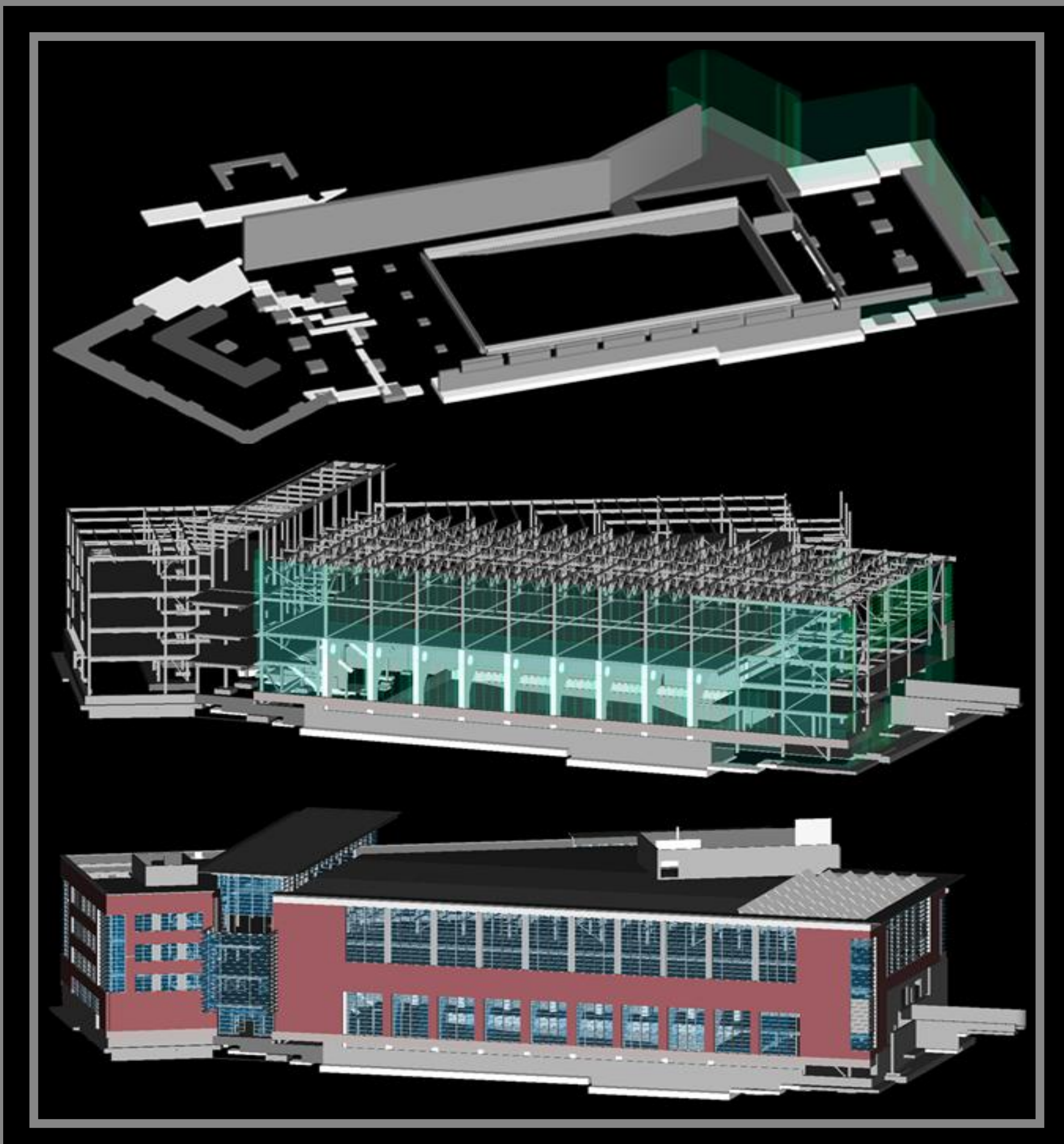
WPI Sports & Recreation Center

Construction Management through 5D Building Information Modeling with Alternative Design Considerations



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WPI

WPI Recreation Center:
Construction Management through Five-Dimensional Building Information Modeling with Alternative Design Considerations

A Major Qualifying Project Report
Submitted to the faculty of Worcester Polytechnic Institute
In partial fulfillment of the requirements for the
Degree of Bachelor of Science

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Sponsoring Agencies:
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Cannon Design
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Submitted To:
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ABSTRACT

This project utilized Building Information Modeling to produce a 5-dimensional model of the WPI Sports and Recreation Center. The model was used to perform a construction schedule performance analysis of major work packages. In addition, alternative analysis and design was performed on the structural, geotechnical and functional aspects of the connection between Harrington Auditorium and the Recreation Center.

CAPSTONE DESIGN STATEMENT

The design capstone requirement of this Major Qualifying Project was met through the exploration of structural, geotechnical and functional design aspects related to the physical connection of the new Sports & Recreation Center and Harrington Auditorium buildings at the WPI campus. We also used Building Information Modeling methods and to review the design constructability of the new Recreation Center and developed a 5D model of for the foundation, structure and façade.

The new Recreation Center is being constructed in close proximity to the pre-existing Harrington Auditorium, therefore there were inherent design considerations relating to this relationship during the design phase. Our analysis addresses three design factors involving the two structures: geotechnical design for excavated soil and underpinning of existing foundations, framing design for the tie-in between the buildings, and space reconfiguration design of the trainer's room which will be directly impacted by the tie-in. We analyzed and designed for each aspect individually and then developed a proposal for the interaction between the buildings based on our findings.

The first feature we explored was the geotechnical design of the foundation along the west side of Harrington Auditorium, which was subjected to a loading condition caused by the loss of support from surrounding soil during excavation. We proposed the use of micropiles as the primary foundation stabilization support during excavation, a type of underpinning that uses grout and steel to support compressive loads. The underpinning layout was designed to produce the most economical solution possible. We tested eight different designs configurations and chose the design that reduces the amount of required material for installation, while maintaining structural stability.

The second aspect we investigated was the connection, or "tie-in" between the Recreation Center and Harrington Auditorium. From the beginning of the design phase of the Recreation Center, it was decided upon to connect the two buildings to provide space for robots to be stored and operated on during robotics competitions held at Harrington. The connection will be on the gymnasium floor level of Harrington Auditorium and on the Robotics Pits level of the Recreation Center, acting as a pathway between the two for Robotics Competitions and for simple circulation purposes. The design would require a portion of the Harrington exterior brick-CMU wall to be removed, so we developed a framing support for the new opening. We decided to use lintels as the primary load support, as oppose to a two-column/beam system. The decision to use lintels would minimize the cost of the tie-in since it uses substantially less material that the alternative design proposal.

The final characteristic of the interaction between the buildings that we studied was the effect the tie-in would have on the trainer's room in Harrington Auditorium. The connection between the buildings runs directly through the trainer's room of Harrington, which will remain fully-operational in the future, despite the addition of a new training area in the Recreation Center. Therefore, the room would need to be reconfigured to allow for the tie-in and the resulting hallway that would run through it to the gymnasium floor. We took into consideration the functional, social, economical and constructible aspects when designing a reconfiguration of the room. We designed a hallway that would function as the primary route for robots during competitions by making it wide enough to support traffic in opposite directions simultaneously. Our design also limits the interference between the hallway and the trainer's room by maximizing the space of the trainer's room given the dimensional constraints. By addressing both the trainer's and robotics team's design recommendations we were able to design a socially accommodating layout. We addressed the economic and constructability aspects by developing a design that reduces amount of exploratory work and demolition/reconstruction needed to perform. This reduces both the cost and the time it takes to reconfigure the area.

In addition to the design considerations pertaining to the two buildings tie-in, we also reviewed constructability aspects of the design of the Recreation Center. We used existing 3D models of the Recreation Center, developed by Cannon Design, and linked them to construction schedules generated by Gilbane, the construction manager. This allowed us to visually display the construction of the Recreation Center design as it progressed over time, commonly referred to as a four-dimensional model. We developed two separate 4D simulations; the first showed the planned schedule developed prior to construction, and the other of the actual progress of the construction project. We tracked the progress of the actual construction by attending project owner meetings, reviewing web-cam time-lapsed footage, and by studying various project-related documentation. By comparing the two models, we were able to determine the schedule performance index (SPI), as well as determine the cost effectiveness of the construction process based on the success of specific trades. By developing this methodology, we were able to conduct an overall five-dimensional review and analysis of the Sports & Recreation Center.

The construction of the Sports & Recreation Center also had various social implications, most prevalent amongst the student body was the campus disruption and coordination required because of the construction site. As with any construction project, the surrounding area will be affected and in the case of the Recreation Center, the quad was reduced in size, haul roads/parking areas reconfigured, and Harrington Auditorium trainer's area reconfigured. We took these aspects into consideration while developing our project. What's more though, is the lasting impact the Sports & Recreation Center will provide for the WPI Community. Prior to construction WPI did not have a facility that allowed for students, faculty, varsity athletes, robotics competitions, and meeting spaces to all coexist in one facility. The creation of the new building on campus will reshape the physical layout of our campus, but it will also force the WPI Community to rethink the way we view our facilities. While this project is but a small part in the development of this change, we are proud to have served our University in this capacity.

AUTHORSHIP PAGE

ABSTRACT - BELIVEAU
CAPSTONE DESIGN STATEMENT - BAKER
1.0 INTRODUCTION - BAKER
2.0 BACKGROUND
- 2.1 WPI Recreation Center - BAKER
- 2.2 Recreation Center Project History - BAKER
- 2.3 Recreations Center Project Team and Organization – BAKER/SYLVIA
- 2.4 Owner's Meetings – BAKER/BELIVEAU
- 2.5 Project Budgeting, Cost Estimating, Payments and Bidding - SYLVIA
- 2.6 Project Scheduling - BAKER
- 2.7 Earned Value Analysis (EVA) - SYLVIA
- 2.8 Building Information Modeling – BAKER/SYLVIA/WILLIAMS
- 2.9 Harrington Tie-In & Geotechnical Aspects - BAKER/SYLVIA/WILLIAMS

3.0 PROJECT MANAGEMENT & BUILDING INFORMATION MODELING -SYLVIA
- 3.1 BIM Execution Plan - SYLVIA
- 3.2 Four Dimensional Analysis (4D) - BELIVEAU
- 3.3 Five Dimensional Analysis (5D) - BELIVEAU
- 3.4 BIM's Potential Uses in Communication – Owner's Meetings – BAKER/BELIVEAU/SYLVIA
- 3.5 Summary of BIM Findings: 4D, EVA, & Communication - SYLVIA

4.0 RECREATION CENTER & HARRINGTON AUDITORIUM CONNECTION - BAKER
- 4.1 Underpinning Design: Methodology & Results – BAKER
- 4.2 Structural Interaction – Tie-In Framing Design – BAKER
- 4.3 Functional Design – Trainer's Room Reconfiguration – BAKER/WILLIAMS

5.0 CONCLUSION – BAKER/BELIVEAU/SYLVIA

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

In May of 2010 construction of a fully operational, state-of-the-art recreational facility began on Worcester Polytechnic Institute's campus in Worcester, MA. The $53 Million building features a 29,000 square foot gymnasium, a natatorium containing a 25-meter competition swimming pool, rowing tanks, squash courts, robotics pits, 11,000 square feet of fitness space, and an additional 5,000 square feet of multipurpose rooms (WPI Press Release, 2010). Despite the massive size of the structure and the complexities of the construction site, the project will be completed within two years. The ability for projects, such as the recreation center, to be completed in such a short amount of time is due to a large extent to changes in the construction industry over the years, including the addition of powerful modeling computer software.

The construction industry is constantly shifting in an effort to streamline the construction process, minimize material waste, decrease overall cost, accelerate project completion, and improve communication between all parties involved. The implementation of Building Information Modeling (BIM) related software, such as Autodesk's Revit and Nemetschek, into construction projects contributes to making these changes in the industry possible. Although BIM-related software has been around since the 1980's, it has only recently found acceptance in the AEC industry, but experts estimate that within a few years BIM will be a standard tool utilized on most projects (Reinhardt, 2010). A Building Information Model is a computer-generated 3D model that allows the user to visualize the project beyond just three dimensions by incorporating time and money. By introducing time, the BIM model becomes "4D" and can be used to track the progress of the project during construction from inception to completion. With the 4D model, project teams can view the proposed structure throughout its different phases of construction and organize the building process before construction even begins. This can help reduce the timeline of the project by creating a better understanding to those parties involved in the construction process as well as by detecting issues before they occur, such as spatial interferences. It also helps in anticipating the difficulty of changes in design as the project progresses. Building Information Models can also include money tracking throughout the course of the project by applying costs to the different elements of the building, thus creating a 5D model. This helps the owner or project manager understand how the money is being spent over the course of the project and recognize how to allocate the funds during different stages of construction. .

Although Building Information Modeling has provided evidence of its capability to significantly improve the efficiency of construction projects, it has still not been adopted throughout the entire industry. Most projects are driven primarily by budget (money) and schedule (time). The 4D-5D capabilities of BIM allows for both the budget and schedule to be visually linked to the 3-dimensional model of the project itself. These models also make it easier to perform Earned Value Analysis, which is a method of assessing how well a project is being managed.

During the design and construction of the Recreation Center, BIM was employed in a limited fashion; during the design phase by creating a 3D model that helped in producing construction documents, and during the construction phase for coordinating M/E/P and Fire Protection. The focus of our Major Qualifying Project explores the extension of BIM modeling by developing 4D and 5D models of the WPI Recreation Center. This was accomplished by tracking the progress of the WPI Recreation Center construction from when concrete was first poured on August 7th, 2010 to when the façade reached substantial completion in March of 2012. BIM modeling and scheduling software was used to evaluate the overall progress of four of the primary construction phases: concrete, steel, roof, and façade. We were able to obtain Revit models and construction schedules of the Recreation Center, which we used as the foundation of our 4D-5D model development. However, these were not sufficient enough to accurately track the project, so we also performed interviews with project staff, studied webcam footage of the construction site and attended weekly Owner's Meetings which gave us greater insight into the week-to-week project decisions over the course of construction. Once the model was complete an Earned Value Analysis was conducted to determine how well the project was managed. From what was learned suggestions were provided as to how using BIM models throughout the construction process could have positively impacted the project, in terms of its ability to improve communications between parties, potentially reduce project costs, and increase the efficiency of the project processes.

An interesting aspect of the construction of the Recreation Center is its connection with Harrington Auditorium, which will be used as the main passageway between these two buildings, and in particular for robotics competitions. In this regard, this study also includes a structural-geotechnical as well as a functional design review of the connection between these buildings. The foundation underpinning and soil nailing is reviewed in detail as well as functional and operational aspects involved in changing the current use of the space currently dedicated to the trainer's room in Harrington,

In its essence, the results obtained from this Major Qualifying Project show the potential benefits of using five-dimensional modeling with regards to time and cost management. Also, the results we obtained regarding Harrington Auditorium's interaction with the Recreation Center outline the necessary procedure and the key aspects that need to be considered when planning and designing the construction of a building near a pre-existing structure.

2.0 BACKGROUND

2.1 WPI Recreation Center

A large construction project is currently taking place at Worcester Polytechnic Institute that will be yet another display of excellence in engineering and design on the WPI campus. The project is the development of a brand new, state-of-the-art Sports and Recreation Center that will promote student and faculty involvement in athletics and fitness. The facility is a 5-level, 140,000 square foot structure located at the west end of the campus quadrangle overlooking Alumni Field. The Recreation Center will feature a natatorium, a fitness center, a four-court gymnasium, a suspended indoor running track, rowing tanks, racquetball courts, dance studios, and office and meeting spaces for the coaches and staff of the Department of Physical Education, Recreation, and Athletics (Mell, 2009). In addition to the athletic features that the building provides, it will also include space for robotics competitions, career fairs, admissions open houses, and alumni events; utilizing the buildings capability for all students, faculty, and alumni to enjoy. A rendering of the WPI Recreation Center provided by Cannon Design can be seen below in Figure 1.

Figure 1: WPI Recreation Center Rendering (View from Quadrangle)

In addition to the many functions that the building will offer, it will also be an excellent display of modern architecture and environmentally friendly design. The majority of the building's exterior will consist of glass curtain walls that will provide excellent views from inside and an aesthetically-pleasing structure on the outside. Also, the building aims to become LEED-certified when complete, meaning that it will meet the highest standard of environmentally-friendly performance (Mell, 2009). WPI plans to achieve a high level of sustainability in the new facility through the use of a Building Management System that will integrate all mechanical and electrical systems in the building. This includes the abilities to balance building-wide power consumption with available renewable, natural power production from both a large array of solar panels and the extensive network of power-generating fitness equipment. Once complete, the new Recreation Center will undoubtedly become a staple of the WPI campus and be treasured by the WPI community for many years.

2.2 Recreation Center Project History

The idea to build a new recreation facility on the WPI campus has been around for years amongst the Institute's community. The combination of a recent growth in student body population and the outdated athletic facilities currently offered at WPI made it apparent that a new, state-of-the art recreational facility would be required on campus to accommodate these needs. In the spring of 2009, construction was scheduled to begin on the project; however it was deferred due to economic conditions (Mell, 2009). Then, on October 30, 2009, the Board of Trustees met at its annual fall meeting and unanimously voted to proceed toward construction of the facility, setting May of 2010 for ground-breaking. The decision to commence with construction was made after reviewing the Institute's continuing financial, academic, and enrollment strength. The building is set to be complete and fully-operational by the start of the 2012-2013 academic year.

2.3 Recreation Center Project Team and Organization

Most projects and contractual agreements consist of three main teams working together: the owner, the designer and the contracting teams. However, there can also be additional parties; such is the case in the WPI Recreation Center, as Cardinal Construction acts as WPI's representative party. Members of the owner's team must provide the project's needs, the level of quality expected, a permissible budget, and the required schedule. They must also provide the overall direction of the project. The design team, chosen to be Cannon Design for the Recreation Center project, generally develops a set of contract documents that meets the owner's needs, budget, required level of quality, and schedule. In addition, the work specified in the contract documents must be constructible by the contractor. The contractor's team, Gilbane Construction in the Recreation Center project, must efficiently manage the physical work required to build the project in accordance with the contract document (Oberlender, 2000). The success of a construction project is often dictated by the ability of the three principal contracting parties to work effectively together.

Before construction began on the Recreation Center, WPI had to choose design and management teams and determine which type of contractual agreement would best suit the project. Determining the contractual agreements provides a blueprint for the hierarchy during construction and to a large extent influences the harmony of the relationships among participants. This choice is based on how well defined the project is before construction begins, as well as the owner's experience in the industry.

2.3.1 Project Manager – Construction Manager at Risk – Gilbane Construction

Project management is "the art and science of coordinating workers, equipment, materials, money, and a project schedule, in order to successfully complete a project on time and within budget" (Oberlender, 2000). An effective project manager must be able to organize people to focus on the goal of the project at hand, in addition to efficiently communicating and motivating their workers. Every project is different due to its location and magnitude, therefore as a project manager it is important to be educated about various aspects of each project. The project manager is typically assigned to a project at its start, and will work closely with the owner until completion (Oberlender, 2000).

Project Managers are utilized on all construction projects regardless of size and the capacity in which they perform is dictated by the contractual agreement of the specific project. There are many different contract arrangements for construction projects but WPI chose to implement a Construction Management (CM) at Risk arrangement for the Recreation Center project, with Gilbane Building Co. (Gilbane) performing the role as Project Manager or CM. A Construction Management (CM) at Risk arrangement is a four-party arrangement involving the owner, designer, CM firm, and contractor. On a CM project, a construction management firm coordinates with a design firm, although they are under separate contracts, and they report to the owner throughout the progress of the project. The basic CM concept is that the owner assigns a contract to a firm that is knowledgeable and capable of coordinating all aspects of construction to meet the intended use of the project by the owner. (Oberlender, 2000) The construction management team is usually responsible for determining and hiring out all of the work to subcontractors. Figure 2 below shows a CM @ Risk contract:

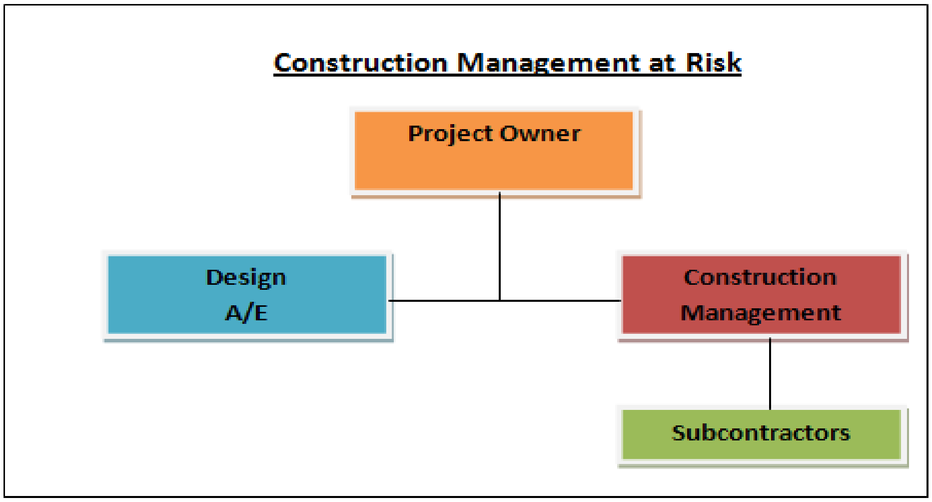


Figure 2: Construction Management at Risk Arrangement

Gilbane is based out of Providence, Rhode Island, and is one of the largest privately held family-owned real estate development and construction firms in the industry. Gilbane has well-established history with WPI, having led the construction of several WPI facilities in the past including East Hall and Bartlett Center. WPI's CM at Risk agreement on the Recreation Center project includes cost-plus compensation with a Guaranteed Maximum Price. As part of Gilbane's role as CM at Risk, they hire and manage the majority of sub-contractors throughout the project, besides several specialty packages which WPI takes direct responsibility. Since they hire the sub-contractors and set the GMP, they are essentially the party taking the greatest financial risk in project if it is to exceed the GMP.

The Guaranteed Maximum Price (GMP) within a CM at Risk contract is beneficial to the owner because it allows them to establish their budget, and hold the CM accountable for any money spent beyond that limit. This is one of the valuable characteristics of a CM at Risk contract and likely the main reason WPI chose it for the Recreation Center project. The WPI Recreation Center agreement holds Gilbane liable for completing all work outlined in the provided plans within the Guaranteed Maximum Price, and it is understood that any change orders can either increase or decrease the overall cost, as they are considered work that is out of the original scope of the project. Although Gilbane was brought onto the project during pre-construction, they didn't officially submit the finalized GMP until late 2010. WPI decided to postpone the submittal of the GMP until after all bidding was completed, including certain specialty items within the facility that delayed bidding. By waiting until all bidding was complete, Gilbane was able to provide a more accurate GMP with fewer contingencies, and ultimately less risk to the owner. The finalized GMP was set at $53M and that includes all work as well as a built-in construction fee to Gilbane.

2.3.2 Designer – Cannon Design

The design team was chosen early on in the project to be Cannon Design. As lead designer, Cannon Design works through a contract directly with WPI, as is the general contractual arrangement in a CM @ Risk project. As part of their contract, Cannon Design remains in direct contact with WPI from inception to completion of the entire project. They coordinated with Gilbane during the design phase however they were under separate contracts with WPI. They also continue to collaborate with the management teams throughout the project, since the work that is performed day-to-day depends solely on the design from Cannon.

2.3.3 Owner's Agent – Cardinal Construction

WPI also chose to hire Cardinal Construction to represent them throughout the construction process through a contract arrangement commonly known as Owner/Agent, which is often implemented not only CM @ Risk projects but many different types of projects. This type of contractual agreement gives Cardinal Construction the authority to perform as the owner's representative for the entire project, and as such, act as the voice of the University in all settings related to the design and construction of the project to ensure that WPI's best interests are always represented. Cardinal Construction has worked for WPI and alongside Gilbane on several previous WPI construction projects and WPI certainly felt comfortable hiring them again based on their experience. Cardinal is not contractually attached to Gilbane or Cannon, however they work very closely to ensure that WPI is being effectively represented.

The organizational breakdown of the Recreation Center project can be seen in Figure 3 below.

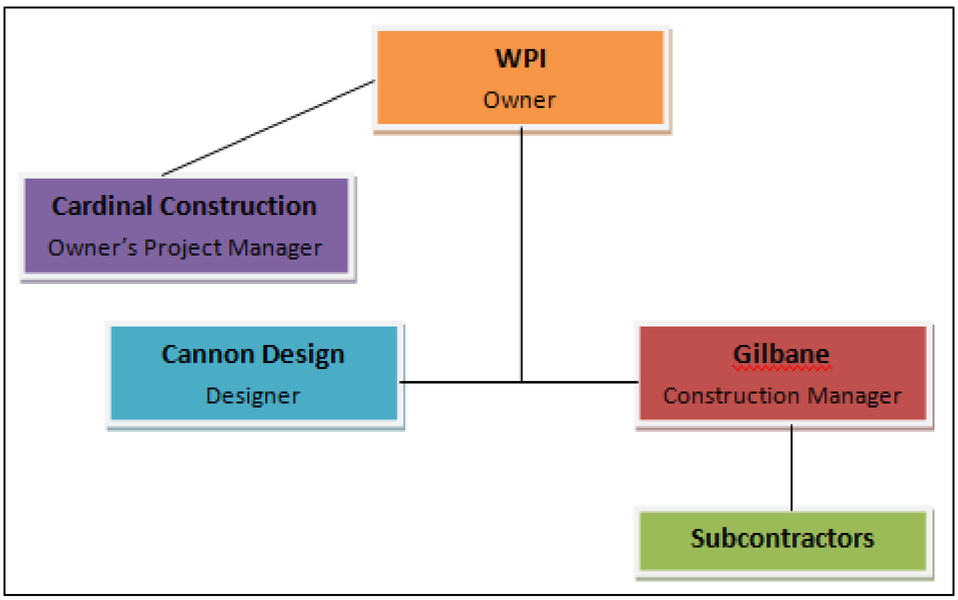


Figure 3: WPI Recreation Center Organizational Breakdown

2.4 Owner's Meetings

Representatives of each of the major participants of this project meet weekly with WPI in the form of an Owner's meeting where they update the owner and other WPI representatives of all progress and potential changes of that week. Each meeting is discussion-based, and serves as an opportunity for all parties involved in given decisions to fully discuss the changes before appropriate action can be taken. The weekly owner's meetings for the WPI Recreation Center project are attended by a number of individuals and organizations whom have their own individual objectives and goals. WPI is represented weekly by Janet Richardson, the VP of

Student Affairs; Dana Harmon, Director of Physical Education, Recreation, and Athletics; Jeffery Solomon, Chief Financial Officer; Alfredo DiMauro, Assistant VP of Facilities; Shawn McAvey, Physical Education Facilities Manager; Anne McCarron, Associate Athletic Director; and Sean O'Connor, Assistant Chief Information Officer. Gilbane is represented by Neil Benner, the lead project manager, Bill Kearney, the project executive, and Melissa Hinton, a project engineer. While Neil organizes and facilitates each weekly meeting, Bill Kearney is still ultimately responsible for all of Gilbane's involvement in the construction of WPI's new Recreation Center. Cannon Design is regularly represented by architects Lynne Deninger and Dominic Vecchione. Cardinal Construction, the construction firm representing WPI is typically represented by Brent Arthaud and Michael Andrews.

Neil Benner prepares the agenda and chairs each meeting, while Project Engineer Melissa Hinton takes notes on updates and changes. An agenda and lately weekly change orders are provided to each attendee, however progress updates are given verbally. Computer generated models or other visual aids are not used during these meetings. In the meetings all parties must work together to achieve a completed project that is under budget and on time, based on the schedule. Although WPI has hired a construction representative, they remain highly involved in the weekly tasks, the schedule and the budget of the project.

Among the obvious benefits of the owner's meetings is the fact that all stakeholders can voice their opinions and stand up for what they see is most important. By hosting a weekly meeting, Gilbane can consistently update WPI regarding time and cost, and WPI can be open and realistic with their expectations. Cannon's presence at the meeting ensures that the design and execution of the agreed upon plans are met appropriately.

2.5 Project Budgeting, Cost Estimating, Payments and Bidding

Along with determining contractual agreements it is imperative to establish how the project will be financed. This includes the budget of the project, as well as the terms of payment to the architect, CM, and sub-contractors; therefore it is essential to select the most practical method for a project, and the members involved.

The bid is created prior to the start of the construction phase, making it crucial for the completeness of the design to determine the most sensible way to finance a project (Oberlender, 2000). If the design is not finalized before the start of construction then it is imperative to finance the project using a cost reimbursable method, however if the design is finished before the bid is placed then a price fixed method can be used.

