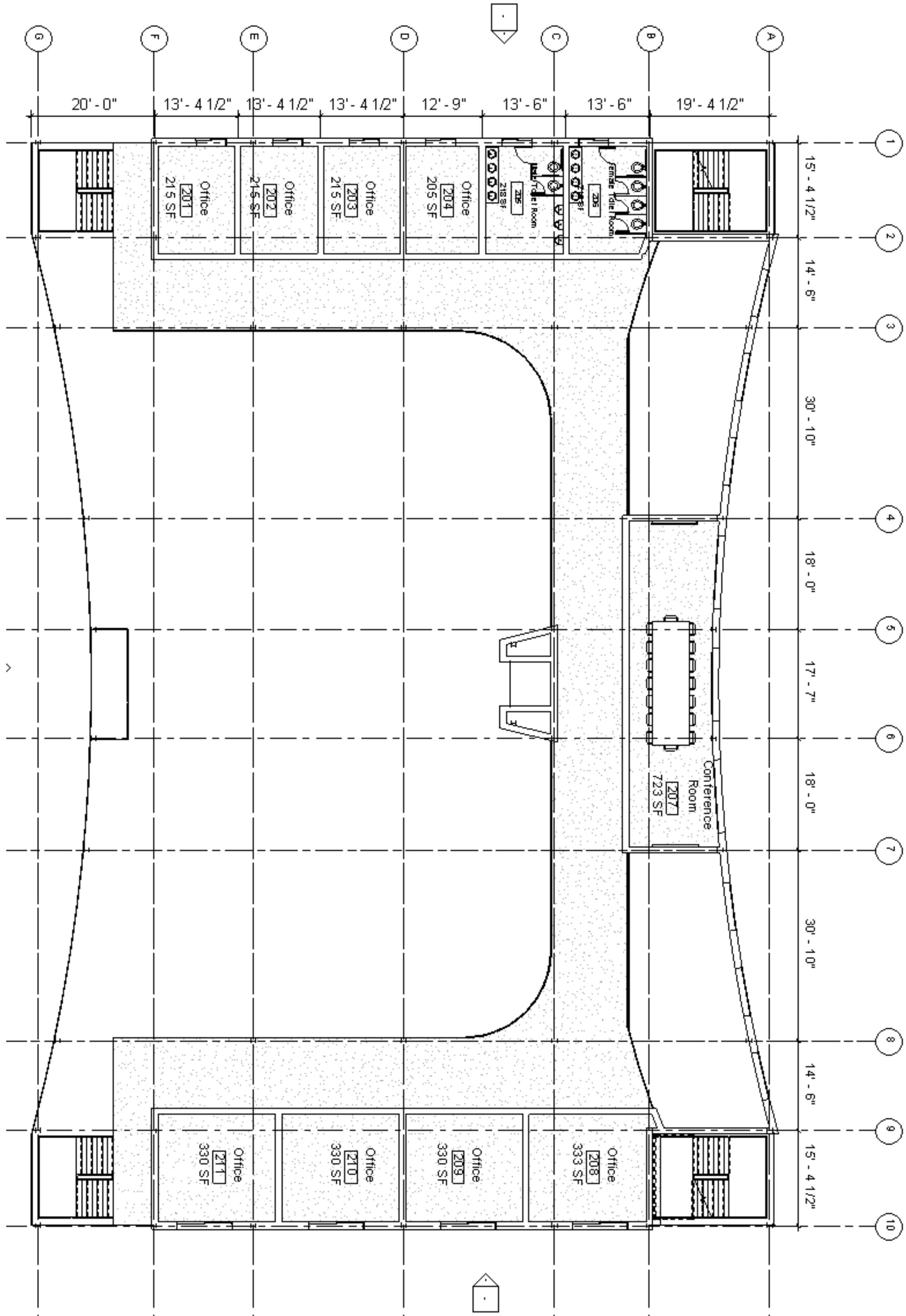
Appendix B: BIM Architectural Images



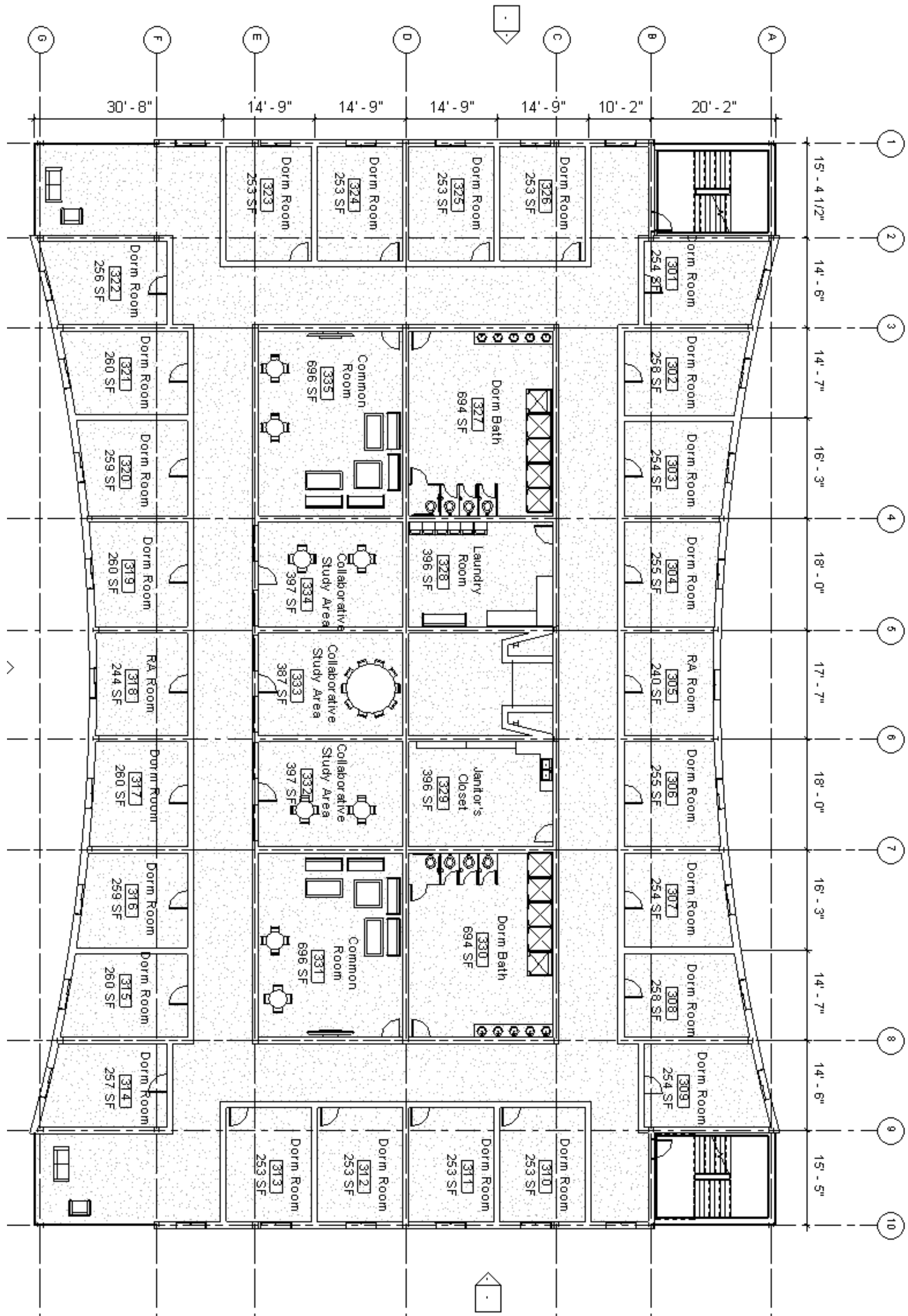
Basement Layout



Main Floor Layout



2nd Floor Mezzanine Layout

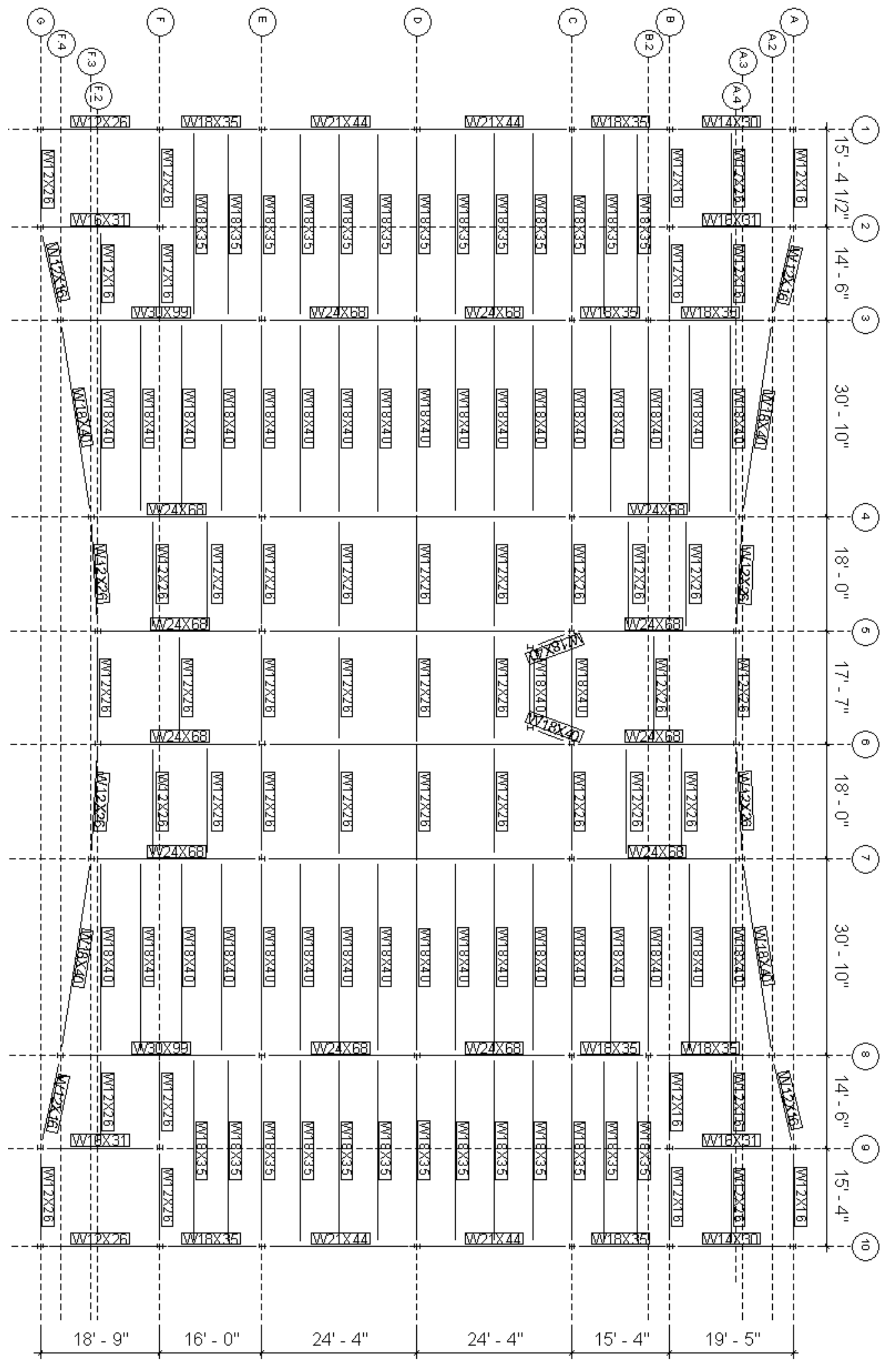


3rd & 4th Residential Floors Layout

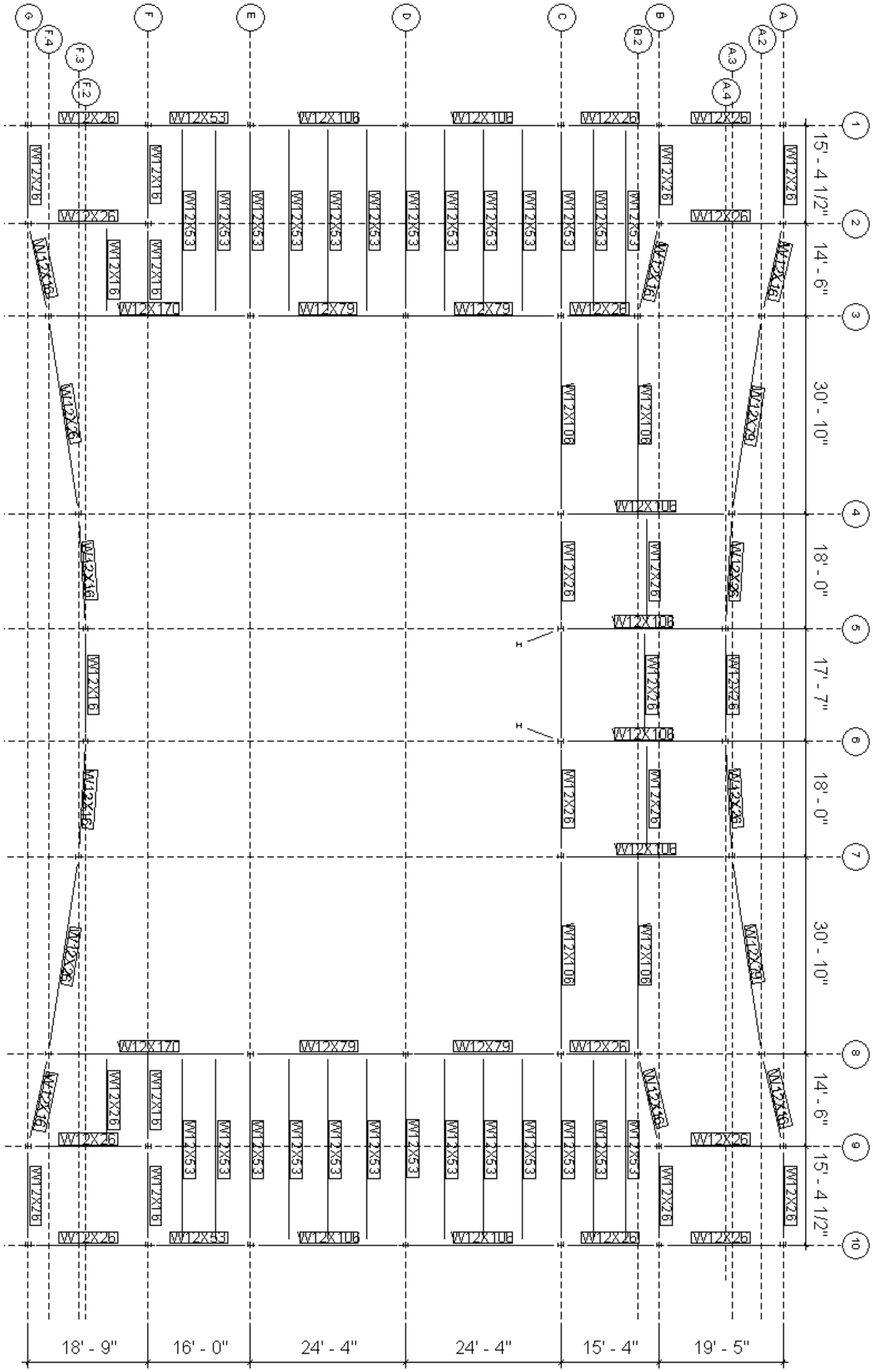
Collaborative Project Display Area

Dorm Room

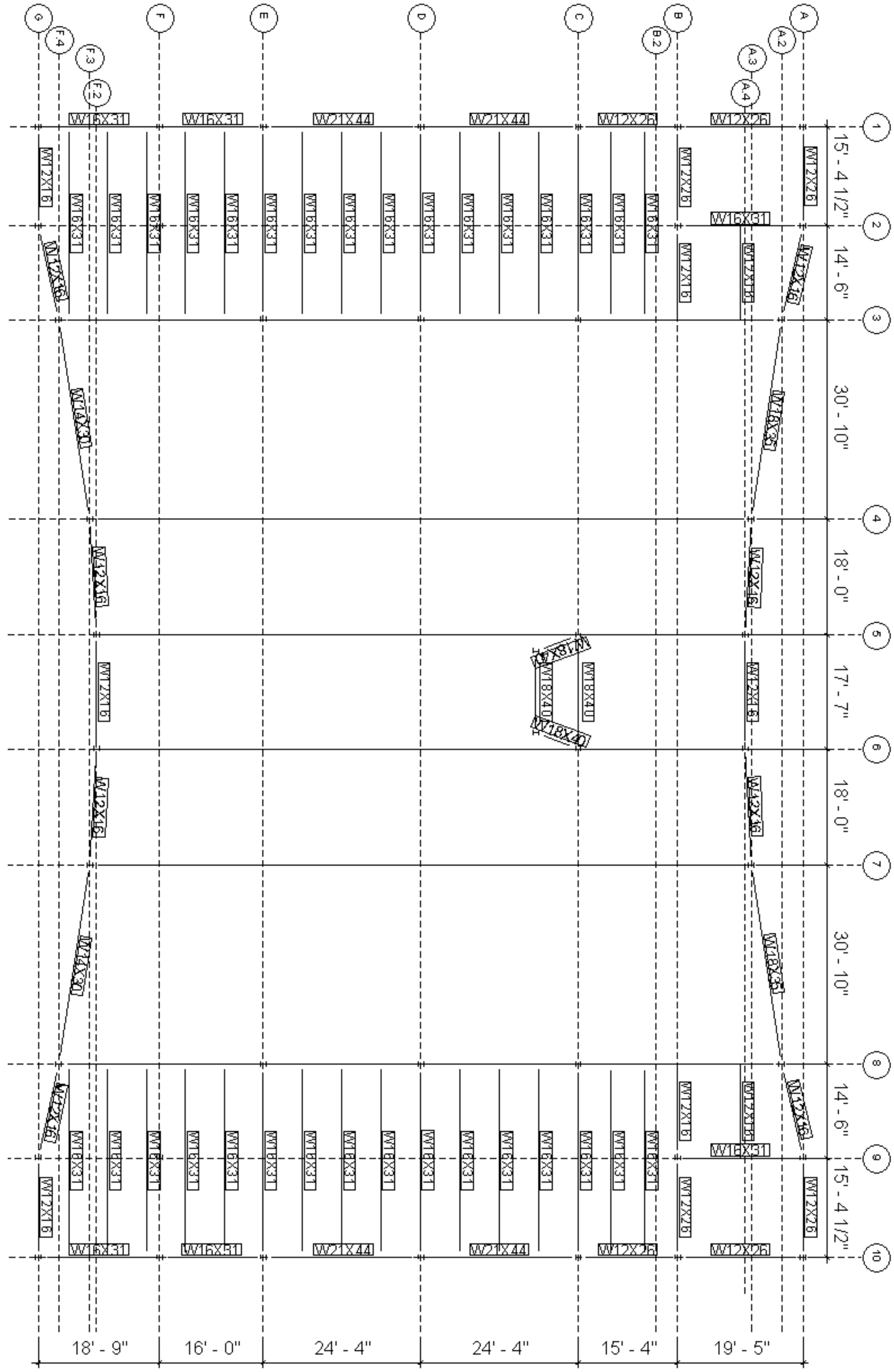
Appendix C: BIM Structural Images



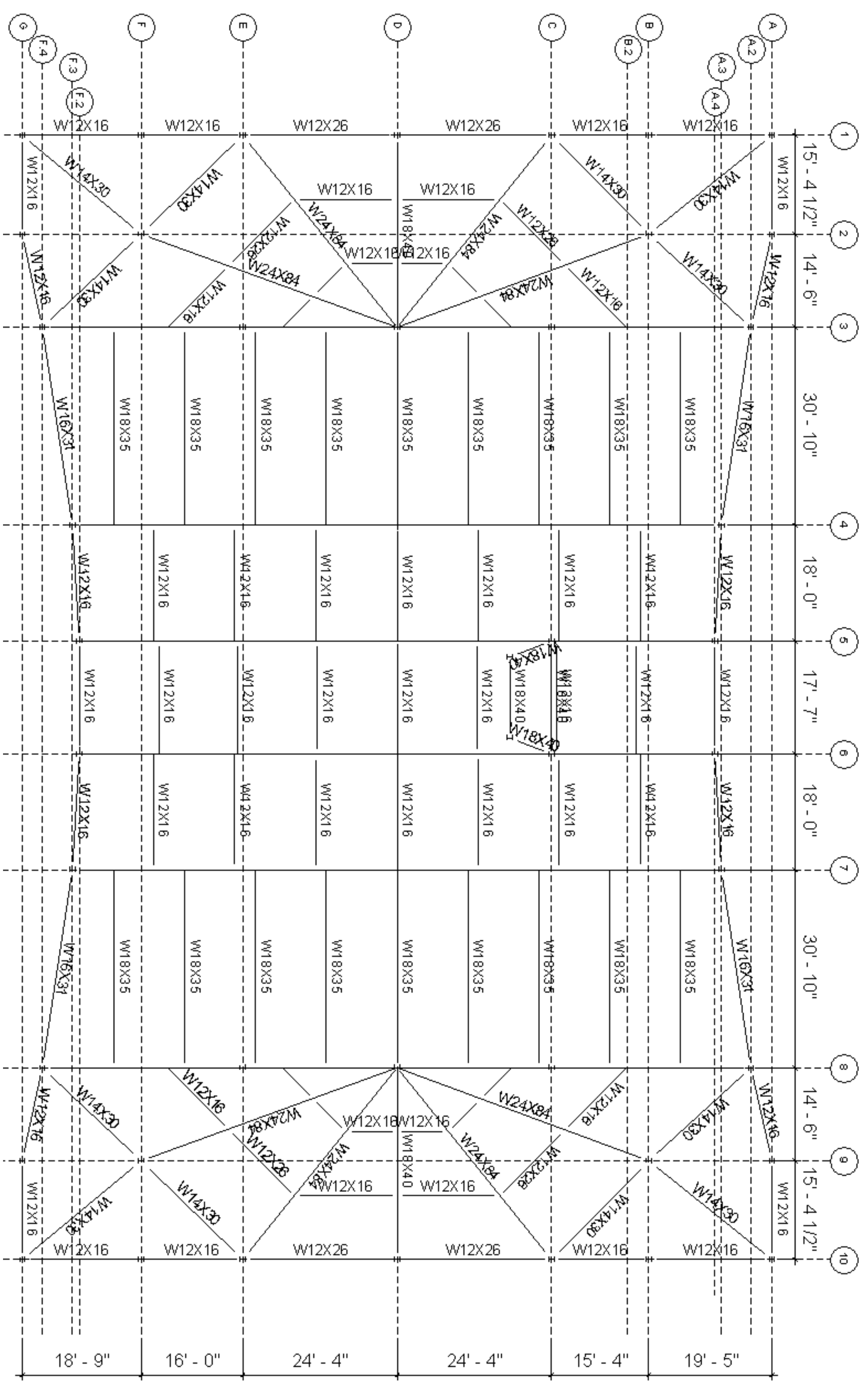
Ground Level Structural Layout



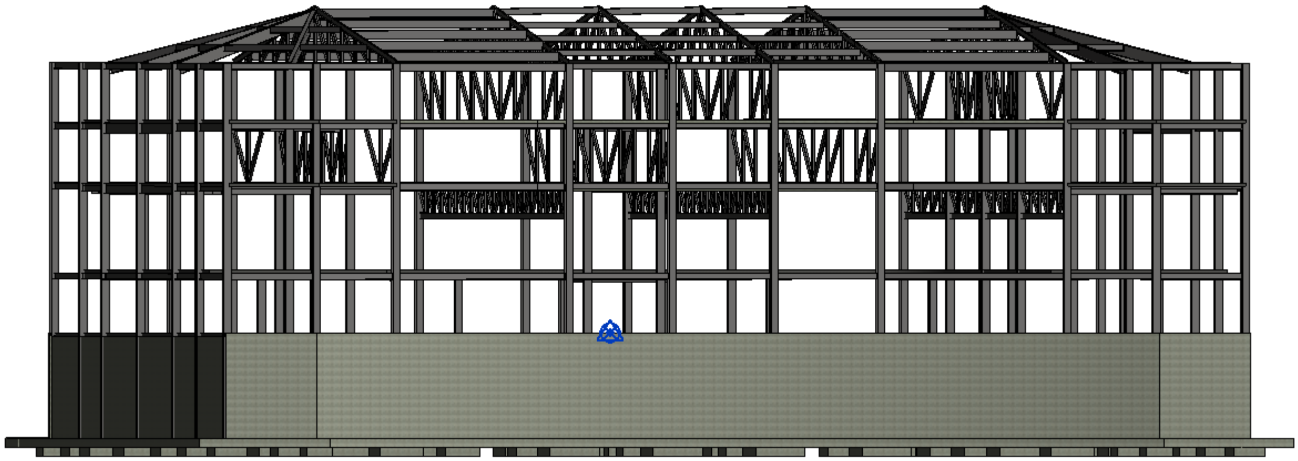
Mezzanine Structural Layout



