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A Construction Project Management Analysis of Foisie Innovation Studio

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A Construction Project Management Analysis of Foisie Innovation Studio

Submitted to the Faculty of the Worcester Polytechnic Institute
In partial fulfillment of the requirements for the
Degree of Bachelor of Science
In Civil Engineering by:

__________________________________________________
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Abstract

The owner, designer and construction managers worked collaboratively on Foisie Innovation Studio to deliver an impressive, multi-use facility in a timely, and cost-effective manner. Using the data collected during construction, this report evaluates the cost and schedule by completing an Earned Value Analysis. This report also analyzed the construction process of this project using Building Information Modeling (BIM), and identifies future potential uses of BIM and other technologies in construction. Finally, an alternative structural design for the second floor roof is proposed and its cost is determined.
Authorship

All members of the team contributed equally to develop and write this report.
Capstone Design Statement

The capstone design of this project focused on the structural design of the low roof of Foisie Innovation Studio. The lower roof of Foisie Innovation Studio was designed to support the loads imposed by a green roof. This study proposes an alternative structural design for this roof with no provisions for additional green roof loading. The design follows the American Institute of Steel Constructions (AISC) guidelines. The capstone design focused on the economic, sustainability, ethics, safety and social aspects of implementing a green roof on the Foisie Innovation Studio.

Economic

This report examined the extra costs that come with adding a green roof to a building and the potential money that a green roof could save WPI during operation. During the completion of this Major Qualifying Project (MQP), the only cost changes associated with the Foisie Innovation Studio were minor changes to the price of change orders based on the actual costs versus the original estimates.

Sustainability

The decision on designing the roof structure without building the green roof created the possibility of adding a sustainable feature to the building in the form of a green roof in the future, thus impacting the investment cost. The proposed alternative structural roof design provides basis for evaluation of the cost impact of this decision.

Constructability

The Foisie Innovation Studio was designed by Gensler Architects. Shawmut Design and Construction was the construction manager at risk, but they also provided
WPI and Gensler with some pre-construction services. By doing so, the project team was able to incorporate the construction knowledge from Shawmut into their design. This led to some potential constructability issues to be resolved before the design phase was complete. The review on the schedule for this project provides the basis for analysis of the level of constructability observed in this project. Additionally, a 4D (3D + time) Building Information Model (BIM) was developed to visually depict the different phases of the construction process over the time of execution.

**Ethics**

During the weekly construction meetings between WPI and the Foisie Innovation Studio team, the authors attended some of the meetings that took place towards the completion of the project. It was observed that all participants were respectful, professional and allowed for all opinions to be heard. All disputes were handled with civility and handled professionally according to the contractual terms of their agreement. All members involved worked collaboratively towards the success of the project. Students participating in these meetings signed non-disclosure agreements.

**Safety**

During each weekly meeting, the first item on the minutes was safety. Each member had an opportunity to present all safety issues they saw during construction. In spite of conducting this project in the midst of an occupied college campus, there were no significant accidents or injuries throughout the construction of the Foisie Innovation Studio. The job site was surrounded by a construction fence, and only authorized personnel with proper personal protective equipment could enter the site. No students were allowed on the site, and no equipment was allowed to be used outside the
restraints of the fence. Visitors, including students occasionally visited the site. These tours were conducted under strict supervision of the construction management firm staff. Visitors were made aware of safety protocols and checked for proper safety gear before entering the site.
Professional Licensure Statement

A Professional Engineering License gives the authority to an engineer to stamp construction drawings. By stamping a drawing with a seal, the engineer is accepting responsibility for their professional work and ensures that the design adheres to the standards of care and practices of civil engineering, as well as federal, state and local government codes.

In order to obtain a Professional Engineering License, one must obtain a Civil Engineering degree from a university with an accredited engineering academic program. The next step is to pass the Fundamentals of Engineering (FE) exam. The exam includes questions from all disciplines of civil engineering. If one passes the FE exam, they become an Engineer in Training (EIT). To become a Professional Engineer (PE), one must work as an EIT under the supervision of a Professional Engineer for four years in most states, then apply to take the PE exam and supplement the application with the relevant work completed as an EIT. If one passes the PE exam, they will become a Professional Engineer and can officially stamp drawings, becoming responsible for the design.

In construction, there are also construction safety licenses. These licenses include a Construction Supervisor’s License, the OSHA 10, OSHA 30 and OSHA 100 certificates. The PE license ensures projects are designed safely and ethically and construction licenses and certificates ensure that projects are built safely and ethically.
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1.0 Introduction

Alumni Gym had been a staple on the WPI campus since a little after the start of the 20th century. According to Joan Killough-Miller, Alumni Gym stood as a “landmark” on the campus (Killough-Miller, 2014). However, the building became obsolete after the construction of the new Sports and Recreation Center. WPI decided Alumni Gym was a dead space and needed to be utilized. They planned to add an Innovation Center in the old gym, completely renovating the inside. However, after realizing that repurposing Alumni Gym was not a cost-effective solution, WPI made the decision to demolish the historic building to make way for Foisie Innovation Center, a brand-new mixed-use innovation studio with dormitories. In 2015, WPI secured the professional services of an owner project management, design, and construction firms that successfully designed and built this new facility, which was completed in 2018.
Upon the completion of the project in 2018, the Construction Project Management firm responsible for the construction of this facility generated a substantial amount of information during the construction. Thus, creating an opportunity to analyze this information from the cost and schedule performance of the construction process using Earned Value Analysis. This is one of the major objectives of this study. The second objective of this study is to use photographic records to produce a visual display of the gradual progression of the construction of this facility using a four dimensional Building Information Modeling (4D). Finally, this study proposes and alternative structural design to support the 2nd floor roof of this building.

The report begins by giving a brief background of the Foisie Innovation Studio and the bidding process leading up to construction. It also provides background information on the project team and the role of a project manager. An investigation into the schedule and cost of the project was completed by creating an Earned Value Analysis (EVA). Using the EVA, a 5D presentation that visually displays the schedule and cost over time was created. The report also includes an overview of the technologies used during the construction of FIS and the possibilities for the use of technology in future construction to aid construction managers. The report concludes with an analysis of an alternative structural design change to the Green Roof steel structure located at the low roof of the Foisie Innovation Studio. The costs associated with the changes are also looked at.
2.0 The Foisie Innovation Studio

Foisie Innovation Studio is home to a makerspace, a prototype lab, active learning classrooms, a robotics laboratory, a collections gallery, a video recording suite, an Innovation & Entrepreneurship Center and multiple floors of student housing that include tech suites and common lounges on each floor. The total development cost for Foisie Innovation Studio was $49 million, with roughly $18 million financed from alumni funding (WPI). Foisie Innovation Studios is described as a unique building because it combines a large academic space with a residence hall on the upper floors, see Appendix D. Daniels and Morgan Halls both have little academic space below their residence floors, however it mostly consists of study spaces and academic offices. Foisie
however has 2 floors of large academic spaces which makes it a rare sight on the WPI campus. In fact, Foisie is the only building on WPI’s campus that combines multiple floors of residence halls along with multiple floors of academic space.

2.1 The Construction of Foisie Innovation Studio

Since 1915, Alumni Gym had stood on the quad at WPI. However, since the construction of Harrington Gym in 1968, Alumni Gym was only used recreationally by the students and faculty until 2013. In 2013, the Sports and Recreation center was built, which rendered Alumni Gym useless. WPI wanted to create a new place where students could get hands-on experiences through project-based learning and faced the challenges of dorms becoming crowded and a lack of available land left in the area. The school’s solution was to re-purpose Alumni Gym into a multi-use, 78,000-square-foot facility called Foisie Innovation Studio. Initially the plan was
to use the structure of Alumni Gym and renovate the inside to create the new space, however after analyzing the structure it was decided that the high cost and low flexibility were too much for the renovation. For this reason, the historic building was torn down to make room for a brand-new mixed-use building in the middle of campus, called the Foisie Innovation Studio.

2.2 The Bidding Process

Like all construction projects, the WPI construction team had to select the design and construction professionals who were best suited to deliver the project. The bidding process is a fundamental aspect of construction projects all organizations, including private companies or the federal government. The owner, architects and engineer work together to create a 3D model and planned schedule of the project. In many cases, the construction plans are sent to contractor’s so they can submit a bid for the work. The owner then chooses which contractor will complete the work. The bidding process allows the owner to determine the costs and quality expectations of each contractor bidding for the job. However, the construction of Foisie Innovation center had a unique bidding process because WPI has their own project manager, and the construction manager was hired before the architect.

2.2.1 Owner Need

The bidding process starts with an owner who has a clear need, and the recognition of that need is what starts the project life cycle. In this case, WPI already
had hired their own project manager who had completed work on campus before. The school also brought on a construction management/design firm to help consult the renovation of Alumni Gym. For WPI, the need was an increase in student population and dorms becoming overcrowded. The solution is a concept for a structure that will fit the needs of the owner (Halpin, 2017). One of the added benefits of FIS is that not only does it provide more student housing and academic spaces, but the dormitory space is an additional source of revenue for WPI. After the need of the owner is recognized and addressed, there is still a massive decision to be made on whether the project will take place. This is called need evaluation, and each owner should have the following listed documents in front of them to make an educated decision (Halpin, 2017).

- Cost/Benefit Analysis
- Graphical Depiction of Project and a layout of the facility
- Cost estimate based on conceptual information

The cost/benefit analysis is a simple tool that compares the estimated total project cost to the assumed revenue that the new structure will make. This is most common in commercial profit-based projects. This is where the idea to renovate Alumni Gym was taken off the table, WPI’s analysis proved that it was not worth the money to renovate when a new building would have much more benefits. WPI was not looking at the assumed revenue of construction project, but rather specifically cost vs benefits. The Alumni Gym presented a lack of flexibility verses a new building that could combine academic space and a dormitory. Unlike many commercial construction projects, WPI decided to hire the consulting construction management firm as the builders of the new building before even having a design.
2.2.2 Design and Bidding

If an owner is heavily interested in pursuing a project, then they will take their ideas and needs to an architect. The architect will put together a rough collection of conceptual drawings and 3D models that will give the owner a better understanding of the project and what it could potentially look like. Conceptual drawings can vary in the amount of detail that is needed. For a smaller, simpler project the amount of conceptual drawings can be small. However, on a complex job, such as a scientific lab, more detailed conceptual drawings are needed. These drawings are also extremely important for an owner to get funding for their project through a bank or other funding agencies (Halpin, 2017).

WPI had already hired their project manager and construction manager for the job, so the architects and engineers were required to competitively submit a bid of their
designs. This is an unusual process, as the architect and engineer are usually hired before the construction manager, who competitively bids on the job using the owner selected design to schedule and price out a bid. The owner would then choose the best bid based on qualifications and pricing. In this scenario involving FIS, WPI was able to choose the best design from a variety of architects with the consulting help of their project manager and the construction manager. Essentially, the bidding process was used to choose the design and not the construction manager. Once the design was chosen from the bids, the project team was complete.

2.3 The Project Team

The team that designed and constructed Foisie consisted of Shawmut Design and Construction, Gensler, and KVA Building Industry Consultants of Boston. All these companies have worked together with the owner, WPI, to construct Foisie. Gensler is the architectural firm that designed Foisie, Shawmut Design and Construction was responsible for the construction management of Foisie, and KVA was WPI’s owner consultant.
2.3.1 Construction Project Manager - Shawmut

Shawmut Design and Construction is a construction management company that has offices in cities across the United States. Their headquarters are in Boston, but Shawmut also have offices in Chicago, New York, Los Angeles, Las Vegas, and Miami. The company is based on a client-first Philosophy, leadership, and being involved with the local community. Shawmut has built classroom and residential facilities for some of the top schools in the nation, including WPI, Harvard University, and the Massachusetts Institute of Technology (Shawmut, 2018). At WPI specifically, Shawmut worked on the renovation of space within the Harrington Auditorium.

2.3.2 Architect - Gensler

Gensler is a well-respected architectural firm with a headquarters in San Francisco, CA and offices all over the world on every continent. With the exception of Africa and Antarctica. They represent 28 of the top 50 Fortune 500
companies and every Top 10 technology based company in the United States. Gensler prides itself on being client-first and having a “global platform for design and delivery”. Gensler has worked on well-known buildings such as The Ritz-Carlton Hotel in Los Angeles and the Shanghai Tower (Gensler, 2018).