Lump sum and unit price are the two systems used under a price fixed project, because they allow for the contractor to price out the project, to completion, before any work is started. A lump sum allows for only one price to be quoted to the owner. This price represents the total cost of the project including the materials and equipment used, labor, subcontracted work, overhead, and profit (Oberlender, 2000). The figure produced will be the exact amount the owner pays, unless the owner decided to change the design after the prices has been established. When fabricating a lump sum the contracture uses Construction Specification Institutes (CSI) MasterFormat (Oberlender, 2000). This format recognizes 16 major divisions within the industries standards. These divisions include general requirements, site work, concrete, masonry, metals, woods and plastics, thermal and moisture, doors and windows, finishes, specialties, equipment, special construction, conveying systems, mechanical, and electrical. Each Division will be further broken down using a Work Breakdown Structure, in order to determine the total cost of everything within the respective divisions.

Table 1 is the actual work breakdown structure developed by Gilbane for the WPI Recreational Center, it includes all bid packages and change orders up-to-date. The first section "Packaged Work" includes the cost for all work packages. The second section includes General Conditions and summarizes costs directed toward the CM such as contingencies and overhead. The third section contains Change Orders and their respective costs. The project GMP is showed at the bottom and consists of all the above costs summed up; over the course of the project this figure changes depending on additional change orders.

DESCRIPTION	GMP Amount	Current Amount
PACKAGED WORK ITEMS (Includes Owner Allowance Amounts)		
Sitework	$3,923,616	$3,923,616
Landscaping – Owner Allowance	$220,550	$220,550
Concrete Foundations	$2,785,421	$2,785,421
Structural Precast	$1,597,000	$1,597,000
Brick & Precast	$1,236,513	$1,236,513
Structural Steel	$3,497,809	$3,497,809
Misc. Metals	$575,319	$575,319
Millwork	$300,000	$300,000
Spray Fireproofing	$224,500	$224,500
Waterproofing and Caulking	$658,081	$658,081
Roofing	$1,602,401	$1,602,401
Firestopping	$123,300	$123,300
Doors/Frames/Hardware	$231,192	$231,192
OHC Doors/Loading Dock Equipment	$39,000	$39,000
Glass & Glazing	$2,985,066	$2,985,066
Drywall	$1,985,500	$1,985,500
Ceilings	$599,500	$599,500
Painting	$284,901	$284,901
Synthetic Sports Flooring	$539,438	$539,438
Carpet/Floor Tile/Rubber/Linoleum	$244,686	$244,686
Ceramic/Porcelain Tile/Precast Terrazzo	$764,760	$764,760
Wood Athletic Flooring	$259,689	$259,689
General Trades/Specialties	$615,000	$615,000
Interior Scaffolding	$193,400	$193,400
Turnstiles	$80,000	$80,000
Fixed Natatorium Seating	$50,000	$50,000
Sports Equipment	$249,715	$249,715
Pool	$2,045,661	$2,045,661
Indoor Rowing Tank – Owner Allowance	$453,000	$453,000
Squash/Racquetball Courts	$181,430	$181,430
Elevators	$262,857	$262,857
Fire Protection	$294,887	$294,887
Plumbing	$1,150,307	$1,150,307
Mechanical/Controls	$5,360,000	$5,360,000
Electrical & Tel/Data	$2,964,677	$2,964,677
Early Site Electrical	$120,275	$120,275
SUBTOTAL – PACKAGED WORK ITEMS	**$38,159,401**	**$38,159,401**
General Conditions		
Original CM Contingency	$801,347	
CM Contingency Added from Buyout	N/A	
CM Contingency Committed to date	N/A	$561,373
CM Contingency Projected to be Spent	N/A	$239,974
CM Contingency Remaining	N/A	$0
CDI – Subguard	$457,913	$457,913
CM Preconstruction Services	$150,000	$150,000
CM General Conditions	$2,527,123	$2,527,123
CM General requirements	$1,160,816	$1,160,816
Permits	$299,151	$299,151
Liability Insurance	$375,470	$375,470
CM Fee	$878,624	$878,624
APPROVED CHANGE ORDERS		
TOTAL APPROVED CHANGE ORDERS:		
Change Order #1		$79,064
Change Order #2		$55,237
Change Order #3		$69,580
Change Order #4		$60,986
Change Order #5		$139,892
Change Order #6		$145,522
Change Order #7		$97,477
Change Order #8		$137,949
Change Order #9		$58,894
Change Order #10		$82,462
Change Order #11		$172,145
PROJECTED FINAL GMP w/o Potential Costs	**$44,809,845**	**$45,909,053**
Potential Out of Scope Costs	N/A	$626,267
PROJECTED FINAL GMP w/ Potential Costs	**$44,809,845**	**$46,535,320**

Table 1: WPI Work Breakdown Structure (2/2/2012)

Cost reimbursable agreements, also known as cost plus agreements, are typically used when unique features, that could not be easily estimated, are a part of the project, or when the construction starts before the design is complete and the owner wants to continue to make small changes on the project (Oberlender, 2000). This type of agreement allows for a rough estimate for labor, equipment and other services to be determined ahead of time along with the contractors commission for the project, in the form of a fixed fee or a percentage of the total price. In order to keep the cost of a project down owners will set a Guaranteed Maximum Price (GMP) with incentives to push the contractor to the lowest achievable price (Oberlender, 2000). These incentives may state that if the price is below the GMP then the owner pays the contracture an extra percentage of the difference in the price, and that if the project goes above the GMP then the contractor will have to pay a percentage of the extra cost (Oberlender, 2000). WPI chose to finance their recreational center using a cost plus agreement with a GMP. This agreement was most suitable due to the unique features of the recreational center, including the rowing tank, robotics pit, hanging running track, and 25 meter competition length swimming pool. In order to keep the cost of the project down, WPI agreed to a $53M GMP set by Gilbane.

2.6 Project Scheduling

The project schedule dictates the pace at which construction is performed and sets a timeline for project completion. It is important to have a well-defined schedule so that all parties understand the activities that need to be completed as well as those that are most critical to the projects on-time completion. Project schedule is subject to change due to many reasons including inclement weather, design change, lack of worker production, poor scheduling, and lack of funds among many others. Since some of these reasons are unpredictable, such as poor weather conditions, there is often extra time built into the schedule to account for the potential additional setbacks.

Computer software has transformed the way in which projects are scheduled. Project schedules are vital to the construction process, making massive projects manageable by breaking them down into individual parts. Construction projects consist of thousands of individual activities that are to be performed over the course of the construction, all of which are interconnected. This vast network of activities makes scheduling a very complex and timely process. However, computer programs, such as Primavera, have been created to make the process of creating a schedule more efficient.

Project schedules are comprised of individual activities that are either critical or secondary. Critical activities are those that have no lag time, meaning they must have no extra time built in for them to be completed. These activities need to be completed on time or the entire schedule will be forced back. Non-critical activities do not dictate the schedule as directly as critical activities since they have lag time built in, however if they are not completed on time they can delay the overall schedule. A single project can have tens of thousands of activities that need to be completed before the project is finished, so it is vital to determine the relationship between them and their level of critical completion.

There are several ways of designing a schedule which include the Critical Path Method, Gantt Chart or a combination of the two. Both methods take the scheduling activities and display them in a way that makes it easier to visualize the overall scheduling process.

2.6.1 Critical Path Method

The Critical Path Method (CPM) is a procedure for using network analysis to identify those tasks which are on the critical path: where any delay in the completion of these tasks will lengthen the project timescale, unless action is taken. (Prensa, 2002). The CPM identifies which tasks can be delayed (those not on the critical path) for a while if resource needs to be reallocated to catch up on the other tasks and also identifies the minimum length of time needed to complete the project.

When creating a CPM, all activities must be identified before starting. Each activity has its own properties which include duration and dependency, which tasks must be completed in order to proceed with the next task. Once these characteristics are determined, a CPM network can be drawn to illustrate the precedence among the activities. Figure 4 below shows a CPM network diagram with eight activities and includes all necessary information to determine to critical activities.

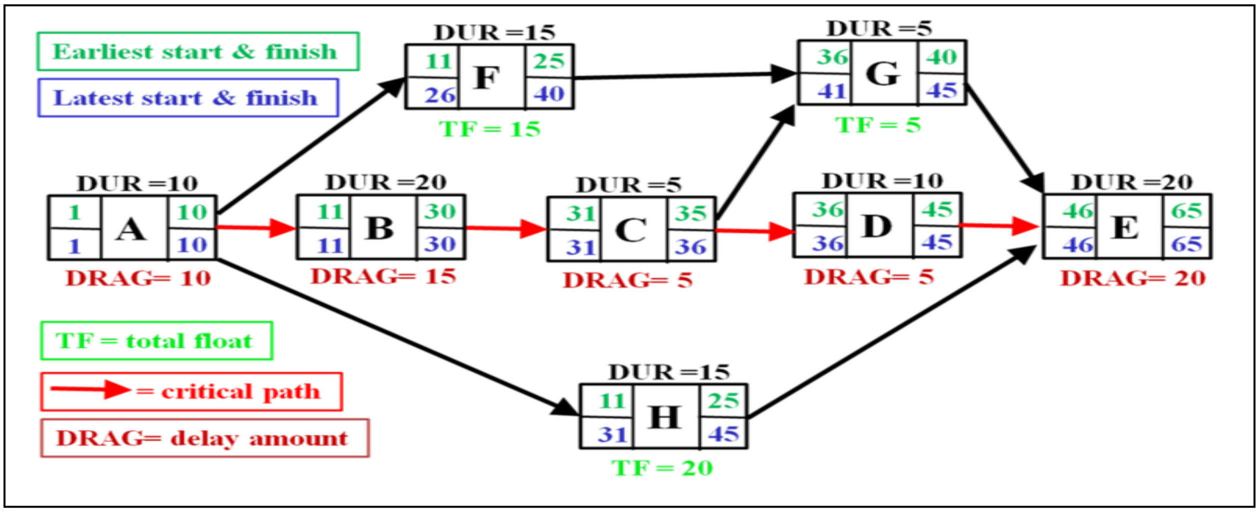


Figure 4: Critical Path Method Network Diagram

Critical Path Analysis is especially effective and powerful in assessing the shortest time in which a project can be completed as well as the sequence of activities, scheduling, and timing involved in reaching completion.

2.6.2 Gantt Chart

A Gantt Chart is a project scheduling model that shows activities in a bar chart. Much like the CPM, a Gantt Chart shows the critical activities and how they are connected but in a easier to visualize model. However, a Gantt chart is more powerful in that you can break activities down into subcategories such as masonry, concrete, or steel to help determine when and for how long different contractors will be working on the construction site (Hall, 2002). This makes cost estimating more accurate since the project manager knows the duration of how long they'll need to hire certain contractors. Figure 5 below is a simplified version of Gantt Chart.

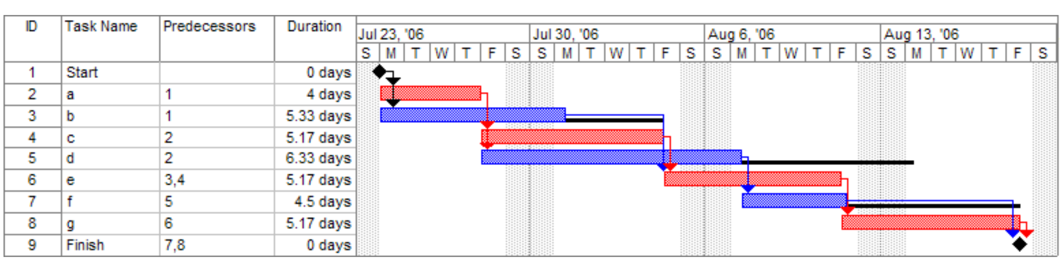
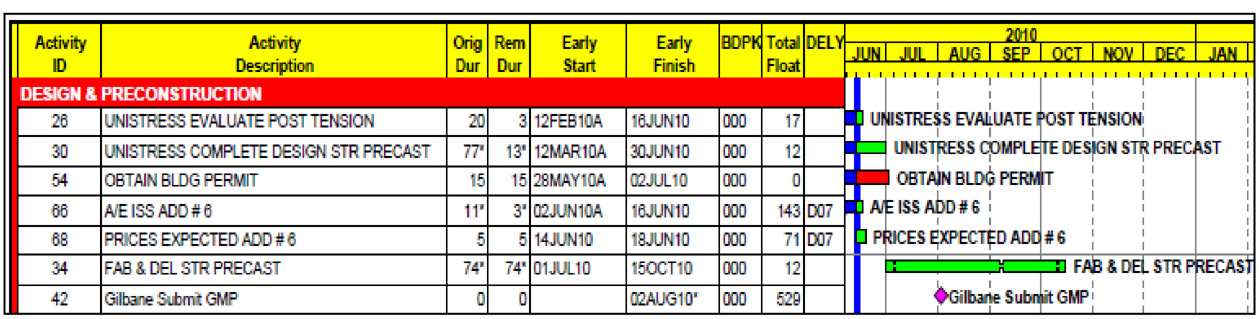


Figure 5: Gantt Chart

2.6.3 Primavera

Primavera is a project scheduling software package that is very powerful and has become the standard in the construction industry. Primavera is the primary scheduling software implemented by Gilbane for the WPI Recreation Center project. In addition to its scheduling capabilities, Primavera software helps companies propose, prioritize and select project investments, and plan, manage and control the most complex projects and project portfolios (Penner, 2008). Primavera allows the project scheduler to submit thousands of activities and link them together to create a working schedule. It has hundreds of features that make organizing and visualizing different aspects of the schedule very easy. For instance, activities can be grouped by work breakdown structure so the scheduler can determine when and for how long to contract out certain aspects of work, such as concrete and steel erection. Also, it is very easy make adjustments to the schedule over the course of project, allowing the project manager to determine how different processes will impact the overall duration of the project. These are only a few of the many advantages of using Primavera during a construction project.

Figure 6 below is a screenshot of Gilbane's construction project schedule for the Recreation Center using Primavera. This particular section of the schedule shows several of the activities for the Design & Preconstruction of the project. The columns include pertinent scheduling information for each activity such as Activity ID, Activity Description, Duration, Early Start/Finish, Bid Package Number, Total Float, and Delay. These columns can be arranged and organized in any fashion that the project scheduler wishes within PRIMAVERA. On the right hand side the activities can be viewed in their relative duration to the calendar, and the color of each bar can be used to distinguish critical activities from secondary activities.



Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	BDPK	Total Float	DELY
DESIGN & PRECONSTRUCTION								
26	UNISTRESS EVALUATE POST TENSION	20	3	12FEB10A	16JUN10	000	17	
30	UNISTRESS COMPLETE DESIGN STR PRECAST	77*	13*	12MAR10A	30JUN10	000	12	
54	OBTAIN BLDG PERMIT	15	15	28MAY10A	02JUL10	000	0	
66	A/E ISS ADD # 6	11*	3*	02JUN10A	16JUN10	000	143	D07
68	PRICES EXPECTED ADD # 6	5	5	14JUN10	18JUN10	000	71	D07
34	FAB & DEL STR PRECAST	74*	74*	01JUL10	15OCT10	000	12	
42	Gilbane Submit GMP	0	0		02AUG10*	000	529	

Figure 6: Gilbane Primavera Schedule

2.6.4 WPI Scheduling Techniques

The scheduling of the WPI Recreation Center is performed by Gilbane using Primavera. During the pre-construction phase of the project, Gilbane developed a schedule for the entire construction process that included thousands of individual activities. Once every month they update the schedule by adding any new design or construction changes and removing all completed activities. As the project progresses, the level of detail of certain construction activities also increases.

Gilbane sometimes changes the organization of activities within Primavera. Some months they will organize activities into Work Breakdown packages, such as sitework, concrete, steel, millwork, etc. This method is helpful in determining the duration of certain package types and hiring subcontractors to complete the work package. Another way they sometimes organize the schedule is by building section: A, B, C, and D. The Recreation Center is broken down into four different sections and when they organize the schedule by these sections it is easier to visualize how the construction will progress throughout the building. Figure 7 shows the four sections of the Recreation Center.

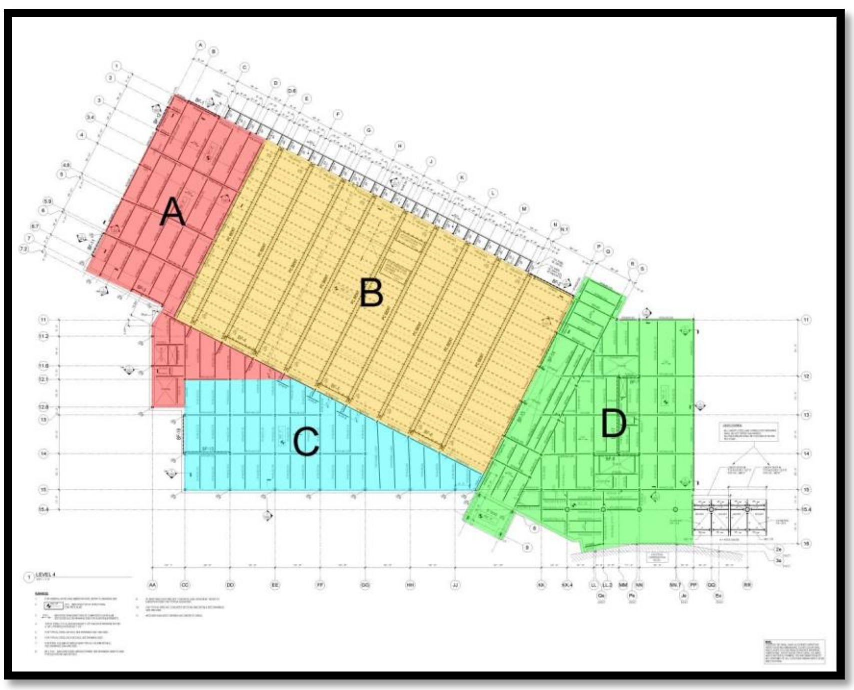


Figure 7: Recreation Center by Sections

2.7 Earned Value Analysis (EVA)

The Earned Value System tracks the work being done on a project by comparing the projected work to the actual work completed. The projected work is found by cost loading the CPM diagram to establish the distribution of the projects cost over the course of the project, therefore finding the budgeted cost of the work scheduled (BCWS) (Oberlender, 2000). The actual cost of the work performed (ACWP) is found by tracking the receipts of the project, to determine the money spent on the project at any given time. The percent of the work completed at any time can then be multiplied by the budgeted amount for the work to determine the amount of money earned at any point. The money earned is known as the budgeted cost of the work performed (BCWP) (Oberlender). A lazy S curve can be created by graphing the BCWS, ACWP and the BCWP. The BCWS, ACWP and the BCWP can also be used to find the Cost Variance (CV), Scheduled Variance (SV), Cost Performance Index (CPI), and the Schedule Performance Index (SPI), as shown below:

- Cost Variance, $CV = BCWP - ACWP$
- Scheduled Variance, $SV = BCWP - BCWS$
- Cost Performance Index, $CPI = BCWP / ACWP$
- Scheduled Performance Index, $SPI = BCWP / BCWS$

The Cost Variance shows the actual work paid for versus the actual work completed, while the scheduled variance shows the actual work paid versus what was planned to be paid. The cost variance explains if a project was overrun or not by the use of a number less the one on the cost performance index (CPI). Overrun projects have more money was paid in a period then was budgeted for that period. The scheduled variance shows if the work is ahead or behind schedule, by determining if the budgeted work hours are less than the earned work hours, or not. If a project is ahead of schedule then the scheduled project index (SPI) will be greater than one, however if the project is behind schedule then the SPI will be less than one (Oberlender, 2000).

The CPI and the SPI are regularly tracked in order to determine if a project in on target. By tracking a project the construction manager can determine where the project fell behind schedule, or is over budget. The construction manager can then use that information to determine the best approach to mitigate the problem. Figure 8 below is an example of a SPI and CPI graph.

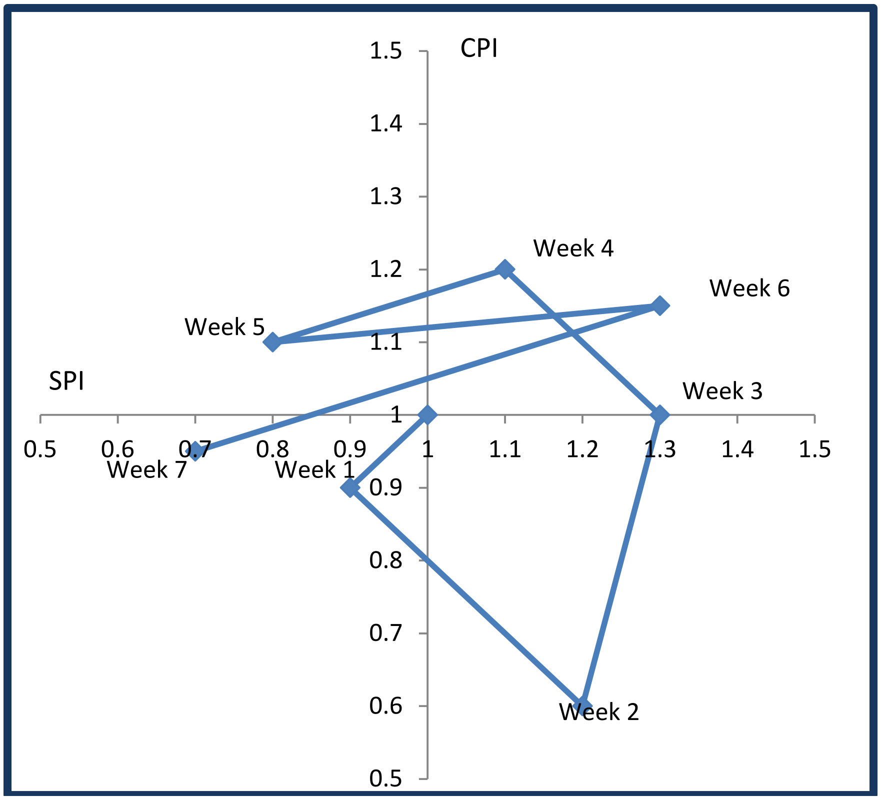


Figure 8: Typical CPI-SPI Graph

2.8 Building Information Modeling

Usually, drawings and computer-aided design (CAD) files (two-dimensional documents) are the primary media for communicating graphic information among project participants. While all participants in this process are assumed to be familiar with 2D documents, the use of these 2D documents could cause situations in which complex details of a project are often not represented accurately causing problems for all parties. Using traditional tools and processes, the complexity of a specific situation often is not fully understood until construction has begun and costly changes have to be done. (Reinhardt, 2010)

A Building Information Model is computer-driven representation of a facility for the purpose of design, analysis, construction and operation. A BIM model consists of geometric, 3D representations of the building elements plus additional information that needs to be captured and transferred in the AEC delivery process and in the operation process of the facility. (Reinhardt, 2010)

2.8.1 BIM History

Even though Building Information Modeling (BIM) has been around since the mid-1980s only recently has it risen in popularity within the Architectural, Engineering and Construction (AEC) industries. Due to rise in popularity the AEC industry has created a demand for well-trained individuals capable of implementing BIM technology in the work place.

Before BIM the use of 2D CAD was used to present information graphically. The program "Sketchpad" was developed by Ivan Sutherland as part of his PhD thesis at MIT in the early 1960s. Sketchpad was especially innovative CAD software because the designer was able to directly interact with the computer by using a light pen to draw on the computer's monitor. First-generation CAD software systems were usually 2D drafting applications developed by a manufacturer's internal IT group and primarily intended to make very repetitive drafting tasks easier to complete. (CAD Software History, 2004)

The first 3D solid modeling program was SynthaVision, from MAGI (Mathematics Application Group, Inc.), which was released in 1972, not to be used for CAD but for performing 3D analysis of nuclear radiation exposure. These models were solid models similar to the CSG (constructive solid geometry) models used by later 3D CAD software. However, despite steadily increasing computer performance, solid modeling was still too computer intensive for 3D Modeling use. With the increase in power of computers, and the introduction of lower cost minicomputers which had an optimized Fortran compiler and graphics capable terminals, were beginning to make 3D CAD software more available to engineers on a wider scale. Throughout the 1980s, the new generation of powerful UNIX workstations and emerging 3D rendering was inevitably shifting the CAD software use to 3D and solid modeling. (CAD Software History, 2004)

The history of BIM dates back to 1982 with Graphisoft's development of ArchiCAD, virtual building solution for the Apple Macintosh computers. Introduced to the public in 1986, it was the first personal computer based product capable of rendering parametric 3D models (Darras, 2011). This was important because architects and engineers were then able to store large amounts of data sets 'within' the building model. These data sets include the building geometry and spatial data as well as the properties and quantities of the components used in the design.

The growth of BIM in the AEC Industry has been remarkable one. Since the first use of Computers to create isometric models of constructed elements in the 1950s, the subject of BIM has intrigued researchers, software developers and visionaries. For a long time BIM found very little acceptance in the AEC industry in the United States. However in the last few years, many major players in the AEC industry have adopted BIM, and experts estimate that in a few years BIM will be a standard tool that will be used on most projects. (Reinhardt, 2010)

2.8.2 BIM Uses in Industry

BIM has many uses that can be of value for the user. The uses usually vary depending on the project delivery method and the timing of the user's initial involvement in a project. BIM can be a useful tool throughout the entire project. The construction uses includes, but not limited to: visualization of design, coordination between trades, visualization of construction sequences and extraction on quantity information from models.

Pertaining to the first use mentioned above, visualization is one of the main construction uses of BIM. Unlike the construction documents typically found at the job site, the BIM allows every member of the construction team to see the relationship between different elements of construction in one place. The BIM Model is extremely helpful for understanding how different elements fit together. With this information in one place one is able to visualize each element which allows for more efficient communication, construction, and more accurate estimating.

Another set of uses of BIM is Spatial Coordination, Clash Detection and Collision Detection. Early communication and coordination between trades potentially has the greatest impact on the project's cost and schedule. The ability to visualize the relationships between each construction element prior to starting construction allows for early procurement of materials, and with this information shop fabrication of equipment and the placement of each trade's work one could avoid clashing with that of the other trades and overall reduce cost and increase productivity.

There is also the Scheduling and 4D Modeling use of BIM. The 4D Model is created when the element of time is added to the 3D Model by creating a link with the model and the critical path method schedule. This can be done using a single application or by combining model collaboration software with standard scheduling software. The 4D Model is an essential tool to the BIM Process because it identifies collision between construction activities. 4D Modeling is used to identify activities that are out of sequence, flow of trade work and relationships between construction equipment. The 4D Model can also be useful for analyzing different construction scenarios and determining the most efficient sequence of work and with this information one can tell whether the work is on time or whether the project is behind.

NavisWorks is a computer program that supports BIM model and project scheduling integration. It acts as a platform for combining a BIM model with a Primavera schedule and creating a 4D model. The 4D model allows the user to simulate construction schedules and logistics to visually communicate and analyze project activities, and help reduce delays and sequencing problems. (Walker, 2010). Although NavisWorks wasn't used on the Recreation Center project, we utilized its features as part of our project to create a 4D model.

The Estimating and 5D Modeling use of BIM entails using the data stored in the BIM to extract information and transfer that information into construction estimates. As the design progresses or changes occur, these estimates can be quickly updated based on information derived from the BIM model. There are many methods to link model quantities to estimating systems, but each company determines which methods suits them the best based on its internal estimating practices. (Reinhardt, 2010)

2.8.3 Use of BIM on the Recreation Center

During the design and construction of the Recreation Center, BIM was employed in several different capacities. During the design phase a 3D Revit model of the Recreation Center was produced by Cannon Design. The model was created to help in producing construction documents as well as providing WPI and the Recreation Center management team with a visual representation of the structure. The Revit model (which is a form of Building Information

Modeling) consists of two separate, but interlinked, files: an Architectural model and a Structural model. The Architectural model consists of elements related to the architectural design of the Recreation Center such as façade, drywall, lighting, flooring, doors, and the location of desks, tables, chairs, sporting equipment, etc. The Structural model is comprised of structural elements of the building such as steel beams, columns, girders, concrete footings, foundations, cast-in-place concrete sections, roofing elements, trusses, etc. Although Cannon created this very detailed Revit model of the proposed structure during pre-construction, no updated versions have been completed since.

Another capacity in which BIM was employed on the Recreation Center project was for its clash detection capabilities. Prior to installing the mechanical, electrical and plumping units (MEP), Gilbane used Navisworks to simulate the MEP installation throughout the Recreation Center building. The simulation helped detect clashes between MEP elements before they occurred during the actual construction. This ability to conceptualize the construction and detect errors beforehand, reduces time that would be spent on the jobsite developing a new plan and saves money that would be required to pay for extra materials to re-route the issue.

2.8.4 Previous MQP BIM Findings

As mentioned before, our project is a continuation of a previous MQP (Fournier, 2011) which tracked the early stages of the Recreation Center construction, including concrete and steel erection. They produced actual and planned BIM for the construction of the Recreation Center from August 15, 2009 to April 15, 2010. Using the Revit model created by Cannon Design as a basis, they created 16 BIM models total (8 actual and 8 proposed), using 30-day phases, starting and ending on the 15th of each month. Figure 9 below shows BIM models produced by the previous MQP group of the proposed and actual construction of the Recreation Center that occurred during the phase of January 15, 2011 to February 15, 2011.