Residential Structural Layout



Roof Structural Layout

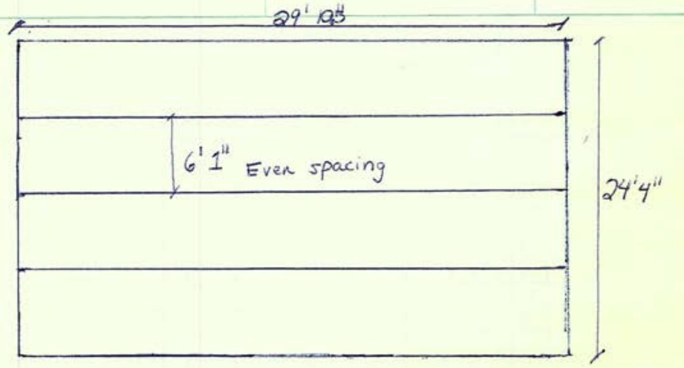


3D Structural View

Appendix D: Sample Calculations

Beam, Girder, Exterior Member Calculation

Floor Joist Design 1



DL = 54 PSF concrete
3 PSF Metal Decking
10 PSF MEP & Partitions } 67 PSF

LL = 50 PSF for Dorm rooms per ASCE 7-05

Load Combinations: 1.4 DL
1.2 DL + 1.6 LL

$w_u = 1.4(67 \text{ PSF})(6.083 \text{ ft}) = 570.6 \text{ lb/ft}$

$w_u = 1.2(67 \text{ PSF})(6.083 \text{ Ft}) + 1.6(50 \text{ PSF})(6.083 \text{ Ft}) = 975.7 \text{ lb/ft}$