2.3.3 Owner’s Project Manager - KVA

KVA is a construction consultant that has experience in both design and construction. They will help the owner of a project with both aspects of the job, ensuring the owner gets the product and quality that they want. They have worked on projects at Berklee College of Music and the Park Square Building in Boston, MA (KVA, 2018). Specifically at WPI, KVA has also overseen the construction of Faraday Hall, which was completed in 2013.
3.0 Construction Project Management

Project management is the art of initiating, planning, executing, monitoring and controlling, and closing during a construction project. A project manager's focus should be on time, money and quality (PMI, 2018). A project manager organizes the necessary personnel to complete the project in a timely manner, and preferably at a low cost to the owner. The project manager must keep the “big picture” in mind, in terms of the entire project, but also pay attention to the small details of the drawings and specifications, to ensure the subcontractors are producing exactly what the owner is paying for. A project manager is responsible for the safety and procedures of the subcontractors.

During the construction phase, a project manager will coordinate which trades need to be on site and which trades need to prepare to begin their work. They will track the number of workers on site each day and the amount of work performed. The project manager typically holds a weekly foreman’s meeting to find out if there are any ongoing issues that need to be resolved, assign a task list for each trade, discuss any safety issues on site and evaluate how each trade is following the proposed schedule (PMI, 2018).

To ensure the project will be completed to standard of the contract documents, a project manager must maintain control of all project documentation. This includes drawings, subcontractor contracts, safety data sheets, submittals, RFIs, change orders, punch lists, inspection reports and the closeout documents.
### 3.1 Submittals, RFIs and COs

In construction, submittals, requests for information (RFIs), and change orders (COs) help the construction and design teams confirm that the job is completed to the owner's contract documents.

Submittals are sent from the subcontractor to the construction manager. The submittals typically include shop drawings, material and product data and samples. This may change based on the language in the specifications. The construction manager will review the submittal. If they approve the submittal they will send it to the architect and engineer to coordinate with the owner to verify that the correct product gets installed in the correct manner. This process also gives the architect and owner an opportunity to review options for colors, patterns and materials that were not specified at the time that the contract documents were completed. Essentially, the contract documents provide the subcontractor with what the owner wants them to build and the submittal process provides the subcontractor with what products to build it with. An approved submittal from the architect does not free the contractor of their responsibility to conform to the contract documents (Procore, 2018).

For this project, Shawmut used a construction management software called “Procore”. Procore stores all information and documents such as submittals and RFI’s in an organized manner. It also lets all parties within the construction management team view these documents on the same platform. While building Foisie Innovation Studios, there were 1579 submittals uploaded into Procore. The number of submittals for each specification vary depending on how much detail is needed and if there are any
problems foreseen before construction that would require a change of the specification. For example, while building FIS, there were two submittals in Procore for FRP paneling, in comparison to 36 submittals for the metal paneling. However, if there is a problem during on-going construction with the design, an RFI is formally issued.

A Request for Information (RFI) is a formal communication method between the construction manager and the architect and owner. An RFI can come from a subcontractor to the construction manager, or straight from the construction manager to the architect and engineers. A survey showed that projects average roughly 10 RFIs for each $1 million of GMP. While building Foisie, Shawmut formally filed 444 RFI’s. According to the survey, Foisie was below the average number of RFI’s filed, with the total being roughly $49 million. This averages out to 10 RFI’s per $1.1 million and indicates that the job was designed fairly well when comparing to the survey. In most contract documents, it is inevitable that drawings and specifications will leave some aspects of the project as undefined, unclear or have conflicting directions (PlanGrid, 2017). The contractors also need to perform the work based on the most updated contract documents, therefore they need to be aware of how an RFI changes the drawings or specifications. If there is an instance that the answer to an RFI results in a change in the drawings, specifications or costs associated with the design or construction of the relevant sections, a change order (CO) must be submitted and approved to document the financial changes. An example of this issue from Foisie would be RFI #413; Cafe Island Power Conflict. A revised drawing (Bulletin) was handed out to the construction team and the electricians had noticed a problem. According to the bulletin, the cafe island now needed power it. The problem was that
there was no conduit put into the concrete slab at the time of the pour, so there was nowhere to get any power from. The electrical subcontractor formally submitted an RFI explaining this problem and asked the architect/engineer how they would like to proceed. When the answer is sent back to the construction manager, changes to the drawings will more than likely have taken place, so a change order would be necessary.

A CO is a document that is used to officially implement a change in the original contract documents. A CO can contain a revised scope of work, new pricing, any modifications of the original contract and the effects on the drawings and schedule and the formal agreement by the contractor and owner. A CO could be a credit for work or materials that were deleted from the contract documents or an increase in cost to the owner due to additional materials or work that were omitted or changed from the contract documents (ESub, 2018). Change orders are important for the construction manager to ensure that the owner gets a product they approve of, and the subcontractors involved are correctly compensated for the work that is performed. In bigger jobs like Foisie Innovation Studios, change orders are essential to budget management and the overall happiness of the owner. Typically, a subcontractor will submit an estimate cost or credit for the CO before the work is performed, so that the construction manager and most importantly the owner can decide if the cost is worth the change. If the CO is accepted by the owner, then the subcontractor can begin work, however in tight budget jobs, the owner can always deny the change order.

Submittals, RFIs and COs protect contractors from performing work that is outside or beyond the agreed scope of work and schedule and protects the contractors from spending more than their anticipated budget. They also ensure that the owner gets
a final product that they approve. Submittals, RFIs and COs prevent the owner and contractors from being treated unfairly.

3.2 Value Engineering

During the design and early phases of construction, a project manager will apply value engineering to the project. Value engineering compares the functionality of something to its cost. The goal of value engineering is to maximize functionality and effectiveness and minimize costs. Value engineering considers all aspects of a project, from the sustainability and availability of materials to the utility efficiency during the building’s operation. A project manager can suggest less expensive alternatives to the specified materials, higher quality alternatives that increase the value of the final product, options that balance initial construction costs and operation costs and products that could reduce the maintenance costs of the lifetime of the building (South Bay Construction, 2015).

3.3 Managing Subcontractors

A construction manager needs to coordinate that the correct subcontractors are on site and completing important tasks. They should push subcontractors to continue working hard and make sure their efforts are in the right areas. For example, if there are electrical issues holding up a certain section of the building from passing an inspection, the project manager should create a worklist or punch list that details exactly what needs to get done. The construction manager should continue to update and distribute
the lists for that section until the work is completed. A daily manpower log of everyone on site is also required to track the workers on site each day. This becomes important when a hired subcontractor continually sends undermanned crews to the job. It is the construction manager’s job to make sure that the job has enough workers and isn’t falling behind schedule. During the construction of FIS, Shawmut had 15 subcontractors working for them. The subcontractors had roughly 180,000 total man hours during the construction of FIS.

3.4 Closeout Documentation

The closeout documentation for a project will vary based on the language of the specifications. In a typical project, the Construction Manager provides the owner with as-built drawings, red-line drawings, an Operation and Maintenance Manual (O&Ms), warranties, attic stock and any training that is necessary. As-built drawings are drawings that document exactly where the ductwork, electrical wire, pipes, valves, etc. are in the building. Red-line drawings typically show where any utilities that are not regularly visible are located. An example of a red-line drawing would be a drawing that shows where the electrical conduit runs across the site to power light poles in a parking lot. As-builtons and red-line drawings are used both used for emergencies or future construction or renovations. An O&M Manual includes information for the equipment and systems used in the project. These things include maintenance recommendations and instructions for minor repairs. Most projects require warranties from subcontractors. The warranties range from 1 year to lifetime. This ensures that if a subcontractor performs
unsatisfactory work, they will fix it free of charge. Attic stock is extras of the materials that were used during the construction project. The importance of attic stock is so if 10 years after the completion of the project, the owner will still be able to determine the manufacturer and model of products used so they can order more. An example of this would be if there is ceiling tile damage in the building, the owner can easily order matching ceiling tiles. Systems and equipment that require trainings are usually video recorded so an owner can find out how to operate the system or equipment without having to track down the manufacturer or installer. An example of a training video is a video explaining and showing how to operate an irrigation system. Closeout documentation ensures that the owner can properly operate and maintain the building after construction is completed.
The SDC compiled all of the closeout documentation on a website, as seen in Figure 10. The website can only be accessed with the approved credentials. The
website also includes a Matter Port model of the building, as seen in Figure 11. The Matter Port model is a 3D model created by scanning the building. The scan is completed just before the walls are closed in, that way subcontractors who need to make repairs or complete future work can take a look at what is behind the walls.

Figure 11: MatterPort File of FIS
4.0 Earned Value Analysis

Earned Value analysis is a method that can track the progress of a project at any point in time. The method takes into account 3 variables: cost, scope, and time (Halpin, 2017). From the Earned Value Analysis, values such as cost variance and time variance can be found. The results of this type of analysis produces a better understanding of the construction process by explicitly comparing planned against actual performance in terms pf cost, schedule and scope of work.

4.1 The Earned Value Analysis of FIS

Earned Value Analysis is a method that can track the progress of a project at any point in time. The method takes into account 3 variables: cost, scope, and time (Halpin, 2017). From the earned value analysis, values such as cost variance and time variance can be found. This value can show if the project is behind, ahead, or on schedule, and also if the project is on-budget. The three curves in the graph below represent the Actual Cost, Budgeted Cost of Work Schedule (BCWS), and Budgeted Cost of Work Performed (BCWP) (Halpin, 2017). Ideally, when EVA’s are conducted, the data collected is pointed towards the chosen variables, however this EVA was conducted by using existing information and data to complete an approximate analysis of the project. The data and information available dictated the variables set for the analysis. The blue curve (BCWS) was calculated by looking at the original schedule submitted by Shawmut. The total time of the project was divided by the number of months to
generate percentages of the total project duration elapsed. Using the average percent per month and the schedule, a percent for each month was found by using the average and then looking at the tasks being completed. For example, it was known that less work was completed in the winter months than the summer because of student population and weather. The average percent per month was between 2% and 3%, however the summer months were given 6%-7% because of the factors explained above.

To find the monetary value, the cumulative percent of each month was multiplied by the proposed total cost of $39 million. The orange curve is the Actual Cost of the Work Performed or ACWP. It was found by taking the cumulative requisition amount per month and dividing it by the total budgeted cost. As an example, the requisition from July 2017 was pulled up and the total amount of money spent on the project in July of
2017 was found. Adding that to all previous months requisition values since the start of the project gives the cumulative cost for the project up until July 2017. The cumulative cost was divided by the total overall cost of the project and the result was the percent complete of the project in July 2017, which was 23.66%. Lastly, the gray curve is the Budgeted Cost of the Work Performed or BCWP. It represents the amount of dollars from the original budget earned by the actual work completed at the time in which performance is evaluated. It was calculated by using a spreadsheet of the daily manpower on site (See Appendix I). For example, by taking the cumulative manpower hours per month and dividing by the total manpower hours, the percent per month was found.

The time variance can be found by subtracting the work performed from the work scheduled (BCWP - BCWS). If the value is equal to zero the project is on time, if it is greater than zero the project is ahead of schedule, and if it is less than zero the project is behind. When looking at the graph it become obvious that for a long period of time, after the first couple months, the project was behind the original schedule. However towards the end the work performed finally is equal to the work scheduled. In July of 2017, the time variance is around -21.4, however a year later right before the project was finished in July of 2018, and the time variance is +1.9. This can be seen visually on the graph by the late jump in May 2018, and can be attributed to classes ending, less students on campus, and more work being performed.

The cost variance can be found by subtracting the Budgeted Cost of Work Performed from the Actual Cost of Work Performed (BCWP – ACWP). Much like the time variance, if the value is equal to zero the project is on budget, if it is greater than
zero it is above budget, and if it is below zero the project is below budget. Unlike the
time variance, the graph clearly shows that from the very start of the project was below
budget due to the gray line being below the orange line. However, much like the time
variance, late in the schedule the project goes above budget. For example, July of 2017
had a cost variance of -12.4, however again 1 year later in July of 2018 the cost
variance is +1.9.

As far as the overall performance of the project, it appears from the start of the
project until about June of 2018 the project was not doing well considering the variances
calculated. However, it is again important to note that this was an approximate EVA
based on the data given, which also dictated the variables used. The variables used
may not be the best when evaluating the cost variance. Although by the end of the
project, not only were the variances showing that the project was ahead of schedule, it
was also above budget. When talking with those involved with the project there were no
accounts of the project being dangerously behind schedule, however in construction
there are many unforeseen delays and difficulties that can have adverse effects on the
original schedule.