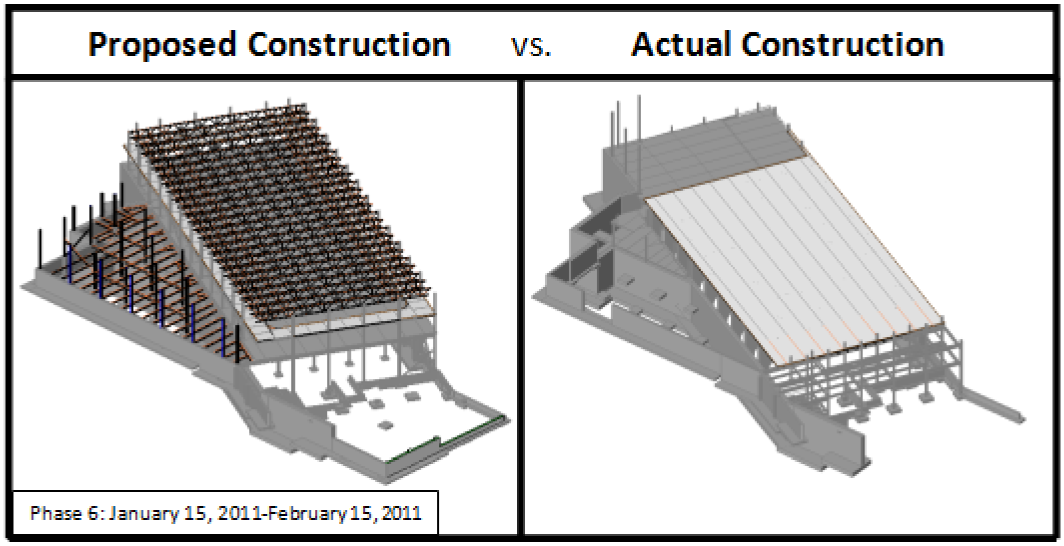


Figure 9: Comparative BIM Models of the Recreation Center Construction 2011 (Fournier, 2010)

The previous group's BIM models and analysis showed that construction was behind schedule to varying degrees for nearly every phase, generally due to unpredictable weather conditions. The models created by the previous MQP group are the only visual representations of the progress Recreation Center.

2.8.5 BIM Execution Plan

A BIM Execution Plan should be created towards that start of the project in order to develop a closer relationship between the different parties involved in the project. The execution plan should outline the various uses of BIM in the project, as well as an extensive plan of the interactions between BIM and the project throughout the extent of the project (BIM Execution Planning Guide, 2009). Each BIM Execution plan should be catered to the project at hand, and therefore should be unique to the project. Throughout the project the execution plan should be revised and updated, in order to be deemed successful for the duration of the ever changing project. By creating an execution plan the many important principles of the team members can be reached. Some of these principles included in the BIM Execution Plan Guide include:

- All parties will clearly understand and communicate the strategic goals for implementing BIM on the project;
- Organizations will understand their roles and responsibilities in the implementation;
- The team will be able to design an execution process which is well suited for each team member's business practices and typical organizational workflows;
- The plan will outline additional resources, training, or other competencies necessary to successfully implement BIM for the intended uses;
- The plan will provide a benchmark for describing the process to future participants who join the project;
- The purchasing divisions will be able to define contract language to ensure that all project participants fulfill their obligations; and
- The baseline plan will provide a goal for measuring progress throughout the project

In order to create an effective BIM Execution Plan four stages must be completed. These stages are to identify the BIM goals and uses, to design a BIM project execution plan, to develop information exchanges and to define supporting infrastructure for BIM implementation (BIM Execution Planning Guide, 2009). When identifying the BIM goals and uses the team must first determine different ways BIM can be used within their project. From these they can then create goals related to project performance and to expanding the team members' skills. Once goals have been determined the team members must decide on the different ways BIM can help achieve these goals. Next a map of the project must be created in order to show the order of each process phase of the project. More detailed maps can be made for each process phase to show the entirety of the phases. Upon making a map the phases can be used to determine any information needed to be exchanged at each phase to allow the project to run more smoothly. Lastly the infrastructure necessary to run this BIM project needs to be fashioned. This includes the technology needed, the communication procedures, and the contractual language (BIM Execution Planning Guide, 2009). Figure 10 below is a map of the four stages taken from the BIM Execution Plan Guide as proposed by the Penn State Research group:

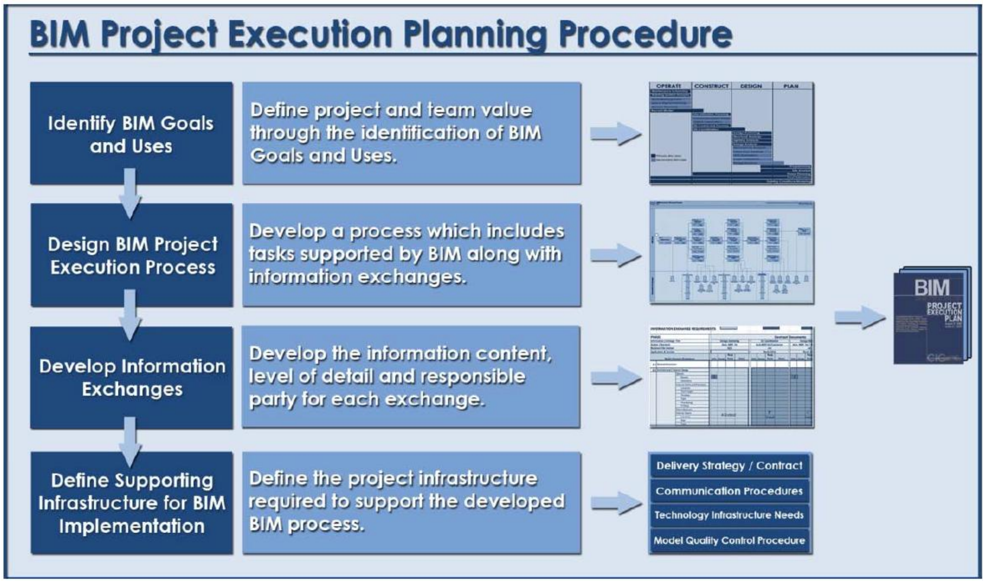


Figure 10: BIM Project Execution Planning Procedure

2.9 Harrington Tie-In & Geotechnical Aspects

As part of our project, our team focused on the connection between the pre-existing Harrington Auditorium structure and the construction of the new Recreation Center. Our review includes analysis of the Harrington substructure during the excavation process, the design of which consists primarily of underpinning and soil nailing. We also explored the tie-in between the two structures and developed a support system design adequate to support the loading system applied to it. Our analysis considers the constructability of the design, functionality of the completed project, and the structural integrity of the total system, as well as a study of the impact on the configuration of the trainer's room, which will be directly affected by the new tie-in.

2.9.1 Harrington Auditorium

Harrington Auditorium is the current gym facility at WPI, and was constructed in the 1960's of steel, concrete, and brick. The building is located on the northwest side of the quadrangle, adjacent to Alumni Auditorium and opposite Daniels/Morgan Dormitories. The new Recreation Center is being constructed perpendicular to Harrington Auditorium, within relatively close proximity, and will therefore play an integral part in the design and construction of the new facility. Harrington Auditorium has a regulation size basketball court and stadium seating and is used not only for basketball and volleyball games but also for large functions and robotics competitions. Due to the importance of these robotics competitions, the two building will be connected, or “tied-in” together on the Harrington gymnasium floor level. This tie-in will act as route between the robotics pits in the Recreation Center to the competition floor in Harrington, as well as a general means of circulation between the buildings. Figure 11 is topographical view of the WPI quad developed by Hadrey Aldrich during Subsurface Exploration; the locations of Harrington Auditorium and the Recreation Center are outlined.

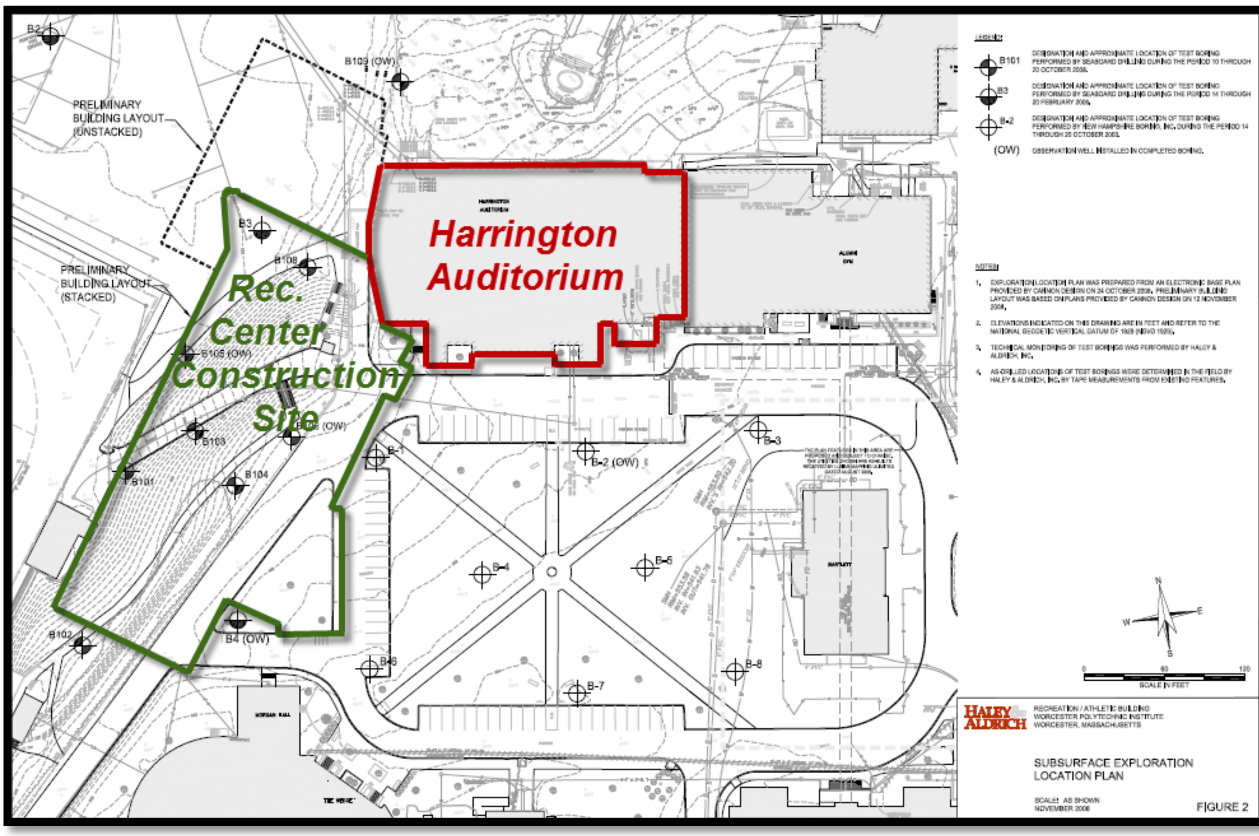


Figure 11: Topographical View of WPI Quadrangle (provided by Hadrey Aldrich)

2.9.2 Geotechnical Aspects of Recreation Center Construction

During the excavation of the new Recreation Center, the design team had to determine a suitable approach to maintain the structural stability of Harrington Auditorium. Since Harrington is in close proximity to the Recreation Center, its structural integrity would be jeopardized by the massive amount of excavation. The large volume of soil removed would decrease the lateral support of the soil surrounding Harrington Auditorium, reducing bearing capacity of the foundation footings underneath Harrington Auditorium and potentially causing a structural failure. To counteract this loss in support, underpinning was placed beneath the west side of Harrington Auditorium, the section most directly affected by the excavation, and also the location of the tie-in between the two buildings.

A considerable amount of soil was excavated along the west side of Harrington Auditorium during the construction of the Recreation Center. To ensure slope stability during excavation, engineers designed a soil nailing layout beneath the existing structure. The soil nails were employed to strengthen the soil and eliminate the risk of slipping or settlement of the Harrington Auditorium foundation. There are many configurations that soil nails can be constructed and the design usually depends on the specific loading conditions and soil properties of the structure.

Soil nailing is a common technique used in the United States to reinforce a sloped area that is subjected to external loading (Zhou, 2009). Soil Nailing is regularly used because it has many advantages along the lines of cost, performance, and construction (Elias, 2003). A soil nails main use is to resist tensile forces caused by the mobilization of frictional forces along the entire soil nail (Cheuk, 2009). These nails are typically steel bars placed in predrilled holes at a 345 degree angle to the horizontal. Grout is applied around each steel bar to help transfer the stress from the ground onto the steel bar (Elias, 2003). A washer, Hex nut, and barring plate is fastened to the head of the steel bar. These components bond the bar to the facing. Figure 12 is a schematic of a soil Nail produced from the Geotechnical Engineering Circular No. 7: Soil Nail Walls document:

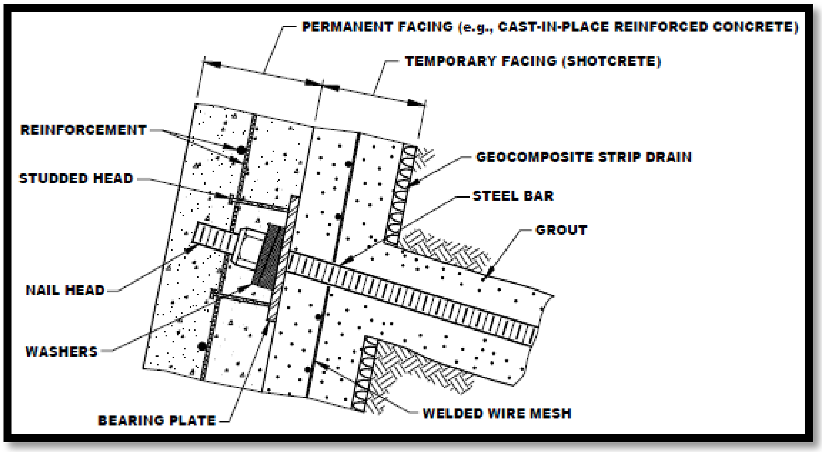


Figure 12: A Typical Soil Nailing Schematic (Elias, 2003)

Soil nailing was not only used beneath Harrington Auditorium, but also throughout the entire face of the hill (East side of the Recreation Center) to support it from failing. The construction team used additional soil nailing beneath Morgan Hall also, to maintain its structural integrity. However our main focus was that of the soil nailing constructed beneath Harrington.

Another feature included in the geotechnical design for Harrington Auditorium was structural underpinning. The main function of the underpinning was to restore load bearing capacity and to prevent excessive lateral movements of the foundation footings of Harrington Auditorium during excavation and while constructing the soil nail wall.

Micropiles were used in this project as the underpinning to help support the existing structure. Micropiles have been used mainly for foundation support to resist static and seismic loading conditions and less frequently as in-situ reinforcements for slope and excavation stability (FHWA, 2000). A micropile is a small-diameter (typically less than 300 mm), drilled and grouted replacement pile that it typically reinforced. A micropile is constructed by drilling a borehole, placing reinforcement, and grouting the hole. Micropiles can withstand axial and/or lateral loads, and may be considered a substitute for conventional piles or as one component in a composite soil/pile mass, depending upon the design concept employed. The installation of micropiles only causes minimal disturbance to adjacent structures, soil, and the environment.

Micropiles can be installed at any angle below the horizontal using the same type of equipment used for ground anchor and grouting projects.

Most of the applied load on conventional cast-in-place replacement piles is structurally resisted by the reinforced concrete; increased structural capacity is achieved by increased cross sectional and surface areas. Micropile structural capacities, by comparison, rely on the high capacity of steel elements to resist most of the applied load. These steel elements have been reported to occupy as much as on-half of the holes volume. The special drilling and grouting methods used in micropile installation enable the development of high grout/ground bond values along the grout/ground interface. The grout transfers the load through friction from the reinforcement to the ground in the micropile bond zone in a manner similar to that of ground anchors. Due to the small pile diameter, any end-bearing contribution in micropiles is generally neglected. The grout/ground bond strength achieved is influenced primarily by the ground type and grouting method used.

The design and construction of underpinning is the primary focus of the design portion of our project. Although soil nailing was also employed as part of the geotechnical design for Harrington Auditorium, the underpinning required more focus an intensive design and planning.

2.9.3 WPI's Harrington Tie-In Proposal

The Harrington tie-in is designed to connect Harrington Auditorium to the Recreation Center. The connection will be on the basketball court level of Harrington and the second floor of the Recreation Center. The exact location in Harrington is on the west end of the building, directly into the wall what is currently occupied as the trainer's rooms. As for the Recreation Center, the tie-in will occur on the second floor on the east side of the building in the robotics pits area. The purpose of the tie-in is to create a route between the two buildings for both circulation purposes and for ease-of-travel during robotics competitions. Figure 13 below shows the floor plan for the design of the tie-in.

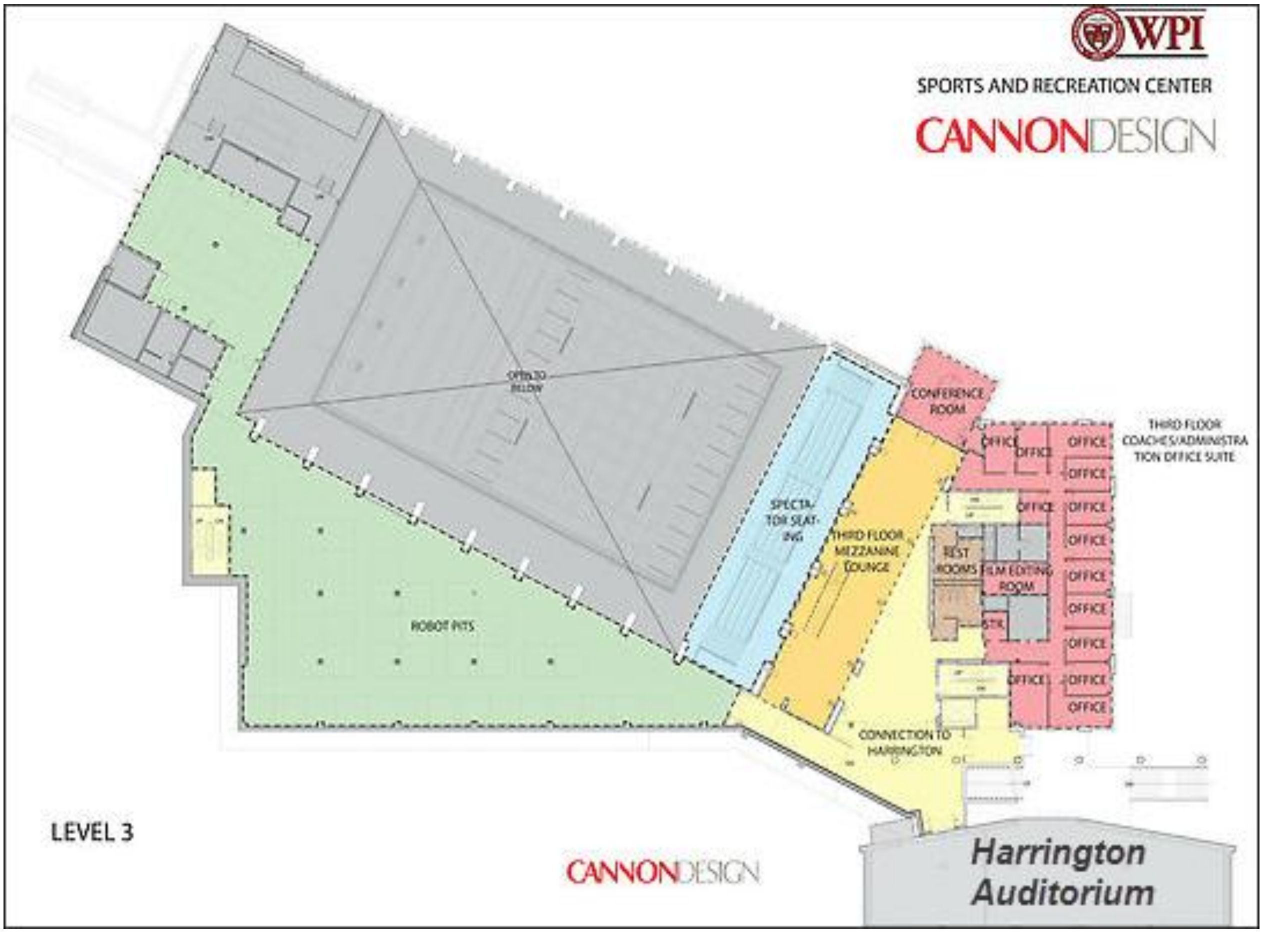


Figure 13: Floor Plan of Harrington Auditorium Tie-In (provided by Cannon Design)

The current design calls for an approximate 8'-6"X8'-0" area of Harrington Auditorium's wall to be removed and supported by a framing system for a basic double door. The wall is an exterior non-load bearing wall comprised of brick, CMU, and an air gap between the two. The plan is to cut an exploratory hole through the wall to determine the exact make-up of the wall as well as its depth. From there, they will continue removing the wall and providing support systems accordingly, noting the location of any support columns. Once they have the desired area removed they will construct a framing system for the doorway, likely a lintel with reinforcement. Figure 14 shows a sketch of the proposed framing system with dimensions.

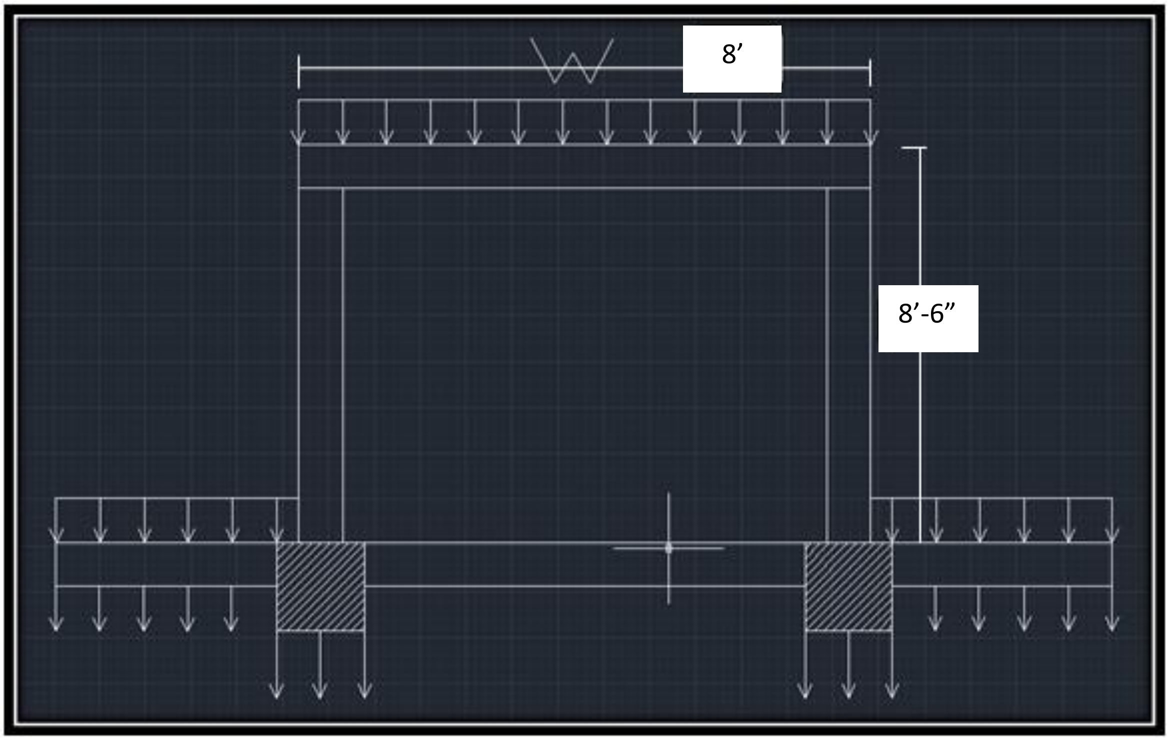


Figure 14: Simplified Harrington Tie-In Loading Sketch

Figure 15 is a Revit model of the West side of Harrington Auditorium; it shows the proposed location and the relative dimension of the tie-in.

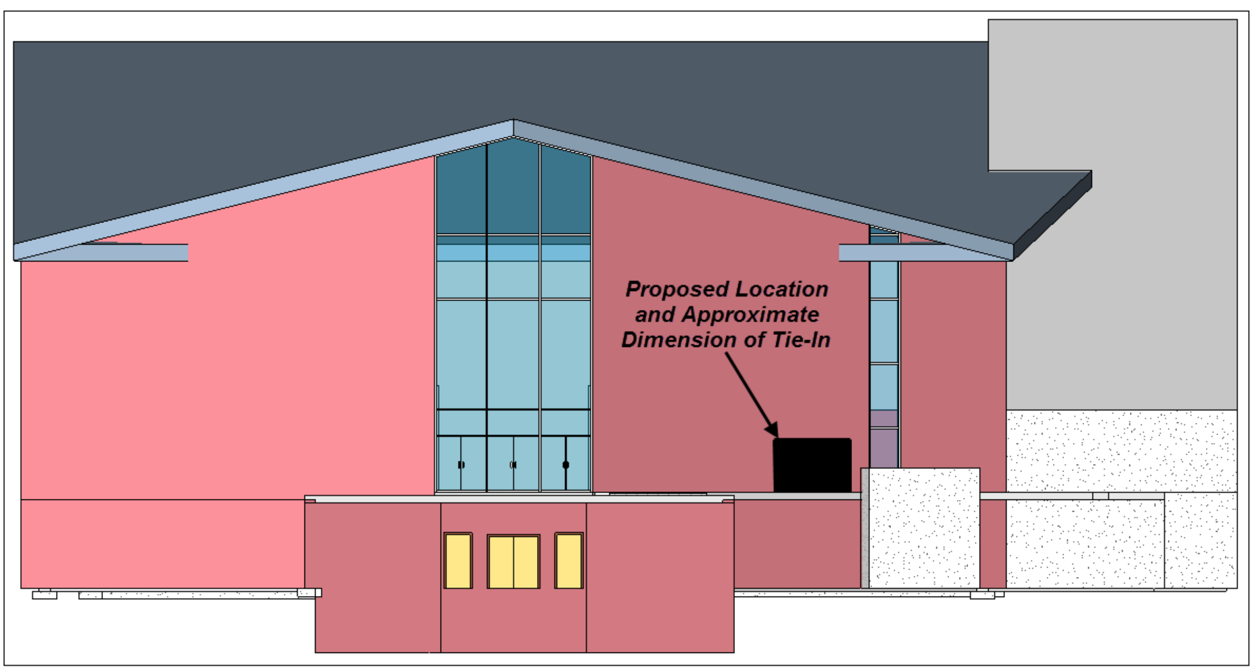


Figure 15: View of the West side of Harrington Auditorium and the Proposed Tie-in

Since the tie-in will be obstructing the use of the trainers rooms, the construction is to take place during a time of limited student activity, likely the break between C- and D-term of 2012. The entire process should take approximately one week, so its interference with the trainer's room during the construction should be minimal. However, after the school year is complete the trainer's room will have to be reconfigured to allow ease of traffic between the two buildings, through the tie-in connection. Figure 16 is an AutoCAD drawing of Harrington Auditorium, specifically the southwest corner on the gymnasium level, where the tie-in will be located. Based on the location of the tie-in, the trainer's room will clearly require rearrangement. The design of the proposed configuration is still under development, however as part of our project we proposed our own design for the reconfiguration of the trainer's area, as well as the expected pathway of traffic from the tie-in to the gymnasium floor.