Select the greater w_u

$$M_u = \frac{w_u L^2}{8} = \frac{(975.7 \text{ lb/ft})(28.875')^2}{8(1000 \text{ lb/k})} = 108.9 \text{ ft-kips}$$

$$Z_x > \frac{M_u}{\phi F_y} = \frac{108.9 \text{ ft-kips}(12 \text{ in/ft})}{.9(50 \text{ ksi})} = 29.0 \text{ in}^3$$

From Table 3-2 in AISC Steel Manual
$W14 \times 22 \Rightarrow Z_x = 33.2$

Adjust for Beam Self-weight:

$w_u = 1.2(67 \text{ PSF} \cdot 6.083 \text{ ft} + 22 \text{ lb/ft}) + 1.6(50 \text{ psf} \cdot 6.083 \text{ ft}) = 1002.1 \text{ lb/ft}$

$$M_u = \frac{(1002.1 \text{ lb/ft})(28.875 \text{ ft})^2}{8(1000 \text{ lb/k})} = 111.8 \text{ ft-kips}$$

$$Z_x > \frac{(111.8 \text{ ft-k})(12 \text{ in/ft})}{.9(50 \text{ ksi})} = 29.81 \text{ in}^3$$

$33.2 > 29.81 \therefore W14 \times 22$ is acceptable.

Next is the deflection check

Utilizing serviceability criteria Maximum deflection $\frac{L}{360}$ using total dead load plus 50% of designed occupancy Live Load.

Maximum Δ:

$$\frac{(29.875')(12"/')}{360} = 0.996 \text{ in}$$

Actual Deflection:

for W14x22 : $E = 29000 \text{ ksi}$
$I_x = 199 \text{ in}^4$

$$\Delta = \frac{5 w_u L^4}{384 E I}$$

$$\Delta = \frac{5(67_{psf} \cdot 6.083' + 22^{lb/ft} + .5(50_{psf})(6.083'))(29.875')^4 (12"/')^3}{384 \cdot 29000 \text{ ksi} \cdot 199 \text{ in}^4 \cdot 1000 \text{ lb/k}} = 1.81 \text{ in}$$

$1.81 \text{ in} \not< .996 \text{ in}$ ∴ W14x22 does not work

Using a W16x31 ⇒ $Z_x = 54$

$$w_u = 1.2(67_{psf} \cdot 6.083' + 31 \text{ lb/ft}) + 1.6(50_{psf} \cdot 6.083') = 1012.9 \text{ lb/ft}$$

$$M_u = \frac{(1012.9 \text{ lb/ft})(29.875')^2}{8(1000 \text{ lb/k})} = 113.01 \text{ ft-kips}$$

$$Z_x > \frac{(113.01 \text{ 'k})(12"/')}{.9(50 \text{ ksi})} = 30.13 \text{ in}^3$$

$54 \text{ in}^3 > 30.13 \text{ in}^3$ ∴ W16x31 is acceptable

$$\Delta = \frac{5(67_{psf} \cdot 6.083' + 31 \text{ lb/ft} + .5(50_{psf})(6.083'))(29.875')^4 (12"/')^3}{384 \cdot 29000 \text{ ksi} \cdot 375 \text{ in}^4 \cdot 1000 \frac{lb}{k}} = .973 \text{ in}$$

$0.973 \text{ in} < .996 \text{ in}$ ∴ W16x31 is acceptable

Next is the Shear check

From AISC Steel Manual
Table 1-1: $W16\times31 \Rightarrow d = 15.9\,in$, $t_w = .275\,in$

$$h/t_w = 51.6 \le 2.24\sqrt{\frac{29000}{50}} = 53.95 \quad \therefore \ \phi = 1.0$$

$C_v = 1.0$ for W shapes w/ $F_y \le 50\,ksi$

$$\phi V_n = \text{Shear capacity} = \phi A_w C_v \cdot .6 F_y$$

$$\cancel{\phi V_n} \quad A_w = d \cdot t_w$$

$$\phi V_n = (1.0)(15.9\,in \cdot .275\,in)(1.0) \cdot .6(50\,ksi) = 131.2\,k$$

$$V_u = \frac{w_u L}{2} = \frac{(1012.9)(29.875')}{2(1000\,lb/k)} = 15.13^k$$

$131.2^k > 15.13^k \quad \therefore$ W16×31 is acceptable.

Beam System Calculation Example Sheet: (Entire Workbook can be found in Appendix F)

DL (PSF)		LL [PSF]	ributary Width [ft	pan Length (L) [f			Beam Properties									
Con	54	60	5.083	29.875			**W 12 x 53**									
Deck	3						Strength (Fy)(Vy) [ksi]	Youngs Modulus (Es)[Steel] PSI	Self Weight [lb/ft]	Moment of Inertia (I) [in^4]	Zx	Area (As)	bf/2tf	h/tw	d (in)	tw
MEP	10						50	29000000	53	425	77.9	15.6	8.69	28.1	12.1	0.345
Other																
TOTAL	67															
Wu=1.2DL +1.6LL				960.2412	lb/ft											
Mu=(Wu * L^2)/8000				107.13	ft-k											
Zx > Mu/.9Fy				28.57	in^3											
MaxDef=L/360				1.00	in	1" max										
Act Def=(5Wu*L4)/(384*E*I)				0.794	in											
Shear Chk Vu=Wu *L/2				14344												
ear Capacity (Phi)Vn = (Phi)*Aw* Cv*.6				125235												

Exterior Beam Calculation Example Sheet: (Entire Workbook can be found in Appendix F)

Wall DL (PSF)		Floor DL (PSF)		LL [PSF]	Trib. Ht. (ft)	Trib Width [ft	pan Length (L) [f	Beam Properties									
Veneer	48	Con	54	100	5	14.9375	15.333	**W 18 x 35**									
Glass	0.00	Deck	3					Strength (Fy)(Vy) [ksi]	Youngs Modulus (Es)[Steel] PSI	Self Weight [lb/ft]	Moment of Inertia (I) [in^4]	Zx	Area (As)	bf/2tf	h/tw	d (in)	tw
		MEP	10		# Beams.	2		50	29000000	35	510	66.5	10	7.06	53.5	17.7	0.3
		Bm Wt.	13.77		Size	18 x 35											
TOTAL	48	TOTAL	80.77		Trib width	5' 1"											
Wu=1.2DL +1.6LL					4167.8023	lb/ft											
Mu=(Wu * L^2)/8000					122.48	ft-k											
Zx > Mu/.9Fy					32.66	in^3											
MaxDef=L/360					0.51	in	1" max										
Act Def=(5Wu*L4)/(384*E*I)					0.187	in											
Shear Chk Vu=Wu *L/2					31952												
Shear Capacity (Phi)Vn = (Phi)*Aw* Cv*.6Fy					159300												

Girder Calculation Example Sheet: (Entire Workbook can be found in Appendix F)

DL (PSF) left		DL (PSF) right		LL [PSF]	Trib Width Left [ft	Width Right	Span Length (L) [f	[redacted]	
Con	54	Con	54	100	7.6875	7.25	19.4167		
Deck	3	Deck	3						
MEP	10	MEP	10						
BM WT.	1.649	BM WT.	1.6						
TOTAL	68.65	TOTAL	69						
		Wu=1.2DL +1.6LL					3657.733325	lb/ft	
		Mu=(Wu * L^2)/8000					172.37	ft-k	
		Zx > Mu/.9Fy					45.97	in^3	
		MaxDef=L/360					0.65	in	1" max
		Act Def=(5Wu*L4)/(384*E*I)					0.530	in	
			Shear Chk Vu=Wu *L/2				35511		
			Shear Capacity (Phi)Vn = (Phi)*Aw* Cv*.6Fy				131175		

Beam Properties									
W 16 x 31									
Strength (Fy)(Vy) [ksi]	Youngs Modulus (Es)[Steel] PSI	Self Weight [lb/ft	Moment of Inertia (I) [in^4]	Zx [in^3]	Area (As)	bf/2tf	h/tw	d (in)	tw
50	29000000	31	375	54	9.13	6.28	51.6	15.9	0.28

Column Calculation Example Sheet: (Entire Workbook can be found in Appendix F)

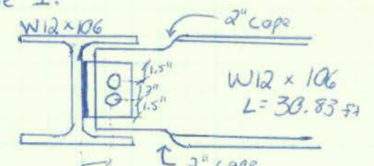
	Column Strength Analysis											
	Loading				Trib. Width [ft]				Column Length(L) [ft]	π	Ky	Kx
	West	East	Southeast	South	West	East	Southeast	South	15	3.142	1	1.2
1st	0	1694.1	0	2787.5	0	7.7	12.45	9.75	180			
2nd	0	3822.8	0	2669.3								
3rd	0	3822.8	0	2669.3								
4th	0	3108.9	0	2229.9								
Roof	0	1349.2	1648	1062.8								
		Pu		238.1	k	==>	Select	W14x48				
	$Pcr = \pi^2 * E * I/L^2$			3197.87	k			W12x40				
	$F_{cr} = (0.658^{F_y/F_e}) F_y$			42.1	ksi			W10x39				
	$F_e = \pi^2 * E/(KL/r)^2$			120.94	ksi			W8x35				
	$P_c = \phi P_n = \phi * F_{cr} * A_g$			1003.0	k							

Beam-Girder Connection

* All members used passed Compact Section Criteria:

$$h/t_w \le 2.24\sqrt{\frac{E}{F_y}} \;\therefore\; \phi = 1.0,\; C_v = 1.0$$

Case 1:



W_u taken from Beam Calculation:

$W_u = 2304$ lb/ft

$$V_u = \frac{W_u \cdot L}{2} = \frac{(2304\ \text{lb/ft})(30.83\ \text{ft})}{2(1000\ \text{lb/kip})} = 35.5\ \text{kips}$$

Check Shear Capacity of Beam: $\phi V_n = \phi\, 0.6 F_y A_w C_v$

From Table 1-1 AISC Manual: $F_y = 50$ ksi, $t_w = 0.610$ in, $d = 12.7$ in

$A_w = t_w \cdot d = 7.87\ \text{in}^2$

$$\phi V_n = (1.0)\ 0.6\,(50\ \text{ksi})(7.87\ \text{in}^2)(1.0)$$
$$\phi V_n = 236.1\ \text{kips} > V_u \checkmark$$

Required # bolts: Using A325-N, $\frac{3}{4}$" diameter bolts

Single Shear bolt strength $\phi R_n = \phi_b F_v A_b$

$F_v = 54$ ksi

$A_b = \frac{\pi}{4} d_b^2 = \frac{\pi}{4}\left(\frac{3}{4}\right)^2 = 0.4418\ \text{in}^2$

$\phi_b = 0.75$

$$\phi R_n = (0.75)(54\ \text{ksi})(0.4418\ \text{in}^2)$$
$$\phi R_n = 17.89\ \text{kip/bolt}$$