4.2 Scheduling Delays Effect on Cost, Time and Scope of Work

Scheduling issues and delays are almost inevitable in a large construction project
and can affect the cost, time and scope of a project. Construction managers can
prevent some delays, but some factors are out of their control. For a project to stay on
track with proposed schedule, it is important for a project manager to obtain the
necessary permits and materials necessary to start the project so there are no delays right off the bat. A project manager needs to keep track of the progress of each phase to notify the subcontractors that having work upcoming, so the subcontractor can schedule crews to perform the work. If a project manager can schedule subcontractors to perform work simultaneously without needing to be in the same spaces, the subcontractors can complete the work in a shorter time frame. They will not be bumping into each other, working over top of each other and distracting each other. A good project manager should be able to determine when and where tasks can be completed and schedule subcontractors accordingly. If these steps are taken, there will be less chances for avoidable delays. However, many of the delays in construction are weather related. In the case of the construction of the Foisie Innovation Studio, the first delay during the project came before the demolition of Alumni Gym even began.

Before the demolition of Alumni Gym could start, WPI needed to secure a loan to ensure the financial security of the project. WPI originally went to the State of Massachusetts to get a loan. One of the requirements for the State to approve a loan is that the Massachusetts Historical Society (MHS) must approve of the project. The MHS provided no feedback one way or the other on WPI tearing down Alumni Gym for over three weeks. After waiting this long, WPI looked elsewhere for a loan, found a better deal, and the bank approved the loan the next day. SDC began the project in the summer of 2016 (Herbert, 2018). This delay was not foreseeable by neither WPI nor Shawmut.
4.2.1 Weather Related Challenges

Many of the delays during the demolition and construction phases were weather-related. During the construction of the steel structure, which spanned from January 2017 to May 2017, there were 18 days that Shawmut noted as weather delays. When it rains or snows, steel becomes slick, and when iron workers are erecting steel beams and girders, they have to walk around on the steel. Because the steel is slick, it is a dangerous work environment. Also, welding in wet conditions is dangerous because water conducts electrical current. If a welder’s protective clothing, such as pants and gloves, get wet, they can conduct electricity. During the construction of the facade, there were 12 days that Shawmut noted as weather delays. During the roughly 2-year construction of FIS, inclement weather stalled progress for a total of 30 days, according to the schedule that Shawmut prepared (Herbert, 2018).

According to a study by the AISC, between .25 in to .50 inches of rain will delay a construction project a full work day (Reyes). The National Oceanic and Atmosphere (NOAA) daily weather reports specify there were 72 days of at least .50 inches of rain during this project (see Appendix H for detailed reports). 56 of the days with inclement weather fell on work days. According to the reports from NOAA and El-Reyes, this project should have been delayed roughly 2 months due to the weather, yet Shawmut only noted roughly 1 month of delays due to weather. Shawmut and their subcontractors could have either worked through the rain prior to closing the building in, or once they closed the building in, they continued to work inside the building during the rain. This shows the hard work and dedication of SDC and their subcontractors.
4.3 Design Challenges Effect on Cost and Scheduling

When designing and constructing a mixed-use facility, there are always difficulties because the end users all have differing needs and opinions. During the design phase, there were minor changes to the original drawings, which is typical in the construction process. Each time the design got changed, the drawings had to be sent to the electrical, mechanical and plumbing engineers for them to edit their drawings and models. These changes can also have an adverse effect on the budget of a project.

When large structures like FIS are built, MEP coordination is essential because of the sheer size of the project. 3D models of their drawings are created using computer software by the individual trades in MEP. Once finished, the drawings are combined to detect overlaps and clashes ahead of catching them in the field while building. This led to some of the discrepancies in the drawings and clashes in the 3D model, since multiple engineers had to make changes to a complete drawing set (Herbert, 2018). An example of a clash can be seen in Figure 13, where the green line shows where an 8” storm pipe was supposed to go, but it ran through 2 foundation walls. The red line shows the approximate location the 8” line was changed to. These design changes had a minor effect on the schedule of the project.

All these changes added in from the original design can also have an adverse effect on the budget of the project. This is especially true when change orders demand fluctuations to objects already constructed because the money to build that object was already spent and it costs more money on top of that to change it. In addition to the effects on the budget, design changes can have a bad effect on the schedule. As
mentioned above, when changes are made, the plans are sent out to the individual MEP engineers to fix their 3D model. Then all 3 models are combined, and the clash detection is run. If there are clashes within the model the engineers must then go fix them before approving their designs. The whole process takes time and every day can have a negative impact on the schedule.

Figure 13: An RFI on Storm Line Relocation
5.0 Technology in Construction

5.1 Building Information Modelling

One of the most used and influential innovations in the construction industry is the use of Building Information Modelling (BIM). BIM is essentially a 3-dimensional model of a project that holds information regarding design, construction, and building operation of the project. A common software used for BIM is Autodesk’s Revit application. The use of BIM becomes essential in advancing performance-based design due to the ability of simulating energy performance, indoor air quality, and lighting through the BIM model while still in the design stage of the project. Not only is BIM useful for better 3D visualization of the project, but many softwares can also be used with the BIM model in innovative ways such as to integrate scheduling, costs, and coordination of the project.

5.1.1 Coordination

The coordination between different parties involved in a project is crucial to the project’s success. Building Information Modelling is beneficial for the coordination of a project. Autodesk’s Navisworks application can be used to integrate 3D models from multiple trades into one Navisworks model. Navisworks has a “Clash Detective” tool which assess any potential clashes/intersections occurring in 3D space of the different trades’ models as well as the location of the clashes. This is useful for project managers...
to identify design flaws before construction takes place. This allows project managers to have better coordination within all the parties involved in a construction project.

5.1.2 Schedule Integration - 4D Modelling

4D Modelling allows the user to visualize the 3D model of the project coming together phase by phase as well as incorporates contextual elements that show how the project impacts logistics. To take a BIM model from 3D to 4D, a time factor must be placed. This is done through integrating a project’s schedule with its BIM model. Two ways to do this are through the computer program Sketchup and Autodesk’s Navisworks application.

In Sketchup, the user can create a 4D model through the use of Sketchup’s “Scenes” tool. With the scenes tool the user can have each scene represent a set time of the project. For example, if the user wants to show the project’s progress on a month by month bases each scene can represent the first of every month. Once all the scenes are created the user can hide certain objects from each scene to show the amount of work that should be completed each month. Once all the scenes have an accurate display of project progress for each month the 4D model is created. The user can now click through the different tabs for the scenes to see the amount of work that should be completed each month as well as animate the scenes to show the project coming together from start to finish.

In Navisworks the user can link a project’s Revit Model with the project’s schedule. One way to do this is by creating a rule that links the user-defined field of your schedule with the Project Parameter name in Revit. Navisworks will identify all objects
in the project scene and map them to the schedule task with the same name (Dodds, Johnson, 2013). The user can also incorporate start and finish dates for the supply and installation of construction components and reveal the importance of them in relation to the overall project (Smith, 2017).

In addition to linking a project’s schedule, a 4D BIM model benefits project managers with planning logistics. 4D modelling can help project managers plan how a project impacts safety, site access, and neighborhood traffic. This is done by including elements in the 4D model such as geo location of the site, site-access, equipment lay down area, trailer location, crane motion and other factors in a project’s logistics. Having these items apart of the BIM model ensures proper logistic planning before the start of construction.

5.1.3 Cost Integration - 5D Modelling

To advance the BIM model from 4D to 5D, the cost impacts of the schedule must be integrated. From the Revit Model, a user can extract information on the quantities of materials for each trade, which can then be used to determine the percent completeness of each trade per month. This allows project managers to determine the percent cost that was spent in comparison to the amount of work completed in a certain time-frame and determine the cost of each task of the schedule.

5.2 The Use of BIM with Foisie

Shawmut Design and Construction provided our team with completed BIM Models. These included files for the structural, architectural, and site models. With these
files we were able to create a 4/5D model of the project and use that to analyze the progress of construction throughout the whole project.

5.2.1 Creating the 4D Model

For the creation of the 4D model the MQP team used the computer program Sketchup. After receiving the 3D Revit models from Shawmut, the team had to export the Revit files as .DWG files in order to be compatible with Sketchup. Once this was done the files were imported to Sketchup. The team created different Sketchup files for the site, structural, and envelope models.

The Revit model for the site work also provided adjacent buildings to Foisie on WPI’s campus. By using Sketchup’s geolocation tool we were able to select our site location on a satellite view similar to google maps. Once the geolocation was set we manually placed the models of the adjacent buildings in their respective locations. Once all buildings were placed, we covered the existing building with a flat plane and assigned it a material of “gravel” to show post-demolition, site readiness, and the start of construction. Below is our site model in Sketchup.

![Figure 14: Sketchup Site Plan](image-url)
For the structural model we first imported the .DWG file that we exported from Revit to a new Sketchup file. Once the complete structural model was imported to Sketchup we evaluated the planned schedule of construction from the schedule that was provided from Shawmut. We found that the structural phase of the project was planned to start in November 2016 and completed in May 2017. From this we created seven scenes in Sketchup to represent the progress on the first of each month throughout the construction. In each scene we used the command “hide in view” to hide certain objects that have not yet been completed in the project. The plan is to show only what should have been completed for each month. In order to determine what to hide we needed to understand the logistics of the project such as steel sequencing and the flow of construction. We did this by going through the photos of the actual construction of Foisie. These photos were provided from Shawmut as well as WPI. Although the planned schedule and the actual construction were not the same, we used the photos to determine the sequencing and applied that to our planned 4D model. Once we determined exactly what was completed by the first of each month we were able to accurately depict month by month progress of the structural phase. For example, below are figures of the schedule and Sketchup model for everything that was planned to be completed by February 1st, 2017. It is evident that by February 1st, 2017 everything above the red line is planned to be completed. Therefore, in our Sketchup model for the “Feb 2017” scene we show only the items that are planned to be completed.
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<th>488</th>
<th>458</th>
<th>19-Sep-16 A</th>
<th>01-Aug-18</th>
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<td>0</td>
<td>19-Sep-16 A</td>
<td>07-Oct-16 A</td>
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<tr>
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<tr>
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<td>5</td>
<td>04-Nov-16</td>
<td>10-Nov-16</td>
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<td>15</td>
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<tr>
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<tr>
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<td>18-Jan-17</td>
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<tr>
<td>L2 Deck and Detail</td>
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<td>26-Jan-17</td>
</tr>
<tr>
<td>L4 Framing</td>
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</tr>
<tr>
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<td>26-Jan-17</td>
</tr>
<tr>
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<td>4</td>
<td>27-Jan-17</td>
<td>01-Feb-17</td>
</tr>
<tr>
<td>L3 Deck and Detail</td>
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<td>09-Feb-17</td>
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<td>L4 Deck and Detail</td>
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<td>10-Feb-17</td>
<td>21-Feb-17</td>
</tr>
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<td>L5 Deck and Detail</td>
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<td>7</td>
<td>22-Feb-17</td>
<td>02-Mar-17</td>
</tr>
<tr>
<td>Roof Deck and Detail</td>
<td>8</td>
<td>8</td>
<td>03-Mar-17</td>
<td>14-Mar-17</td>
</tr>
</tbody>
</table>

*Figure 15: Screenshot of Project’s Planned Schedule as of 10/31/2016, (Source: SDC)*
The creation of the 4D architectural model is done through the same methods as the structural 4D model. We choose to create separate 4D models to work quicker within the files while. Working with one file with everything in it would slow down the whole model. After the 4D architectural model was created we then emerged it with the structural model to create a complete 4D model of the project. Below is a figure of the 4D model. For a detailed instruction on creating 4D models in Sketchup see Appendix G: Sketchup Methodology.
5.2.2 Planned vs Actual Construction Analysis

To analyze the planned schedule of construction to the actual schedule the costs of the project must be integrated with the 4D model. The comparison is in a Microsoft PowerPoint presentation with each slide showing the percent completion and costs for the first of each month throughout the project’s duration. By doing this we can perform an Earned Value Analysis of the project by determining planned vs actual work percent completeness and cost association for each month of the project’s duration. Below is an example of the PowerPoint slide for January, 2017. The 4D Sketchup model, PowerPoint, and all Revit files can be found in Appendix A: E-Files.
5.3 Emerging Technologies in Construction

Building Information Modelling has proven to be a substantial advancement in technology for construction. BIM benefits construction managers in visualizing the project, planning logistics, and foreseeing problems before they occur. Currently the construction industry is seeing many new innovations starting to emerge in addition to BIM. Some technologies include Artificial Intelligence and Augmented/Virtual Reality.
5.3.1 Artificial Intelligence

Artificial Intelligence is utilized in construction as an aid for planning logistics and managing/controlling tasks. For planning logistics, AI helps to inform engineers how a specific project should be constructed. It does this by using past projects and verifying pre-existing blueprints for the design and implementation stages of the project (Debney, 2018). Artificial Intelligence can also digest a 3D model of a proposed building and spit out a detailed schedule for its construction. In as little as a day the AI can come up with hundreds of millions of ways to assemble a building (Baraniuk, 2018). The user can also add certain parameters such as number of cranes and the AI will choose potential schedules that incorporate that parameter. Once construction has begun, AI can help manage the project by adapting the project accordingly when workers input sick days, vacation days, and anytime missed into a data system. The AI can move the tasks that the worker missed onto another employee.