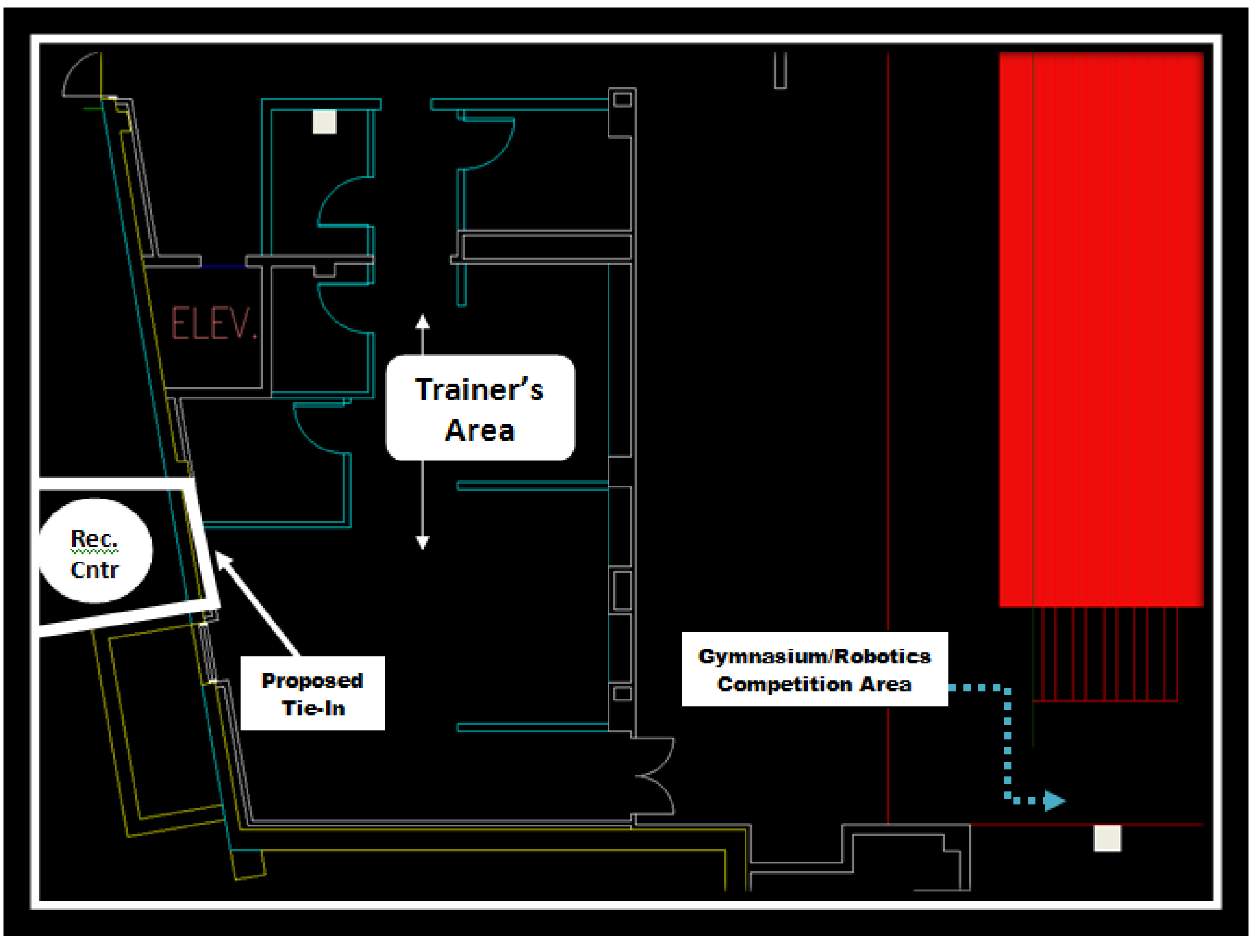


Figure 16: An AutoCAD Sketch of the current layout of the Harrington Gym Training Room

As the basis of the design capstone of our project, we performed a structural analysis of this entire process and determined a framing system design based on our review. We also considered the project management aspect of the tie-in, specifically the interaction with the trainer's rooms during construction and the constructability of the tie-in. We outline in greater detail the processes we took to obtain the necessary information to conduct the analysis and also provide our proposed design further in our report.

3.0 PROJECT MANAGEMENT & BUILDING INFORMATION MODELING

We employed various methods to reach our goal of creating a 5D model of the Recreation Center and performing an Earned Value Analysis. As mentioned before, our project is to some extent a continuation of a previous Major Qualifying Project (MQP) completed by a group of students in 2011 who tracked the Recreation Center during the first 6 months of construction and produced a 4D model and Earned Value Analysis (EVA) for this process (Fournier et al, 2011). We used their project as a foundation for ours, using many of the same methods they used and expanding upon them. The previous MQP project tracked the Recreation Center construction throughout the entire excavation and concrete foundation phase and into the majority of steel erection. We used this information to help develop the schedule for the steel and concrete work performed early on in the project, and continued by tracking the progress of the remaining steel and concrete, as well as the façade and roof. Just as the previous group, we used various computer software programs, reviewed old and new schedules, and examined photos and time-lapsed videos. Prior to the initiation of this work we created a BIM Execution Plan that outlines in further detail the methods used in the development of this project.

3.1 BIM Execution Plan

The methods used in completing the phasing, scheduling, and EVA analysis of the Recreation Center project were outlined in the BIM Execution plan we developed. The Execution Plan identified the major goal of this project as well as the objectives accomplished over the course of the project. It also includes team member responsibilities and distribution of work. The BIM Execution Plan also summarizes the different phases of the project and the relationship between each phase. Creating this network allowed each team member to understand how his/her work relates to the others'. This resulted in a better understanding of the project.

3.1.1 Project Goal

The ultimate goal of our project was to investigate BIM's efficiency and effectiveness in determining the work completed on a monthly basis and to demonstrate this usefulness to the project owner. The goals we aimed to achieve and their corresponding potential BIM use can be seen in Table 2.

Goal Description	Potential BIM Use
Tracking progress during construction	Visualizing project performance through a 4D model
Tracking percent complete in terms of quantities	Determine Earned Value of work in progress

Table 2: BIM Execution Plan Goal Description

3.1.2 Team Member Responsibilities

In order to reach our goal it was determined that the team would need to be responsible for the entirety of the project; however we also decided to elect different members of our team to be in control of different aspects of the project. We created and signed a non-binding contractual agreement stating our roles and responsibilities of the project at the start of the project. This contractual agreement can be found in Appendix A. Our head of the scheduling department was Christopher Baker. He was in charge of creating the projected schedule as well as the actual schedule. In order to fulfill his responsibilities Mr. Baker used both Primavera Project Management software and NavisWorks. In charge of the modeling department were Andrew Beliveau and Machell Williams. Mr. Beliveau and Mr. Williams were in control of creating three dimensional models for the provided schedules, as well as performing a quantity comparison of these models. They used the Revit and NavisWorks software to complete their tasks. Nica Sylvia was in charge of the analysis between the scheduling and the modeling, and therefore helped Mr. Baker, Mr. Beliveau and Mr. Williams. Ms. Sylvia was also in charge of using the quantities found of materials to create the cost analysis. To complete her tasks Ms. Sylvia used 7 Zip, Primavera, NavisWorks, Revit, and Microsoft Excel software.

3.1.3 Project Phasing Network

To determine the necessary steps to reach our goal we broke the project down into six different phases and found the important details of each phase. These phases included scheduling, three dimensional modeling, four dimensional modeling, tracking and monitoring, material quantities, and Earned value analysis. Table 3 below is a chart explaining the details of each project phase:

FIGURE TOO LARGE FOR SPACE: SEE NEXT PAGE

Project Phase	**Phase Details**
Scheduling	Identified work packages to be tracked and included into the 4D model Condensed Gilbane's Primavera file activities to a manageable number of activities Retained all critical activities to determine time constraints Created Activity ID's using a coding system developed through the use of the CSI MasterFormat. Separated schedule into monthly phases starting on the first day of the month, and ending on the last day of the month Made sure that each activity ID correspond to an ID element within the Revit model
3D Modeling	Created a model which represents the activities chosen in our schedule Formatted each of these activities in the model so that they have the matching activity ID's Determined the total quantities of materials (part of 5D)
4D Modeling	Displayed the 3D Model in progressive monthly increments Showed quantities (5D) of each material that accrued each month Displayed both the total percent of material used since tracking began, and the total percent of material used in each one-month period
Tracking and Monitoring	Determined the actual timeline of the project using photographic evidence, time-lapse videos and information gained from owners meetings. Determined the actual quantities of materials
Quantities	Calculated quantities used in each monthly phase
Earned Value Analysis	Determined the cost of each material from Gilbanes work breakdown structure Determined the expected cost of each material and activity at given time periods Generated graphical analysis to display our results Compared the actual cost and actual work done, to the expected cost and expected work done Determined the project's progress and overall value

Table 3: Project Phasing Network

From these detailed phases we created a map, which links each phase to show the overall flow of the project, as well as showing the necessary information needed to complete the phase. Figure 17 below is our project map:

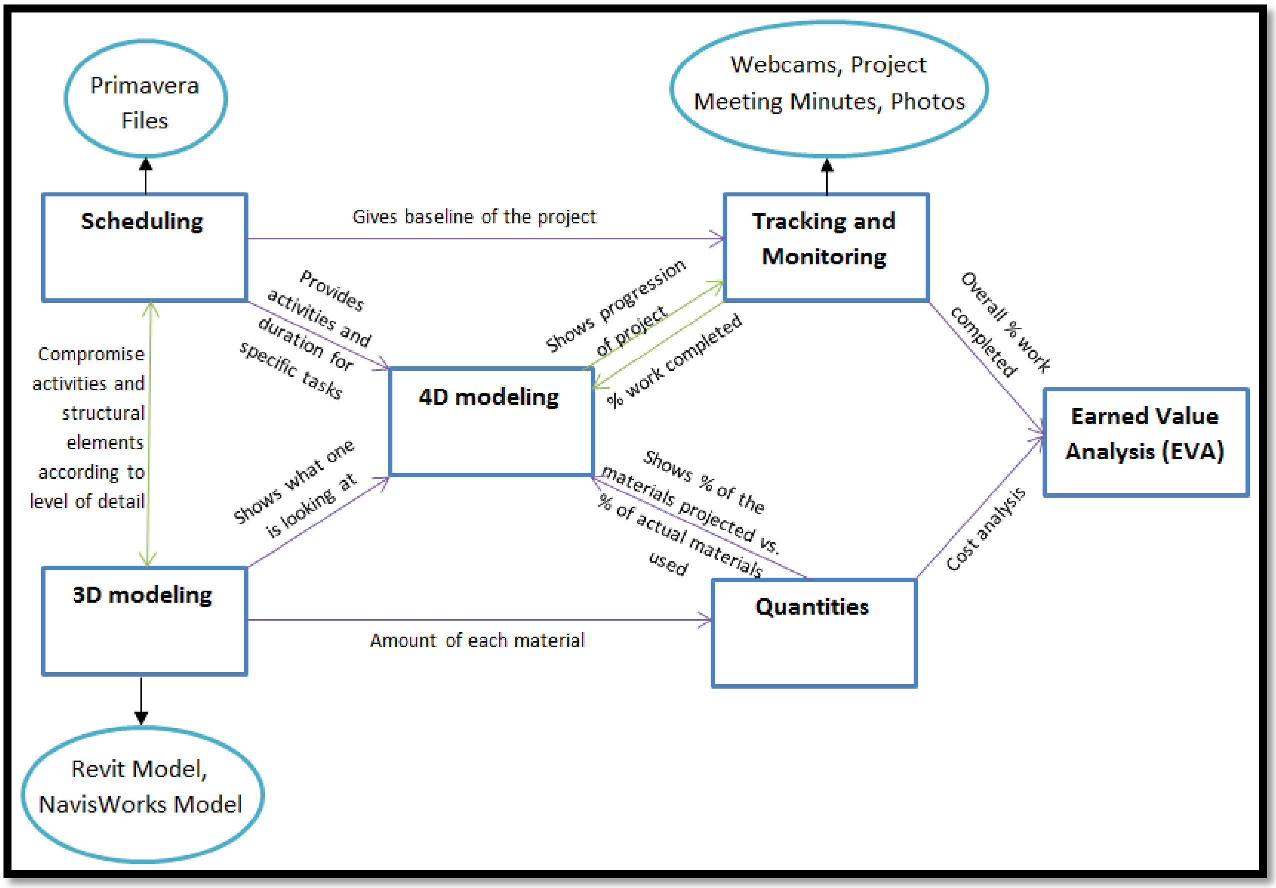


Figure 17: BIM Project Map

3.1.4 Software for Each Phase

Next we determined the software necessary to complete each project phase. To do this we created a chart of the phases and the relative software. Table 4 shows the software used for each project phase.

Project Phase	Relative Software
Scheduling	Primavera
3D Modeling	Revit Architecture Revit Structures
4D Modeling	Revit Architecture Revit Structures NavisWorks Primavera
Tracking and Monitoring	7 Zip Primavera NavisWorks
Quantities	Revit Architecture Revit Structures Microsoft Excel
Earned Value Analysis	Primavera Microsoft Excel

Table 4: Project Phase-Software Relationship

There are several software tools that can be utilized in the process of creating and tracking construction projects. The software we used to track the WPI Recreational Center building included Primavera, Revit Architecture, Revit Structure, NavisWorks, Microsoft Excel, and 7 Zip. Primavera is used for tracking the progress of the project and for contrasting the planned schedule of construction against the actual schedule of activities completed. The Revit programs are modeling software tools that enable designers and construction managers to visually conceptualize the project in three-dimensions. The model can then be employed to find quantities of different materials. Also each part of the model can hold information stating not only size and type of material but also an activity ID, which can be linked to the activities in the Primavera schedule. NavisWorks has the ability to integrate both a Revit model and a Primavera schedule, and can be used to track the scheduled activities from the Primavera schedule within the Revit model, thus showing how a building is built in time. Microsoft Excel is a simple tool we used to analyze information and display our findings graphically. 7 Zip is a utility that allows us to transfer large files, and is particularly useful when working with BIM. These files when used in conjunction allowed us to create an accurate and effective BIM model.

3.1.5 Detailed Project Phase Procedures

Our last step to completing the BIM Execution Plan was to create in-depth explanations of the project phase procedures. We created both a readable explanation of each phase procedure, found below, as well as step by step directions, which can be found in Appendices B-G.

We followed methodical approaches to create the planned schedule and the actual progress of constructions. We used previous schedules generated by Gilbane to determine the planned schedule and a combination of photographs, information received from the owners meetings, and webcam footage of construction to determine the actual progress of construction. We also used excel to organize and consolidate the activities into packages that were easier to manage. Then using Primavera we imported the activities and created the schedules.

We focused on four different major work packages for the construction and tracked their progress: steel, concrete, roofing, and façade. These four work packages make up approximately 30% of the total cost of work package items for this project. We chose these work packages since they would be occurring during the time that we spent on the project and would be easier to track and also because of their structural importance to the building. We began by reviewing old schedules created by Gilbane and choosing the activities that related to the work packages we would be modeling and tracking. We created an excel file with individual sheets for each work package, and imported all of the activities from the Gilbane schedule into the excel sheets for organization. This excel file included a description of the activity, the Gilbane ID code, the work package, the planned start and finish date, our MQP ID code, as well as other relevant information. The dates we received from the previous Gilbane schedule would become the foundation for our planned schedule.

We used the same activities from the planned schedule, but a slightly different approach to create the actual schedule. We studied photographs of construction, time-lapsed video and attended weekly owners meetings to determine the actual start and finish dates of each activity. This process was far more in-depth comprehensive and required greater attention to detail. Once we had all of the dates secured we exported the excel file into Primavera. We ran into some troubles while exporting the excel file and had to troubleshoot as we proceeded. The dates did not transfer correctly so we had to input each date into Primavera individually, as well as organize each activity into its respective work package. The step-by-step process we followed to import the Excel schedule into Primavera is outlined in Appendix C. Once we had the dates in Primavera we were able to visualize the activities and the flow of the project progress using the powerful software.

For every activity in our schedule an ID was created in order to easily identify the activity without reading its description. Each ID was made using an activity coding system made up of a sequence of thirteen numbers and letters. This sequence first identifies the project phase, then one of the sixteen trades found in the CSI MasterFormat, the level of the building, next area of the building in which the activity exists, and lastly the type of structural element. For example if one were to identify the activity "concrete slab third floor area A" he or she would first chose the project phase, for this activity the project phase would be under construction, so the letters "CO" would start the ID. Next he or she would determine under which division of the CSI MasterFormat concrete is, which is under concrete, so he or she would add the numbers "03" to the ID. Since the activity exists on the third floor the next set of numbers added to the ID would be "03", followed by an "A" because the activity is in area A. Lastly "00100" would be added to the end of the ID because the activity is a slab. Therefore the whole ID for this activity would be "CO0303A00100". Once every ID had been created they were used within the Revit Structural model, in order to identify the object linked to the scheduled activity. The Activity Identification Coding System is outlined entirely in Appendix B.

Once every activity had been identified the ID was used in the Cannon 3D Revit Model in order to link the corresponding objects to the activities found in the Primavera Schedules. To identify these objects we created a Parameter to hold the information for the ID. To do this we went to the Project Parameters and created a parameter labeled “Activity ID” whose future use was to contain the text data of the code for each activity.

Once the Activity ID Parameter had been defined we went into the 3D Model and highlight the different objects corresponding to the same activities in the Primavera Schedule. With all the objects highlighted we inputted the ID code pertaining to that specific activity. This was done to each object in the model which pertained to the activities in the Primavera Schedule. Once completed, we were able to show the progress of the construction of our four chosen work packages using the 3D Model on a daily, weekly, or monthly basis. We used two different Revit models – Structural and Architectural – because all elements are not included in one centralized model, however we used the same exact process for each. The Structural model contained the concrete, steel, and roof elements, while the Architectural model contained the façade elements. This entire Revit Identification Process is clearly outlined in Appendix D.

Once both the structural and architectural models identification process had been completed we conducted a materials quantity takeoff. This takeoff gave us the needed quantities (in both square and cubic meters) of each material identified by its activity ID. To learn the step by step Revit process used to complete a material quantity takeoff turn to Appendix E The information we received from the quantity takeoff we later used to establish our earned value analysis.

Successive to the completion of the Primavera schedule and the object identification in the Revit Structural and Architectural Models both the Revit models and the Primavera schedule were exported in a manner which would allow them to import into NavisWorks. Upon the exportation of the schedule and models, each model was opened in NavisWorks. From there we imported the schedule and created a rule which we labeled “LinkElemementToSchedule”. This rule allowed NavisWorks to link that object ID from the Revit model to the matching activity ID in the schedule. Once the rule was created we went to the simulation tab in NavisWorks and clicked “construct” on each activity. Lastly we ran the simulation and reviewed it for any potential identification errors. We created different simulations for both the planned schedule and the actual schedule so that a viewer could watch the two simulations simultaneously. The detailed directions on how to export both Revit and Primavera files into Navisworks and running the subsequent simulation can be found in Appendix F.

Once the simulation was created we were able to pause the simulation on the last day of each month in order to obtain the month-by-month pictures. These pictures would be used in the future for our quantity takes-off and ultimately for our earned value analysis.

NavisWorks can not only run simulations to construct models, but the program also has many other useful features. One of these features includes color coding or transparency coding object in the simulations. We chose to change the color of each work breakdown structure so that each when constructed different activities would show up in different colors. We chose to have all concrete activities show up in yellow, steel in blue, façade in red, and the roofing to be green. We also created a transparency change so that when an activity's construction started the its object would show up in the model with 60% transparency and when the construction on that activity was completed the object would become opaque, allowing the viewer to acknowledge that construction was finished without looking at the schedule. The step-by-step directions on how to change activities color and transparency is outlined in Appendix G.

Our last step to creating our five dimensional model was to create an earned value analysis. To do this we first exported both the planned and actual schedule from Primavera to Microsoft Excel. We made two separate tables, one for the planned schedule and one for the actual schedule. In both schedule we matched each activity ID to their respective quantities, which we had found during the material quantity takeoff. We then created a month-to-month schedule breaking down the quantities of each activity into the months associated with that activity. For example in the actual schedule activity ID CO0507D02001 "Erect Area D Steel & Deck" started on January 10th, 2011 and ended on May 7th, 2011. This activity spanned over 85 workdays, 16 of them in January, 20 in February, 23 in March, 21 in April, and 5 in May. For each of these five months we multiplied the material quantity by the number of workdays in that month over the total number of workdays. Using this equation we found the amount of material that was used for that activity each month. Once we had completed this process with all the activities we calculated the total material quantity per month of each of our different material types. We then found the work packages from Gilbane's work breakdown structure that was associated with the different materials that we were monitoring. We multiplied the percent of material used each month by its work package to determine the total cost of the materials and work associated with those materials each month. From there we created bar charts representing the planned vs. actual cost each material and work per month. As well as the planned and actual total cost of the project on a month-to-month basis of the steel, concrete, façade, and roofing.

Through the use of our goals, project phases, including their phase detail and related software, and our project map we will have determined the necessary components of the project. With the use of the responsibilities assigned we were able to utilize the components of the project and transform them into a finished 4D design with a cost and material quantity analysis.

3.2 Four Dimensional Analysis (4D)

The four dimensional analysis of the Recreation Center considers the 3D model that graphically displays all of the building's information, and the time that construction took and was planned to take to complete the project. When compared, there is much that can be learned from examining the planned build of the project to the actual construction schedule. Nowhere in the project is the comparison more clear than in the Navisworks models that were assembled to display the 3D models building themselves over the time periods that the scheduled. In order to most effectively show the progress of the building, images were taken from both models at the conclusion of each month. More than just determining if the building was on or behind schedule, the 4D model allows for an understanding of the difference in materials based on schedule or construction changes.

In order to build the 4D model, and to integrate all models and schedules in Navisworks, we developed a link between each aspect of the project. By adding data to the schedule, and then having that data be tied to each model, we could coordinate changes across all platforms without any loss of data. Below in Figure 18 you can see part of the project schedule, complete with the additional data column, "Activity ID."

Gilbane ID	Activity ID	Activity Name	Area	Planned Start	Planned Finish	Actual Start	Actual Finish	Start	Finish
RCMQP4-2.4 Facad				28-Mar-11	15-Sep-11	05-May-11	04-May-12	05-May-11 A	04-May-12 A
4018.B	C00300B01000	Precast Base - Area B	B	26-Apr-11	02-May-11	06-Jun-11	10-Jun-11	06-Jun-11 A	10-Jun-11 A
4018.C	C00300C01000	Precast Base - Area C	C	07-Jun-11	13-Jun-11	08-Aug-11	12-Aug-11	08-Aug-11 A	12-Aug-11 A
4018.D	C00300D01000	Precast Base - Area D	D	21-Jun-11	27-Jun-11	19-Sep-11	23-Sep-11	19-Sep-11 A	23-Sep-11 A
4020.A	C00407A00900	Brick Veneer - Area A	A	28-Mar-11	22-Apr-11	09-Aug-11	26-Aug-11	09-Aug-11 A	26-Aug-11 A
4030.A	C00407A01400	Metal Panels - Area A	A	22-Jun-11	06-Jul-11	26-Dec-11	10-Feb-12	26-Dec-11 A	10-Feb-12 A
4020.B	C00407B00900	Brick Veneer - Area B	B	03-May-11	13-Jun-11	13-Jul-11	08-Aug-11	13-Jul-11 A	08-Aug-11 A
4030.B	C00407B01400	Metal Panels - Area B	B	04-Aug-11	24-Aug-11	01-Nov-11	23-Dec-11	01-Nov-11 A	23-Dec-11 A
4020.C	C00407C00900	Brick Veneer - Area C	C	15-Jun-11	13-Jul-11	29-Aug-11	02-Sep-11	29-Aug-11 A	02-Sep-11 A
4030.C	C00407C01400	Metal Panels - Area C	C	25-Aug-11	08-Sep-11	13-Feb-12	23-Mar-12	13-Feb-12 A	23-Mar-12 A
4020.D	C00407D00900	Brick Veneer - Area D	D	14-Jul-11	03-Aug-11	05-Sep-11	23-Sep-11	05-Sep-11 A	23-Sep-11 A
4030.D	C00407D01400	Metal Panels - Area D	D	01-Sep-11	15-Sep-11	26-Mar-12	04-May-12	26-Mar-12 A	04-May-12 A
4025.A	C00807A01100	Windows & Curtain Wall - Area A	A	25-May-11	21-Jun-11	20-Jun-11	14-Oct-11	20-Jun-11 A	14-Oct-11 A
4025.B	C00807B01100	Windows & Curtain Wall - Area B	B	22-Jun-11	03-Aug-11	05-May-11	16-Sep-11	05-May-11 A	16-Sep-11 A
4025.C	C00807C01100	Windows & Curtain Wall - Area C	C	14-Jul-11	24-Aug-11	01-Aug-11	18-Nov-11	01-Aug-11 A	18-Nov-11 A
4025.D	C00807D01100	Windows & Curtain Wall - Area D	D	04-Aug-11	31-Aug-11	19-Sep-11	15-Dec-11	19-Sep-11 A	15-Dec-11 A
RCMQP4-2.3 Roofing				15-Mar-11	01-Jun-11	25-Oct-11	04-Nov-11	25-Oct-11 A	04-Nov-11 A
B4.4020	C00706B01901	Roof, B-4, GYM	B/A	15-Mar-11	28-Mar-11	25-Oct-11	04-Nov-11	25-Oct-11 A	04-Nov-11 A
4080.C	C00706C01900	Roof Area C	C	13-Apr-11	26-Apr-11	25-Oct-11	04-Nov-11	25-Oct-11 A	04-Nov-11 A
D5.5001	C00706D01901	Install Roof, D Area	D	18-May-11	01-Jun-11	25-Oct-11	04-Nov-11	25-Oct-11 A	04-Nov-11 A
RCMQP4-2.2 Steel				19-Oct-10	14-Apr-11	25-Oct-10	21-May-11	25-Oct-10 A	21-May-11 A
5161	C00505B02002	Erect Steel/Decking for Track	B	15-Feb-11	28-Feb-11	24-Mar-11	08-Apr-11	24-Mar-11 A	08-Apr-11 A
5157	C00506A02001	Install Roof Trusses/Deck Area A/B	A/B	01-Feb-11	14-Feb-11	23-Feb-11	19-Mar-11	23-Feb-11 A	19-Mar-11 A
5155	C00507A02001	Erect Area A Steel	A	19-Oct-10	25-Oct-10	25-Oct-10	25-Feb-11	25-Oct-10 A	25-Feb-11 A
5159	C00507A02002	Complete Steel @ Top Area A	A	03-Jan-11	07-Jan-11	16-May-11	21-May-11	16-May-11 A	21-May-11 A
5255	C00507B02001	Erect Area B Steel & Deck	B	10-Jan-11	31-Jan-11	02-Mar-11	18-Mar-11	02-Mar-11 A	18-Mar-11 A
4050.C	C00507C02001	Erect Structural Steel, Area C	C	15-Feb-11	17-Mar-11	30-Mar-11	12-Apr-11	30-Mar-11 A	12-Apr-11 A
5275	C00507D02001	Erect Area D Steel & Deck	D	18-Mar-11	14-Apr-11	10-Jan-11	07-May-11	10-Jan-11 A	07-May-11 A
RCMQP4-2.1 Concrete				19-Aug-10	12-May-11	07-Aug-10	14-Oct-11	07-Aug-10 A	14-Oct-11 A
5134	C00300A00301	FRF Footings Area A & Retaining Wall	A	23-Aug-10	17-Sep-10	07-Aug-10	19-Aug-10	07-Aug-10 A	19-Aug-10 A
5131	C00300A00302	FRP FTGS/Found Walls Load Dock	A	24-Nov-10	08-Dec-10	22-Nov-10	08-Dec-10	22-Nov-10 A	08-Dec-10 A
5135	C00300A00500	FRP Conc Found & Retaining Walls A Line	A	25-Aug-10	01-Sep-10	14-Sep-10	08-Oct-11	14-Sep-10 A	08-Oct-11 A
5240	C00300B00101	Concrete Diaphrams Slab	B	15-Dec-10	22-Dec-10	02-Apr-11	24-May-11	02-Apr-11 A	24-May-11 A
5140	C00300B00301	FRP Conc FTGS 1 Line - Area B	B	19-Aug-10	03-Sep-10	16-Aug-10	20-Aug-10	16-Aug-10 A	20-Aug-10 A
5141	C00300B00500	FRP Conc Foundation Walls 1 Line - Area B	B	23-Aug-10	13-Sep-10	20-Aug-10	13-Sep-10	20-Aug-10 A	13-Sep-10 A
5170	C00300C00301	FRP Footings Area C	C	20-Sep-10	25-Oct-10	19-Nov-10	26-Nov-10	19-Nov-10 A	26-Nov-10 A
5171	C00300C00501	FRP Conc Found Walls Area C	C	08-Nov-10	22-Nov-10	29-Nov-10	31-Dec-10	29-Nov-10 A	31-Dec-10 A
5245	C00300D00301	Conc FTGS Sect D (Cold Weather Placement)	D	20-Sep-10	01-Oct-10	16-Sep-10	01-Oct-10	16-Sep-10 A	01-Oct-10 A
5246	C00300D00501	Conc Found Wall Sect D (Cold Weather Placement)	D	04-Oct-10	15-Oct-10	04-Oct-10	22-Oct-10	04-Oct-10 A	22-Oct-10 A
A1. 1015	C00301A01700	FRP SOG, 1st FL, Area A	A	24-Feb-11	02-Mar-11	11-Oct-10	15-Oct-10	11-Oct-10 A	15-Oct-10 A

Figure 18: Primavera Schedule with Activity ID link

When compared side by side, the differences between the actual construction of the project and the planned schedule of construction can be seen easily. During the beginning of the project, Gilbane was ahead of schedule, and the pouring of the concrete footings were moving much faster than expected. Unfortunately this progress and good fortune only lasted a few months. Figures 19 shows models of the planned progress and the actual progress in August 2010.