# of bolts $n = \dfrac{V_u}{\phi R_n}$

$$n = \frac{35.5\ \text{kips}}{17.89\ \text{kip/bolt}}$$

$n = 1.98 \Rightarrow 2$ bolts

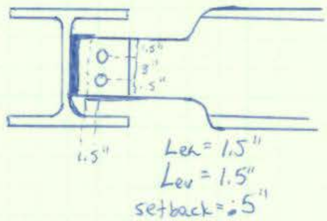
Ensure Connection Stability: $T > L_A > T/2$

From Table 1-1: W12×106 $\Rightarrow T = 9.125"$

Angle length $\Rightarrow L_A = 2\cdot(1.5") + (n-1)\cdot 3" = 2\cdot 1.5" + (2-1)\cdot 3"$

$L_A = 6"$

$9.125" > 6" > \frac{9.125}{2} = 4.56"$ ✓



Choose Angle Size by Gage:

Gage = L_{eh} + setback = 1.5" + .5" = 2"

Reference Table 1-7A

$L\ 3\frac{1}{2} \times 3\frac{1}{2} \times t$ has gage 2in

Determine Angle Thickness:

① Bolt Bearing on Angle (Tear out vs Bearing): $\phi_b R_n = \overbrace{\phi_b 1.2 L_c t F_u}^{\text{tear out}} \leq \overbrace{\phi_b 2.4 d_b t F_u}^{\text{bearing}}$

$L_c = L_{ev} - \frac{1}{2}(d_b + \frac{1}{8}") = 1.5" - \frac{1}{2}(\frac{3}{4}" + \frac{1}{8}")$

$L_c = 1.0625"$

total capacity: 1 bolt tear out
1 bolts bearing

$(0.75)\,1.2(1.0625")\,t\,(58\ ksi) + (0.75)\,2.4(\frac{3}{4}")\,t\,(58\ ksi) \geq V_u = 35.5\ kips$

$t \geq 0.266 in$

② Angle Shear Rupture: $\phi R_n = 0.6\phi_b F_u (L_A - n(d_b + \frac{1}{8}"))\,t \geq V_u = 35.5 kips$

$0.6(0.75)(58 ksi)(6" - 2(\frac{3}{4}" + \frac{1}{8}"))\,t \geq 35.5 kips$

$t \geq 0.320 in$

③ Angle Shear Yield: $\phi_b R_n = 0.6 \phi_b F_y L_A t$

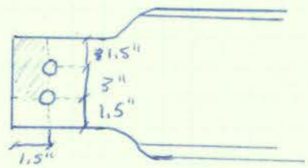
$0.6(0.75)(36 ksi)(6")\,t \geq 35.5 kips$

$t \geq 0.365 in$ ⇐ governs

from Table 1-7

$t = \frac{3}{8}"$

Beam & Girder checks: $R_n = 0.6 F_u A_{nv} + U_{bs} F_u A_{nt} \le 0.6 F_y A_{gv} + U_{bs} F_u A_{nt}$



Net Shear A_{nv} = Net Length • Web thickness
Net Tension Area A_{nt} = Tension plane • Web thickness
Gross Shear Area A_{gv} = gross Length • Web thickness
$U_{bs} = 1.0$ for 1 row of bolts

Block Shear Rupture: $0.6 F_u A_{nv}$

$$A_{nv} = (4.5" - 1.5_{holes}(\tfrac{3}{4}" + \tfrac{1}{8}"))(0.61 in) = 1.94 \, in^2$$

$$0.6 F_u A_n = 0.6(65 ksi)(1.94 in^2) = \underline{75.83 \text{ kips}}$$

Tension Rupture: $U_{bs} F_u A_{nt}$

$$A_{nt} = (1.5" - \tfrac{1}{2}((\tfrac{3}{4}") + \tfrac{1}{8}"))(0.61 in) = 0.65 \, in^2$$

$$U_{bs} F_u A_{nt} = (1.0)(65 ksi)(0.65 in^2) = \underline{42.13 \text{ kips}}$$

Shear Yield: $0.6 F_y A_{gv}$

$$A_{gv} = (4.5")(0.61 in) = 2.75 \, in^2$$

$$0.6 F_y A_{gv} = 0.6(50 ksi)(2.75 in^2) = \underline{82.35 \text{ kips}}$$

$$R_n = 75.83 + 42.13 \le 82.35 + 42.13$$
$$R_n = 117.96k \le 124.48k$$
$$\phi R_n = (.75)(117.96) = \boxed{88.47 \text{ kips} > 35.5 \text{ kips}} \checkmark$$

Bolt Bearing on Beam Web: $\phi R_n = 1.2 \phi_b L t_w F_u \le 2.4 \phi_b d_b t_w F_u$

$$L_c = L_{ev} - \tfrac{1}{2}(d_b + \tfrac{1}{8}") = 1.5" - \tfrac{1}{2}(\tfrac{3}{4}" + \tfrac{1}{8}") = 1.0625$$

$$\phi R_n = 1.2(.75)(1.0625)(0.61")(65 ksi) \le 2.4(0.75)(\tfrac{3}{4}")(0.61")(65 ksi)$$
$$\phi R_n = 37.92 \text{ kips} \le 53.53 \text{ kips}$$

tear out governing for 1 bolt

$$\phi R_n = 1(1.2)(.75)(1.0625)(0.61")(65 ksi) + 1(2.4)(.75)(\tfrac{3}{4})(0.61)(65 ksi)$$
$$\boxed{\phi R_n = 91.44 \text{ kips} > 35.5 \text{ kips}} \checkmark$$

Check Girder Web for Bearing: $t_w \ge t$ of bearing on angle

from table 1-1

$$W12 \times 106 = t_w = 0.61" \ge t = 0.266" \checkmark$$

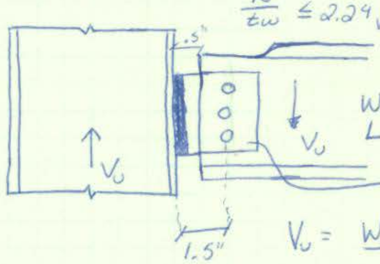
Beam-to-Girder Example Excel Sheet: (Entire Workbook can be found in Appendix F)

Compact Section					$V_u = W_u*L/2$	35.5	[kips]	
					$\phi V_n = \phi_v.6*F_y*A_w*C_v$	236.07	[kips]	
All of the members used were					$\phi R_n = \phi_b*Fv*Ab$	17.89	[k/bolt]	
passed compact section criteria:					#bolts $n = V_u/\phi R_n$	1.98		
h/tw≤ 2.24√(E/Fy)						2.00		
W 12x106 Beam					used n	2.00		
W_u	2304	[lb/ft]			Use angle 3.5" x 3.5" x t (gage dist. = 2")			
L	30.83	[ft]			L_A = 2*Le"+(n-1)*3"	6	[in]	
ϕ_v	1.0			Cope:	Necessary	YES		
F_y	50	[ksi]			Cope min	2		
F_u	65	[ksi]			Determine Angle Thickness (t)			
A_w	7.87	[in^2]		Bolt Bearing	$\phi R_n = 1.2*\phi_b*L_c*t*F_u \le 2.4*\phi_b*d_b*t*F_u$			
C_v	1.0			on Angle:	L_c = 1.5"-0.5(d_b+1/8")	1.0625	[in]	
T	9.125	[in]			$1.2*\phi_b*L_c*t*F_u + (n-1)2.4*\phi_b*d_b*t*F_u \ge V_U$			
t_w	0.61	[in]			t ≥	0.266	[in]	
d	12.9	[in]		Angle Shear	$\phi R_n = 0.6\phi_b F_u(L_A-n(d_b+1/8"))t \ge V_u$			
Cope	2	[in]		Rupture:	t ≥	0.320	[in]	
W 12x106 Girder				Angle Shear	$\phi R_n = 0.6\phi_b F_y L_A t \ge V_u$			
ϕ_v	1.0			Yield:	t ≥	0.365	[in]	
F_y	50	[ksi]			Use angle 3.5" x 3.5" x 3/8" (gage dist. = 2")			
F_u	65	[ksi]			Beam Checks			
A_w	7.87	[in^2]		$R_n = 0.6F_uA_{nv}+U_{bs}F_uA_{nt} \le 0.6F_yA_{gv}+U_{bs}F_uA_{nt}$				
C_v	1.0			Block Shear	Net Shear Area A_{nv} =	1.94	[in^2]	
T	9.125	[in]		Rupture:	0.6 F_u A_{nv}	75.83	[kips]	
t_w	0.61	[in]		Tension	Net Tension Area A_{nt}=	0.65	[in^2]	
t_f	0.99	[in]		Rupture:	$U_{bs}F_uA_{nt}$	42.13	[kips]	
d	12.9	[in]		Shear Yield:	Gross Shear Area A_{gv}=	2.75	[in^2]	
A325-N 3/4" Dia. Bolts					0.6 F_y A_{gv}	82.35	[kips]	
F_v	54	[ksi]			R_n =	117.96	≤	124.48
$A_b = \pi/4 * d_b^2$	0.4418	[in^2]			ϕR_n =	88.47	[kips]	
ϕ_b	0.75							
U_{bs}	1.0			Bolt Shear	$\phi R_n = \phi_b*Fv*Ab$	17.89	[k/bolt]	
Angle Properties				Check:		35.78	[kips]	
F_y	36	[ksi]		Bolt Bearing	$\phi R_n = 1.2*\phi_b*L_c*t_w*F_u \le 2.4*\phi_b*d_b*t_w*F_u$			
F_u	58	[ksi]		on Beam	$L_c = L_{ev}$-0.5(d_b+1/8")	1.0625	[in]	
t	0.375	[in]		Web:	R_n =	37.92	≤	53.5275
Connection Geometry:					ϕR_n =	91.44	[kips]	
L to angle edge	1.5	[in]			tw ≥ t of bolt bearing			
L_{ev} (beam)	1.5	[in]		Check Girder web for	t =	0.266	[in]	
L_{eh}	1.5	[in]		Bearing:	t_w =	0.610	[in]	

Girder-Column Calculation:

All members used passed Compact Section Criteria

$\frac{h}{t_w} \le 2.24\sqrt{\frac{E}{F_y}}$ $\therefore$ $\phi = 1.0$
$C_v = 1.0$



W 30 × 99
L = 31.6'
A36 Steel $\angle$ $F_y = 36\,ksi$, $F_u = 58\,ksi$

W_u taken from Girder Calculation:
$W_u = 8214.1\ ^{lb}/_{ft}$

$V_u = \frac{W_u \cdot L}{2} = \frac{8214.1\ \frac{lb}{ft} \cdot 31.6\,ft}{2\ (1000\ \frac{lb}{kip})} = 129.8\ kips$

Check Shear Capacity of Girder: $\phi V_n = \phi\, 0.6 F_y A_w C_v$

$F_y = 50\ ksi$
$A_w = t_w \cdot d = 15.44\ in^2$

From Table 1-1 AISC Steel Manual $\begin{cases} t_w = (.520") \\ d = (29.7") \end{cases}$

$\phi V_n = (1.0)\,0.6(50ksi)(15.44 in^2)(1.0)$
$\phi V_n = 463.32\ kips$

Required # of bolts: Using A325-N, $\frac{3}{4}$" diameter bolts.