5.3.2 Augmented/Virtual Reality

The adoption of Augmented and Virtual Reality (AR/VR) has grown in the construction industry. AR has revolutionized how field teams leverage information and contextual knowledge to build safer, with high quality, and make the best-informed decisions (Virtual and Augmented Reality Ready to Redefine Construction, 2016). AR can provide real-time installation guidance to jobsite crews. Unlike virtual reality, where the user is completely immersed, augmented reality lets the user see real life objects with pieces of the virtual model overlapping real life. This is safer to use on site because
the user is still aware of his/her surroundings. VR, however, is useful for improving
design-phase outcomes. The virtual reality model can be integrated with the BIM model.
This lets the user visualize the project while fully immersed in virtual reality. The user
can also virtually fly through the model and inspect different parts of the project.
6.0 Green Roof Structure

Sustainable building structures are becoming more and more popular. When constructing a building, the architects and designers will work towards earning a Leadership in Energy and Environmental Design (LEED) Certification. LEED is a program that accredits and certifies a building for its sustainable design and the impact that the construction has on the community. There are four types of certifications: LEED Certified, LEED Silver, LEED Gold, and LEED Platinum. Each category represents a more sustainable building that had a lesser impact on the surrounding community.

To earn a LEED certification, there are various LEED points that can be awarded during the design and construction phases. These points are categorized into: Building Design and Construction, Building Operations and Maintenance, Interior Design and Construction, Homes, and Neighborhood Development. The criteria range from using recycled materials during construction, project distance from public transportation, pollution prevention and green spaces (LEED, 2018). In part, architects will design a sustainable building with LEED points in mind. Building a sustainable structure can also lower operational costs.

A green roof can earn LEED points in the following categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere and Material and Resource (LEED, 2018). A green roof substitutes a traditional roof top, typically black tar or a white poly-membrane, with vegetation. The vegetation can range from small plants in planter boxes covering the roof, to a roof with shrubs, trees, walkways and benches. Green roofs last longer, better insulate the building, absorbs storm water, which will result in a
simpler, cheaper drainage system, and it provides a natural home insects and animals (Dowdey, 2007). An example of a green roof can be seen in Figure 19.

Although a green roof is beneficial when the building is in operation, the initial design and construction costs are not cheap. A traditional roof costs roughly $1.25 per square foot, whereas a green roof can cost nearly $8 per square foot. The weight of adding a green roof is the biggest reason for the cost increase. Adding a green roof can add anywhere between 20-150 pounds per square foot (Dowdey, 2007). To allow for this, the structural steel must be large enough to support the weight of the green roof. With larger steel being used, the cost will go up. Another reason for the cost increase is that green roofs require professional design and structural analysis.

Figure 19: Chicago's City Hall's Green Roof
6.1 Foisie Innovation Studio’s Potential Green Roof

During the design phase of FIS, there was debate of adding a green roof to the low roof. The school ultimately decided to overdesign the steel beams so that they could add a green roof at some point in the future, and not have to worry about changing the steel structure to account for the extra loads associated with a green roof.

Although there are economic benefits of having a green roof, WPI felt that having a green roof that was easily visible from the student’s dorm rooms would be unappealing. The school felt that students would not like looking out their windows at large areas of dirt and plants, and therefore decided not to include a green roof for now (Laythe, 2018). As of now, there are no plans to add a green roof, but WPI can easily add one if they choose to do so (Clay, 2018).

6.2 Green Roof Structural Analysis

This report performs a structural analysis of the loads that a green roof applies onto the steel structure of the low roof in the FIS. The purpose of this is to resize the steel as if there was no green roof. The loads that the steel will undergo include: self-weight, utilities, the ceiling, the roof structure, the roof membrane, the sky lights, and the green roof itself. The green roof is heavy due to the planter boxes, the soil and vegetation. When it rains, the soil and vegetation get fully saturated with water. The green roof could also include waterproofing, erosion control and irrigation. The structural steel must be designed that the steel does not fail during construction and occupancy. The design is for 50 ksi steel.
There are two different design approaches that are used in structural engineering: Load and Resistance Factor Design (LRFD) and Allowable Stress Design (ASD). Until 1986, the design of steel structures was based on ASD loads. LRFD has become more popular among structural engineers. The only difference between the ASD and LRFD methods for designing steel structures is the load combinations used to size the beams and girders. LRFD uses a higher safety factor, which will lead to larger steel and higher costs.

For ASD, the load combination is:

1. \( W_u = D + 0.75L + 0.75(0.6W) + 0.75S \)

Where,
- \( W_u \) = ultimate weight
- \( D \) = Dead Load (lbs/ft)
- \( L \) = Live Load (lbs/ft)
- \( W \) = Wind Load (lbs/ft)
- \( S \) = Snow load (lbs/ft)

For LRFD, the load combinations are:

1. \( W_u = 1.4D \)
2. \( W_u = 1.2D + 1.6L + .5S \)
3. \( W_u = 1.2D + 1.6W + 1L + .5S \)

Where,
- \( W_u \) = ultimate weight
- \( D \) = Dead Load (lbs/ft)
- \( L \) = Live Load (lbs/ft)
- \( W \) = Wind Load (lbs/ft)
- \( S \) = Snow Load (lbs/ft)
For the ASD and LRFD methods, the following steps are the same. The ultimate bending moment a beam or girder can withstand with the designed loads was calculated using the following equation:

**Bending Moment equation:**

\[ M_u = W_u L^2 / 8 \]

Where,
- \( M_u \) = ultimate bending moment
- \( W_u \) = ultimate weight
- \( L \) = length of beam

A beam or girder must pass the following tests.

A beam must have a sufficient plastic section modulus, \( Z_x \), according to the following equation:

**Plastic Section Modulus equation:**

\[ Z_x \geq M_u / \phi_b F_y \]

Where,
- \( Z_x \) = plastic section modulus
- \( M_u \) = ultimate bending moment
- \( \phi_b \) = correction factor of .9
- \( F_y \) = yield strength steel (50 ksi)

Beams also have to be sized for serviceability in terms of deflection. Deflection is the distance the beam will move under the expected combined loads. The Specifications of the project call for all steel members to have a deflection of less than \( \frac{3}{8} \)”.

**Deflection equation:**

\[ \Delta_T = 5 * W_T * L^4 / 384 * E * I \] (floor and roof slab)

\[ \Delta_T < L / 240 \text{ or } 3/8” \text{ max} \]

Where,
- \( \Delta_T \) = total load deflection
\[ W_t = \text{total combined load} \]
\[ L = \text{length of span} \]
\[ E = \text{Young’s modulus, } 29 \times 10^6 \]
\[ I = \text{Moment of inertia, in}^4 \]

The beam must be sized in order to pass the buckling tests. The beam could fail in web local buckling or flange local buckling. The web local buckling equation is:

\[ \frac{Bf}{2Tf} < 0.38 \sqrt{\frac{E}{F_y}} \]

Where,

- \( Bf/2Tf \) = compact section criteria
- \( E \) = Young’s modulus, \( 29 \times 10^6 \)
- \( F_y \) = yield strength steel (50 ksi)

The web local buckling equation is:

\[ \frac{H}{Tw} < 3.76 \sqrt{\frac{E}{F_y}} \]

Where,

- \( H/Tw \) = compact section criteria
- \( E \) = Young’s modulus, \( 29 \times 10^6 \)
- \( F_y \) = yield strength steel (50 ksi)

The Plastic capacity of the beam must pass the following test:

\[ \phi M_p > M_u \]

\[ \phi M_p = \phi Z_x F_y \]

Where,

- \( \phi \) = correction factor of .9
- \( Z_x \) = plastic section modulus
- \( F_y \) = yield strength steel (50 ksi)
If a beam passes all of these criteria, the size is adequate and the process is repeated for a girder. The only difference for a girder is that a girder will have a distributed load from the weight of the beams. This load is factored into the dead load when calculating the load combinations. The distributed load equation is:

\[ D.L. = \frac{(Wb \times Tw_g)}{Tw_b} \]

Where,

- **D.L.** = distributed load along girder (lb/ft)
- **Wb** = average nominal weight of adjacent beam (lb/ft)
- **Tw_g** = tributary width of the girder (ft)
- **Tw_b** = tributary width of adjacent beams (ft)

The same process for sizing a beam is used to size the girder after determining the dead load. If the girder passes all the criteria, the beam and girder system will be sufficient. The resulting design can be seen in Figure 20. The beams are the vertical structural members, and the girders are the horizontal structural members on the page.

*Figure 20: FIS Steel Structure Design*
6.3 Green Roof Cost Analysis

This report will compare the cost of constructing and retrofitting FIS with steel that would be strong enough to support a green roof if the building was constructed without strong enough steel. This comparison will show WPI how much money they saved by deciding to install the stronger steel before the steel was fabricated. The original construction costs will be determined by the payment record from the construction project. The analysis will consider 3% annual inflation based on WPI completing the work 10 and 20 years in the future.

6.3.1 Cost Analysis of the Potential Designs

After the beams and girders have been sized, the cost per square foot for the original construction phase can be calculated. The beams and girders for the design without a green roof can be seen in Table 1 and the calculations can be seen in Appendix F.

<table>
<thead>
<tr>
<th></th>
<th>Nominal Beam Size</th>
<th>Nominal Girder Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASD Design</td>
<td>W14 x 34</td>
<td>W33 x 354</td>
</tr>
<tr>
<td>LRFD Design</td>
<td>W14 x 48</td>
<td>W36 x 798</td>
</tr>
</tbody>
</table>

*Table 1: Beam and Girder Sizes for the Low Roof Design*

The cost per square foot for a steel structure can be estimated with the following equation:

\[
\text{Cost ($/sf)} = \left( \frac{\text{Beam weight (ton/ft)}}{\text{Beam Spacing (ft)}} + \frac{\text{Girder weight (ton/ft)}}{\text{Girder Spacing (ft)}} \right) \times 3500/\text{ton}
\]

The cost per square foot for the construction of the different low roof designs can be seen in Table 2 and the cost calculations can be seen in Appendix F.
<table>
<thead>
<tr>
<th>Design</th>
<th>Cost ($/sq ft)</th>
<th>Total Cost of Low Roof ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASD</td>
<td>$38.12</td>
<td>$339,649.20</td>
</tr>
<tr>
<td>LRFD</td>
<td>$79.91</td>
<td>$711,998.10</td>
</tr>
<tr>
<td>Actual FIS Design</td>
<td>$44.03</td>
<td>$392,307.30</td>
</tr>
</tbody>
</table>

*Table 2: Cost per square foot of each Low Roof Design*

The structural engineers that designed FIS used the ASD design. The LRFD method has a higher design load combination which results in larger beams and higher costs, which is why the LRFD design has a cost that is higher than the actual design. The ASD design is cheaper than the actual costs of the FIS design. The design had larger beams and girders, but different span lengths than those used in the ASD design. While this may increase the material costs, the labor costs were much lower since we made all the beams the same size. This is because the beams used in FIS are of many different sizes, which makes it more labor intensive for the steel fabricator and for the iron workers. The steel fabricators had to change the size of the beams and girders as they were manufacturing them for FIS, as opposed to our design, where they could keep the fabrication machines in the same orientation. This design also lowers the installation costs because the iron workers don’t have to spend time sorting out which beams go where, almost like puzzle pieces. All the beams and girders in our design are the same size, so any beam can go where a beam belongs, and any girder can go where a girder belongs.

**6.3.2 Retrofitting Steel Structures for Higher Loads**

If WPI decided to incorporate a Green Roof after constructing FIS without having designed the building to include a green roof, they would have to add more supports to the steel beams to support the new loads. A few of the possible solutions would be to add more beams and girders, add more columns, or weld stiffeners to the web or flange of the steel beams and
girders. Adding beams, girders or columns to the structure is a difficult task to complete after construction. It would be difficult to protect the facilities in the building and difficult to bring entire steel beams into the building. The most logical solution would be to weld stiffeners along the bottom of the beams and girders. This will be the easiest method because of the open ceiling plan in FIS. Adding a stiffener along the flanges will increase the beams bearing and deflection capacity.