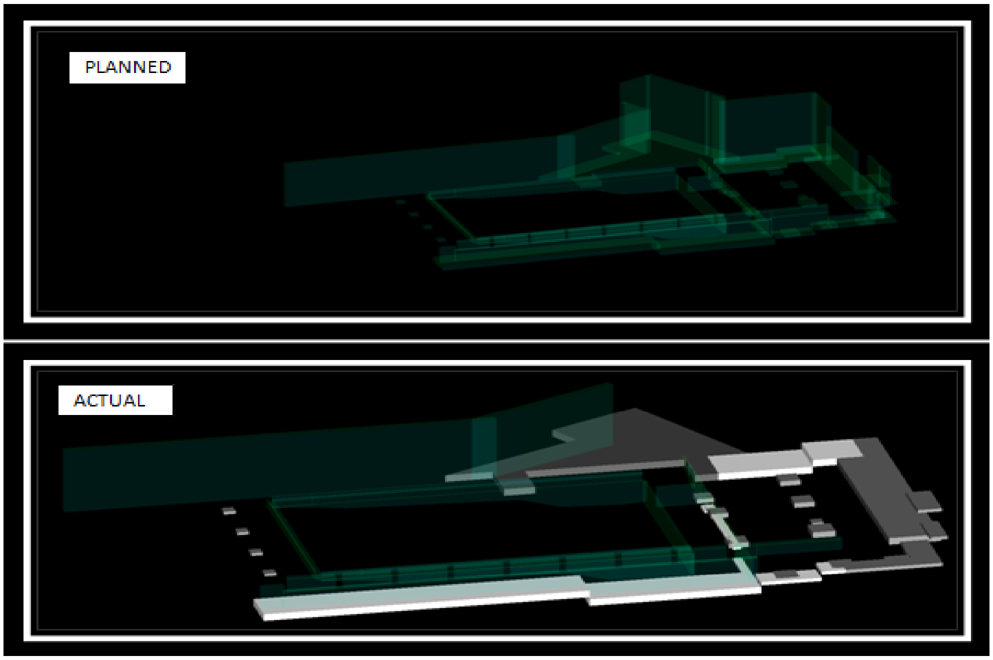


Figure 19: Planned vs. Actual Construction Progress – August 2010

Further, in September 2010, the schedule becomes even further ahead. This can be seen below in Figure 20.

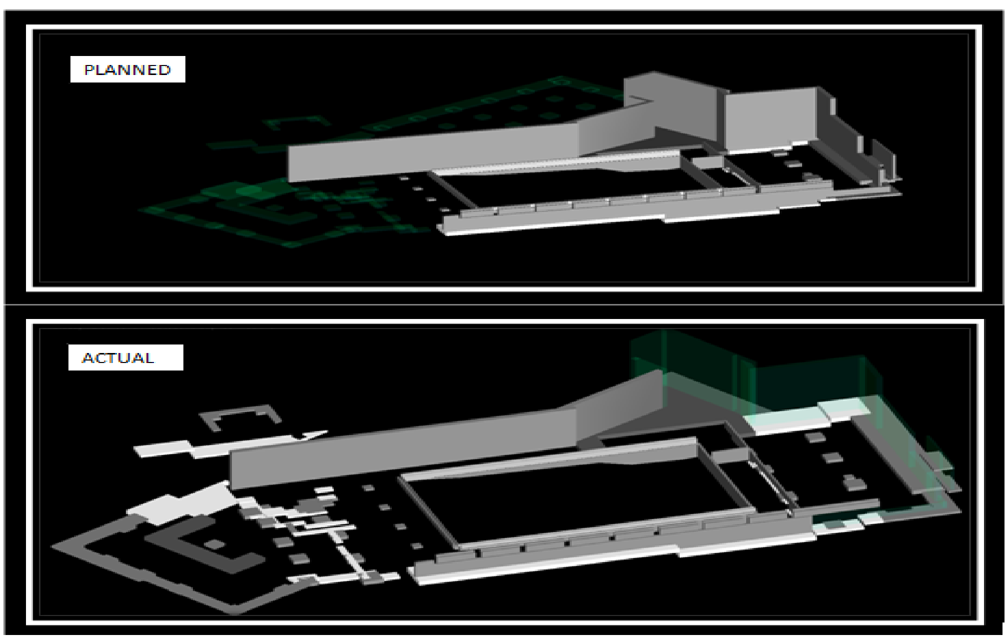


Figure 20: Planned vs. Actual Construction Progress – September 2010

As you can clearly see in these pictures, a significant amount of work was completed on the cast-in-place foundations and footings before it was expected to have occurred. In each of these cases additional materials had to be ordered to meet the faster-than expected pace of the project. This impacts not only the way in which Gilbane can procure materials, but also to the overall cost per time of the project that WPI budgeted for when the project was proposed. Interestingly though, while the concrete roared ahead of schedule, the erection of the steel significantly stalled progress on the building.

The steel structure in area A of the building was the first steel to be built. While the steel started construction on schedule, it immediately fell behind schedule. In Figures 21 and 22, you can see the differences between the planned schedule and the actual construction of the building, and how the two schedules began to deviate significantly. At first, we notice that the steel in area A wasn't completed on time, but then we realize that the construction of precast concrete in area B and the steel in area D are behind schedule and out of the scheduled order.

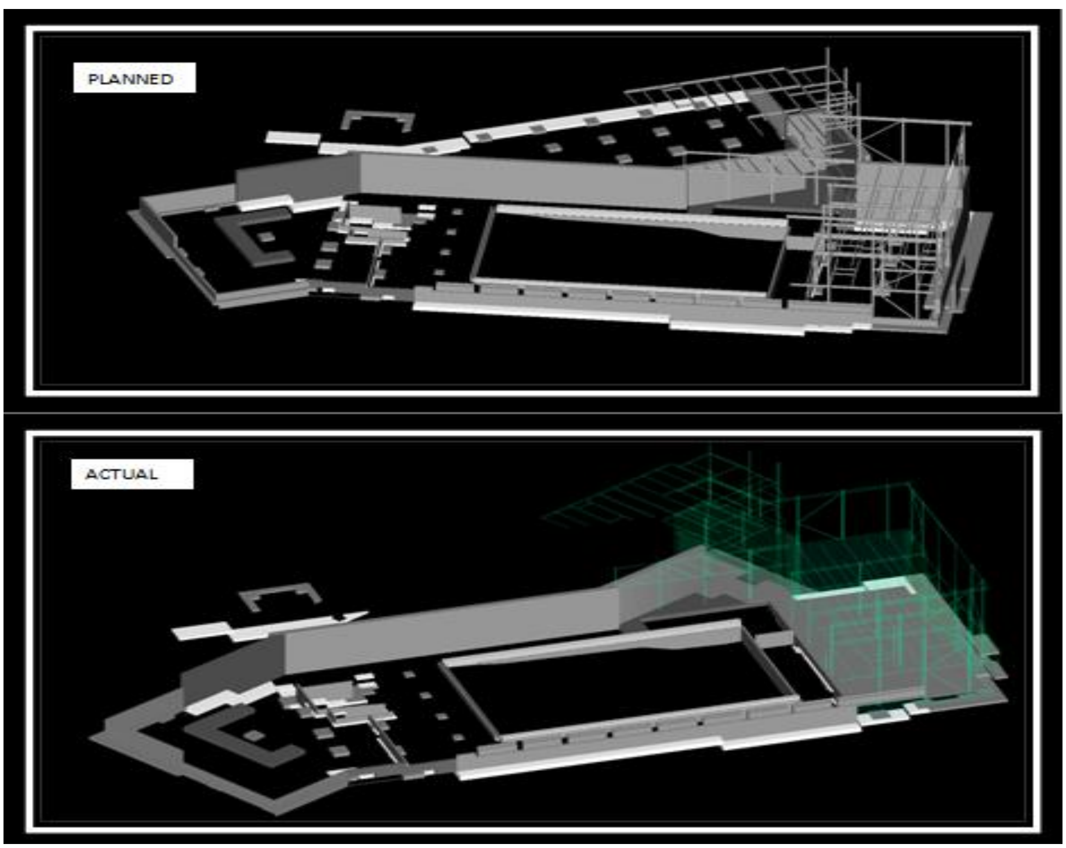


Figure 21: Planned vs. Actual Construction Progress – October 2010

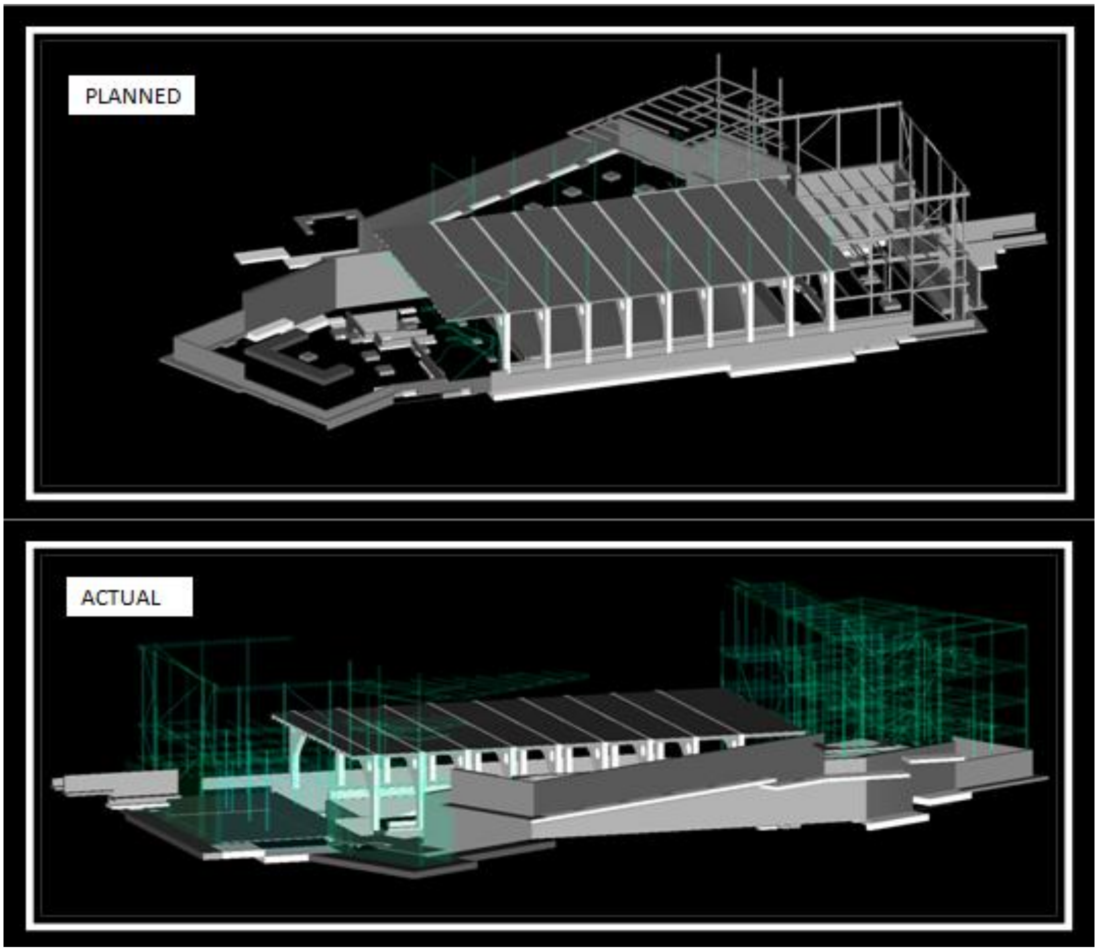


Figure 22: Planned vs. Actual Construction Progress – January 2011

As you can see, the steel slowed the progress of the project, and forced a reevaluation of the schedule. Since work cannot cease, other activities that were planned for later construction began much earlier, while at the same time, work on the steel areas was pressured to continue. Unfortunately the slow steel process only worsened, and looking at the comparison between planned and scheduled events in April 2011 (Figures 23) definitively shows how far behind schedule the project had fallen. Notice that the planned schedule called for completion of the steel trusses, the completion of the roof structure, most major work on steel was to have been already completed, and that brick veneer was expected to be appearing on the façade. In the actual progress, you can see that the trusses are still under construction, that the roof hadn't begun work yet, and that the steel in area A, the first area to receive steel, was still under construction. In the actual progress data, the façade didn't receive brick veneer until August 2011, a considerable four months behind schedule.

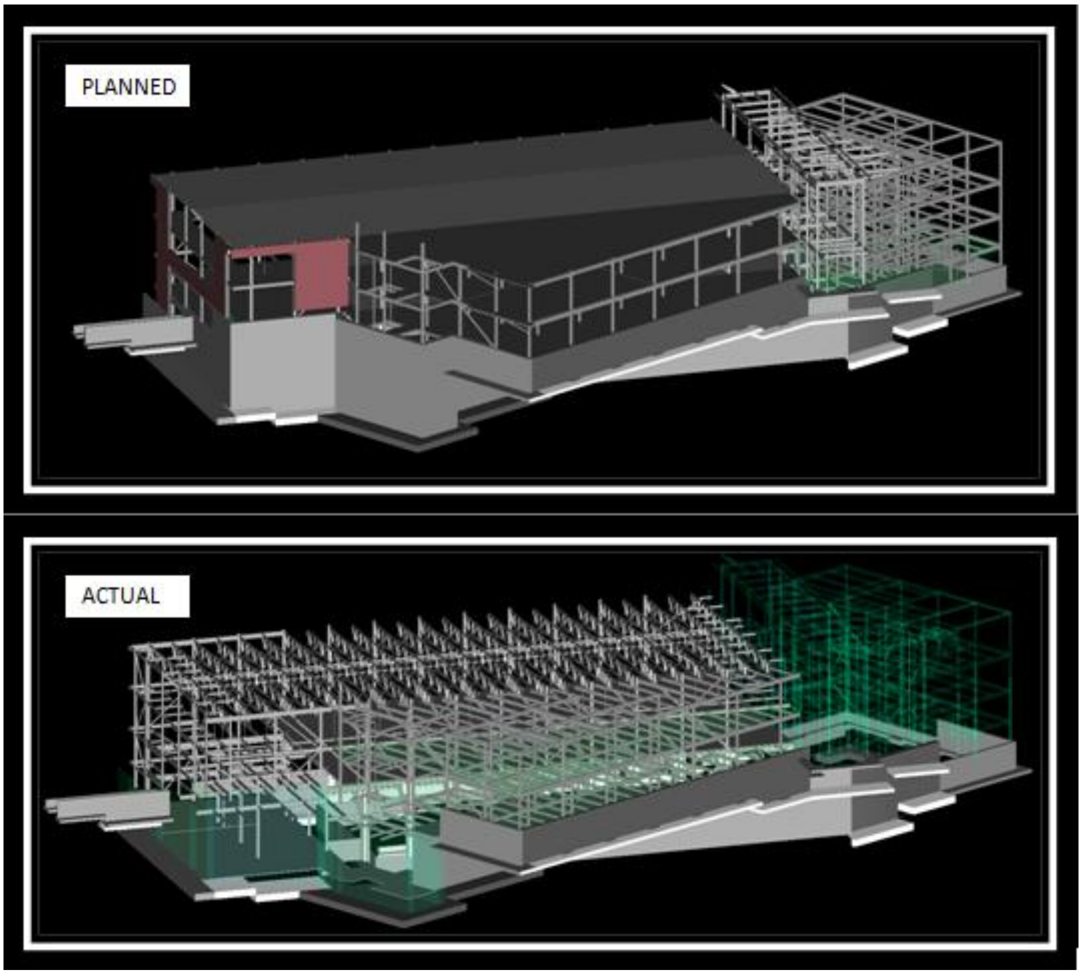


Figure 23: Planned vs. Actual Construction Progress – April 2011

Ultimately the result of the four dimensional model that we developed was a greater understanding of the progress of the project, and how that impacts the parties involved in the construction process. By linking the project schedules to a visual model of what is actually happening, it becomes exponentially more imaginable what the issues may be, and what solutions we may use to solve them. By understanding the progress, we can also begin to predict other resultants from altered schedules. More than just the erection of the building, the schedule depicts the timing of the cost of labor, the timing of the cost of materials, and it lays the foundation for determining the earned value as the project progresses. The difference between the actual and planned schedules can be seen easily in the four dimensional model, and the scheduled variance (SV) can be determined by comparing the models. Ultimately the four dimensional model proved to be an easy method of estimating the schedule performance index (SPI) of the specific trades that were modeled. Appendix I and K show the all of the monthly phases of progress (actual and planned) and their corresponding percent complete.

3.3 Five Dimensional Analysis (5D)

In order to advance our project from a four dimensional model to a five dimensional model, we took the existing visual model paired with the project schedule and integrated the cost impacts of the changing schedule. In order to fully examine the cost distribution of the project and to determine the value of the service WPI had received, we conducted an Earned Value Analysis. By extracting the quantities of materials for trades we examined directly from Revit, we were able to accurately determine the percent completeness of each trade per month. This information then allowed us to determine the percent cost that had been spent in comparison to the amount of work that had been completed. We then also compared the amount spent to the amount expected to be spent for the work performed. In general, our EVA for the Recreation Center compared the Budgeted Cost of Work Scheduled (BCWS) to the Budgeted Cost of Work Performed (BCWP), which yielded an accurate estimation of the cost performance index (CPI) for the trades modeled in our project.

The first major result that our EVA produced was the evaluation of the SPI. The schedule performance index determines if the work performed on the project is over or under valued based on the money that they project has cost the owner to date. In our project we compared the amount of work performed to the expected amount of work performed. In this project, an SPI value of greater than 1.0 meant that the project was under-valued for the amount of work performed. More commonly though, if the value was less than 1.0, than less work than expected had been completely. Since the cost of the project did not vary based on man-hours or work packages, it can be argued that being behind schedule is also a sign of being over-budget for the amount of work performed. A display of the Recreation Center's SPI can be seen below in Figure 24.

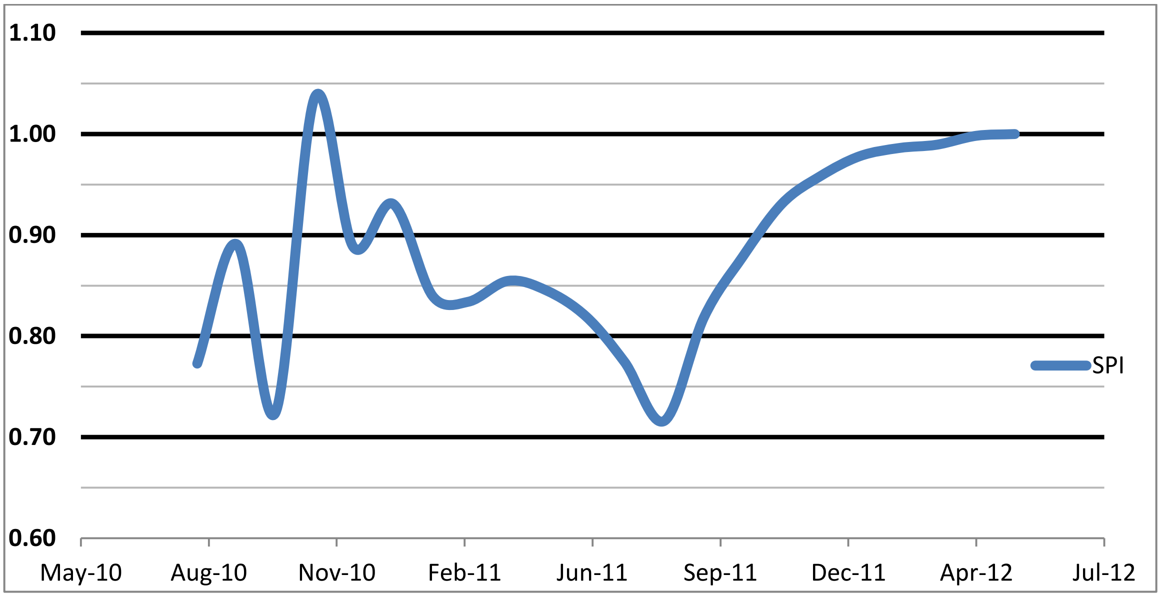


Figure 24: Schedule Performance Index (SPI) of WPI Recreation Center Project

The second result from the project's EVA was a direct comparison from month to month of the expected cost to the actual spent cost of the project. This information is based on the expected cost of the work package as provided by Gilbane Co. Based on the percent complete of each schedule activity at the end day of each month, we calculated the percent of the total cost that was spent. As the schedule changed, so did the value of work that was completed. As you can clearly see in Figure 25, the façade was behind scheduled for the entirety of its construction. What's more, is that time allotted for assembling the façade was shortened drastically, but that the materials purchased and the cost of the work increased.

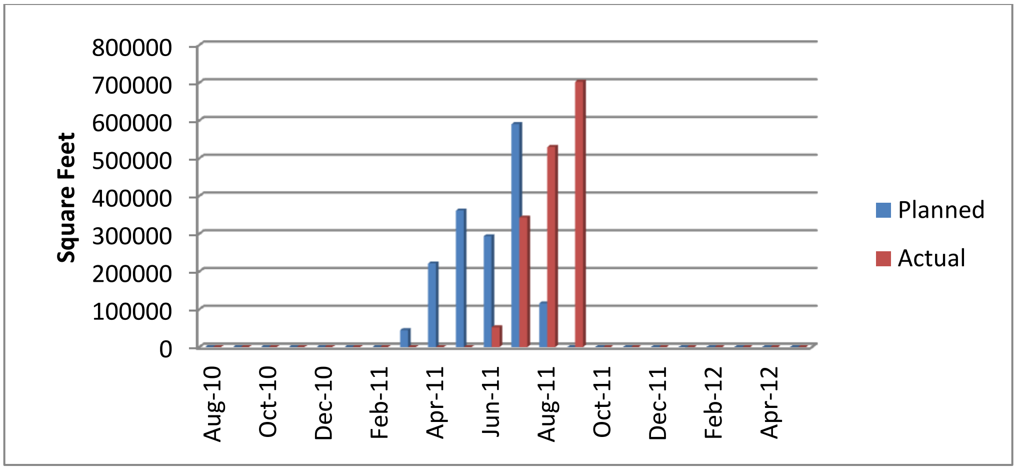


Figure 25: Monthly Brick and Precast (Façade) Concrete Quantities

Most importantly though, is the impact the schedule has on the cost distribution on a project. In the case of the Recreation Center, Figure 31 shows just how offset the project schedule became. Figure 26 also shows the effects on the project's total cost that they construction delays had. Looking closer, you can easily see that the final cost of the project increased by a significant amount simply by extending the number of months that construction took place. Originally the schedule called for the completion of certain trades by September 2011, and in this model, the actual work performed for those same trades extends to May 2012.

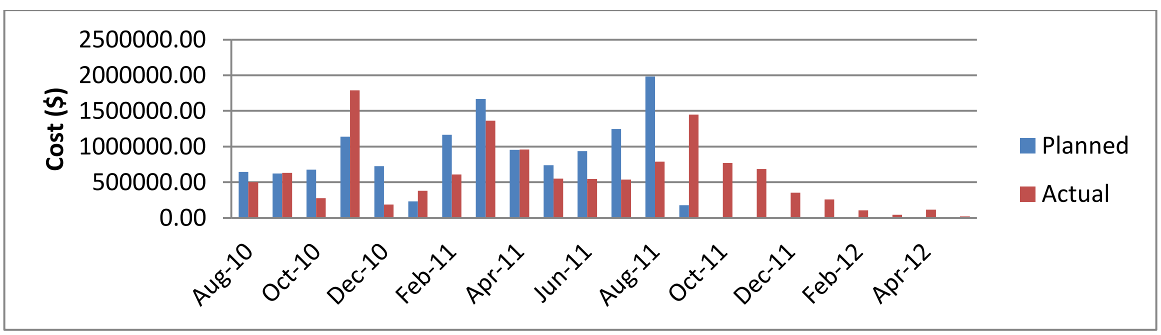


Figure 26: Total Monthly Project Cost

By extending the working months, WPI was then liable for payments they could not have previously anticipated. Further, when shown side by side linearly, you can easily see how the delays from the beginning of the project compounded and created a consistent delay in construction. Figure 27 clearly compares the expected construction performance to the actual construction performance. A more extensive version of this information is displayed in Appendix K, which outlines the cost computations used to derive this graph.

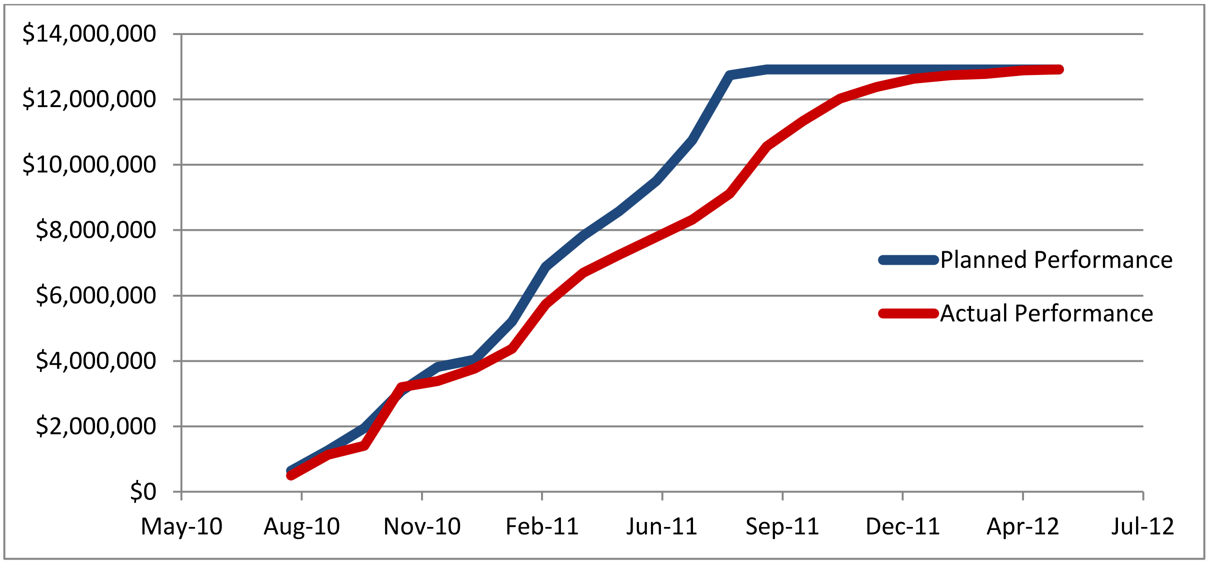


Figure 27: Project Performance Comparison

Potentially the most useful part of any five dimensional analyses is the ability to appropriately budget for and correct budgets of construction projects. By tracking the progress of a project via its performance to its schedule and understanding that performance's impact on the budget, smarter financial decisions can be made regarding project scope, project changes, and any additional work necessary to complete the project. Appendix J includes all of the quantity takeoffs for each trade and is organized by each month for the duration of tracking

3.4 BIM's Potential Uses in Communication - Owner's Meetings

Our group attended the weekly WPI Recreational Center Owner's meetings for first-hand insight into the progress of construction, as well as to determine if the implementation of Building Information Modeling (BIM) during meeting could improve communication between the parties. To gain a better understanding about how BIM could advance meetings we found that it was important to actively participate in the meetings. Therefore we took detailed notes, obtained and studied the weekly agenda, engaged in discussions where we felt we could provide useful input, and spoke directly with representatives after meetings on issues that were relevant at that time.

Through our experience attending the Owner's Meeting, we were able to see firsthand the potential usefulness of BIM in a meeting setting. We recognized several instances where BIM could have been used during the meetings to help solve misunderstandings about the construction. Although the Recreation Center can be seen from the meeting room, it is often difficult to visualize certain locations of the building during discussions, sometimes resulting in parties being confused. Due to lack of visualization it was apparent that not every person was always aware of what was being discussed or decided upon. This confusion often led to a longer than expected debate with parties typically going in circles trying to explain their best solution to a problem. Many times the discussion had no clear outcome and failed to produce a decision, requiring the project manager to wait longer to take action and raising the cost of construction. With a few simple clicks BIM would be able to show any aspect of the construction project, which would allow for all interested parties to have a better understanding of what is being discussed, all available options, and the costs associated with each option. BIM would therefore allow for shorter discussions that ultimately result in more effective and logical solutions.

During the owners meeting we attended, we noticed many instances where confusion could have been alleviated with the use of BIM. One specific example was during a discussion in early October when Gilbane was explaining an issue with the framing system on the roof designed to block the mechanical systems from view on the quad. The problem was that one of the crossbars in the frame was designed too low, resulting in limited access to a door on one of the mechanical systems, requiring a change order. This dilemma was presented to the group at the owners meeting, however there was immediately confusion as to the location of this issue and an overall misunderstanding of the problem altogether. It took nearly 15 minutes for the issue to be further described but there were still some members whom remained unsure and a solution was still not obtained. If a model were available in the meeting, the problem would have been clarified almost immediately, allowing the group substantial time to focus on a proper solution as oppose to wasting time trying to figure out the nature of the issue.

Another example we recognized was during a discussion about the location of the bathing suit dryers. The locker-room with pool access will include bathing suit dryers, which require drainage below them. This requirement was not shown in the drawing, and therefore became a change order. The change order became a discussion spanning several owners meetings. They considered alternative locations from the original design; however there was confusion as to where they were talking about and whether drainage could be provided that these new locations. Excessive time was spent on this issue, especially considering that it was discussed several times. If a computer model was implemented at the meeting, they could have clearly identified the locations they were considering as well as examine the potential availability for drainage and provide information about the dimensions and area of each potential location. This could have greatly reduced time spent on this issue and allowed the group to continue onto other pressing matters.