Bolt Strength $\phi R_n = 2(\phi F_v A_b)$ because of double shear

$F_v = 54\,ksi$
$A_b = \frac{\pi}{4} d_b^2 = \frac{\pi}{4}(\frac{3}{4})^2 = 0.4418 in^2$
$\phi_b = .75$

$\phi R_n = 2(.75)(54ksi)(0.4418\ in^2)/bolt$
$\phi R_n = 35.78\ \frac{kip}{bolt}$

# of bolts $n = \frac{V_u}{\phi R_n}$

$n = \frac{129.8\ kips}{35.78\ \frac{kip}{bolt}}$

$n = 3.63 \Rightarrow 4\ bolts$

Choose Angle size by gage:

minimum edge distance for $\frac{3}{4}$" dia. bolts = 1"

Reference Table 1-7A in AISC Steel Manual

$L\ 3\frac{1}{2} \times 3\frac{1}{2} \times t$ has gage 2in

Ensure Connection Stability: $T > L_A > \frac{T}{2}$

Angle Length $\Rightarrow L_A = 2 \cdot (\text{Edge dist.}) + (n-1) \cdot 3'' = 2(1.5'') + (4-1) \cdot 3'' = 12''$

from table 1-1

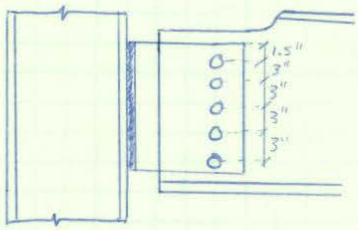
$W30 \times 99 \Rightarrow T = 26.5''$

$L_A = 12'' \not> \frac{26.5}{2} = 13.25''$

Thus add a bolt:

$n = 5$

$L_A = 2(1.5'') + (5-1) \cdot 3'' = 15''$ $\quad 26.5'' > 15'' > 13.25''$ ✓



Determine Angle Thickness:

① Bolt Bearing on Angle (Tearout vs. Bearing): $\phi R_n = \overbrace{\phi 1.2 L_c t F_u}^{\text{tearout}} \le \overbrace{\phi 2.4 d_b t F_u}^{\text{bearing}}$

$L_c = (\text{Edge dist.}) - \frac{1}{2}(d_b + \frac{1}{8}'') = 1.5'' - \frac{1}{2}(\frac{3}{4} + \frac{1}{8}'') = 1.0625''$

total capacity: $1((.75) \cdot 1.2 \cdot (1.0625'')\, t\, (58\,ksi)) + 4((.75) 2.4 (\frac{3}{4}'')\, t\, (58\,ksi)) \ge \frac{V_u = 129.8}{2}$

$t = 0.176$ in

② Angle Shear Rupture: $\phi R_n = 0.6\, \phi F_u (L_A - n(d_b + \frac{1}{8}''))\, t \ge \frac{V_u}{2}$

$0.6(.75)(58\,ksi)(15'' - 5(\frac{3}{4}'' + \frac{1}{8}''))\, t \ge \frac{129.8}{2}$

$t = 0.234''$ in

③ Angle Shear Yield: $\phi R_n = 0.6\, \phi_v F_y L_A t \ge \frac{V_u}{2}$

$0.6(.75)(36\,ksi)(15'')\, t \ge \frac{129.8}{2}$

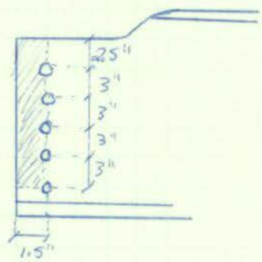
$t = 0.267$ in

Angle Shear Yield governs

from table 1-7

$t = \frac{5}{16}''$

Girder & Column Checks: $R_n = 0.6 F_u A_{nv} + U_{bs} F_u A_{nt} \le 0.6 F_y A_{gv} + U_{bs} F_u A_{nt}$



Net Shear Area A_{nv} = Net Length · Web thickness

Net Tension Area A_{nt} = Tension plane · Web thickness

Gross Shear Area A_{gv} = Length · Web thickness

$U_{bs} = 1.0$ for 1 row of bolts

Block Shear Rupture: $0.6 F_u A_{nv}$

$$A_{nv} = (14.5'' - 4.5_{holes}(\tfrac{3}{4}'' + \tfrac{1}{8}''))(.52'') = 5.49 in^2$$

$$0.6 F_u A_{nv} = 0.6(65ksi)(5.49 in^2) = \underline{214.2 \text{ kips}}$$

Tension Rupture: $U_{bs} F_u A_{nt}$

$$A_{nt} = (1.5'' - \tfrac{1}{2}_{hole}(\tfrac{3}{4}'' + \tfrac{1}{8}''))(.52'') = 0.55 in^2$$

$$U_{bs} F_u A_{nt} = (1.0)(65ksi)(0.55in^2) = \underline{35.9 \text{ kips}}$$

Shear Yield: $0.6 F_y A_{gv}$

$$A_{gv} = (14.5'')(0.52'') = 7.54 in^2$$

$$0.6 F_y A_{gv} = 0.6(50ksi)(7.54in^2) = \underline{226.2 \text{ kips}}$$

$$R_n = 214.2 + 35.9 \le 226.2 + 35.9$$
$$R_n = 250.12 \text{ kips} \le 262.1 \text{ kips}$$

$$\phi R_n = (0.75)(250.12 \text{ kips}) = \boxed{187.6 \text{ kips} > 129.8 \text{ kips.}} \checkmark$$

Bolt Bearing on Girder Web: $\phi R_n = 1.2 \phi L t_w F_u \le 2.4 \phi d_b t_w F_u$

$$L = L_{ev} - \tfrac{1}{2}(d_b + \tfrac{1}{8}) = 2.5'' - \tfrac{1}{2}(\tfrac{3}{4}'' + \tfrac{1}{8}'') = 2.0625''$$

$$\phi R_n = 1.2(.75)(2.0625'')(.52'')(65ksi) \le 2.4(.75)(.75)(.52)(65ksi)$$
$$\phi R_n = 62.7 \text{kips} \nleq 45.63$$

tearout does have effect

$$\phi R_n = 5(2.4(.75)(.75)(.52'')(65ksi)) = \boxed{228.2 \text{ kips} > 129.8 \text{ kips}} \checkmark$$

Check Column Flange for Bearing: $t_f \ge t$, $t_w \ge t$ of bolt bearing on angle.

from table 1-1

$W14\times90 \Rightarrow t_f = 0.710''$

$t_w = 0.440'' \ge t = 0.176''$ ✓

Girder-Column Connection Example Excel Sheet: (Entire Workbook can be found in Appendix F)

Compact Section					$V_u = W_u*L/2$	129.8	*[kips]*	
					$\phi V_n = \phi_v.6*F_y*A_w*C_v$	463.32	*[kips]*	
All of the members used were passed compact section criteria:					$\phi R_n = 2\,\phi_b*Fv*Ab$	35.78	*[k/bolt]*	
					#bolts $n = V_u/\phi R_n$	3.63		
h/tw≤ 2.24√(E/Fy)						4.00		
W 30x99 Girder					used n	5.00		
W_u	8214.1	*[lb/ft]*			Use angle 3.5" x 3.5" x t (gage dist. = 2")			
L	31.6	*[ft]*			$L_A = 2*1.5"+(n-1)*3"$	15	*[in]*	
ϕ_v	1.0				Determine Angle Thickness (t)			
F_y	50	*[ksi]*		Bolt Bearing on Angle:	$\phi R_n = 1.2*\phi_b*L_c*t*F_u \leq 2.4*\phi_b*d_b*t*F_u$			
F_u	65	*[ksi]*			$L_c = 1.5"-0.5(d_b+1/8")$	1.0625	*[in]*	
A_w	15.44	*[in^2]*			$1.2*\phi_b*L_c*t*F_u + (n-1)2.4*\phi_b*d_b*t*F_u \geq 0.5\,V_U$			
C_v	1.0				t ≥	0.176	*[in]*	
T	26.5	*[in]*		Angle Shear Rupture:	$\phi R_n = 0.6\phi_b F_u(L_A-n(d_b+1/8"))t \geq 0.5\,V_u$			
t_w	0.52	*[in]*			t ≥	0.234	*[in]*	
d	29.7	*[in]*		Angle Shear Yield:	$\phi R_n = 0.6\phi_b F_y L_A t \geq 0.5\,V_u$			
Cope	0	*[in]*			t ≥	0.267	*[in]*	
A325-N 3/4" Dia. Bolts					Use angle 3.5" x 3.5" x 5/16" (gage dist. = 2")			
F_v	54	*[ksi]*			Girder & Column Checks			
$A_b = \pi/4 * d_b^2$	0.4418	*[in^2]*		$R_n = 0.6F_uA_{nv}+U_{bs}F_uA_{nt} \leq 0.6F_yA_{gv}+U_{bs}F_uA_{nt}$				
ϕ_b	0.75			Block Shear Rupture:	Net Shear Area A_{nv} =	5.49	*[in^2]*	
U_{bs}	1.0				$0.6\,F_u\,A_{nv}$	214.21	*[kips]*	
Angle Properties				Tension Rupture:	Net Tension Area A_{nt}=	0.55	*[in^2]*	
F_y	36	*[ksi]*			$U_{bs}F_uA_{nt}$	35.91	*[kips]*	
F_u	58	*[ksi]*		Shear Yield:	Gross Shear Area A_{gv}=	7.54	*[in^2]*	
t	0.31	*[in]*			$0.6\,F_y\,A_{gv}$	226.20	*[kips]*	
Connection Geometry:					R_n =	250.12	≤	262.11
L to angle edge	1.5	*[in]*			ϕR_n =	187.59	*[kips]*	
L_{ev}	2.5	*[in]*						
L_{eh}	1.5	*[in]*		Bolt Shear Check:	$\phi R_n = 2\,\phi_b*Fv*Ab$	35.78	*[k/bolt]*	
						178.92	*[kips]*	
				Bolt Bearing on Girder Web:	$\phi R_n = 1.2*\phi_b*L_c*t_w*F_u \leq 2.4*\phi_b*d_b*t_w*F_u$			
					$L_c = L_{ev}-0.5(d_b+1/8")$	2.0625	*[in]*	
					R_n =	62.74125	≤	45.63
					ϕR_n =	228.15	*[kips]*	
				Check Column Flange for Bearing:	$t_f \geq$ t of bolt bearing			
					t =	0.176	*[in]*	
					t_f =	0.710	*[in]*	
					t_w =	0.440	*[in]*	

Base Plate and Footing Calculation

Base Plate & Footing Design 1

A36 steel Plate $F_y = 36$ ksi

Concrete strength $f'_c = 4$ ksi

W14×90 column : $P_u = 327.3$ k $b_f = 14.5''$ $d = 14.0''$

$$P = \frac{P_u \text{ From Column}}{1.4} = \frac{327.3^k}{1.4} = 233.8 \text{ k}$$

$S = 7.255$ ksf for 36'' depth of footing

Area of footing $\rightarrow A_F = \frac{P}{S} = \frac{233.8^k}{7.255^{ksf}} = 32.22 \text{ ft}^2$

Dimensions: $\sqrt{A_F}$

$$\sqrt{32.22 \text{ ft}^2} = 5.68 \text{ ft} \approx 6 \text{ ft}$$

$\therefore$ 6' × 6' × 3' Column Footing

For Base Plate use P_u:

Determine Base Plate Area:

for Base Plate on Footing $\sqrt{\frac{A_2}{A_1}} = 2.0$, $\phi_c = .65$

$$A_1 = \frac{P_u}{\phi_c\, 0.85\, f'_c \sqrt{\frac{A_2}{A_1}}} = \frac{327.3^k}{(0.65)(0.85)(4 ks)(2.0)} = 74.05 \text{ in}^2$$

$$A_{min} = d \cdot b_f = 14.0'' \cdot 14.5'' = 203 \text{ in}^2$$

$$\Delta = \frac{0.95(d) - .8(b_f)}{2} = \frac{.95(14.0'') - .8(14.5'')}{2} = 0.85''$$

$$N = \sqrt{A_{1min}} + \Delta = \sqrt{203 \text{ in}^2} + 0.85 = 15.1'' \approx 16''$$

$$B = \frac{A_{1min}}{N} = \frac{203 \text{ in}^2}{16''} = 12.69'' \Rightarrow \text{round to } 16'' \text{ to use square plate.}$$

$$A_1 = B \cdot N = 16'' \cdot 16''$$
$$\Rightarrow A_1 = 256 \text{ in}^2$$

Check Bearing Strength of Concrete:

$$\phi_c P_p = \phi_c\, 0.85\, f'_c\, A_1 \sqrt{\frac{A_2}{A_1}} = (0.65)(.85)(4 ksi)(256 \text{ in}^2)(2.0) = 1131.5^k > 327.3^k\ P_u \checkmark$$

Determine thickness of Base Plate:

$$m = \frac{N - 0.95d}{2} = \frac{16'' - 0.95(14.0'')}{2} = 1.35''$$

$$n = \frac{B - 0.8\,b_f}{2} = \frac{16'' - 0.8(14.5'')}{2} = 2.2''$$

$$n' = \ell = \frac{\sqrt{d \cdot b_f}}{4} = \frac{\sqrt{203}}{4} = 3.56''$$

$$\text{thickness } t_{req} = \ell\sqrt{\frac{2P_u}{0.9F_y BN}} = 3.56''\sqrt{\frac{2(327.3)}{0.9(36ksi)(16'')(16'')}}$$

$$t_{req} = 1.00$$

Use a 16" × 16" × 1" A36 steel Plate.