Using the ASD design, the team recalculated the load combinations as if WPI had decided to add a green roof to FIS. Based on the estimate of a green roof weighing 20-150 pounds per square foot, the load used to calculate the green roof was 85 pounds per square foot. After adding this dead load to the structure, the only criteria that the system no longer passes is in deflection. In order to increase the deflection capacity of the beam, it is recommended to weld a flat plate stiffener to the bottom of the beams and girders. This will increase the moment of inertia of the beam which will increase the deflection capacity. Adding a flat plate with a thickness of 1.515 inches to the bottom of the beams and adding a flat plate with a thickness of .9375 inches to the bottom of the girders will result in the system passing all criteria, including deflection. The structural analysis and inertia calculations can be found in Appendix F. The hand calculations in Appendix F show the Inertia value that is needed for the beams and girders to pass the deflection criteria and the Inertia Calculator was used to change the bottom flange thickness to produce a sufficient moment of inertia (Ix). For the beam, the bottom flange thickness had to be increased to 1.9 inches from .385 inches. This means that a flat plate of 1.515 inches thick must be added to the bottom of the beams, assuming that the flat plate is welded to the beam over its entire length. For the girder, the bottom flange thickness had to be increased to 3 inches from 2.0625 inches. This means that a flat plate with a thickness of 1 inch must be added to the bottom of the girders, assuming that the flat plate is
welded to the girder over its entire length. By adding these flat plates, the structure will withstand the loads of a green roof.

6.3.2 Retrofitting Cost Estimate

In order to estimate the costs of the Retrofit design determined in 6.3.1, the team used the RSMeans book from 2011. The materials used for the retrofit include a .9375 inch steel plate and a 1.515 inch steel plate. The team made the assumption that 1 inch and 1.5 inch steel plates were similar enough in size that the cost estimates would be close enough. The only labor included in the retrofit would be a ¼” fillet weld on both sides of the plate, continuous on the entire length of the beam. The data can be found in Table 3.

<table>
<thead>
<tr>
<th>Material or Activity</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot; Thick steel plate</td>
<td>46 $/sq-ft</td>
</tr>
<tr>
<td>1.5&quot; Thick steel plate</td>
<td>69 $/sq-ft</td>
</tr>
<tr>
<td>¼&quot; fillet weld</td>
<td>14.20 $/linear foot</td>
</tr>
</tbody>
</table>

*Table 3: RSMeans Cost Estimate Data*

To determine the total cost of materials, the total square-footage of all the beams was calculated, and multiplied by the value of a 1.5” thick steel plate. The same process was completed for a girder, but multiplied by the value of a 1” thick steel plate instead. The two values were combined to calculate a total material cost of $75,011. Next, the labor costs had to be calculated. The total length of the beams and girders had to be calculated. The total length was doubled to account for the welds on both sides, then multiplied by the RSMeans cost value. The total cost of labor was $47,286, making the total cost of the retrofit $122,297, if the work was performed in 2011.
Since the analysis is based on the retrofit occurring 10 or 20 years after construction, a yearly inflation rate of 3% had to be incorporated to our costs. Since the majority of the steel was erected in 2017, the total cost of retrofitting was calculated in 2027 and 2037. The costs values for retrofitting in 2011, 2027 and 2037 can be found in Table 4.

<table>
<thead>
<tr>
<th>Year of Retrofitting</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>$122,297</td>
</tr>
<tr>
<td>2027</td>
<td>$196,250</td>
</tr>
<tr>
<td>2037</td>
<td>$263,744</td>
</tr>
</tbody>
</table>

*Table 4: Retrofitting Costs for FIS Steel by Year*

To determine the cost effectiveness of WPI’s decision to construct FIS with the larger steel for the green roof, the actual cost of the low roof steel was compared to the cost of the design without the green roof and retrofitting costs. The comparison can be seen in Table 5. The actual FIS low roof design is $100,000 less than if WPI had not designed the steel to account for a green roof, and then changed their minds 10 years down the road.

<table>
<thead>
<tr>
<th>Design</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual FIS Design</td>
<td>$392,307.30</td>
</tr>
<tr>
<td>Retrofit Design (2027)</td>
<td>$535,899.20</td>
</tr>
<tr>
<td>Retrofit Design (2037)</td>
<td>$603,393.20</td>
</tr>
</tbody>
</table>

*Table 5: Total Cost of Low-Roof Structure by Design*
7.0 Conclusion

Having just been opened at the beginning of the 2018/2019 school year Foisie Innovation Studio (FIS) has certainly been a bright spot on the WPI campus. All the way back in 2015 in efforts to construct the building WPI paired alongside their construction project team consisting of Shawmut Construction and Design, Gensler Architects, and KV Associates. At first, KV Associates was hired to be the owner’s (WPI) project manager and Shawmut was hired to be a consultant for a renovation. FIS was certainly not the first thought from WPI as they aspired to renovate the inside of the historical Alumni Gym. However, after looking at the current state of the building and the cost to renovate it for robotics labs, WPI and their two consultants decided it was a better idea to construct a whole new building, the Foisie Innovation Studio.

The project includes a structural redesign of the low-roof steel structure without the loads of a green roof. During the design phase, WPI was debating whether or not they wanted to have a green roof, and made the decision to design the roof structure to withstand the loads of a green roof, and then decide later on if they wanted a green roof or not. The analysis includes a structural and cost analyses to determine the size of the steel beams they would have used without a green roof, the method of retrofitting the steel to withstand the loads, and how much it would have cost. Based on our analysis, WPI saved over $100,000 by starting with the larger steel, as opposed to having to retrofit the building.

This project also analyzes the construction management of the Foisie Innovation Studio. To do this the project team compared the planned schedule of construction to
the actual construction and performed an earned value analysis. To compare the planned and actual construction the project team created a 4D BIM model based on the project’s planned schedule, logistics, and flow of construction. We compared the 4D BIM model to photos that were taken on the first of every month during the project’s duration. The project team created a PowerPoint to show the planned and actual project progress for the first of each month. Slides of each month include the percent work completion and accumulated costs. From the PowerPoint it is evident that the project fell behind in the beginning but fast-tracked to meet its deadline at the end. The earned value analysis is also shown on each slide.

When completing the analysis, it became clear that there would be heavy limitations. The monetary values for the Budgeted Cost of Work Schedule (BCWS) were not input into the Primavera schedule file. Therefore there was no way to gain exact amounts for these values. The BCWS was calculated by taking the average percent of the project complete per month and adding or subtracting to that number based on known variables during construction. The earned value was determined based on number of worker hours for each month of the project’s duration. By taking the cumulative manpower per month and dividing by the total manpower for every month, the percent per month was found. The Budgeted Cost of Work Performed (BCWP) was taken from the cumulative sum of the requisitions and dividing by the total cost of work performed.

This project can serve as a reference for WPI as they look forward to constructing another new building. WPI can use the green roof cost analysis to help make future decision regarding the constructability and serviceability of the design. The
students of CE 3030 and CE 3031 and future MQP groups can use this report to help make a 5D simulation, perform an Earned Value Analysis with limited data and retrofit a steel structure.
Bibliography


Virtual and augmented reality ready to redefine construction.


Appendices

Appendix A: E-Files

Foise 4D Model:
*Foise 4D Model.skp*
This is a Sketchup model of Foisie. The planned project schedule has been manually integrated into the 3D model to make it 4D. This model shows the project being completed overtime. This model is a combination of the Site, Structural, and Core/Shell revit files that have been imported to Sketchup.

Powerpoint Planned vs Actual Project Comparison:
*Foise Innovation Studio Powerpoint*
This powerpoint compares the planned schedule of construction vs the actual construction vs the earned value of the project. Each slide represents the first of each month of the project’s duration. Project percent completion, cost accumulation, and photos/sketchup screenshots are shown for each slide.

Revit Files:
*Foise CORE SHELL Model.rvt*
*Foise SITE Model.rvt*
*Foise STRUCTURAL Model.rvt*
Many revit files were provided from Shawmut but the ones used in our project include the site model, structural model, and core/shell model. These revit files were imported into sketchup to create our 4D model.

Monthly Manpower Report:
*FISManpowerLog2016-2018.xlsx*
This is an excel sheet that was generated using Procore’s daily reports that shows the monthly manpower on FIS. This data was used for the Earned Value Analysis.

Link to E-Files:
https://drive.google.com/open?id=1qpesew7amtqnE42KQq5LJg71ta8E82zK
Appendix B:

Interview Questions for Josiah Herber Project Manager of FIS for Shawmut Design and Construction

Currently we have a lot of information regarding the construction of FIS. Information such as meeting minutes, photographic documentation, monthly schedule reports, drawings/schematics, daily logs, and BIM models. For our project we are thinking on doing an analysis of the construction of the FIS. One of our ideas is to create a 4D BIM model of the project based on the planned pre-construction schedule and compare it to the actual construction. One other idea is to conduct a productivity analysis based on the subcontractor’s daily logs. We are not 100% on what our project will be yet so we want to ask you for some guidance.

Our MQP:

1. How can our project be of most value to SDC and WPI? Where will our efforts be most effective in being of value?
2. Can you provide some direction on what you think we can do for our project given the information we have?

Personal Experience With the Project:

3. How is this project different than most of the University buildings you have worked on?
4. What aspects of the design made your job easier?
5. What aspects of the design made your job tougher?
6. Did you have any problems with subcontractors and why?
7. What delays did you have, if any?
8. If you could change anything about this project, what would it have been?
Appendix C:

Questions for Construction Management/Facilities Interviewees

The following text was provided to the members of SDC and WPI at the beginning of their interviews:

We are an MQP group here at WPI analyzing the construction management of the Foisie Innovation Studio project. Our project is going to look into things such as the delays/difficulties with the project, technology in the construction management industry, and include a Capstone design section on the Green Roof. Also we are going to do a 4D/5D model of FIS with visuals of progress and cost estimates for every month of the project leading up to the closure of the exterior. We are conducting interviews to gain more knowledge on the project from a construction/financial/user viewpoint and from people who were involved. We believe this will give us a better understanding of the project and the construction management process. This interview should take approximately 25-30 minutes and please remember that if you would not like to answer a question at any time let us know. No names or identifying information will appear in any of the project reports or publications unless consent is given. Your participation is greatly appreciated.

1. Do you have any previous work experience with construction projects?
2. What was your involvement with FIS?
3. Have you ever been involved with a project like FIS?
4. What are your thoughts on FIS?
5. Is there anything our project could provide you with that would be beneficial?
6. Was WPI responsible for anything needed for FIS outside of Shawmut contract?
7. Since you’ve been here, have you witnessed any major delays or problems?
8. What do you think of technology in the construction industry?
9. Do you know anything about the Green Roof design that was added into the design?
10. What are your thoughts on conducting Overtime work to close the exterior before Winter?

11. Were you here for any value engineering decisions?

12. Do you have any recommendations for us?
Appendix D:

Eric Beattie Interview

VP for Campus Planning and Facilities
Location: 37 Lee St Worcester, MA 01609
Date: 10/2/2018

Do you have any previous work experience with construction projects?
- Started at WPI in January as the VP for campus planning and facilities management
- Has previously worked for Gilbane Construction
- Has previously held the title of director of planning and design at Syracuse University, University of Vermont, and Williams College.

What was your involvement with FIS?
- Started here in January after the building was closed, so handled a lot of the interior, however did not have to make any big decisions about FIS. The GMP was already set when he got here, however he does attend the weekly project meetings.