As the construction of the recreation center got closer to its completion dates it became apparent that there was less time to discuss change orders. During the meetings both Cannon and Gilbane started bringing in visual representations of necessary information regarding the change orders to help explain exactly what needed to be adjusted to the project. One example of this was during a discussion regarding the drainage issue of the canopies. Scott Lindberg, a Construction Administrator for Cannon Design created a Google Sketch Up representation to help show a possible solution to the proposed drainage problems. Figure 28 shows two photos from the Owner's Meeting when Scott was demonstrating the Google Sketch Up model. The photo on the left shows Scott using the mouse to manipulate the drawing and show it from different angles. The photo on the left shows the television screen that the image was projected on. This visual representation provided equal awareness to everyone in the meeting and expedited the decision-making process. Seeing the benefits of BIM in this specific setting through this example made it apparent just how much more could have been accomplished at each owners meeting if every person in the room could easily understand the issue being discussed.

Figure 28: Owner's Meeting with Google Sketch Up Representation

Through attending the owners meetings we also noted that the meeting updates were delivered only verbally and in the form of change orders. A BIM model could allow for the project manager to give the updates visually as well as verbally. This would provide the attendees at the meeting a more accurate understanding of the progress and in turn allow them to participate more actively during the meetings.

3.5 Summary of BIM Findings: 4D, EVA, & Communication

Throughout the process of creating a schedule, tracking the construction, identifying the model and running a cost analysis we learned about the efficiency of BIM for both tracking a project and problem solving at an owners meeting. Through the use of our schedules, models and quantity takes offs we determined that while the WPI Sports & Recreation Center's construction started by pouring the concrete ahead of schedule it quickly fell behind schedule when erecting the steel. After construction fell behind schedule Gilbane had to move around their schedule, overlapping some activities and completely switching the order of other activities in order to complete the project on time. Due to the scheduling changes the cost of the work groups was not necessarily distributed as planned, causing the earned value analysis to show as behind schedule or over budget.

Sitting in on owners meetings gave us firsthand knowledge into the construction of the project. This helped us gain a better feel for the target completion dates of different activities. It also allowed us to get to know the key members involved in the project and to determine possible uses for BIM in owners meetings. From these meetings we learned that incorporating BIM into an owners meeting could be a very useful tool for explaining to current construction phases of the project as well as for explaining issues within the project and for exploring the best possible solutions to solve those issues. Sitting through meetings we saw exactly how implementing visual models can substantially decrease the time it took to establish and agree upon a solution for a construction problem rather than verbally explaining the issues and possible solutions.

From this project we determined that BIM may be a key aspect in the future for tracking construction projects and relating construction knowledge to an owner in a simple way.

4.0 RECREATION CENTER & HARRINGTON AUDITORIUM CONNECTION

For the design portion of our project, we analyzed the geotechnical, structural and functional aspects relating to the connection between Harrington Auditorium and the new Recreation Center. Our analysis included a review of the geotechnical design beneath Harrington necessitated by the excavation at the adjacent Recreation Center construction site. Based on our review, we developed an alternative underpinning design to address the issues induced by excavation and the building connection. Another focus of our analysis was the tie-in between the two buildings, in which we explored both the structural components and the inherent functional implications of connecting the building directly into a fully-operational trainer's room. We employed multiple methods to address each issue effectively. The procedures we followed and the results we obtained are outlined in the following sections.

4.1 Underpinning Design: Methodology & Results

The first thing we examined when beginning the design portion of our project was the geotechnical design beneath Harrington Auditorium. Due to the massive amount of excavation that occurred during the construction of the Recreation Center, part of the original foundation of Harrington Auditorium will experience a reduction in loading capacity. Thus, geotechnical engineers had to devise a plan to ensure the stability of Harrington Auditorium. Gilbane hired GZA GeoEnvironmental, a geotechnical engineering firm, to perform the soil analysis and develop a stabilization design for Harrington. We reviewed both their design and other related, well-established sources and established a potential alternative.

We began by contacting Gilbane directly and they provided us with the documentation we needed to perform effective and accurate analysis. The documents included GZA GeoEnvironmental design specifications as well as correspondence documents between the two firms that occurred during the planning stage. The correspondence documents tracked how the design changed and developed over time as new pertinent information became available. By examining the changes that were made before a final design was agreed upon we were able to understand the exact needs of the design given the conditions of the site. We used the documents primarily to understand pre-existing conditions and dimensions of the area. The GZA design documents provided data pertaining to loading conditions and dimensions of the foundation wall and footing, information we would not have been able to determine elsewhere. However, when creating our own alternative design we performed calculations independently from the GZA design. Instead, we based our design on underpinning design procedures developed by the Federal Highway Administration and other related sources (FHWA Pub. RD-75-129).

4.1.1 Loading Conditions & Dimensions

The first step of designing the underpinning was verifying the loading conditions applied to the footing of Harrington. The loading conditions consist of the weight of the roof which is comprised of a waffle slab, T&G roof, and snow load, as well as the weight of the wall resting on the footing. The roof load has a tributary width of 8 feet and the wall has a height of 14 feet. Figure 29 shows the basic dimensions of the structure that will be underpinned. We used the same quantities used by GZA to determine a distributed load of 3.9 kips per linear foot of footing. The calculations for determining the load as well as all calculations steps that follow in this methodology section can be found in Appendix L.

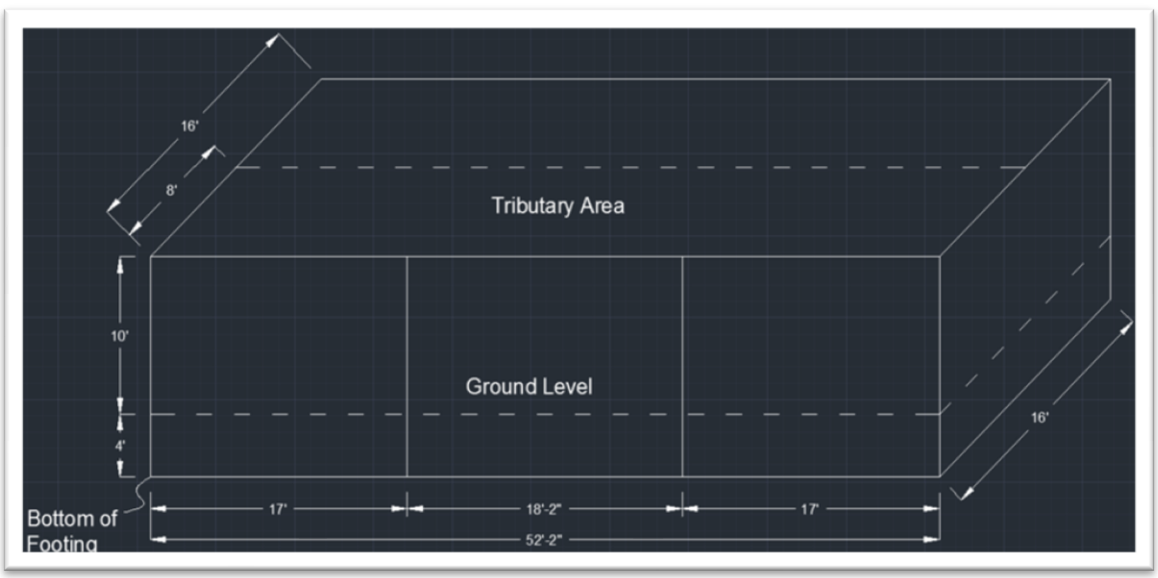


Figure 29: Dimensions of the Harrington Auditorium Section Used for Designing Underpinning

4.1.2 Pile Size/Surface Area Calculations

Micropiles were chosen as the type of underpinning to be used for the geotechnical design of the Recreation Center. We also used micropiles as the primary geotechnical component of our design. There are several essential design aspects of underpinning micropiles to prevent all possible failures, including axial loading capacity, allowable maximum compression stress, contact bonding between the micropile and the existing footing. Axial loading capacity deals with the resistance of the soil against the micropile and failure occurs when the soil does not properly support the micropile and slipping occurs. Compression stress failure occurs when the compressive strength of the materials within the micropile cross section cannot support the applied compressive load and usually results in the fibers/materials breaking down. Contact bonding failure occurs when the contact surface between the micropile and existing footing does not remain static and slips. We addressed each of these failure modes when developing our micropile design to ensure that it is structurally sound.

After determining the loading conditions, the next step was calculating the minimum pile sizes required to support the distributed load of 3.9 kips per linear foot (klf) along the footing. The maximum allowable spacing of piles for Harrington is 8', so we calculated the total load per pile to be 31.2 kips (8' x 3.9 klf). In essence, each pile would experience a maximum load of 31.2 kips individually and would need to be designed with a loading capacity greater than this. The available capacity of a pile is predominantly dictated by its surface area and structural capacity of both the steel and grout combined. Safety factors require the allowable stresses of steel piles to be no more than 40% of its yield strength ($0.4F_y$) and for concrete piles no more than 33% of its compressive strength ($0.33f'_c$), (FHWA, 1983). Once factored, the strength of both steel and concrete (typically in ksi or psi) are multiplied by each respective area and added together to get the overall allowable capacity.

We considered several different configurations for micropiles with different grout-to-steel cross sections and calculated their available capacity. For example, one configuration we considered was a 6" diameter pile size comprised of 5000 psi grout, a #8 steel reinforcement bar (Grade 75ksi), and a 3" diameter steel pipe. A cross section of this particular micropile configuration is shown in Figure 30.

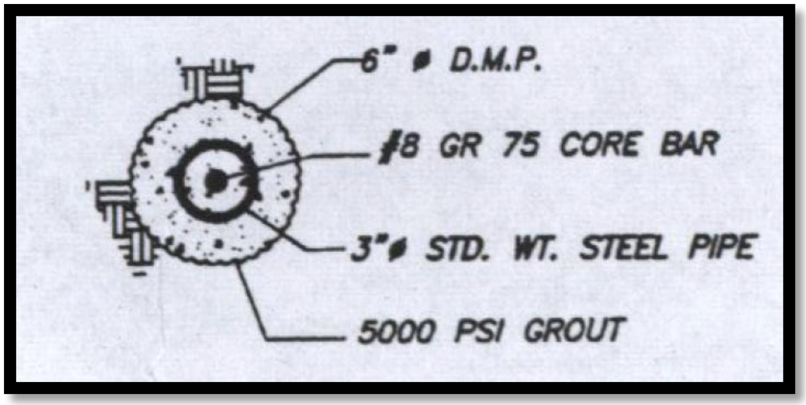


Figure 30: Cross Section of Underpinning Used Beneath Harrington Auditorium

Based on the area and structural capacity of both the steel and grout combined (steel pipe is not considered since it is only installed for construction purposes), we determined the overall capacity of the micropile. These calculations are organized within Table 5. Based on this specific design, the micropile has a compressive failure loading limit of 68.9 kips, which is greater that the applied load of 31.2 kips (calculated previously), ensuring that it is structurally sound under the compressive load of 31.2 kips.

	AREA (IN^2)	REDUCTION FACTOR	STRENGTH	CAPACITY (kips)
STEEL	0.79 in^2	0.4	F_y = 75 ksi	23.7 k
GROUT	27.4 in^2	0.33	f'_c= 5000psi (5 ksi)	45.2 k
COMPRESSIVE LOAD LIMIT FOR 6" PILE w/ 5000 PSI GROUT & #8 STEEL REINFORCEMENT:				68.9 KIPS

Table 5: Compressive Load Limit Calculations for 6" Diameter Micropile w/5000psi Grout & #8 Rebar

The configuration previously discussed was the actual design used for the Harrington Auditorium underpinning. Although this design met structural requirements, we tested several other designs to determine if there were other configurations that could have been applied that would reduce material but also be structurally sound. We tested the structural capacity for preventing compressive failure of several different grout-to-steel combinations and determined if they would withstand the actual compressive loading forces applied to (31.2kips). We organized them and performed our calculations within an Excel spreadsheet and created a table which can be seen in Table 6.

	MATERIAL	AREA (sq. inches)	SAFETY FACTOR	STRENGTH	CAPACITY (kips)
DESIGN 1: **5" DIAMETER; #8 STEEL**	STEEL	0.79	0.40	75	23.7
	GROUT	18.84	0.33	5.0	31.09
	Maximum Compression Load: 54.79 kips				
DESIGN 2: **6" DIAMETER; #8 STEEL**	STEEL	0.79	0.40	75	23.7
	GROUT	27.4	0.33	5.0	45.21
	Maximum Compression Load: 68.91kips				
DESIGN 3: **7" DIAMETER; #8 STEEL**	STEEL	0.79	0.40	75	23.70
	GROUT	37.69	0.33	5.0	62.19
	Maximum Compression Load: 85.89 kips				
DESIGN 4: **5" DIAMETER; #7 STEEL**	STEEL	0.60	0.40	75	18.00
	GROUT	19.03	0.33	5.0	31.40
	Maximum Compression Load: 49.40 kips				
DESIGN 5: **6" DIAMETER; #7 STEEL**	STEEL	0.60	0.40	75	18.00
	GROUT	27.67	0.33	5.0	45.66
	Maximum Compression Load: 63.66 kips				
DESIGN 6: **7" DIAMETER; #7 STEEL**	STEEL	0.60	0.40	75	18.00
	GROUT	37.88	0.33	5.0	62.50
	Maximum Compression Load: 80.50 kips				
DESIGN 7: **5" DIAMETER; #6 STEEL**	STEEL	0.44	0.40	75	13.20
	GROUT	19.19	0.33	5.0	31.66
	Maximum Compression Load: 44.86 kips				
***DESIGN 8*:** **6" DIAMETER; #6 STEEL**	STEEL	0.44	0.40	75	13.20
	GROUT	27.83	0.33	5.0	45.92
	Maximum Compression Load: 59.12 kips				
DESIGN 9: **7" DIAMETER; #6 STEEL**	STEEL	0.44	0.40	75	13.20
	GROUT	38.04	0.33	5.0	62.77
	Maximum Compression Load: 75.97 kips				

Table 6: Structural Compressive Failure Capacity for Potential Design Configurations

4.1.3 Axial Loading Capacity Calculations: Design Bond Length & Embedment Depth

Next, we determined the minimum bond length using the FHWA chart of Allowable Bond Values seen in Figure 31 (NHI/FHWA, 2006). Based on the "Compact Sand" soil parameter, the range of bond values is 5-10 k/ft. The calculation for bond length is determined by dividing the actual load by these bond values (both 5k/ft and 10k/ft) in two separate calculations. Whichever produces the largest value for bond length will be used as the minimum bond length. In the case used by GZA this was the 5k/ft value which produced a minimum length of 6.24 feet when using the actual load value of 31.2 kips.

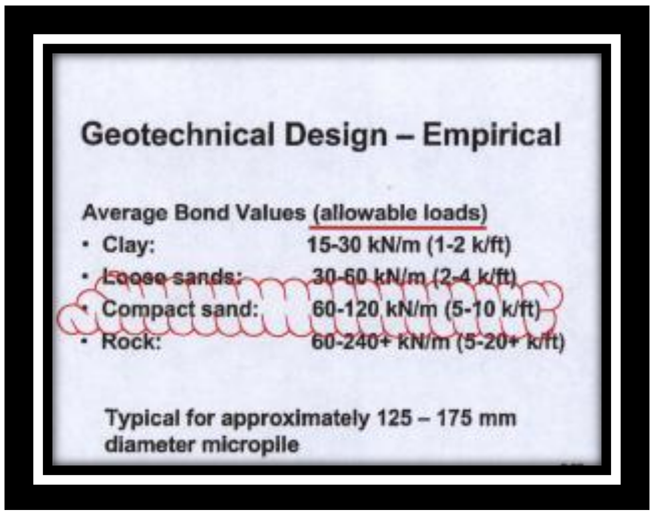


Figure 31: Average Bond Values for Various Soil Parameters (NHI/FHWA, 2006)

The next step in designing the underpinning was determining the necessary depth that it needs to be embedded into the soil, which is based primarily on the soil properties and the design load to be resisted. The soil underlying Harrington Auditorium is composed primarily of very dense cemented glacial till which has a unit weight of 125 pcf (GZA, 2009). We used several different well published sources, mainly the Federal Highway Administration, to determine embedment depth requirements and calculations. The sources as well as calculation procedures we used to determine the embedment depth can be seen in Appendix L.

The first step of determining embedment depth is choosing an anchor length and finding the corresponding ultimate load. Figure 32 shows a chart of Ultimate Load (kips) vs. Length of Anchor (ft) with varying soil parameters (Goldberg/FHWA, 1976). The soil underlying

Harrington Auditorium falls under the “Sandy Gravel” consistency, as shown in the Figure. By choosing a test anchor length you can plot what the estimated Ultimate Load will be. We used the minimum design length of 6.25 feet which we calculated earlier as a starting point and then tested other designs with greater lengths and found their corresponding ultimate loads. The Ultimate Load factor is then used to calculate the Safety Factor (Ultimate Load divided by Actual Load). According to the FHWA, the ultimate load should be at least 150% of the actual load, which is also a factor of safety greater than or equal to 1.5

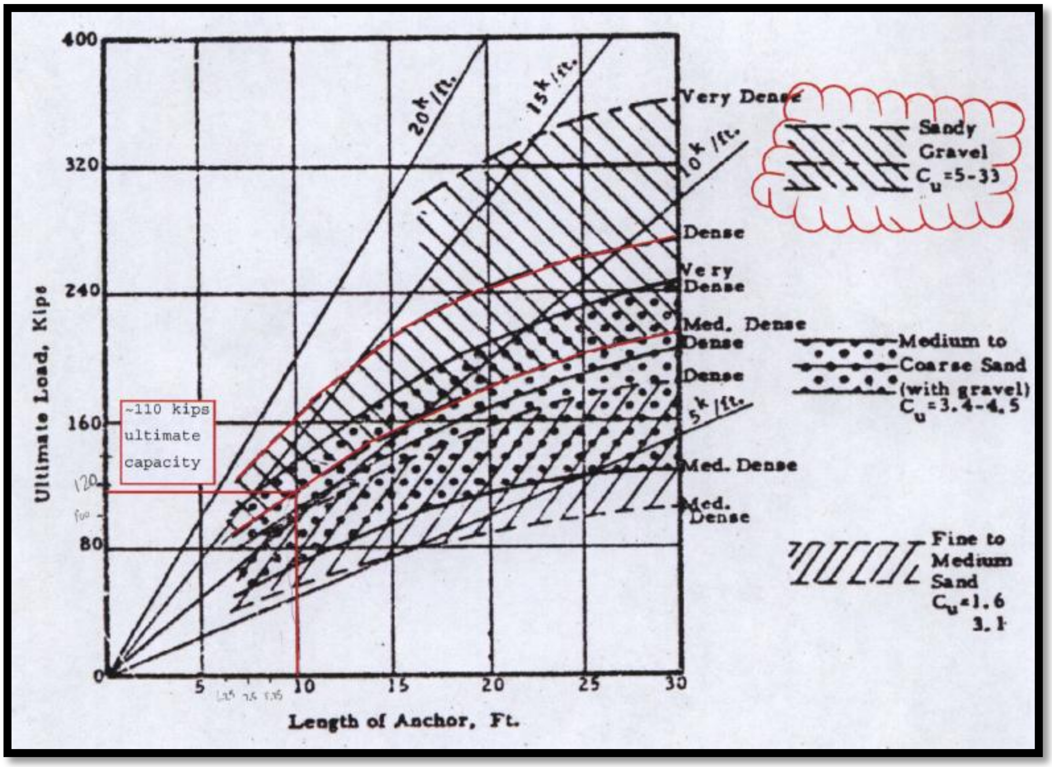


Figure 32: Ultimate Load vs. Length of Anchor for Various Soil Parameters (FHWA)

We organized and performed our calculations within an Excel spreadsheet. Table 7 shows the design calculations for different embedment depths of the underpinning corresponding to different FS values. We examined seven different embedment depths to determine the minimum depth necessary to properly secure the footing while minimizing the amount of material. We chose a design depth of 9’ for our underpinning design because it easily meets safety design requirements but also reduces material compared to longer designs. Our design recommendations are discussed in further detail later in this section.

Footing Load (kips)	Minimum Depth (ft)	Design Depth (ft)	Ultimate Load Capacity (kips)	Safety Factor	Minimum Safety Factor	S.F.>Minimum S.F.?
31.2	6.25	6.25	85	2.72	1.5	YES
31.2	6.25	7	90	2.88	1.5	YES
31.2	6.25	8	100	3.21	1.5	YES
31.2	6.25	9	105	3.37	1.5	YES
31.2	6.25	10	110	3.53	1.5	YES
31.2	6.25	12	130	4.17	1.5	YES
31.2	6.25	15	150	4.81	1.5	YES

Table 7: Alternative Design Depths and Their Corresponding Safety Factor

4.1.4 Grout-to-Concrete Connection Calculations

The final step is checking the grout-to-concrete connection and assuring its contact bonding strength will not result in failure. The grout-to-concrete connection is the product of surface contact area between the grout and the footing and the bond strength between them.

Bond Strength

We began by finding the ultimate bond value, which is the strength between two surfaces in pounds per square inch and depends on the type of materials in contact. Table 8 contains ultimate bond values between grout and various types of rock. Using this table of rock/grout bond values from the PCI publication “Foundations in Tension” we obtained the ultimate bond value for “Weathered Granite” which is in the range of 217-365psi. The reason we used Weathered Granite is because it is very similar concrete in bond value, which is 200-400psi (Williams, 2011).

Table 4.2 (a)
Rock/grout bond values which have been recommended for design
(After Littlejohn and Bruce, 1976)

Rock type	Working bond (N/mm²)	Ultimate bond (N/mm²)	Factor of safety	Source
Igneous				
Medium hard basalt		5.73	3—4	India-Rao (1964)
Weathered granite		1.50—2.50 (217–365 psi)		Japan-Suzuki et al. (1972)
Basalt	1.21—1.38	3.86	2.8—3.2	U.K.
Granite	1.38—1.55	4.83	3.1—3.5	U.K.
Serpentine	0.45—0.59	1.55	2.6—3.5	U.K.
Granite & basalt		1.72—3.10	1.5—2.5	USA-PCI (1974)

Table 8: Rock/grout Bond Values for Calculating Grout-to-Concrete Connection (PCI)

Factor of Safety & Ultimate Capacity

Next, we determined ultimate capacity of the anchor which is a function of the allowable capacity and the Factor of Safety. According to the FHWA, the minimum safety factor for a rock-grout bond should be no less than 2.0. Using a factor of safety of 2.0 and the already know allowable capacity of 31.2 kips we calculated ultimate capacity to be greater than or equal to 62.4 kips. The following calculations show this procedure quantitatively:

- $P_u = F.S. \times P_a = 2.0 \times 31.2$ *kips* $= 62.4$ *kips* $= 62{,}400$ *lbs*

  Where:
  P_u = *ultimate capacity*
  P_a = *allowable capacity*
  F.S. = Factor of Safety

Contact Area

Next, we calculated the contact area between the grout and concrete footing. Figure 33 shows a schematic of a micropile/footing connection. Since micropiles are installed at an angle, the contact area between the pile and the footing is a function of the angle at which the pile is installed:

- *Contact area* $= (\pi \times D_p \times L_f) / \cos\phi$

  Where:
  D_p = *diameter of pile hole (in)*
  L_f = *length/thickness of footing (in)*
  ϕ = *Effective pile angle*

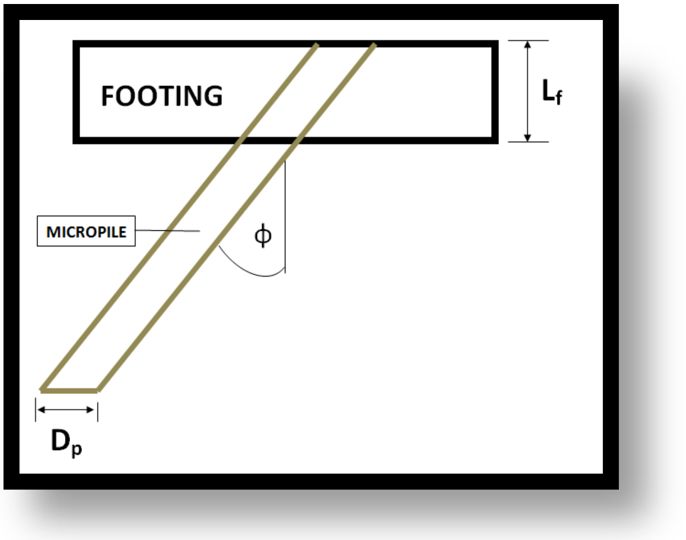


Figure 33: Simple Schematic of a Footing with an Angled Micropile

If you think of this calculation conceptually, when the angle is increased, the contact between the pile and footing is also increased, thus increasing the overall surface area. Also, when the diameter is increased, the surface area is also increased. The issue when developing our design was that we had to find both a diameter and angle that would satisfy the grout-to-concrete connection. Since these factors were unknown (or undecided) we had to develop a calculation where we had the angle as a function of the diameter. We did this by reorganizing the ultimate capacity equation, which can be seen below.

- $P_u = [\pi \times D_p \times L_f \times \delta\ ] / \cos \phi$
  Where:
  D_p = diameter of pile hole (in)
  L_f = length/thickness of footing (in)
  δ = Bond strength (psi)
  ϕ = Effective pile angle
- *In terms of Effective Angle,* $\phi = \cos^{-1}[(\pi \times D_p \times L_f \times \delta) / P_u]$

After plugging in all of the known factors (L_f = 12"; δ = 200psi; P_u = 62,400 lbs), we were able to develop a simple relationship between the diameter and the angle: $\phi = \cos^{-1}(0.1208D_p)$. With this relationship, when testing different micropile designs, we could find the necessary minimum embedment angle necessary for any diameter micropile. Figure 34 shows this relationship graphically given the constant, known factors of the Harrington footing.

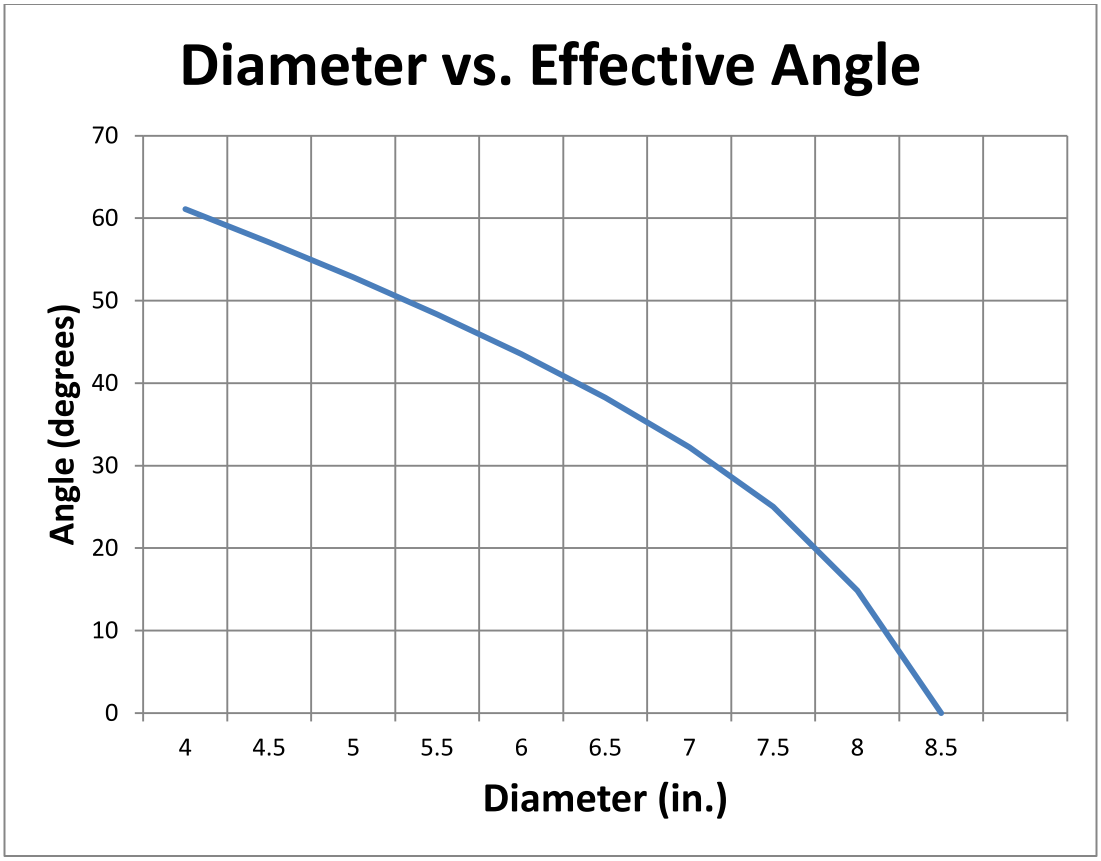


Figure 34: Effective Angle vs. Diameter of Micropile Hole

We used this graph to develop the optimum diameter/angle combination. According to FHWA, the effective angle should not exceed 45^o and it general designs are within the range of 20^o to 40^o. By simply looking at the graph you can see that all diameter sizes before 5.75 in require an angle greater than 45^o, so any size larger would be suitable at its given angle. Figure 35 better shows this point.