Base Plate & Column Footing Example Excel Sheet: (Entire Workbook can be found in Appendix F)

f'c *[ksi]*		4
fy *[ksi]*		36
Column Properties: W14x90		
b_f *[in]*	14.5	
d *[in]*	14	
P *(column load) [kips]*		233.8
S *(allowable soil pressure)[ksf]*		7.255
P_u *(factored P) [kips]*		327.3
$\sqrt{\frac{A_2}{A_1}}$		2.0
ϕ_c		0.65

$A_f = P/S$	32.22	$[ft^2]$	
Dimensions of Footing	5.68		
	6.00		
	6	*[ft]*	
$A_1 = \frac{P_u}{0.85\phi_c f_c' \sqrt{\frac{A_2}{A_1}}}$	74.05	$[in^2]$	
$A_{1\,min} = d * b_f$	203.00	$[in^2]$	
$\Delta = \frac{0.95d - 0.8b_f}{2}$	0.85	*[in]*	
$N = \sqrt{A_1} + \Delta$	15.10		
	16	*[in]*	
$B = \frac{A_1}{N}$	12.69		
	16	*[in]*	
A_1	256	$[in^2]$	
$\phi_c P_p = 0.85\phi_c f_c' A_1 \sqrt{\frac{A_2}{A_1}}$	1131.52	*[kips]*	>Pu
$m = \frac{N - 0.95d}{2}$	1.35	*[in]*	
$n = \frac{B - 0.8b_f}{2}$	2.2	*[in]*	
$n' = \frac{\sqrt{db_f}}{4} = l$	3.56	*[in]*	
$t = l\sqrt{\frac{2P_u}{0.9F_y BN}}$	1.00		
	1	*[in]*	

BASE PLATE
16 in x 16 in x 1 in
COLUMN FOOTING
6 ft x 6 ft

Appendix E: Reinforced Concrete Alternative Preliminary Design

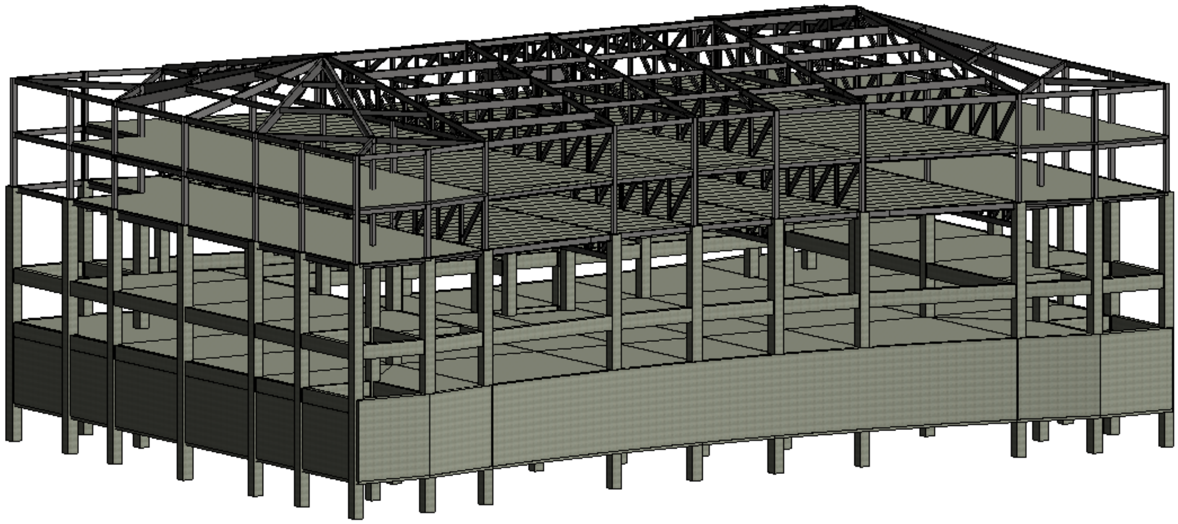
Floor Slab Calculation Sheet:

f'c *[ksi]*		4	4000	Wu=1.2 DL +1.6 LL	364	*[lb/ft] for 12" strip*			
fy *[ksi]*		60	60000						
$h_{min} = \frac{l}{20}$		10.80		Midspan $M_u = \frac{w_u l_n^2}{14}$	8.42	*[ft-kip]*			
				Exterior $M_u = \frac{w_u l_n^2}{24}$	4.91	*[ft-kip]*			
l [ft]		18		Interior $M_u = \frac{w_u l_n^2}{9}$	13.10	*[ft-kip]*			
DL *[psf]*	-MEP	10							
	-Flooring	10		$\rho = .85\,\beta_1 \frac{f'c}{f_y} \frac{\varepsilon_u}{\varepsilon_u + \varepsilon_t}$	0.0181				
	-Self	135.0							
	-Partitions	15.0							
	Total	170		$d = \sqrt{\frac{M_{max}}{\varphi \rho f_y b (1 - .59\rho \frac{f_y}{f'_c})}}$	3.999	*[in]*			
LL *[psf]*		100							
column dim *c [in]*		14							
l_n *[ft]*		16.83							
b [in]		12.00		Assume #5 bars d_{bars}	0.625				
h [in]		13.00							
d *[in]*		12.00		Check d=*h-cover-*d_{bars}/2	9.74				
				Assume *a= 1/2*	0.5	*[in]*			
				$As_{mid} = \frac{M_u}{\varphi f_y (d - \frac{a}{2})}$	0.197	$[in^2]$	$As_{int} = \frac{M_u}{\varphi f_y (d - \frac{a}{2})}$	0.307	$[in^2]$
β_1		0.85		$a = Asf_y/.85f'cb$	0.290	*[in]*	$a = Asf_y/.85f'cb$	0.451	*[in]*
ε_u		0.003		$As_{mid} = \frac{M_u}{\varphi f_y (d - \frac{a}{2})}$	0.195	$[in^2]$	$As_{int} = \frac{M_u}{\varphi f_y (d - \frac{a}{2})}$	0.306	$[in^2]$
ε_t		0.005							
φ		0.9		$a = Asf_y/.85f'cb$	0.287	*[in]*	$a = Asf_y/.85f'cb$	0.450	*[in]*
φ (shear)		0.75		$As_{mid} = \frac{M_u}{\varphi f_y (d - \frac{a}{2})}$	0.195	$[in^2]$	$As_{int} = \frac{M_u}{\varphi f_y (d - \frac{a}{2})}$	0.306	$[in^2]$
ρ_{min}		0.0018							
				$a = Asf_y/.85f'cb$	0.287	*[in]*	$a = Asf_y/.85f'cb$	0.450	*[in]*
				$As_{ext} = \frac{M_u}{\varphi f_y (d - \frac{a}{2})}$	0.115	$[in^2]$			
				$As_{min} = \rho_{min} bh$	0.233	$[in^2]$			
				$V_u = 1.15 w_u l/2 - w_u d$	3.472	*[kips]*			
				$\varphi V_c = \varphi 2 \sqrt{f'_c} bd$	11.085	*[kips]*			

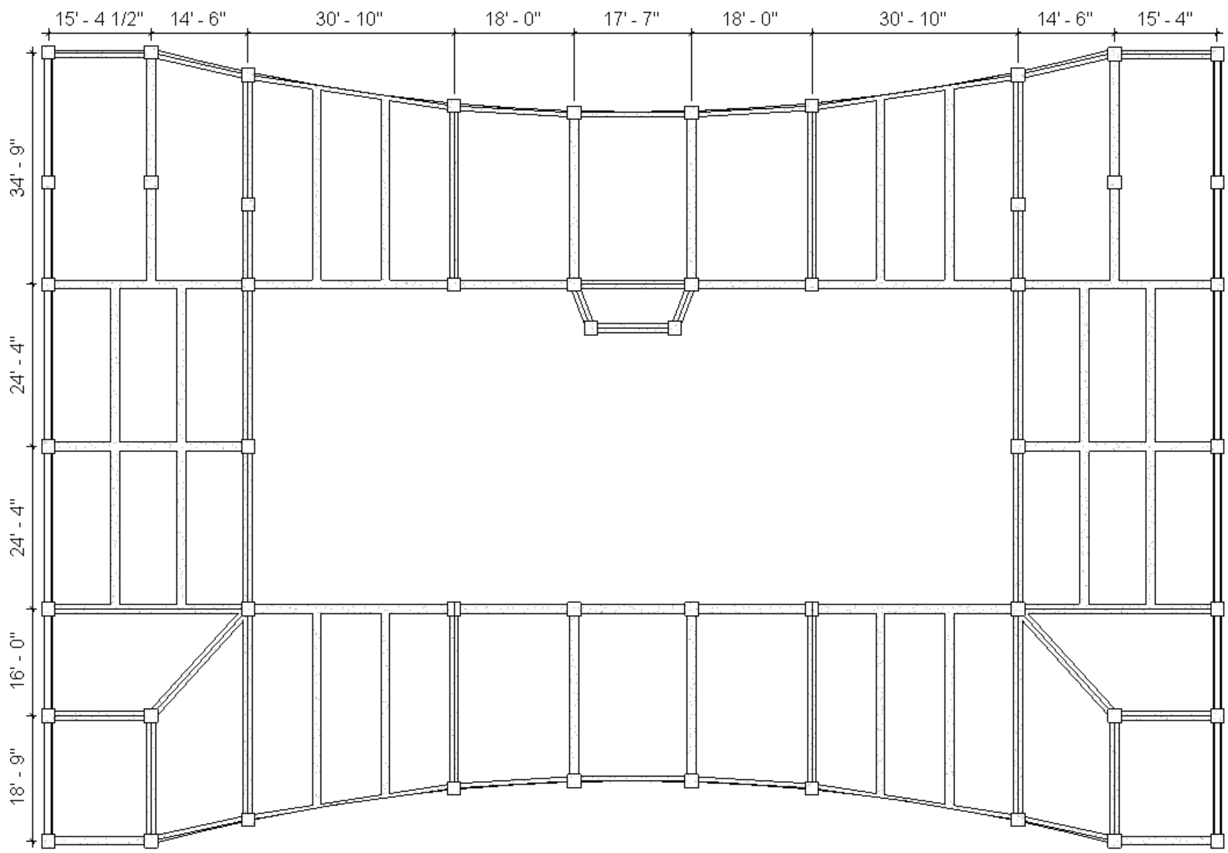
Beam Calculation Sheet:

f'c [ksi]	4	4000		Wu=1.2 DL +1.6 LL	1497.5	*[lb/ft]*
fy [ksi]	60	60000			74875	*[lb-ft]*
DL [psf]	170				898.5	*[k-in]*
LL [psf]	100					
l [ft]	20					
Trib Width [ft]	3.125				0.0181	
Self Wt. [lb/ft]	300					
initial b [in]	12			bd2 ≥	1096.46	
initial h [in]	24			0 = d3 +2.5d2 - 2(bd2)		
β1	0.85			d	12.5	*[in]*
εu	0.003			b	7.02	*[in]*
εt	0.005				8	*[in]*
ϕ	0.9			h = d + 2.5	15	*[in]*
ϕ (shear)	0.75			Self Wt.	125	*[lb/ft]*
				Wu=1.2 DL +1.6 LL	1287.5	*[lb/ft]*
					64375	*[lb-ft]*
					772.5	*[k-in]*
					0.10007	
				ρ	0.01292	
				As = ρbd	1.29223	*[in2]*
				3 #6 bars with 1.5" cover and #3 ties As=1.32[in^2]		