Have you ever been involved with a project like FIS?
- Never built a building with so much academic space combined with a residence hall

What are your thoughts on FIS?
- Unique building for the WPI campus
  - Tried to use Alumni Gym structure and renovate inside but too many problems would arise so decided best option was to knock the building down and add a residence hall on top of the academic space as a bonus
  - CFO loved this idea and was extremely interested in the multi-use facility because he saw that the “beds generate revenue”

Is there anything our project could provide you with that would be beneficial?
- Cannot think of anything he would need
- Shawmut is going much further with documentation for WPI than any project Eric has been on

Was WPI responsible for anything needed for FIS outside of Shawmut contract?
- Parts of building were subbed out by WPI
  - AV/IT (Telecommunications, security, etc.)
  - This is a common practice in most University projects

Since you’ve been here, have you witnessed any major delays or problems?
- No, there were no contractors that failed to perform, and the project was done on time
- Drawings were pretty good which meant there was no need for major design changes or excessive change orders

What do you think of technology in the construction industry?
- Agrees that the industry is way behind as far as technology
- Think prefabricated construction will start to get big in the industry because of the time it saves however the industry is still evolving

**Do you know anything about the Green Roof design that was added into the design?**
- Yes, green roof design was added in the structural integrity of the low roof, however it is not actually a green roof yet, was done for future purposes
- Eric likes our ideas for the Capstone design and recommended looking into the economic benefit of having a green roof

**What are your thoughts on conducting Overtime work to close the exterior before Winter?**
- Thought it was a good idea
- Eric’s theory on Overtime work: You get a much bigger benefit from doing OT earlier on in the project rather than later
  - If you know you will need OT on the project, why not do it early?

**Were you here for any value engineering decisions?**
- Was not here for any major decisions
- There was an addition to the scope to add landscaping over towards the Rec Center and to add pavers connecting Foisie all the way to the fountain

**Do you have any recommendations for us?**
- Recommends for us to investigate the chilled water system on top of Foisie that will eventually feed four buildings
- Talk to Jeff Lussier and Dan Sullivan of KVA
- Try and meet with Sean O’Connor of the IT department but it is hard to find him with any free time
Appendix E: Interview With Phillip Clay

Phillip Clay: Student Affairs
Location: Rubin Campus Center: Room 227
Date: 10/10/2018

What are your thoughts on the brand new Foisie Innovation Studios?
- 1st building on campus that combines learning space and residence
- The labs are great because they are not major specific, intended for everyone
- The spaces are being used by the students like WPI thought

Were there any major issues with the design or specifications?
- Not to his knowledge
  o Didn’t become involved until the residence halls were being built because he is affiliated with student affairs
    § Was part on project teams for east hall, faraday, and campus center
    § Working at WPI since 1993
- The architects met with individual major department leaders and asked them what would make a good space for their major
- Active Learning’
  o The faculty that use active learning for teaching were consulted
    § Asked what they would want different from the current retrofitted classrooms they were in
- Site visits were completed to other schools in the area trying to look at what they had in their makerspaces and innovation studio type buildings

What were the major challenges when trying to design and construct the building?
- The project was originally going to be a renovation of Alumni Gym
  o Unfortunately, there was no infrastructure for labs because it was constructed as a gym
  o A new building would cost around the same as a renovation would – project evolved over time
- Many people that were here at the beginning of the project to make key decisions about FIS had left during the project and new associates did not always agree with the prior’s decisions

Over your professional career, how has technology in construction changed?
- More deliverable now because of technology
- BIM
- Back around 2000, tech was very limited
- FIS Specific
  o The Oculus
    §§ New to project
    §§ Could show students a virtual reality view of their new rooms in the residence hall
    §§ The 3D camera goes through the whole building and the floor plan is laid over it.
    §§ They also did this twice with the exterior, once when it was to be finished and again when it finished
    §§ Phillip never saw anything like it, “It was awesome”
Any documentation that while working with the residence halls would be useful?
- Doesn’t get involved in any documentation or closeout documents. Involved in design ideas and changes. Speaks on behalf of WPI and what the students would want in the living space and building
- WPI tries to get the facilities workers involved with decisions regarding documentation because they will be the ones taking care of the building and using the documentation

What are your thoughts about the Green Roof on East Hall?
- All buildings on campus ever since the Bartlett Center must be built LEED certified
  - WPI saw potential to get more LEED points
    § Must make decision on steel very early in the process, if they had said no initially then the Green Roof would not have been built
- Nobody can see the Green Roof, only from the library
  - The FIS proposed green roof could only be seen by the students of its residence hall and Higgins laboratories
- Deploying crews to go take care of the Green Roof cost money
  - Cost/Benefit analysis came back negative

Thoughts about accelerated schedule used when closing the exterior of FIS?
- They went 7 days week
- Brought in trades on the weekend that were falling behind to catch up for the next work week
- It was a very significant decision
  - Once the building was closed there would be no more weather-related delays
  - The exterior cannot be completed when it is snowing so it was essential to speed the process up

Any Value Engineering?
- Not that comes to mind
Appendix F: Structural Steel and Cost Calculations

LRFD Approach
Typical Beam: W14x48
Typical Girder: W36x798

ASD Approach
Typical Beam: W14x30
Typical Girder: W33x354
**Typical I Beam**

**Dead Load**
- Try W14x34
  - I = 340 in^4
  - Z = 54 in
  - E = 29,000 ksf
- Self-weight: 34 psf
- \( D = \frac{W_{D}}{I} \)
- \( D = (40 \times 34) \text{ psf} \times (8.33 \text{ ft}) \)
  - \( D = 1016.42 \text{ lb/ft} \)

**Live Load**
- \( L_{ass} = D \text{ psf} \)

**Snow Loads**
- \( SL = 0.1 \text{ CeC}_{1\text{a}} SL_{b} \)
  - \( = 0.1(1.1)(1.1)(55 \text{ psf}) \)
- \( SL = 42.35 \text{ psf} \)
- \( S = \frac{W_{L}T_{w}}{L} \)
  - \( S = 42.35 \text{ psf} \times (8.33 \text{ ft}) \)
  - \( S = 352.78 \text{ lb/ft} \)

**Wind Loads**
- \( WL = 25 \text{ psf} \)
- \( W = \frac{W_{L}T_{w}}{L} \)
  - \( W = 25 \text{ psf} \times (8.33 \text{ psf}) \)
  - \( W = 208.25 \text{ lb/ft} \)
Load Combinations - ASD: ASCE 7-10

\[ W_0 = D + 0.75L + 0.75(g \cdot w) + 0.75S \]

\[ W_0 = 6(14.92 \text{ kips}) + 0.75(0.75(208.25 \text{ kips})) + 0.75(352.78 \text{ kips}) \]

\[ W_0 = 974.7 \text{ kips} \]

Design Moment

\[ M_0 = \frac{W_0 L^2}{8} = \frac{974.7(25) \text{ kips} \cdot \text{ft}}{8(1000 \text{ kips}/\text{ft})} \]

\[ M_0 = 43.7 \text{ kips} \cdot \text{ft} \]

Deflection

\[ \Delta = \frac{5W_0 L^4}{384EI} = \frac{5(974.7) \cdot 25^4}{384 \cdot 29,000 \cdot 12} \cdot \left(\frac{14}{12} \frac{\text{in}}{\text{ft}}\right) \]

\[ \Delta = 0.356 \text{ in} \leq 0.375 \text{ in} \]

Required E

\[ 2x > \frac{M_0}{F_y} \]

\[ 54.6 > 43.7 \text{ kips} \cdot \text{ft} \cdot 12 \left(\frac{\text{in}}{\text{ft}}\right) \cdot 0.9 \left(\frac{\text{ksi}}{\text{in}}\right) \]

\[ 54.6 > 54.4 \text{ ksi} \geq 12.99 \text{ in}^3 \]

Web Load Buckling

\[ \frac{bh^2}{2t_f} \leq 0.38 \sqrt{F_y} \]

\[ 7.4 \leq 9.2 \]


Flange-Load Buckling

\[ \frac{h}{t} \leq 3.70 \sqrt{\frac{E}{F_{y}}} \]

\[ 43.1 \leq 90.5 \checkmark \]

Plastic Capacity

\[ \phi M_p = \phi Z \cdot F_y = \frac{9 \left(54.6 \text{ in}^3 \times 50 \text{ ksf} \right)}{12 \text{ in} \cdot A} \]

\[ \phi M_p = 271.5 \text{ kip} \cdot \text{ft} \]

\[ \phi M_p > M_0 \\
271.5 > 48.7 \checkmark \]

\[ \therefore \text{ A W14x34 beam will suffice.} \]
**Typical I Girders**

**Distributed Load**

\[
\text{Distributed Load (lb/ft)} = \frac{\text{Avg. span load (lb/ft)} \times \text{Tributary width (ft)}}{\text{Tributary width of adjacent beam (ft)}}
\]

\[
= \frac{34 \text{ lb/ft} \times (20 \text{ ft})}{8.33 \text{ ft}}
\]

\[
\text{Distributed Load} = 81.6 \text{ lb/ft}
\]

**Dead Loads**

**Allowances:** 40 psf

**Self-weight:** 71 psf

**Distributed Load:** 81.6 lb/ft

\[
D = W_{dl}(tw) + D.L.
\]

\[
= (40 \times 71) \text{ psf}(20 \text{ ft}) + 81.6 \text{ lb/ft}
\]

\[
D = 2301.6 \text{ lb/ft}
\]

**Live Loads**

\[
L = 0
\]

**Snow Loads**

\[
SL = 0.7 \cdot C_{o} \cdot C_{s} \cdot S_{Lg}
\]

\[
= 0.7 \times (1.1)(1)(55 \text{ psf})
\]

\[
SL = 42.35 \text{ psf}
\]

\[
S = 42.35 \text{ psf}(20 \text{ ft})
\]

\[
S = 847.1 \text{ lb/ft}
\]
Wind Load

\[ W_L = 25 \text{ psf} \]
\[ w = 25 \text{ psf} \times (20 \text{ ft}) \]
\[ w = 500 \text{ lb/ft} \]

Load Combinations - ASD, ASCE 7-10

\[ D \times 0.75 \times L \times 0.75(w_L + w + w_e) \times 1.0 \]
\[ w = 230 \text{ lb/ft} \times 0.75(6) + 0.75(4 \times 500) + 0.75(847 \text{ lb/ft}) \]
\[ w_0 = 3161.85 \text{ lb/ft} \]

Design Moment

\[ M_0 = \frac{w_0 L^2}{8} = \frac{3161.85 \text{ lb/ft} \times (20 \text{ ft})^2}{8 (1000 \text{ lb}) \times \text{in}} \]
\[ M_0 = 430.4 \text{ kip-ft} \]

Deflection

\[ \Delta = \frac{5 \times w_0 L^4}{384 \times E} = \frac{5 \times 3161.85 \text{ lb/ft} \times (33 \times 12 \text{ in})^4 \times (1 \text{ in}^6)}{384 \times (29000 \text{ lbs}) \times (1170,000 \text{ psi})} \]
\[ \Delta = 2.5'' \leq 0.375 \times X \]
\[ \therefore \text{ This girdler size fails in deflection.} \]

Try \[ W33 = 354 \]
Try W33 x 354

Try W33 x 354
$I = 21400 \text{ in}^4$
$E_a = 1420 \text{ in}^3$
$E = 29000 \text{ lb}$

$T_w = 20 \text{ ft}$
$L = 33 \text{ ft}$

**Distributed Load of Beams**

$DL = 81.4 \text{ lb/ft}$

**Dead Load**

Allowances: 40 psf
Self-weight: 354 psf
Distributed Load: 81.4 lb/ft

$D = W_6 T_w + DL$
$= (40 \cdot 354 \text{ psf})(20 \text{ ft}) + 81.4 \text{ lb/ft}$
$D = 7941.8 \text{ lb/ft}$

**Live Load**

$L = 0$

**Snow Loads**

$s = 847.1 \text{ lb/ft}$

**Wind Loads**

$W = 500 \text{ lb/ft}$

**Load Combinations**

ASCE 7-10, ASD

$W_0 = D + .75L + .75(0)W + .75S$

$W_0 = 7941.8 \text{ lb/ft} + .75(0) + .75 (.6)(500 \text{ lb/ft}) + .75(847.1 \text{ lb/ft})$

$W_0 = 8821.9 \text{ lb/ft}$
Design Moment

\[ M_u = \frac{W_1 L^2}{8} = \frac{8821.9 \text{ lb} \cdot \text{ft} \cdot (3.8)}{8 \times 1000 \text{ lb/ft}} \]
\[ M_u = 1200.9 \text{ kips} \cdot \text{ft} \]

Deflection

\[ \Delta = \frac{5 W_2 L^4}{384 E I} \]
\[ = \frac{5 \times 8821.9 \text{ lb} \cdot \text{ft} \cdot (33 \text{ ft} \cdot 12 \text{ in})^3}{384 \times 29000 \text{ kips} \cdot \text{in}} \times \frac{1 \text{ in}^3}{3 \times 1000 \text{ in}^4} \]
\[ \Delta = 0.371 \text{ in} \leq 0.375 \text{ in} \]