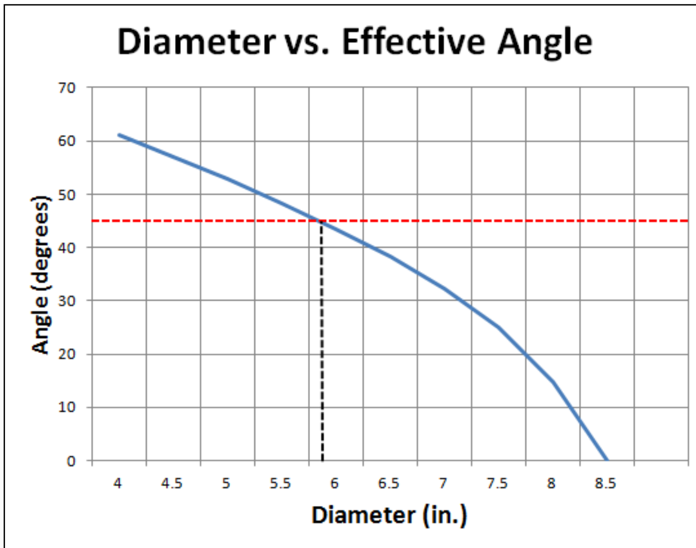


Figure 35: Minimum Diameter and Angle Requirements

4.1.5 Final Underpinning Design Recommendations

Based on all of the design criteria that we determined, we developed a design for the underpinning that would be both structurally sound and have a relatively minimal material requirement. Since the minimum diameter hole is 6" we decided to use a 6" cross area micropile which creates a 7" hole during drilling, so it is on a conservative measure by one inch. We didn't want to go much larger than this in an effort to minimize material. We also chose a 5000psi grout cross section reinforced with #7 steel rebar (Grade 75 ksi), which can be seen in Figure 37. This design results in a compressive capacity of 63.6 kips, which is over twice the required capacity of 31.2 kips. Also, the axial loading strength we determined was based on a 9 foot pile embedment which results in a 105 kips capacity. Although this is a very conservative measure, we couldn't really reduce size since it was constrained by the required diameter. Also, the available capacity would have reduced significantly if we chose a rebar size any smaller. Lastly, when choosing the effective angle we wanted to use a conservative approach that would meet the grout-to-concrete requirements but also supply lateral support to the structure. Therefore we chose an effective angle of 40^{o}, which met the required angle of at least 30^{o} for a 7" drilling hole.

In addition to the cross section and effective angle we proposed, we also designed for micropile spacing and bond length. Since the max pile spacing is 8 feet and the total length of footing is 52 feet, the resulting minimum number of piles is 6.5, which rounded up is 7. After viewing the layout of the footing, we decided to have 8 piles total: one at each end of the footing (2), one at each indent for the doorway (2), and four more evenly dispersed between. Figure 36 shows this layout schematically in a plan view. As for the length of the piles, we chose 9' which meets the minimum requirement of 6.25'.

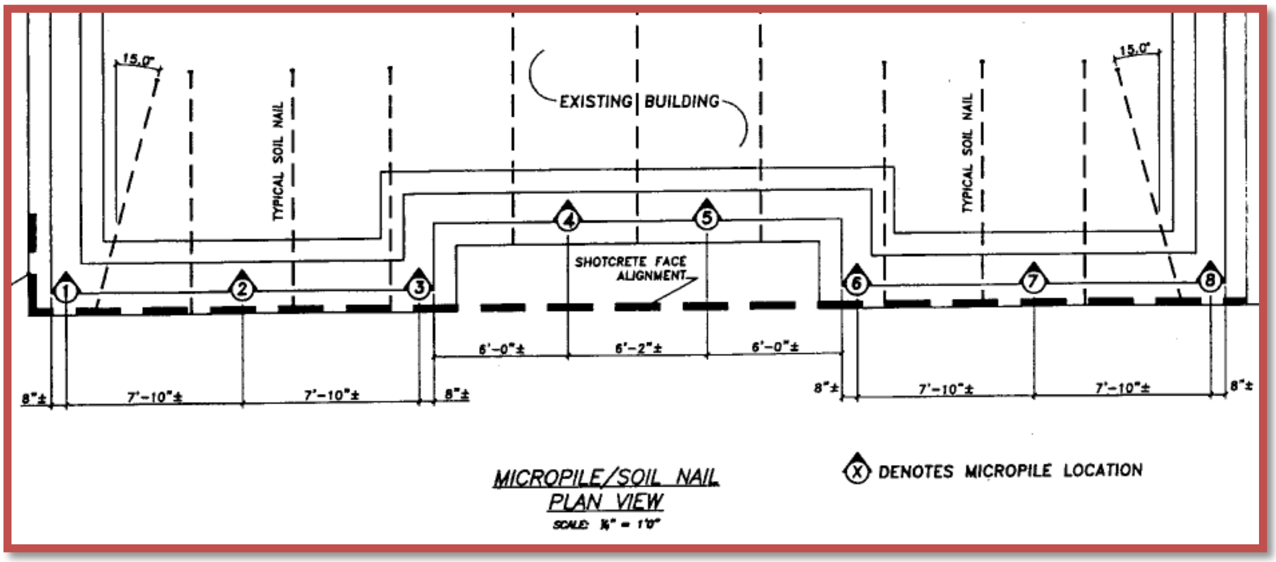


Figure 36: Plan View of Location of Underpinning at Harrington Footing

Our design meets all design specifications and also reduces material while maintaining structural stability. Our final design can be seen in Figure 37. Compared to the design used by WPI, our design uses one less foot of material per footing and 0.19 in^2 less steel (#7 bar vs. #8), reducing the amount of steel necessary by 31.6%. All results and calculations are outlined in Appendix L.

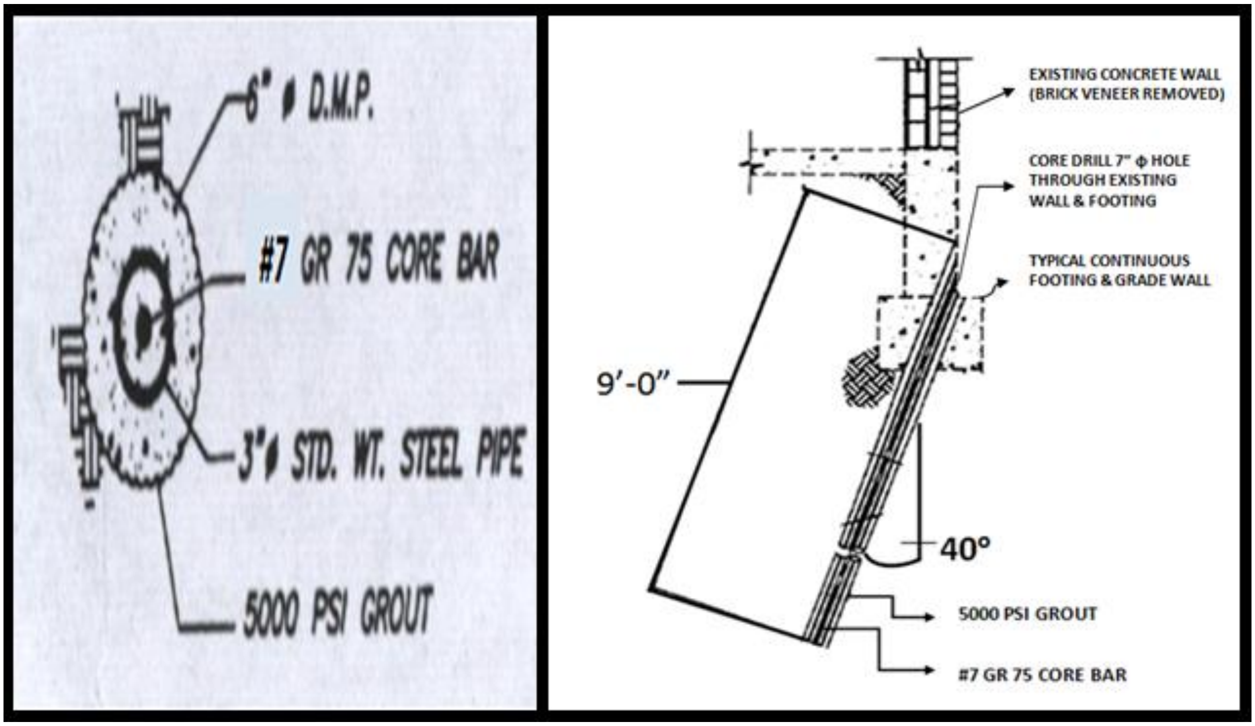


Figure 37: Final Proposed Underpinning Design

4.2 Structural Interaction – Tie-In Framing Design

In addition to analyzing the geotechnical design beneath Harrington Auditorium, we also examined the connection between Harrington and the Recreation Center and developed a framing system design for the tie-in. We designed the system to adequately support the loading system applied to it and to minimize lateral deflection. Figure 38 shows a plan view of the proposed connection between the Recreation Center and Harrington Auditorium.

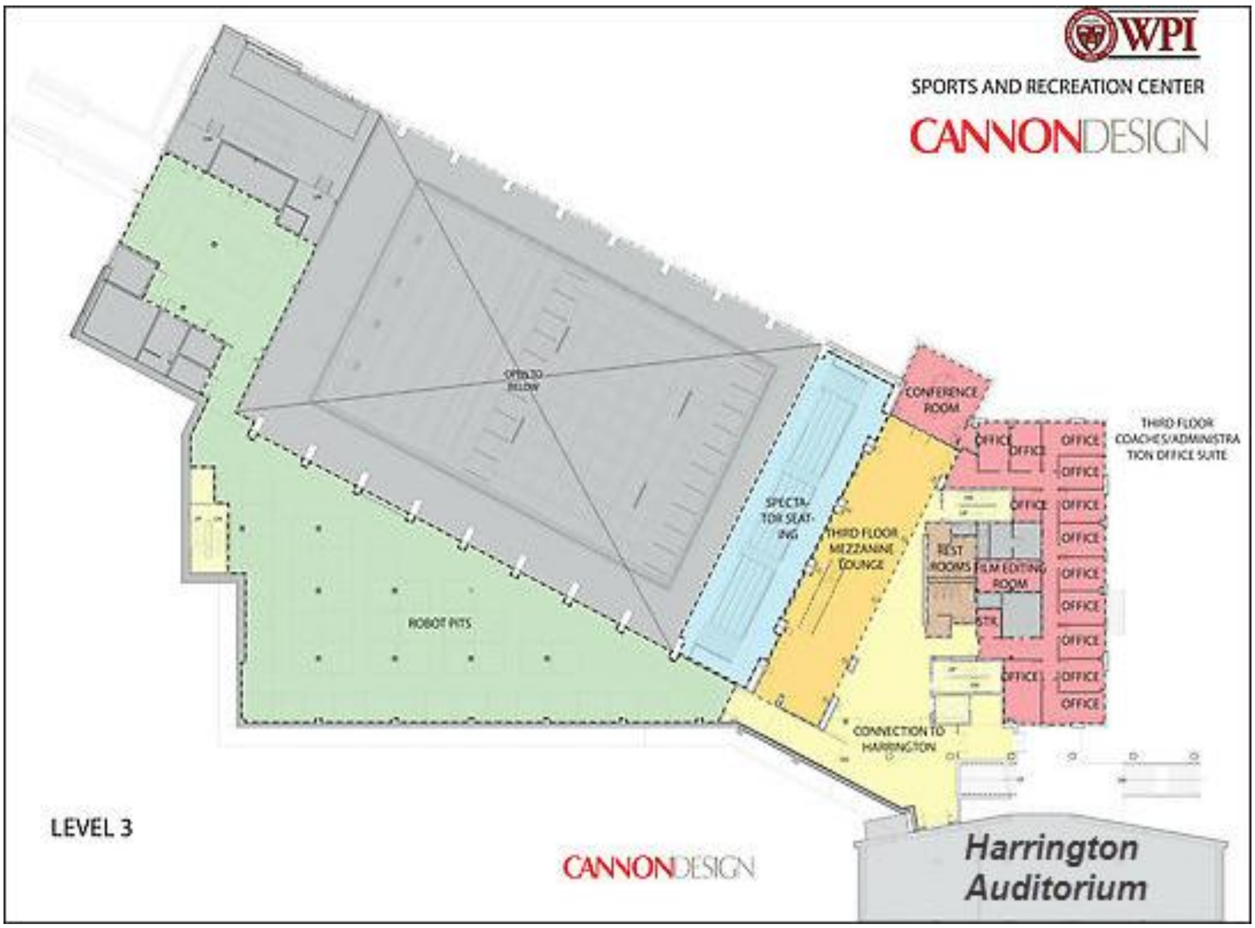


Figure 38: Recreation Center/Harrington Auditorium Tie-In Plan View

Before we began the design of the framing system for the tie-in, we studied structural models of both Harrington and the Recreation Center to gain a better understanding of how the two buildings will interact with each other. There was limited information on the structural components of Harrington since it was built in 1960, however Cannon developed a Revit model of Harrington based on observation. The model was not in-depth but it did allow us to view the floor plans and gain a better understanding of the dimensions and location of the tie-in. Cardinal Construction also supplied us with AutoCAD files of Harrington that were used by SMMA, the subcontractor hired to perform the construction of the tie-in. We used the AutoCAD file in conjunction with the Revit model to improve our overall comprehension of the proposed tie-in.

As for the Recreation Center, we reviewed their structural Revit model which was incredibly detailed, providing us with elevations, dimensions, areas, and location of the tie-in. We originally thought that the connection was to occur at the foundation wall, which would have a large structural impact on the underlying footing and geotechnical structures. However through reviewing the models and speaking with construction representatives, we discovered that the wall was simply an exterior wall, with basic loading properties, and with little impact on the underlying structure. Although this reduced the level of structural analysis we had to perform, we still had to design the framing system to withstand the distributed load and meet all safety criteria.

4.2.1 Determining Tie-In Dimensions

We began our design by first determining the dimensions of the tie-in. We used several methods to estimate the height and width of the connection. First, we examined the area while taking a tour of the Recreation Center during construction with Michael Andrews of Cardinal Construction, prior to breaking through the wall. We didn't take any measurements but instead just made visual observations. We observed that the right wall (south side of the connection) runs parallel to an entrenchment for a mechanical unit attached to the exterior wall of the trainer's room. We used this information when viewing Revit models later on in the project. We also observed that the concrete slab in the Recreation Center was within 2 inches of the exterior wall of Harrington, which we expected would be sealed when the connection was made. Also during our tour, Mr. Andrews explained how the width of the wall would be restricted by an interior column within the Harrington Auditorium wall on the left side of the connection. Therefore, our tour made us aware of the confinements of the connection: the interior column and the entrenchment. The location of both the column and entrenchment are identified in Figure 39.

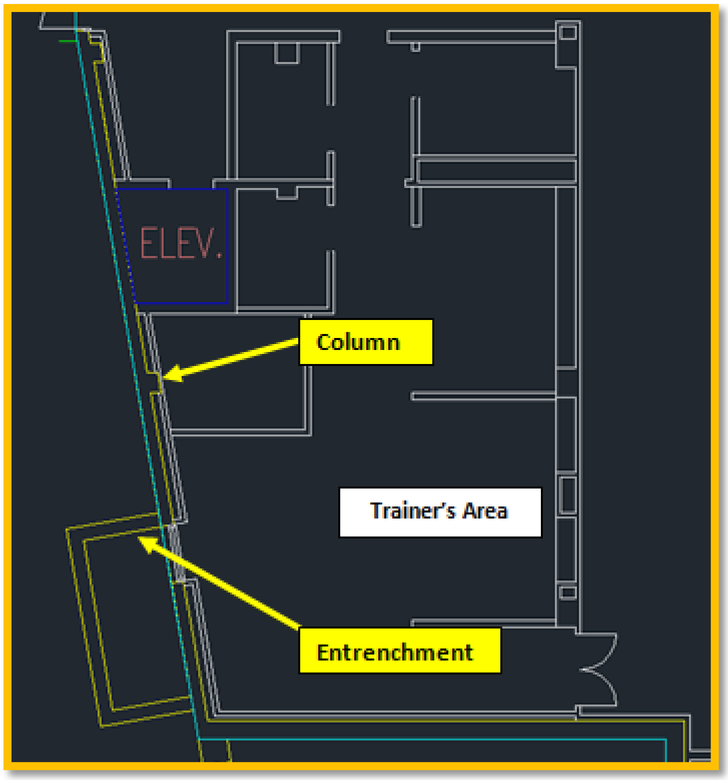


Figure 39: Trainer's Room w/ Location of Column and Entrenchment

We then studied the AutoCAD floor plans of the gymnasium level of Harrington Auditorium, the floor in which the tie-in will be taking place. The drawings showed the location of the column that restricts the width of the tie-in, however the dimensions were not specified, and we could not make exact measurements because we didn't know the accuracy of the drawing since it was developed many years ago and then put into CAD format. However, we found it safe to assume that the location of the beam and estimate it within 2feet of its location.

The final step we took in estimating the dimensions of the tie-in was taking measurements of the trainer's room in the area of the proposed tie-in. We were able to locate the entrenchment since it was also the same location of a window in the trainer's room. We also spoke with the Assistant Athletic Trainer Aimee Sevigny who was working in the trainer's room when we visited. She explained how construction workers had performed an exploratory drill hole in the wall in her office recently and showed us the location. The hole had been covered up, but we used that as an assumed location of the column and measured the distance between that and the entrenchment. We found the width to be approximately 10 feet and estimated that the tie-in width would be about 8 feet which is the width of a large double door with a few extra inches to spare.

As for determining the height of the tie-in, we spoke with construction representative of Cardinal Construction and Cannon Design and they said the height would be 8'-6" (102"). We also measured the height of the ceiling within the trainer's room to be 93". The difference between the height of the tie-in and the height of the trainer's room ceiling would then be 11", which we were told would be evened out using drywall. The final dimensions we settled on for the tie-in was 8'-6" x 8'-0", which is shown in Figure 40.

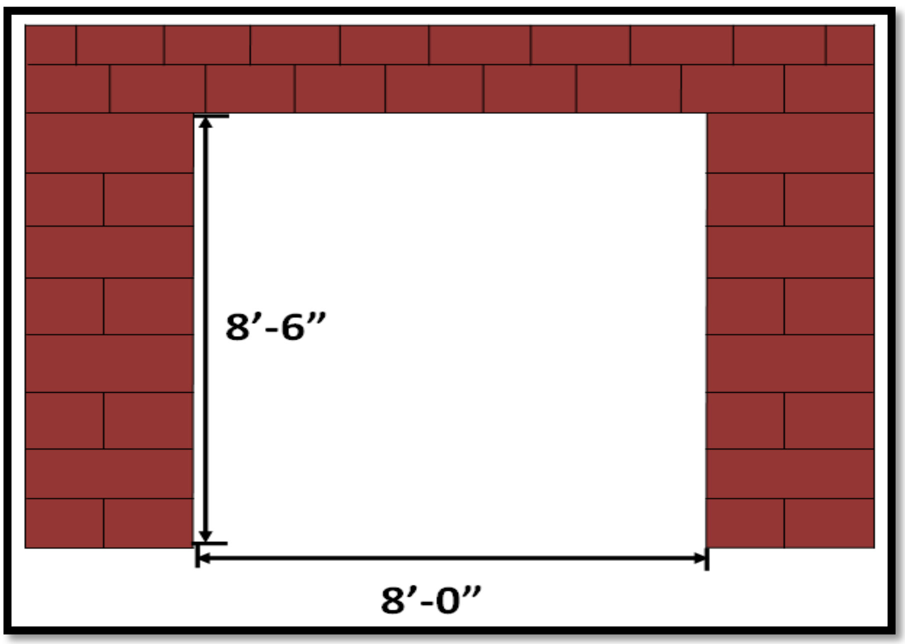


Figure 40: Tie-In Dimensions

4.2.2 Calculating Loading Conditions

After establishing the dimensions of the tie-in, we had to determine the loading system that would be applied to it. Through speaking with Michael Andrews during our tour of the Recreation Center, we found that the wall is a simple exterior wall composed of brick and concrete masonry units (CMU) with an air gap of approximately 9" between. The brick portion of the wall runs the entire height of the building, while the CMU units run from floor to floor. Therefore, we would have to provide separate calculations and designs for the brick and CMU.

The fact that the wall is an exterior wall means that the tie-in would only have to resist forces caused by the weight of the materials (dead load) as opposed to a load-bearing wall which resists structural loads of the building. Once we knew this we researched the average weight of both bricks and CMU's per square footage according to industry standards. Table 8 shows different types of masonry sizes and their corresponding weights (Muller, 1995).

Masonry Walls	Load (psf)
4" Brick	42
8" Concrete Block	55
12" Concrete Block	80

Table 9: Masonry Units and Weights

Once we knew the composition of the wall and its corresponding weight, we were able to determine the distributed load across the horizontal span of the tie-in. When analyzing the distributed load above an opening, the span experiences a triangular load acting at 45^o angles from both ends from the above material as shown in Figure 41 (Stuart, 2009). The maximum concentrated load, which acts at the center of the span, is the product of weight of material per square foot (psf) and the tributary height triangle (L/2). Since the length of the span is 8', the corresponding height of the triangular load is 4'. Therefore, the peak load is 168plf, or the height (4') times the weight per square footage of the brick (42 psf).

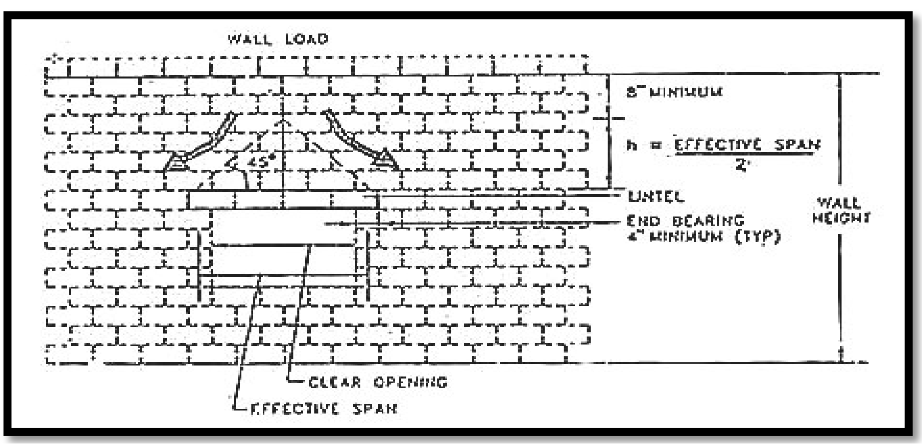


Figure 41: Triangular Load Distribution Acting on an Exterior Wall Opening

When designing a support system it is essential to know the internal forces that will be acting upon it, which is a direct result of the loading system that is supporting. We developed shear-moment diagrams based on the distributed load and span, following the standard statics model for triangular distributed loads in Figure 42. The resulting maximum shear and maximum moment experienced over the span are 336 lb and 816 lb-ft, respectively.

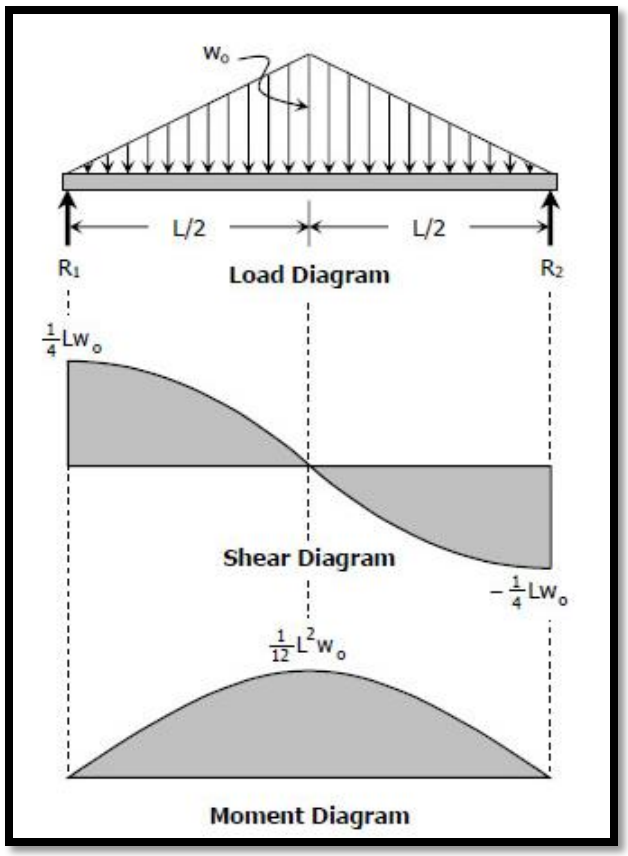
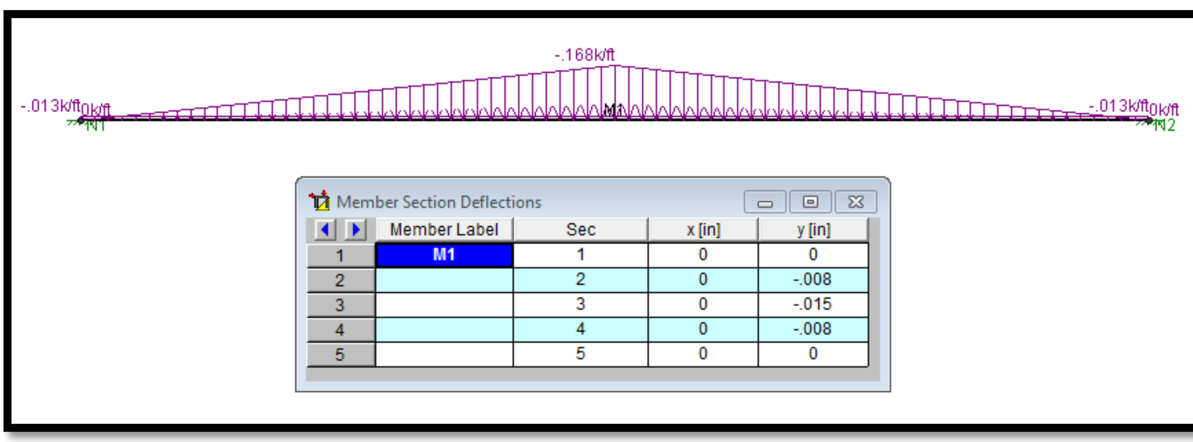


Figure 42: Shear-Moment Diagrams for Distributed Triangular Loads (Mathalino, 2021)

4.2.3 Lintel Size Calculations

After determining the dimensions and loading conditions of the tie-in we were able to design a lintel size to support the brick exterior wall. The primary design parameter for lintels is to minimize deflection. The maximum allowed deflection for any steel lintel, per the Brick Industry Association (Technical Notes 31B, 5/87), is L/600, where “L” is the span of the lintel in inches. Therefore, we knew we had to minimize the deflection to 0.16 in., calculated from the 8 foot (96 inches) span divided by 600.

We used RISA 2D, a structural analysis computer program, to perform deflection calculations. This program generates minimum and maximum values of moment, shear, displacement, and deflection based on the load, boundary conditions, moment of inertia, and steel area. We recreated the lintel and loading conditions of the tie-in to find the maximum deflection. We tested several different lintel sizes by plugging in their respective moment of inertia and area, and checked deflection of each to ensure it meets the design requirement of 0.16 in maximum deflection. When plugging in the values for different lintel sizes, we also had to consider its own dead weight, which is considered a distributed load across the span. Figure 43 is a screenshot of RISA 2D that shows the loading conditions and span of the tie-in, and the corresponding deflection for an L - 4x4x$^{1}/_{2}$ steel lintel. This lintel size, given its specific area, dead weight, and moment of inertia, will undergo a deflection of 0.015 inches. The technical step-by-step approach of creating such a beam and loading conditions in RISA 2D is outlined in Appendix M.



	Member Label	Sec	x [in]	y [in]
1	M1	1	0	0
2		2	0	-.008
3		3	0	-.015
4		4	0	-.008
5		5	0	0

Figure 43: RISA 2D Screenshot for the Tie-In Loading Conditions on an L- 4x4x1/2 Steel Lintel

We followed these steps for several different lintel sizes, using a trial-and-error approach in attempt to find the most economical size that could also meet the deflection requirement of 0.16 inches. Table 10 shows a variety of different size lintels that we tested and their corresponding properties and deflection.