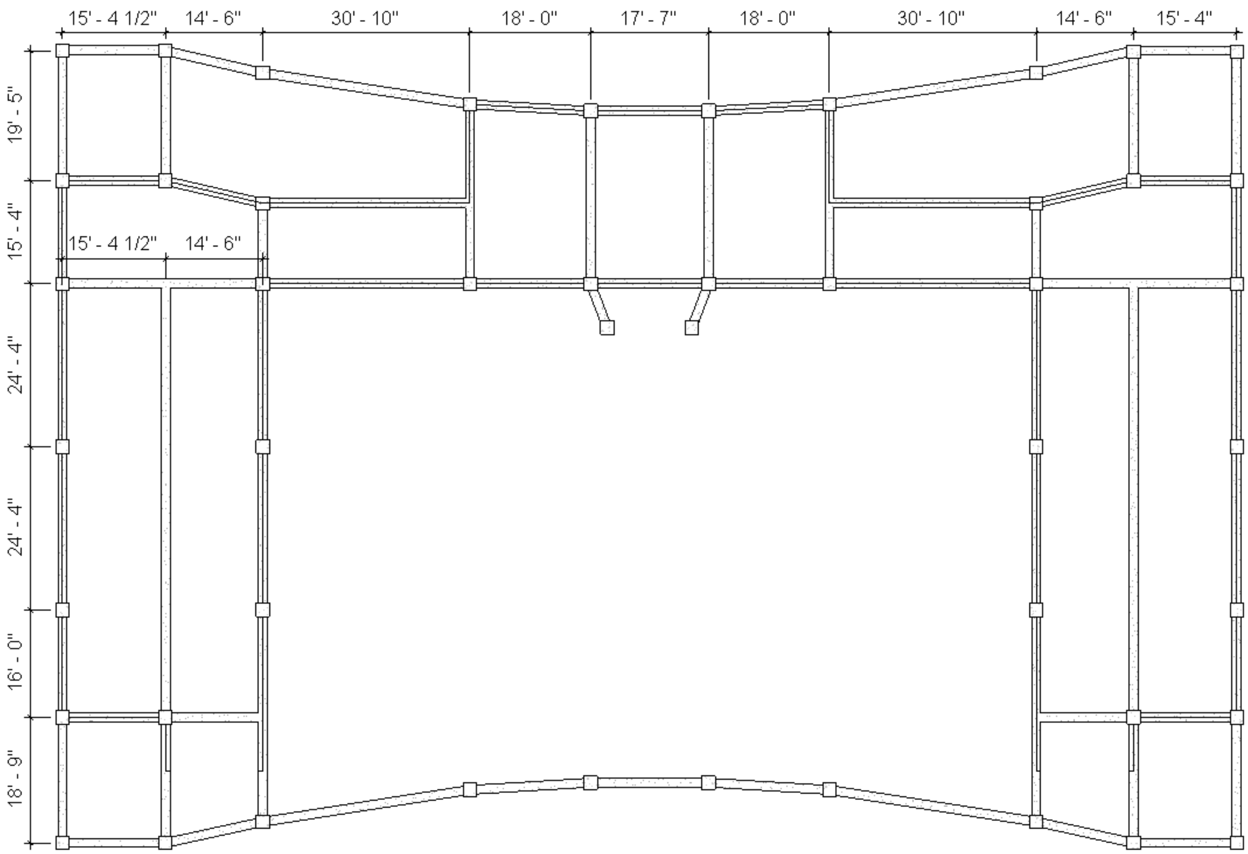
During the preliminary design, a concrete alternative for the bottom two floors was considered instead of steel. Calculations were done to determine the adequacy of the alternative. The necessary depth of a one way slab was calculated to be between 9”-11” in various parts of the building with necessary supports of 8”x15” beams. The slab thickness was greater than expected due to the extensive spans and open rectangular bays in the building. With this information, construction cost and duration were calculated. Overall, the concrete alternative was determined to be more expensive and time consuming and, since the bays were too large, did not prove to be an efficient alternative. Therefore, we chose steel for the structure of the bottom two floors.



3D view of Reinforced Concrete Alternative



1st Floor Structural Layout of Reinforced Concrete Alternative



Mezzanine 2nd Floor Structural Layout for Reinforced Concrete Alternative

Appendix F: Primavera Activity List

Activity ID	Activity Name	Original Duration	Remaining Duration	Schedule % Complete	Start	Finish
Foisie Innovation Studio		573	573	0%	16-May-16	25-Jul-18
A1010	Project Starts	0	0	0%	16-May-16	
A1020	Electrical Systems Design	20	20	0%	23-May-16	17-Jun-16
A1030	On-Site Utilities Design	20	20	0%	23-May-16	17-Jun-16
A1040	Mechanical Systems Design	20	20	0%	23-May-16	17-Jun-16
A1050	Structural Design	25	25	0%	23-May-16	24-Jun-16
A1060	Architectural Design	40	40	0%	23-May-16	15-Jul-16
A1070	Develop Work Plan	5	5	0%	16-May-16	20-May-16
A1080	Procure Contractor Bids	5	5	0%	16-May-16	20-May-16
A1090	Acquire Permits	5	5	0%	16-May-16	20-May-16
A1100	Move In	7	7	0%	17-Jul-18	25-Jul-18
A1110	Erect Fences, Erosion Control	5	5	0%	01-Nov-16	07-Nov-16
A1120	Determine Spaces	5	5	0%	16-May-16	20-May-16
A1130	Site Surveying	20	20	0%	13-Sep-16	10-Oct-16
A1140	Site Clearing After Demolition	15	15	0%	26-Jul-16	15-Aug-16
A1150	Evaluation of Soil Conditions	10	10	0%	13-Sep-16	26-Sep-16
A1160	Preserve Grotesques	1	1	0%	23-May-16	23-May-16
A1170	Install On-Site Signage	5	5	0%	25-Oct-16	31-Oct-16
A1180	Site Grading	20	20	0%	16-Aug-16	12-Sep-16
A1190	Excavation for Utilities	7	7	0%	08-Nov-16	16-Nov-16
A1200	Install Temporary Power	8	8	0%	16-Aug-16	25-Aug-16
A1210	Install Sewer Lines	10	10	0%	26-Jan-17	08-Feb-17
A1220	Underground Storm Line	10	10	0%	26-Jan-17	08-Feb-17
A1230	Install Utilities	15	15	0%	15-Jan-18	02-Feb-18
A1240	Electric Work	5	5	0%	15-Jan-18	19-Jan-18
A1250	Install Pedestrian Sidewalk	5	5	0%	26-Jun-18	02-Jul-18
A1260	Prep Temporary Access Road	15	15	0%	13-Sep-16	03-Oct-16
A1270	Pave Temporary Access Road	10	10	0%	11-Oct-16	24-Oct-16
A1280	Pour Footings	10	10	0%	15-Dec-16	28-Dec-16
A1290	Pour Foundation Walls	15	15	0%	15-Dec-16	04-Jan-17
A1300	Curing of Concrete	5	5	0%	05-Jan-17	11-Jan-17
A1310	Applying Finishing Coats	5	5	0%	26-Jan-17	01-Feb-17
A1320	Insulate / Moistureproof Foundation	10	10	0%	12-Jan-17	25-Jan-17
A1330	Install Drainage Piping	10	10	0%	09-Feb-17	22-Feb-17
A1340	Backfilling	5	5	0%	23-Feb-17	01-Mar-17
A1360	Erect Eastern 1st Floor Steel	3	3	0%	07-Mar-17	09-Mar-17
A1370	Erect Eastern Pod 4th Floor Steel	3	3	0%	20-Mar-17	22-Mar-17
A1380	Erect Eastern Pod 2nd Floor Steel	3	3	0%	10-Mar-17	14-Mar-17
A1400	Erect Eastern Pod Basement Structure	3	3	0%	02-Mar-17	06-Mar-17
A1410	Install Eastern Pod 3rd Floor Steel	3	3	0%	15-Mar-17	17-Mar-17
A1420	Building Dedication	1	1	0%	16-Jul-18	16-Jul-18
A1450	Erect Central Pod 1st Floor Steel	3	3	0%	28-Mar-17	30-Mar-17
A1460	Erect Central Pod 4th Floor Steel	3	3	0%	10-Apr-17	12-Apr-17
A1470	Erect Central Pod 2nd Floor Steel	3	3	0%	31-Mar-17	04-Apr-17
A1480	Erect Central Pod Basement Structure	3	3	0%	23-Mar-17	27-Mar-17
A1490	Erect Central Pod 3rd Floor Steel	3	3	0%	05-Apr-17	07-Apr-17

Activity ID	Activity Name	Original Duration	Remaining Duration	Schedule % Complete	Start	Finish
A1500	Excavation for Foundation	20	20	0%	17-Nov-16	14-Dec-16
A1540	Erect Western Pod 1st Floor Steel	3	3	0%	18-Apr-17	20-Apr-17
A1550	Erect Western Pod 2nd Floor Steel	3	3	0%	21-Apr-17	25-Apr-17
A1560	Erect Western Pod 4th Floor Steel	3	3	0%	01-May-17	03-May-17
A1570	Erect Western Pod Basement Structure	3	3	0%	13-Apr-17	17-Apr-17
A1580	Erect Western Pod 3rd Floor Steel	3	3	0%	26-Apr-17	28-Apr-17
A1600	Pour Slab on Grade	15	15	0%	15-Jun-17	05-Jul-17
A1620	Install Basement Metal Studs	10	10	0%	26-Mar-18	06-Apr-18
A1630	Install 1st Floor Metal Studs	10	10	0%	26-Mar-18	06-Apr-18
A1640	Install 2nd Floor Metal Studs	10	10	0%	26-Mar-18	06-Apr-18
A1650	Install 3rd Floor Metal Studs	10	10	0%	26-Mar-18	06-Apr-18
A1660	Install 4th Floor Metal Studs	10	10	0%	26-Mar-18	06-Apr-18
A1670	Basement Partition Finishes	6	6	0%	17-Apr-18	24-Apr-18
A1680	1st Floor Partition Finishes	6	6	0%	17-Apr-18	24-Apr-18
A1690	2nd Floor Partition Finishes	6	6	0%	17-Apr-18	24-Apr-18
A1700	3rd Floor Partition Finishes	6	6	0%	17-Apr-18	24-Apr-18
A1710	4th Floor Partition Finishes	6	6	0%	17-Apr-18	24-Apr-18
A1720	Install Basement Stairs	10	10	0%	13-Jul-17	26-Jul-17
A1730	Install 1st Floor Stairs	10	10	0%	03-Aug-17	16-Aug-17
A1740	Install 2nd Floor Stairs	10	10	0%	24-Aug-17	06-Sep-17
A1750	Install 3rd Floor Stairs	10	10	0%	14-Sep-17	27-Sep-17
A1760	Install 4th Floor Stairs	10	10	0%	05-Oct-17	18-Oct-17
A1770	Install Basement Stair Rails	4	4	0%	27-Jul-17	01-Aug-17
A1780	Install 1st Floor Stair Rails	4	4	0%	17-Aug-17	22-Aug-17
A1790	Install 2nd Floor Stair Rails	4	4	0%	07-Sep-17	12-Sep-17
A1800	Install 3rd Floor Rails	4	4	0%	28-Sep-17	03-Oct-17
A1810	Install 4th Floor Stair Rails	4	4	0%	19-Oct-17	24-Oct-17
A1820	Install Basement Interior Doors	6	6	0%	06-Apr-18	13-Apr-18
A1830	Install 1st Floor Interior Doors	6	6	0%	06-Apr-18	13-Apr-18
A1840	Install 2nd Floor Interior Doors	6	6	0%	06-Apr-18	13-Apr-18
A1850	Install 3rd Floor Interior Doors	6	6	0%	06-Apr-18	13-Apr-18
A1860	Install 4th Floor Interior Doors	6	6	0%	06-Apr-18	13-Apr-18
A1870	Install Basement Interior Windows	8	8	0%	16-Apr-18	25-Apr-18
A1880	Install 1st Floor Interior Windows	8	8	0%	16-Apr-18	25-Apr-18
A1890	Install 2nd Floor Interior Windows	8	8	0%	16-Apr-18	25-Apr-18
A1900	Install 3rd Floor Interior Windows	8	8	0%	16-Apr-18	25-Apr-18
A1910	Install 4th Floor Interior Windows	8	8	0%	16-Apr-18	25-Apr-18
A1920	Install Basement Ceiling Grid	5	5	0%	26-Mar-18	30-Mar-18
A1930	Install 1st Floor Ceiling Grid	5	5	0%	26-Mar-18	30-Mar-18
A1940	Install 2nd Floor Ceiling Grid	5	5	0%	26-Mar-18	30-Mar-18
A1950	Install 3rd Floor Ceiling Grid	5	5	0%	26-Mar-18	30-Mar-18
A1960	Install 4th Floor Ceiling Grid	5	5	0%	26-Mar-18	30-Mar-18
A1970	Install Basement Acoustic Ceiling Tiles	4	4	0%	02-Apr-18	05-Apr-18
A1980	Install 1st Floor Acoustic Ceiling Tiles	4	4	0%	02-Apr-18	05-Apr-18
A1990	Install 2nd Floor Acoustic Ceiling Tiles	4	4	0%	02-Apr-18	05-Apr-18
A2000	Install 3rd Floor Acoustic Ceiling Tiles	4	4	0%	02-Apr-18	05-Apr-18
A2010	Install 4th Floor Acoustic Ceiling Tiles	4	4	0%	02-Apr-18	05-Apr-18