Required \( z_n \)

\[ z_n \geq \frac{M_u}{F_y} \]
\[ 1420 \text{ in}^3 \geq \frac{1200.9 \text{ kips} \cdot \text{ft} \cdot (12 \text{ in})}{0.9 \times 50 \text{ ksi}} \]
\[ 1420 \geq 320.2 \text{ in}^3 \]

Web Load Buckling

\[ \frac{b_f}{2 t_f} \leq 0.3 \left( \frac{E}{F_y} \right)^{\frac{1}{2}} \]
\[ 3.8 \leq 9.2 \text{ in} \]

Flange Load Buckling

\[ \frac{h}{t_w} \leq 3.16 \left( \frac{E}{F_y} \right)^{\frac{1}{2}} \]
\[ 25.8 \leq 90.5 \text{ in} \]
<table>
<thead>
<tr>
<th>Typical I Girders</th>
<th>W32 x 354</th>
<th>ASD</th>
<th>5.45</th>
</tr>
</thead>
</table>

**Plastic Capacity**

\[ \phi M_p = \phi z \cdot F_y = \frac{0.9 \cdot (1420 \text{ in}^2)(50 \text{ ksi})}{12 \text{ in} / \text{ ft}} \]

\[ \phi M_p = 5325 \text{ kips} \]

\[ \phi M_p > M_u \]

\[ 5325 > 1200 \text{ kips} \]

\[ \therefore \text{ A W32 x 354 girdor will suffice} \]
Typical I Beam Calculations

Load
Try W14 x 48 \( L = 20' \) \( T_w = 8.4'' \)

DL
Allowance 40 psf
Self-weight 98 psf

\[ D = \frac{W_{DL} T_w}{(40 + 98) S L_y (8.39 \text{ ft})} \]

\[ D = 738.09 \text{ lb/ft} \]

LL

\[ LL = W_{LL} T_w = 0 \text{ psf} (8.39 \text{ ft}) \]

\[ LL = 0 \text{ lb/ft} \]

SL

\[ SL = 0.7 \cdot C_{C_y} E_s S_{L_y} \quad \text{(Eq. 7.3 ASCE)} \]

\[ SL_y = 55 \text{ psf} \]

\[ SC = 0.7 (1.14/1)(55 \text{ psf}) \]

\[ SL = 42.35 \text{ psf} \]

\[ S = 42.35 \text{ psf} (8.33 \text{ ft}) \]

\[ S = 352.8 \text{ lb/ft} \]

WL

\[ WL = 25 \text{ psf} \]

\[ wL = 25 \text{ psf} (8.33 \text{ ft}) \]

\[ wL = 208.25 \text{ lb/ft} \]

Load Combinations - ASCE 7-05

1. \( 14D = 14(733.04 \text{ in}) = 10263 \text{ lb/ft} \)

2. \( 1.2D + 1.6L + .5S = 1.2(733.04) + .6(0) + .5(352.8) \)

\[ W = 1056.2 \text{ lb/ft} \]

3. \( 1.2D + 1.6W + 1L + .5S = 1.2(733.04) + 1.6(208.25) + 0 + .5(352.8) \)

\[ W = 1387.2 \text{ lb/ft} \]
Design Moment

\[ Mu = \frac{Wu^2}{8} = \frac{138.70 \times 44^2}{8} = 69.5 \text{ kip-ft} \]

Required \( z \): \( 2. > \frac{Mu}{F_y} = \frac{69.5 \text{ kip-ft}}{50000} = 78.5 \text{ in}^3 \)

2. For W14 x 98: 78.4 in. > 78.5 in.3

Web-Flange Bending

\[ \frac{h}{2t_a} \leq 38 \sqrt{\frac{F_y}{E}} \]
\[ 6.7 \leq 9.2 \]

Flange Thickness

\[ \frac{h}{4} \leq 370 \sqrt{\frac{F_y}{E}} \]
\[ 33.5 \leq 90.5 \]

Deflection

\[ \Delta_{pl} = 5 \frac{Wu l^4}{384 EI} = 5 \left( 10^{-6} \right) \frac{(20 \times 12)^4}{384 \times 290000 \times 8814} \]
\[ \Delta_{pl} = 0.38^6 \]

\[ \Delta_{tot} = 0.27 \leq 0.38^6 \]

Plastic Capacity

\[ \Phi M_p = \Phi 2 x F_y = 0.9 \left( 78.4 \text{ in}^3 \right) \left( 50000 \right) \left( \frac{1 \text{ ft}}{12 \text{ in}} \right) \]
\[ \Phi M_p = 294 \text{ kip-ft} \]
\[ \Phi M_p > Mu \]
\[ 294 > 69.5 \]

\[ . A \text{ W14 x 98 beam will be sufficient} \]
Typical I Girders

Try: W36 x 798

Tw: 20 ft
L: 33 ft

Distributed Load

Distributed Load = \frac{\text{Any Nominal Weight (lb/ft)} \cdot \text{Trallong Width of adjacent beam (ft)}}{\text{Tributary width of adjacent beam (ft)}}

DL = \frac{48 \text{ lb/ft} \cdot (20 \text{ ft})}{8.33 (\text{ft})}

DL = 115.2 \text{ lb/ft}

Dead Load

Allowance: 40 psf
Self-weight: 798 psf
Distributed Load: 115.2 lb/ft

D = \text{Wt. of } + \text{DL}

= (40 - 798) \text{ psf} \cdot (20 \text{ ft}) + 115.2 \text{ lb/ft}

D = 16875.2 \text{ lb/ft}

Live Load:
L = 0

Snow Load:

SL = \text{MCe} + \text{IE} \cdot \text{SLg}

= 7(11)(20)(55 \text{ psf})

SL = 42.35 \text{ psf}

S = 42.35 \text{ psf} \cdot (20 \text{ ft})

S = 847 \text{ lb/ft}

Wind Load:

WL = 25 \text{ psf}

W = 25 \text{ psf} \cdot (20 \text{ ft})

W = 500 \text{ lb/ft}
Load Combinations - LRFD, NCEA 7-05

1. 1.4D = 1.4(168752 lb/ft)

\[
W_0 = \frac{23425.3 \text{ lb/ft}}{12(168752 \text{ lb/ft}) - 76(0.8) + 0.5(24.7 \text{ lb/ft})}
\]

= 20473.74 lb/ft

2. 1.2D + 1.6L + 0.5S = 1.2(168752 lb/ft) + 0.6(50 lb/ft) + 0.5(847 lb/ft)

= 20473.71 lb/ft

Design Moment

\[
M_0 = \frac{W_0 L^2}{8} = \frac{23425.3 \text{ lb/ft}(32^2 \text{ ft})}{8(1000 \text{ kips})}
\]

\[
M_0 = 32380.12 \text{ kips-ft}
\]

Deflection

\[
\Delta = \frac{5WL^4}{384EI} = \frac{5(23425.3 \text{ lb/ft})(32^4 \text{ ft}^4)(1000 \text{ kips})}{384 \times (29002800)(1200 \text{ in}^3)}
\]

\[
\Delta = 0.16 \text{ in} \leq 0.375 \text{ in}
\]

Required \(E_x\)

\[
E_x > \frac{M_0}{\phi_k}
\]

1840 in^3 > \frac{32380.12 \text{ kips-ft}(12 \text{ in}^2)}{1.0 \times (50 \text{ kips})}

1840 in^3 > 874.8 \text{ in}^3

Web-Load Buckling

\[
\frac{d_0}{d_e} \leq \frac{0.81}{k_1}
\]

\[
2.1 \leq 9.2
\]
Typical I Girder

**Flange-Load Buckling**

\[
\frac{h}{tw} \leq 3.76 \sqrt{\frac{E}{F_y}}
\]

13.2 ≤ 90.5 \checkmark

**Plastic Capacity**

\[
\Phi M_p = \Phi Z x F_y = \frac{9}{12} \left(19.6 \times 10^3 \right) \left(50 \text{ kips} \right)
\]

\[
\Phi M_p = 16975 \checkmark
\]

\[
\Phi M_p > M_o
\]

16975 > 3280.60 \checkmark

\therefore A W36 x 798 girder will suffice
<table>
<thead>
<tr>
<th>ASD</th>
<th>Beams - Girders</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W14 x 3 1/4</td>
<td>52 beams @ 20'</td>
</tr>
<tr>
<td>Total Length:</td>
<td>13 beams @ 10'</td>
<td></td>
</tr>
<tr>
<td>TL = 52(20 ft) + 13(10 ft)</td>
<td>TL = 1170 ft</td>
<td></td>
</tr>
<tr>
<td>Total Weight:</td>
<td>Typical I Beam = 34 lb/ft</td>
<td></td>
</tr>
<tr>
<td>W = 1170 ft(34 lb/ft)</td>
<td>W = 39,780 lbs = 19.89 tons</td>
<td></td>
</tr>
<tr>
<td>Girders</td>
<td>Total Length:</td>
<td>15 girders @ 33 ft W33 x 3 1/4</td>
</tr>
<tr>
<td>TL = 15(33 ft)</td>
<td>TL = 495 ft</td>
<td></td>
</tr>
<tr>
<td>Total Weight:</td>
<td>Typical I Girders = 354 lb/ft</td>
<td></td>
</tr>
<tr>
<td>W = 495 ft(354 lb/ft)</td>
<td>W = 175,280 lbs = 87.6 tons</td>
<td></td>
</tr>
</tbody>
</table>

**Structure Weight**

\[ W_{beams} + W_{girders} = 215,010 \text{ lbs} = 107.5 \text{ tons} \]
<table>
<thead>
<tr>
<th><strong>LRFD</strong></th>
<th><strong>Beans: Girders</strong></th>
<th><strong>Total Weight</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams: 6⅝ x 9⅛</td>
<td>52 beams @ 20 ft</td>
<td><strong>Total Length</strong></td>
</tr>
<tr>
<td></td>
<td>13 beams @ 10 ft</td>
<td>TL = 52(20 ft) + 13(10 ft)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>TL = 1170 ft</strong></td>
</tr>
<tr>
<td>Girders: 6⅝ x 7⅞</td>
<td></td>
<td><strong>Total Weight</strong></td>
</tr>
<tr>
<td>Total Length</td>
<td>15 girders @ 33 ft</td>
<td><strong>Typical I Beam = 498 lb/ft</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TL = 15(33 ft)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>TL = 495 ft</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Total Weight</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Typical I Girders = 798 lb/ft</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tw = 495 ft(798 lb/ft)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Tw = 395,010 lbs = 197.5 tons</strong></td>
</tr>
<tr>
<td>Structure Weight</td>
<td></td>
<td><strong>Total Beams &amp; Girders</strong> = 451,170 lbs = 225.6 tons</td>
</tr>
</tbody>
</table>
Cost: LRFD Approach

\[
\text{Cost} (\$/\text{sf}) = \left( \frac{\text{Beam weight (lb/ft)}}{\text{Beam spacing (ft)}} \right) \times 3000 \text{ \$/ton} + \left( \frac{\text{Girder weight (lb/ft)}}{\text{Girder spacing (ft)}} \right) \times 3500 \text{ \$/ton}
\]

\[
\text{Cost} = \frac{0.024 \text{ ton/ft}}{8.33 \text{ ft}} \times 3000 \text{ \$/ton} + \frac{0.399 \text{ ton/ft}}{20 \text{ ft}} \times 3500 \text{ \$/ton}
\]

\[
\text{Cost} (\$/\text{sf}) = 0.099 \text{ \$/sf}
\]

\[
\text{Area} = 99 \text{ ft} \times 10 \text{ ft} = 990 \text{ sf}
\]

\[
\text{Cost} (\$) = 990 \text{ sf} \times 0.099 \text{ \$/sf} = \$98.91
\]

Cost: ASD Approach

\[
\text{Cost} (\$/\text{sf}) = \left( \frac{\text{Beam weight (lb/ft)}}{\text{Beam spacing (ft)}} \right) \times 3500 \text{ \$/ton} + \left( \frac{\text{Girder weight (lb/ft)}}{\text{Girder spacing (ft)}} \right) \times 3500 \text{ \$/ton}
\]

\[
\text{Cost} (\$/\text{sf}) = \frac{0.017 \text{ ton/ft}}{8.33 \text{ ft}} \times 3500 \text{ \$/ton} + \frac{0.177 \text{ ton/ft}}{20 \text{ ft}} \times 3500 \text{ \$/ton}
\]

\[
\text{Cost} (\$/\text{sf}) = 0.58 \text{ \$/sf}
\]

\[
\text{Area} = 9910 \text{ sf}
\]

\[
\text{Cost} (\$) = 9910 \text{ sf} \times 0.58 \text{ \$/sf} = \$5771.80
\]
Beams
W14 x 34

The new dead load will include 85 psf for the green roof. All other loads remain the same.

**Dead Load**
- Allowance: 40 psf
- Self-weight: 34 psf
- Green roof: 85 psf

\[
D = w_1 + w_2 = (40 + 34 + 85) \text{psf} \times (8.334) \\
D = 1224.47 \text{lb/ft}
\]

**Live Load**
- \( L = 0 \)

**Snow Load**
- \( 352.78 \text{lb/ft} \)

**Wind Load**
- \( w_w = 208.25 \text{lb/ft} \)

**Load Combination**

\[
w_f D = 0.75 L + 0.75(w_1) + 0.75(w_2) \\
w_f = 0.75(352.78) + 0.75(1224.47) + 0.75(208.25) + 0.75(352.78) \\
w_f = 1682.76 \text{ lb/ft}
\]

**Design Moment**

\[
M_o = \frac{w_f L^2}{8} = \frac{1682.76 \times (20^2)}{8(1000 \text{ lb/ft})} = 84.14 \text{ kips-ft}
\]
Required $Z_v$

$$Z_v > \frac{Mu}{\phi F_y} = \frac{84.14}{0.9(50)}$$
$$54.6 > 22.44\, \text{N}$$

Web Local Buckling

$$\frac{bh}{2t_e} \leq 9.2$$
$$7.4 \leq 9.2$$

Flange Local Buckling

$$\frac{h}{t_w} \leq 90.5$$
$$43.1 \leq 90.5$$

Plastic Capacity

$$\phi M_p = 0.86 F_y = \frac{9(54.6)(50)}{12.16/4}$$
$$\phi M_p = 271.5 > 84.14$$

Deflection

$$\Delta = \frac{SW_{sl}L^4}{384EI} = \frac{5(1882.76 \times 12^4/\text{ft}) \times (\frac{1872}{102015}) \times 12^3/12^2}{384 \times (29000) \times (3300 \times 10^{-6})}$$
$$\Delta = 0.01\, \text{in}$$

Width $= 375\, \text{in} \times F_e / 15$

I must be increased to pass the deflection criteria

$$I = 375 = \frac{5(1882.76) \times (20.12 \times 4) \times (1/12)}{384(29000)} \Rightarrow I = 560\, \text{in}^4$$
Calculator for Moment of Inertia of H or I section

This calculator gives the values of moment of inertia as well as maximum and minimum values of section modulus about x-axis and y-axis of the section. It will help in deciding whether the failure will be on the compression face or on the tension face of the beam. Please enter the "Input Values" in the form given below and click "Calculate". You should enter all the values in same units and this calculator will provide the "Output Results" in the corresponding units (unit^2, unit^3, unit^4 etc.). You can also visit Instructions for Moment of Inertia Calculator.

**Input Values**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Flange width - bf1 (unit)</td>
<td>6.73</td>
</tr>
<tr>
<td>Top Flange thickness - hf1 (unit)</td>
<td>3.85</td>
</tr>
<tr>
<td>Bottom Flange width - bf2 (unit)</td>
<td>6.73</td>
</tr>
<tr>
<td>Bottom Flange thickness - hf2 (unit)</td>
<td>1.9</td>
</tr>
<tr>
<td>Web Thickness - tw (unit)</td>
<td>0.27</td>
</tr>
<tr>
<td>Web height - hw (unit)</td>
<td>13.07</td>
</tr>
</tbody>
</table>

Please make sure that the input values are positive

**Output Results**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of section (unit^2)</td>
<td>18.90695</td>
</tr>
<tr>
<td>Position of centroid - Xc (unit)</td>
<td>3.365</td>
</tr>
<tr>
<td>Position of centroid - Yc (unit)</td>
<td>4.294754951</td>
</tr>
<tr>
<td>Moment of Inertia Ix (unit^4)</td>
<td>563.681175</td>
</tr>
<tr>
<td>Moment of Inertia Iy (unit^4)</td>
<td>58.0547813</td>
</tr>
<tr>
<td>Max. Section Modulus Zxx (unit^3)</td>
<td>131.248666</td>
</tr>
<tr>
<td>Min. Section Modulus Zxx (unit^3)</td>
<td>50.95468806</td>
</tr>
<tr>
<td>Section Modulus Zyy (unit^3)</td>
<td>17.25541698</td>
</tr>
<tr>
<td>Radius of gyration rxx (unit)</td>
<td>5.460170906</td>
</tr>
<tr>
<td>Radius of gyration ryy (unit)</td>
<td>1.752445520</td>
</tr>
</tbody>
</table>
Design of Green Roof

Girders - W33x354

Dead Load

40°F
Self-weight: 354 psf
Green Roof: 85 psf
Distributed Load: 81.6 lb/ft

\[ D = Wd + Tw + DL = (40, 354, 85) \text{ psf}(20\text{ ft}) + 81.6 \text{ lb/ft} \]

[\boxed{D = 9461.4 \text{ lb/ft}}]

Live Load

[\boxed{L = 0}]}

Snow Load

\[ S = 8471 \text{ lb/ft} \]

Wind Load

\[ W = 500 \text{ lb/ft} \]

Load Combinations

\[ W_o = D + 1.75L + 1.65(S - 75) + 1.75(S - 75) + 1.75(S - 75) \]

\[ W_o = 10521.85 \text{ lb/ft} \]

Design Moment

\[ M_o = W_o \frac{L}{2} = 10571.85 \frac{(20\text{ ft})}{81 \text{ 000 kips/ft}} \]

\[ M_o = 1432.3 \text{ kips ft} \]

Required Z

\[ Z_x > \frac{M_o}{F_y} = \frac{1432.3}{1.9(50)} \]

\[ 1420 > 381.9 \]
Web-Local Buckling
\[
\frac{bc}{2t} \leq 9.2
\]
\[3.8 \leq 9.2\sqrt{v}\]

Flange-Local Buckling
\[
\frac{h}{tw} \leq 90.5
\]
\[25.3 \leq 90.5\sqrt{v}\]

Plastic Capacity
\[
\Phi M_p = \Phi Z_x F_y = \frac{.9(1420)(50)}{12''/ft}
\]
\[
\Phi M_p = 5325 \text{ kip-ft}
\]
\[
\Phi M_p > M_U
\]
\[5325 > 1432\]

Deflection
\[
\Delta = \frac{5wL^4}{384EI} = \frac{5(10521.85)(33.12)^4(1/1000)(1/12)}{384(29000)(21000)}
\]
\[
\Delta = 0.44'\text{ in}
\]
\[0.44'\text{ in} < 0.375'\text{ in} \times \text{Fails}
\]

I must be increased to pass the deflection criteria.
\[
0.375'\text{ in} = \frac{5(10521.85)(33.12)^4(1/1000)(1/12)}{384(29000)I}
\]
\[
I = 25900 \text{ in}^4
\]
Calculator for Moment of Inertia of H or I section

This calculator gives the values of moment of inertia as well as maximum and minimum values of section modulus about x-axis and y-axis of the section. It will help in deciding whether the failure will be on the compression face or on the tension face of the beam. Please enter the "Input Values" in the form given below and click "Calculate". You should enter all the values in same units and this calculator will provide the "Output Results" in the corresponding units (unit^2, unit^3, unit^4 etc.). You can also visit Instructions for Moment of Inertia Calculator.

<table>
<thead>
<tr>
<th>Input Values</th>
<th>Output Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Flange width - bf1 (unit): 16.125</td>
<td>Area of section (unit^2): 118.890625</td>
</tr>
<tr>
<td>Top Flange thickness - hf1 (unit): 2.0625</td>
<td>Position of centroid - Xc (unit): 8.0625</td>
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<td>Moment of Inertia bx (unit^4): 26052.98546</td>
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<td>Moment of Inertia Iyy (unit^4): 1773.195506</td>
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<td>Web height - hw (unit): 31.375</td>
<td>Max. Section Modulus Zxx (unit^3): 1591.415766</td>
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Please make sure that the input values are positive.

[Reset, Calculate]
Material Costs

Data from RS Means (2011):

- For 1" thick plate: $40.83/sq.-ft. (girders)
- For 1.5" thick plate: $71.85/sq.-ft. (beams)

Beams: 52 beams @ 20' wide of wood: 13 beams @ 10'
width of wood = 6.75 in = .5625 sq. ft
Total area of plates (beams)

\[(52 \text{ beams})(20')(.5625') + (13 \text{ beams})(10')(.5625') = 658.125 \text{ sq. ft}\]

\[
\text{Material Cost} \quad (\text{beams}) = \$45410
\]

Girders: 15 girders @ 33 ft
width of wood 36 x 7/8" = 7.5" = 0.625 sq. ft
Total area of plates (girders)

\[(15 \text{ girders})(33')(0.625') = 643.5 \text{ sq. ft}\]

\[
\text{Material Cost} \quad (\text{girders}) = \$29601
\]

Total Material Cost = $75011
Labor Costs

Data from RS Means (2011)

$14.20 per linear foot (1/8" fillet weld)

Total length of beams and girders

(52 beams) (20') + (15 beams) (10') + (15 girders) (33')

Total Length = 1065 ft

Total Cost = 1065 ft ($14.20/ft) (2 sides)

Total Cost (Labor) = $4728.0

Total Cost = $4728.0 + $750.1

Total Cost = $5478.1 (Time & Material)

Total Cost = $12229.7

At 3% interest, $12229.7 will become

$263,744 in 2037
Appendix G: Sketchup Methodology

Importing Revit Files to Sketchup
- In the revit model click File>Export as a .DWG file to be compatible with sketchup. The user can export the revit file in any view because revit will export the whole model.
- In sketchup click File>Import to import the .DWG file.
- When importing the 3D revit model the user must place the model manually on the site. If the model automatically placed somewhere in space the user must move the model to the desired location on the topographical terrain (see below).

Creating the Site Model
- To create a topographical terrain in sketchup click File>Geolocation>Add Imagery and then input an address/location of the site.
- Crop the desired region to be used in the model.

Integrating Project’s Schedule to the 3D Model
- Sketchup’s scenes tool is used to create the 4D model. With the scenes tool the user is able to save different views of the model. By having each scene represent a certain month in the projects duration the user can show what the project should look like at the start of each month. To do this the user must hide certain elements to show only work completed for each month.
- To create a scene click Window>Scenes. For this project I have scenes going from November 2016 to November 2017.
- Since Nov 2017 was the planned month for completion I did not have to hide anything for the scene.
- I went backwards through the months and hide certain elements based on the planned schedule of construction.
- To hide an element right-click on the object desired to be hidden and click hide. Then save the view by right-clicking on the scene’s tab and clicking “update scene”.
- I did this for each month until each scene had an accurate representation of the work completed for each month.
- The user is now able to click through the scenes to see the project coming together overtime.

Changing Materials
- To change the materials of objects first open up the materials window by clicking Window>Materials.
- From here there is a list of many materials such as brick, glass, metals, etc. to be used.
- After choosing the desired material click on the object to apply the material.
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Record of Climatological Observations

Recorded on 10/10/2018
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<th>Date</th>
<th>Max (°C)</th>
<th>Min (°C)</th>
<th>Max (°F)</th>
<th>Min (°F)</th>
<th>Snow (in)</th>
<th>Rain (in)</th>
<th>How Many billed for 4 hour period</th>
<th>Total</th>
<th>Snow Fall (in)</th>
<th>Rain Fall (in)</th>
<th>Temp. Change (°F)</th>
<th>Humidity (%)</th>
<th>Wind Speed (mph)</th>
<th>Wind Direction</th>
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<tbody>
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<td>Date</td>
<td>Min (°F)</td>
<td>Max (°F)</td>
<td>Rainfall (in)</td>
<td>Snowfall (in)</td>
<td>Temp (°F)</td>
<td>Humidity</td>
<td>Pressure (in Hg)</td>
<td>Wind Speed (MPH)</td>
<td>Wind Direction</td>
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This is an example of a weather observation record.
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<th>Date</th>
<th>Max Temperature (°F)</th>
<th>Min Temperature (°F)</th>
<th>Rainfall (in)</th>
<th>Snowfall (in)</th>
<th>Wind (mph)</th>
<th>Visibility (mi)</th>
<th>Humidity (%)</th>
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*Note: Data is subject to change and may not be definitive.
<table>
<thead>
<tr>
<th>Date</th>
<th>Station</th>
<th>Total Precipitation (in)</th>
<th>24 Hour Accumulation (in)</th>
<th>12 Hour Accumulation (in)</th>
<th>6 Hour Accumulation (in)</th>
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