Activity ID	Activity Name	Original Duration	Remaining Duration	Schedule % Complete	Start	Finish
A2020	Install Basement Millwork	5	5	0%	26-Apr-18	02-May-18*
A2030	Install 1st Floor Millwork	5	5	0%	03-May-18	09-May-18*
A2040	Install 2nd Floor Millwork	5	5	0%	10-May-18	16-May-18*
A2050	Install 3rd Floor Millwork	5	5	0%	17-May-18	23-May-18*
A2060	Install 4th Floor Millwork	5	5	0%	24-May-18	30-May-18*
A2070	Install Loft Handrail	6	6	0%	26-Mar-18	02-Apr-18
A2080	Install Basement Floor Carpets	7	7	0%	04-Apr-18	12-Apr-18
A2090	Install 1st Floor Carpets	7	7	0%	09-Apr-18	17-Apr-18
A2100	Install 2nd Floor Carpets	7	7	0%	09-Apr-18	17-Apr-18
A2110	Install 3rd Floor Carpets	7	7	0%	09-Apr-18	17-Apr-18
A2120	Install 4th Floor Carpets	7	7	0%	09-Apr-18	17-Apr-18
A2130	Install Basement Tiling	7	7	0%	26-Mar-18	03-Apr-18
A2140	Install 1st Floor Tiling	10	10	0%	26-Mar-18	06-Apr-18
A2150	Install 2nd Floor Tiling	10	10	0%	26-Mar-18	06-Apr-18
A2160	Install 3rd Floor Tiling	10	10	0%	26-Mar-18	06-Apr-18
A2170	Install 4th Floor Tiling	10	10	0%	26-Mar-18	06-Apr-18
A2180	Install Eastern Exterior Brick and Stone Walls	12	12	0%	25-Oct-17	09-Nov-17
A2190	Install North Exterior Brick and Stone Walls	12	12	0%	25-Oct-17	09-Nov-17
A2200	Install Western Exterior Brick and Stone Walls	12	12	0%	25-Oct-17	09-Nov-17
A2210	Install Eastern Curtainwall Frame	5	5	0%	10-Nov-17	16-Nov-17
A2220	Install North Curtainwall Frame	5	5	0%	10-Nov-17	16-Nov-17
A2230	Install Western Curtainwall Frame	5	5	0%	10-Nov-17	16-Nov-17
A2240	Install Eastern Mullions	7	7	0%	17-Nov-17	27-Nov-17
A2250	Install North Mullions	7	7	0%	17-Nov-17	27-Nov-17
A2260	Install Western Mullions	7	7	0%	17-Nov-17	27-Nov-17
A2270	Eastern Curtain Wall Trim and Seal	5	5	0%	28-Nov-17	04-Dec-17
A2280	North Curtain Wall Trim and Seal	5	5	0%	28-Nov-17	04-Dec-17
A2290	Western Curtain Wall Trim and Seal	5	5	0%	28-Nov-17	04-Dec-17
A2300	Install Exterior Doors	5	5	0%	08-Jan-18	12-Jan-18
A2310	Install 1st Floor Exterior Windows	5	5	0%	08-Jan-18	12-Jan-18
A2320	Install 2nd Floor Exterior Windows	5	5	0%	08-Jan-18	12-Jan-18
A2330	Install 3rd Floor Exterior Windows	5	5	0%	08-Jan-18	12-Jan-18
A2340	Install 4th Floor Exterior WIndows	5	5	0%	08-Jan-18	12-Jan-18
A2350	Install Main Floor Vestibules	5	5	0%	01-Jan-18	05-Jan-18
A2360	Erect Roof Frame	25	25	0%	11-May-17	14-Jun-17
A2370	Install Roof Chillers	5	5	0%	11-Dec-17	15-Dec-17
A2380	Install Roof Exhaust Fans	5	5	0%	11-Dec-17	15-Dec-17
A2390	Install Roof Condenser	5	5	0%	11-Dec-17	15-Dec-17
A2400	Install Roof Water Pump	5	5	0%	11-Dec-17	15-Dec-17
A2410	Install Roof Drains	5	5	0%	11-Dec-17	15-Dec-17
A2420	Install Roof Venting	5	5	0%	11-Dec-17	15-Dec-17
A2430	Re-Install Grotesques	5	5	0%	19-Jun-18	25-Jun-18
A2440	Install Elevator	20	20	0%	15-Jan-18	09-Feb-18
A2450	Test Elevator	5	5	0%	12-Feb-18	16-Feb-18
A2460	Install Plumbing System (Vertical Waste Stacks, etc.)	15	15	0%	15-Jan-18	02-Feb-18
A2470	Install Toilet Fixtures	10	10	0%	19-Feb-18	02-Mar-18
A2480	Install Rainwater Drainage Sytems	12	12	0%	11-Dec-17	26-Dec-17

Activity ID	Activity Name	Original Duration	Remaining Duration	Schedule % Complete	Start	Finish
A2480	Install Rainwater Drainage Sytems	12	12	0%	11-Dec-17	26-Dec-17
A2490	Install Sinks	10	10	0%	19-Feb-18	02-Mar-18
A2500	Install Showers	10	10	0%	05-Mar-18	16-Mar-18
A2510	Install Water Fountains	10	10	0%	05-Feb-18	16-Feb-18
A2520	Ductwork	8	8	0%	31-May-18	11-Jun-18
A2530	Mechanical Trim and Finishes	5	5	0%	19-Mar-18	23-Mar-18
A2540	Install Heating Systems	15	15	0%	15-Jan-18	02-Feb-18
A2550	Install Cooling Systems	15	15	0%	15-Jan-18	02-Feb-18
A2560	Install Sprinkler System	4	4	0%	15-Jan-18	18-Jan-18
A2570	Install Sprinkler Heads	5	5	0%	05-Feb-18	09-Feb-18
A2580	Install Standpipes	5	5	0%	15-Jan-18	19-Jan-18
A2590	Install Alarms	5	5	0%	15-Jan-18	19-Jan-18
A2600	Alarm Testing	5	5	0%	05-Feb-18	09-Feb-18
A2610	Install Electrical Panels	10	10	0%	22-Jan-18	02-Feb-18
A2620	Install Switchboard Panels	10	10	0%	22-Jan-18	02-Feb-18
A2630	Install Switch Gear	10	10	0%	12-Feb-18	23-Feb-18
A2640	Hook-Up Switchboard Panels	5	5	0%	05-Feb-18	09-Feb-18
A2650	Install Emergency Generator	15	15	0%	11-Dec-17	29-Dec-17
A2660	Install Internet Communication System	5	5	0%	22-Jan-18	26-Jan-18
A2670	Phone Wiring and WIFI Installation	5	5	0%	05-Feb-18	09-Feb-18
A2680	Install Laundry Equipment	5	5	0%	05-Feb-18	09-Feb-18
A2690	Install Sofas	5	5	0%	12-Jun-18	18-Jun-18
A2700	Install Tables	5	5	0%	12-Jun-18	18-Jun-18
A2710	Install Residential Desks	5	5	0%	12-Jun-18	18-Jun-18
A2720	Install Residential Chairs	5	5	0%	12-Jun-18	18-Jun-18
A2730	Install Residential Bureaus	5	5	0%	12-Jun-18	18-Jun-18
A2740	Instal Residential Closets	5	5	0%	12-Jun-18	18-Jun-18
A2750	Install Beds	5	5	0%	12-Jun-18	18-Jun-18
A2760	Install Office Equipment	5	5	0%	12-Jun-18	18-Jun-18
A2770	Install Lab Equipment	5	5	0%	12-Jun-18	18-Jun-18
A2780	Install Lecture Hall Furnishings	5	5	0%	12-Jun-18	18-Jun-18
A2790	Install Televisions	5	5	0%	12-Jun-18	18-Jun-18
A2800	Install Mirrors	5	5	0%	12-Jun-18	18-Jun-18
A2810	Pave Pedestrian Walkway	5	5	0%	26-Jun-18	02-Jul-18
A2820	Install Exterior Lighting	5	5	0%	26-Jun-18	02-Jul-18
A2830	Final Landscaping	5	5	0%	05-Jul-18	11-Jul-18
A2840	Install South Curtainwall Frame	5	5	0%	10-Nov-17	16-Nov-17
A2850	Pour 1st Floor Slab on Deck	15	15	0%	06-Jul-17	26-Jul-17
A2860	Pour 2nd Floor Slab on Deck	15	15	0%	27-Jul-17	16-Aug-17
A2870	Pour 3rd Floor Slab on Deck	15	15	0%	17-Aug-17	06-Sep-17
A2880	Pour 4th Floor Slab on Deck	15	15	0%	07-Sep-17	27-Sep-17
A2890	Demolition of Alumni Gym	45	45	0%	24-May-16	25-Jul-16
A2920	Prep Basement Stair Frame	5	5	0%	06-Jul-17	12-Jul-17
A2930	Prep 1st Floor Stair Frame	5	5	0%	27-Jul-17	02-Aug-17
A2940	Prep 2nd Floor Stair Frame	5	5	0%	17-Aug-17	23-Aug-17
A2950	Prep 3rd Floor Stair Frame	5	5	0%	07-Sep-17	13-Sep-17
A2960	Prep 4th Floor Stair Frame	5	5	0%	28-Sep-17	04-Oct-17

A2960	Prep 4th Floor Stair Frame	5	5	0%	28-Sep-17	04-Oct-17
A2970	Install South Mullions	7	7	0%	17-Nov-17	27-Nov-17
A2980	Install South Exterior Brick and Stone Walls	12	12	0%	25-Oct-17	09-Nov-17
A2990	South Curtain Wall Trim and Seal	5	5	0%	28-Nov-17	04-Dec-17
A3000	Hang Basement Drywall	5	5	0%	09-Apr-18	13-Apr-18
A3010	Hang 1st Floor Drywall	5	5	0%	09-Apr-18	13-Apr-18
A3020	Hang 2nd Floor Drywall	5	5	0%	09-Apr-18	13-Apr-18
A3030	Hang 3rd Floor Drywall	5	5	0%	09-Apr-18	13-Apr-18
A3040	Hang 4th Floor Drywall	5	5	0%	09-Apr-18	13-Apr-18
A3060	Final Grade and Seed	7	7	0%	26-Jun-18	04-Jul-18
A3070	Install Hardware	3	3	0%	12-Jun-18	14-Jun-18
A3080	Final Building Cleaning	2	2	0%	26-Jun-18	27-Jun-18
A3090	Final Building Inspection	1	1	0%	13-Jul-18	13-Jul-18
A3100	Punch Out - Walk Thru List	1	1	0%	12-Jul-18	12-Jul-18
A3120	Stock Drywall	1	1	0%	06-Dec-17	06-Dec-17
A3130	Remove Scrap Drywall	1	1	0%	16-Apr-18	16-Apr-18
A3140	Stock Shingles	1	1	0%	05-Dec-17	05-Dec-17
A3150	Install Shingles	3	3	0%	06-Dec-17	08-Dec-17
A3160	Set Roof Trusses	5	5	0%	04-May-17	10-May-17
A3170	Stair Finishes	2	2	0%	25-Oct-17	26-Oct-17
A3180	Install Roof Decking	5	5	0%	15-Jun-17	21-Jun-17

Appendix G: List of E-Files

- Proposed Foisie Cost Estimate ……………………..…Proposed Foisie Cost Estimate.xlsx
- Proposed Foisie 5D Model …………………………..……Proposed Foisie 5D Model.nwf
  ....Proposed Foisie 5D Model.nwd
  …………………………………………………………..………..Proposed Architectural.nwc
  ………………………………………………………………………..Proposed Structural.nwc
- Proposed Foisie Schedule ………………………...……….Proposed Foisie Schedule.xer
- Proposed Foisie Construction Simulation …………………………...……………………….
  ……………………………………..…… https://www.youtube.com/watch?v=dGwUXYA23gs
- Proposed Foisie Walkthrough ……......https://www.youtube.com/watch?v=GLzmuD22c8Y
- Proposed Foisie Structural Model ……………………Proposed Foisie Structural Model.rvt
- Proposed Foisie Architectural Model ……………..Proposed Foisie Architectural Model.rvt
- Proposed Foisie Structural Analysis Models…………………………………………………
  …………………………………………………………..……Proposed Foisie East Frame.rtd
  …………………………………………………...………....Proposed Foisie South Frame.rtd
- Proposed Foisie Design Workbooks…………………………………………………………..
  ……………………………………..Proposed Foisie Beam System Design Workbook.xlsx
  ……………………………………………….. Proposed Foisie Girder Design Workbook.xlsx
  ………………………………….Proposed Foisie Exterior Member Design Workbook.xlsx
  ………………………………………Proposed Foisie Stair Bearing Design Workbook.xlsx
  ……………………………………..Proposed Foisie Roof Member Design Workbook.xlsx
  …………………………………………….Proposed Foisie Column Design Workbook.xlsx
  ……………………………….Proposed Foisie Base Plate & Footing Design Workbook.xlsx
  ………………………………………..Proposed Foisie Connection Design Workbook.xlsx
  ………………………………………………………..Proposed Foisie Truss Workbook.xlsx