Designation	Depth	Width	Thickness	Sectional Area	Weight	Moment of Inertia - I	Deflection
	in	in	in	in^2	lb/ft	in^4	in
L8 x 8 x 1	8	8	1	15	51	89	0.001
L8 x 8 x 3/4	8	8	0.75	11.4	38.9	69.7	0.002
L8 x 8 x 1/2	8	8	0.5	7.75	26.4	48.6	0.003
L6 x 6 x 1	6	6	1	11	37.4	35.5	0.003
L6 x 6 x 3/4	6	6	0.75	8.44	28.7	28.2	0.004
L6 x 6 x 1/2	6	6	0.5	5.75	19.6	19.9	0.005
L5 x 5 x 3/4	5	5	0.75	6.94	23.6	15.7	0.007
L5 x 5 x 1/2	5	5	0.5	4.75	16.2	11.3	0.009
L4 x 4 x 3/4	4	4	0.75	5.44	18.5	7.67	0.013
L4 x 4 x 1/2	4	4	0.5	3.75	12.8	5.56	0.015
L4 x 4 x 1/4	4	4	0.25	1.94	6.6	3.04	0.033
L3 x 3 x 1/2	3	3	0.5	2.75	9.4	2.22	0.045
L3 x 3 x 1/4	3	3	0.25	1.44	4.9	1.24	0.081
L2 x 2 x 1/4	2	2	0.25	0.938	3.2	0.348	0.222

Table 10: Lintel Sizes, Properties & Deflections (Size Information from Engineering Toolbox)

4.2.4 Tie-In Design Results & Recommendations

Since the brick veneer and CMU interior wall were essentially two separate entities, we developed different design proposals for each. For the brick veneer exterior wall, we chose to use a lintel to span the 8-foot tie-in and support the overlying load. Based on the loading conditions and the Building Code Requirements for maximum deflection in lintels, we chose to support the brick veneer with an L- 4x4x1/2 lintel. We tested over ten different lintel sizes and calculated if they could effectively withstand the applied loading conditions (weight of the brick above the opening). Nearly all of them passed, however we chose a size that would also be economical and practical. The 4x4x1/2 lintel would easily support the load above the span and it was also a size that was not too small or too large, making it the most practical choice.

As for the CMU, we decided to completely eliminate all of the units up to the height of the ceiling. The CMU units in Harrington Auditorium are stacked from floor-to-floor, as oppose to the brick which runs the height of the building. So instead of installing a lintel to support only one CMU unit, we decided to demolish all CMU units from the width of the tie-in up to the height of the ceiling. This approach requires far less construction efforts and material than installing a lintel for the CMU. The difference of heights between the brick lintel and the ceiling of the trainer's room could then be transitioned using drywall. This design would result in a smooth transition from the brick veneer facing the Recreation Center to the CMU wall on the interior of Harrington Auditorium. Also, this approach would be economical and reduce the amount construction necessary.

4.3 Functional Design – Trainer's Room Reconfiguration

In addition to the structural analysis we performed on the Harrington tie-in, we also considered how the new connection would interact with the spacing and function of the trainer's room in Harrington Auditorium, which will be directly affected by this construction. The space occupied by the trainer's room will require a reconfiguration to allow for a hallway to run through, starting at the location of the tie-in. The hallway will function as a route between the gymnasium floor and the Recreation Center robotics pits, and must include design considerations for the size and traffic of the robots during competitions. We used several different methods to gain a better understanding of the trainer's room area and develop a plan of reconfiguration of the space.

4.3.1 Current Trainer's Room Layout & Proposed Tie-In Location

We began the process of designing a reconfiguration for the location directly affected by the tie-in in Harrington Auditorium by studying the layout of the trainer's room. As mentioned before, Cardinal Construction provided us with AutoCAD files of Harrington Auditorium blueprints. These blueprints were very helpful in showing the scale of the trainer's room in relation to the gymnasium and also in locating walls, elevator shafts, columns and doorways. However this file was based on the blueprints that were developed when the building was constructed in 1968 and the building has undergone changes since then. The room now used as trainer's room was originally used as a Food Service Area during sporting events. So not only has the space changed, but its function has also changed. Also, the drawings showed no indications of dimensions. Figure 44 shows the trainer's room as represented in the AutoCAD file based on original as-built drawings.

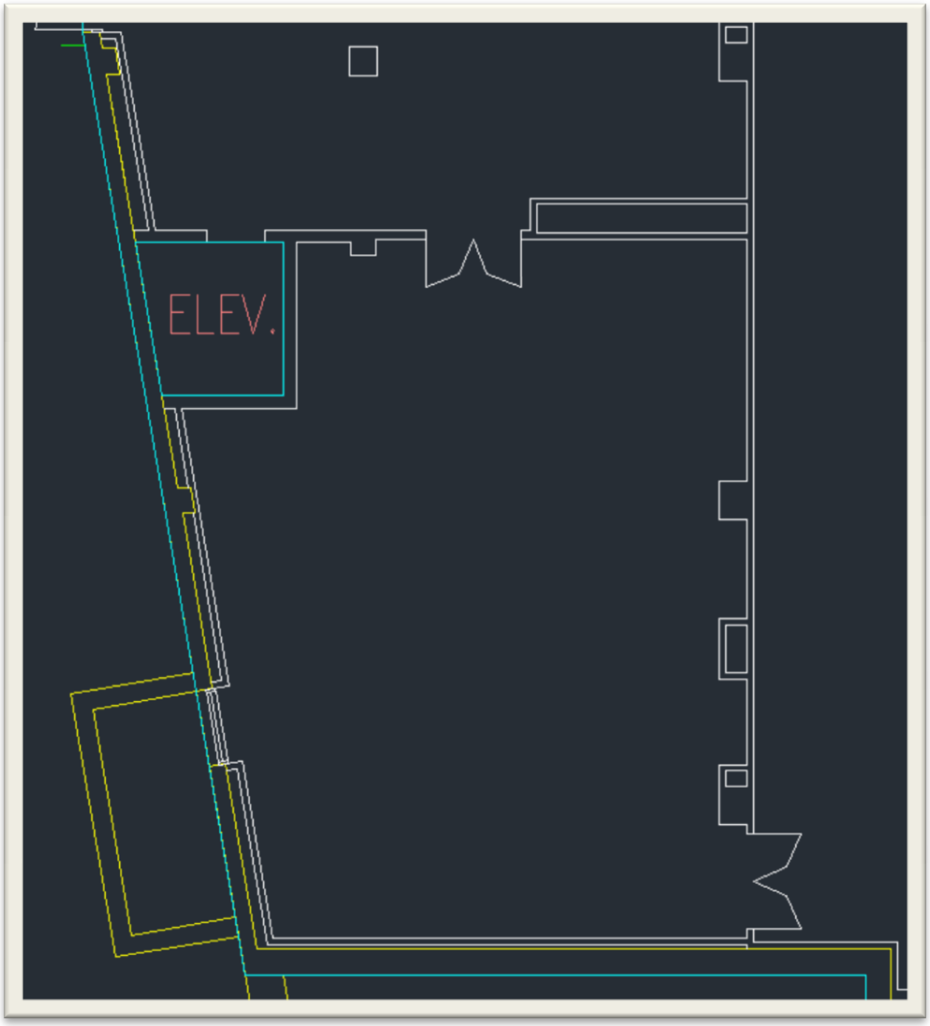


Figure 44: AutoCAD Drawing of Trainer's Room as Originally Constructed

Although the drawing didn't portray the up-to-date layout of the trainer's area, we used it as a foundation for creating a new version that accurately represents the current conditions. We visited the trainer's room and took measurements throughout the entire area and applied the dimensions to an updated AutoCAD drawing of the room. We also took note of type of materials used for each wall (CMU or drywall) as well as the location of fixtures (lighting, electrical, and plumbing). We used this information when considering different reconfiguration designs for the trainer's room/robotics hallway. Figure 45 shows the updated AutoCAD drawing of the current trainer's room layout. The blue lines in the drawing indicate walls we drew into the file which were constructed after the original construction (drywall), and the white walls are

CMU walls constructed during initial construction of the building. Dimension lines are also included and are measured in "inches." The tie-in is also located on the left side of the drawing.

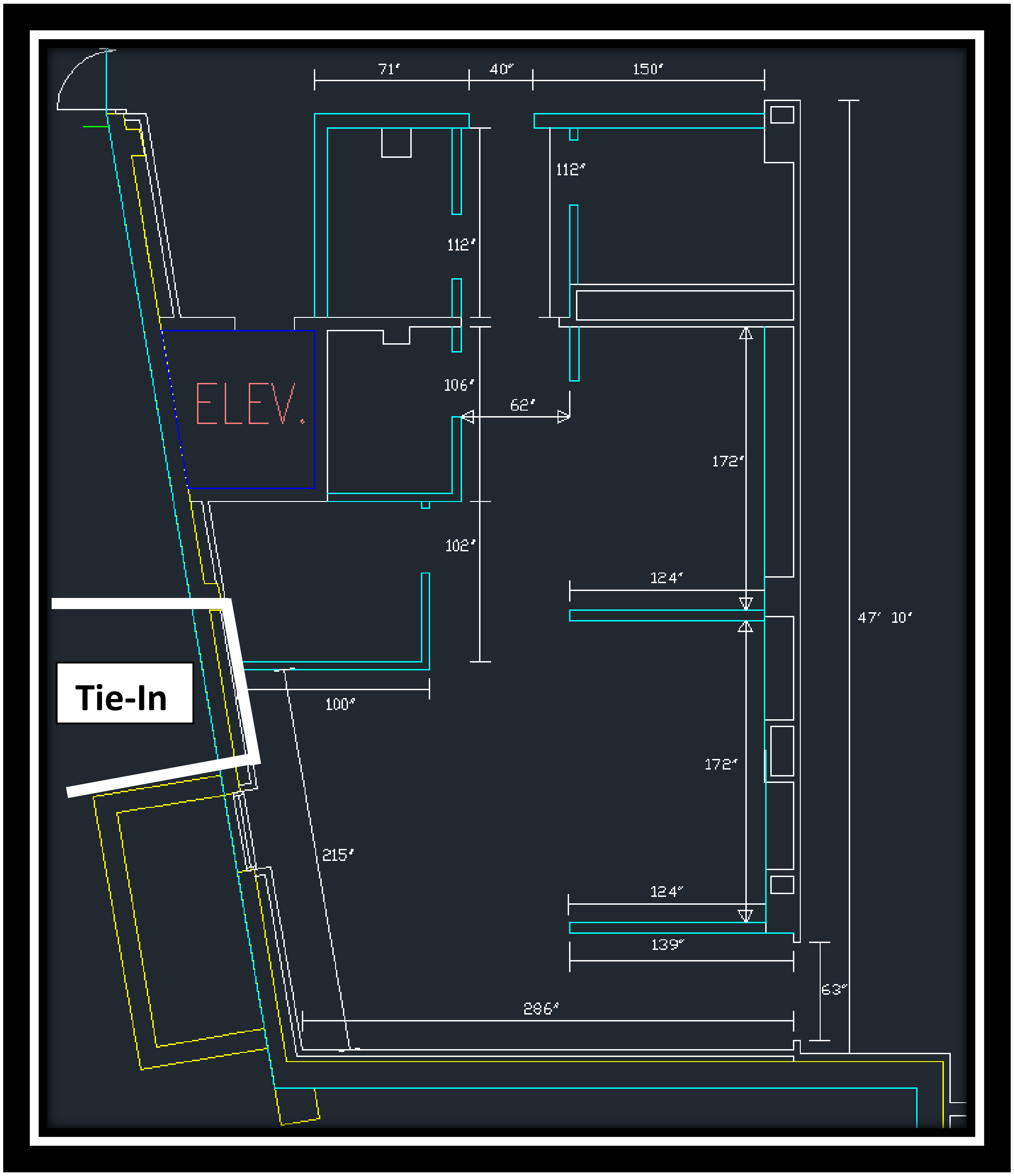


Figure 45: Current Layout of Trainer's Room w/ Dimensions

We also developed a drawing with labels to provide a qualitative representation of the trainer's room layout, as well as show the location of the tie-in and the location of the trainer's room in context of the entire gymnasium floor; this drawing can be seen in Figure 46.

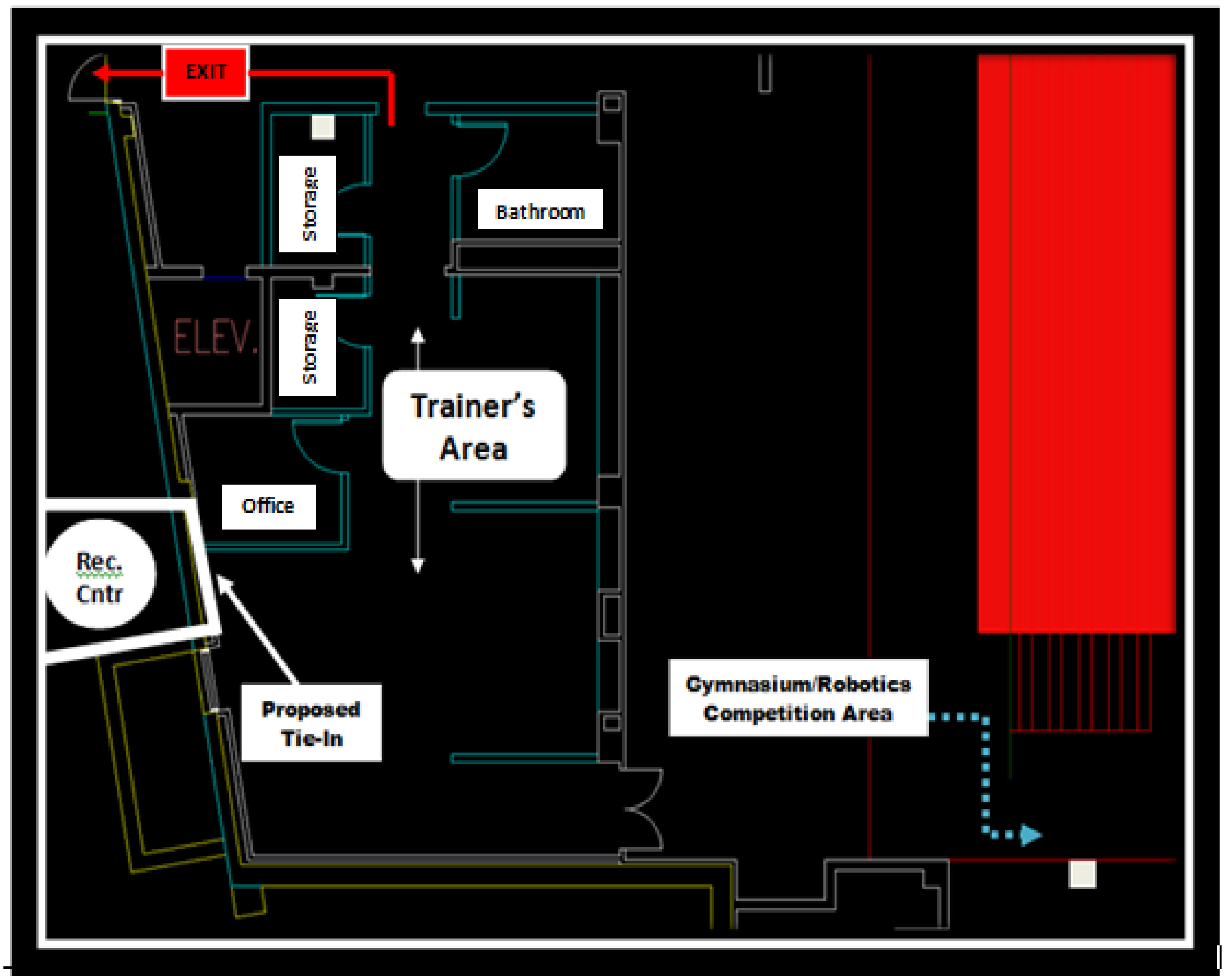


Figure 46: Trainer's Area with Labels

4.3.2 Design Requirements – Trainer's Room/Robotics Hallway

Before beginning our design for the reconfiguration of the trainer's room, we had to consider the design requirements of the hallway to support traffic during robotics competitions. We gathered all necessary information related to the robotics hallway by interviewing Professor Kenneth Stafford, Director of the Robotics Resource Center and also an Architectural Advisor for the Robotics Pits in the new Recreation Center, appointed directly by WPI President Berkey. Notes from the interview with Professor Stafford can be found in Appendix N. In summary, the ideal design parameters for the robots hallway are a width of 8 feet and a height of 8 feet throughout the length of the hallway. This would allow traffic in both directions between the robotics pits in the Recreation Center and the competition floor in Harrington Auditorium and also allow for easy clearance. This was a critical design requirement and dictated our design suggestion for the reconfiguration of the hallway through the Harrington trainer's room.

Another consideration we examined was the needs of the trainer's room. We spoke in an informal conversation with the Assistant Athletic Trainer Aimee Sevigny to determine the requirements for the trainer's room after reconfiguration. The trainer's room will remain fully operational in the future despite the fact that the new Recreation Center includes a newer, larger training area. The reason it will remain open is to offer training room assistance to athletes playing in sports that will continue competing in Harrington Gymnasium, including basketball, volleyball, and wrestling. On the other hand, the trainer's room in the new Recreation Center will be utilized to support athletes who compete on the field levels such as football, field hockey, baseball, softball, track and field, etc. So the occupancy of the Harrington trainer's rooms will be drastically reduced since the majority of sports will now report to the Recreation Center instead. However, it will still need to support all of the basic functions of a standard trainer's room.

4.3.3 Proposed Reconfigurations – Trainer's Area/Robotics Hallway

Using the dimensions of the trainer's room that we determined in conjunction with the location of the tie-in and the necessities of both the trainer's area and the robotics hallway, we devised several potential reconfigurations of the space, and chose one that would best optimize the area. We drew the potential designs within AutoCAD and compared them. We based our comparison on functionality, constructability, and how well they met the requirements of both the trainer's and robotics users.

Within each drawing the proposed Robotics Hallway is designated by the red lines; and yellow lines represent pre-existing walls that would have to be demolished in order to either accommodate for the new hallway or to connect separate areas to make one primary trainer's room. Also, all Robotics Hallways were designed to have a minimum width of 8feet and this design criteria is reflected in each drawing.

Option #1: Our first design configuration, Option #1, consists of having the Robotics Hallway enter the trainer's area and turn northward through the pre-existing hallway. This hallway would exit into a lobby behind the bleachers, where the robotics competitors would then have to navigate around to reach the gymnasium floor. The design drawing can be seen in Figure 47. The advantage of this design is that it would allow competitors to choose which side of the bleachers they'd like to enter onto the gymnasium floor at from the lobby area. Another advantage is that the trainer's room would still have a relatively large area. The disadvantages are that both storage areas would be demolished or at the very least, greatly reduced in size. The trainer's office would also have to be demolished, however regardless of configuration this room will have to be removed so we did not consider this while factoring in each options potential. Also, the bathroom wall would potentially have to be reconstructed which is a more major issue than other walls since it contains plumbing utilities. Another disadvantage, from the robotic standpoint, is that this option would require some maneuvering of the robots since it contains a nearly 90^0 turn. And finally, although the trainer's area would remain quite large, it would require a wall to either be demolished to connect the two areas or a door frame to be installed. Also, it would have an awkward layout which could impact its overall function. Overall, this option has its pros and cons from each viewpoint: trainers, robotics, and construction.

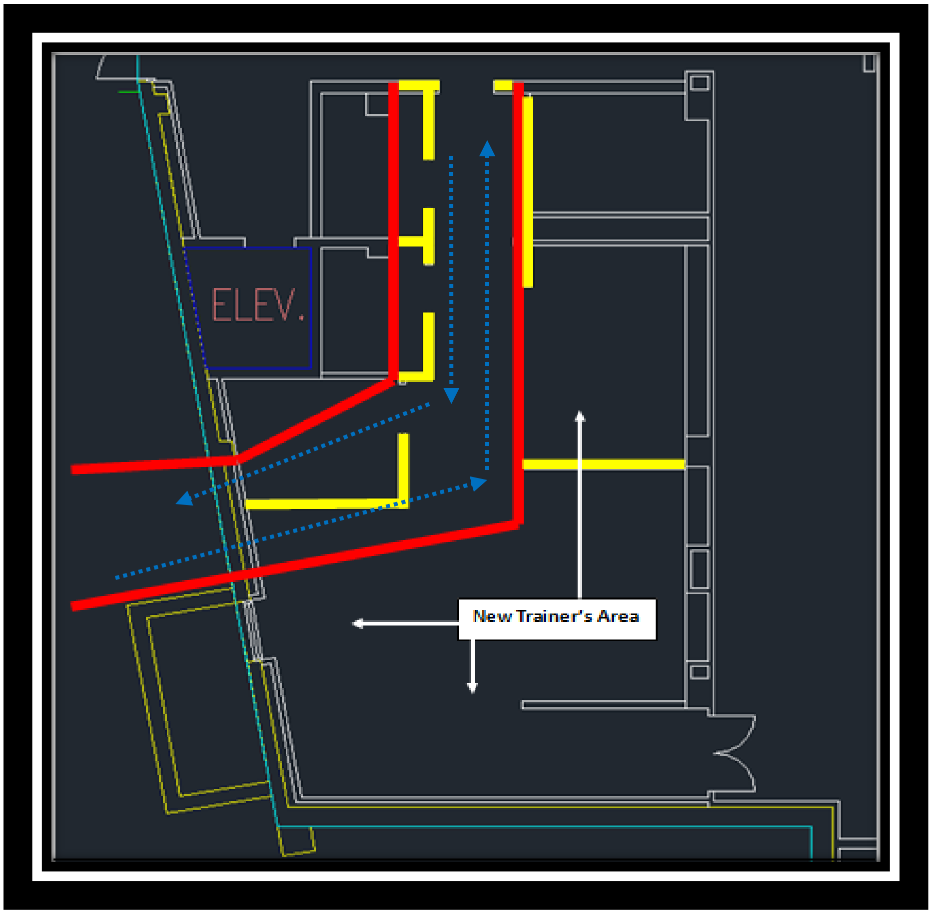


Figure 47: Reconfiguration Option#1

<u>Option #2</u>: The second reconfiguration layout we considered, Option #2, consists of the Robotics Hallway running straight through the trainer's room, perpendicular to the east wall of the room. This proposed layout can be seen in Figure 48. The advantages of this design are that it would minimize the distance that the robots would have to travel and would completely eliminate any complicated maneuvering since there are no turns or curves. The disadvantages are that the hallway would completely dissect the trainer's room, leaving two open spaces on both sides, and interfering greatly with the function of the trainer's area. Also the wall that the hallway would break through would require exploratory work and may potentially contain columns or plumbing utilities running through it. Overall this option is highly favorable from the robotics standpoint, but unfavorable from both a trainer's and a constructability point-of-view.

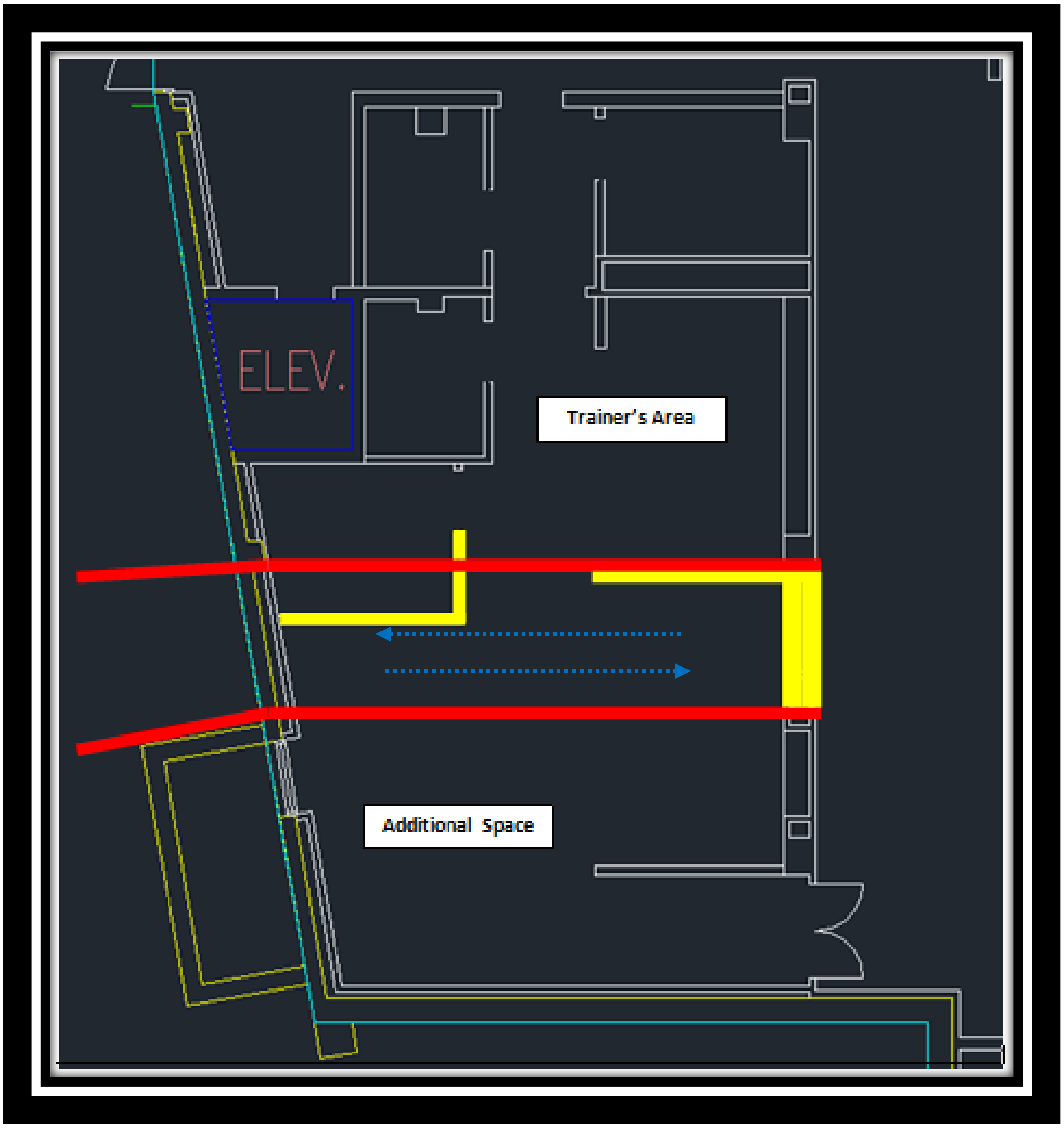


Figure 48: Reconfiguration Option #2

<u>Option 3</u>: The third and final configuration we considered, Option #3, includes the Robotics Hallway running flush with the west and south walls of the trainer's room and exiting out of the pre-existing doorway onto the gymnasium floor. This layout can be seen in Figure 49. The advantages of this design are that it would utilize a pre-existing exit and would require only demolition of drywalls which contain only electrical utilities (no plumbing). Also, the trainer's areas would be combined leaving a large open space, easily large enough to support the expected activity within the room. Also, the two storage areas and bathroom would remain untouched. Another advantage, from the robotics standpoint, is that the hallway would exit directly onto the gymnasium floor/competition area. The disadvantages are that the hallway contains a turn, which would require some maneuvering of the robots, although minimally. Also, although the hallway will be utilizing a pre-existing exit, the doorframe would need to be extended an extra two feet from its original size to accommodate for the robotics traffic. Overall, this option is highly favorable for the trainers, relatively favorable for robotics, and evenly favorable from a constructability point-of-view.

FIGURE TOO LARGE FOR SPACE: SEE NEXT PAGE

Figure 49: Reconfiguration Option #3

4.3.4 Recommendations for Trainer's Area/Robotics Hallway

After developing the three different potential reconfiguration designs, we analyzed the advantages and disadvantages of each to determine which would be the best design overall. We performed our analysis from a completely unbiased point-of-view and took into consideration the necessities of each individual party, weighing them equally. We organized our information with a table that shows the pros and cons of each design and from the standpoint of the robotics people, the trainers, and constructability, which can be seen in Table 11. This made it easier for us to compare and contrast each design, and inevitably develop a more accurate and well-thought recommendation.

	Option #1	Option #2	Option#3
Trainer's Area	**PROS**: Sufficient Space **CONS**: Awkward Setup; Demolition of both storage areas	**PROS**: Storage & Bathrooms Unaffected **CONS**: Dissects Trainers Area	**PROS**: Large, Open, Sufficient Size Room; Storage & Bathrooms Unaffected
Robotics Hallway	**PROS**: Exits into lobby **CONS**: Long, Curved Route	**PROS**: Minimizes Travel Distance; No Curves/Turns; Smooth Transition	**PROS**: Exits Directly To Gym Floor/ Competition Area **CONS**: Includes a Turn
Construct-ability	**CONS**: Clashes with a lot of drywall; interferes w/ CMU wall containing plumbing	**CONS**: Exploratory Work Required; Wall May Contain Plumbing or Column	**PROS**: Pre-existing Exit **CONS**: Doorframe Must Be Extended 2'

Table 11: Pros & Cons of Each Reconfiguration Design

After carefully considering each design proposal, we determined that Design Option #3 provided the best overall layout. The final design can be seen in Figure 50 with dimensions and approximate square footage of both the Robotics Hallway and Trainer's Area. The major advantages we found when looking at this design is that it maximizes the space for the trainer's room while meeting all the design criteria of the Robotics Hallway. The Robotics Hallway will be a minimum of 9 feet which is at least 1 foot wider than the design standard of 8 feet, resulting in a smooth, uninhibited transition between the Robotics Pits and the Harrington Gymnasium floor. This design also minimizes the interference that the construction would have on the trainer's room considering both storage areas and the bathroom would remain untouched, and the trainer's room would undergo only minimal reduction in size. Also, this design provided benefits from the constructability standpoint in that it would take advantage of a pre-existing doorway and no exploratory work would be required. In general, this design offers favorable advantages from all points of view and minimizes negative aspects.

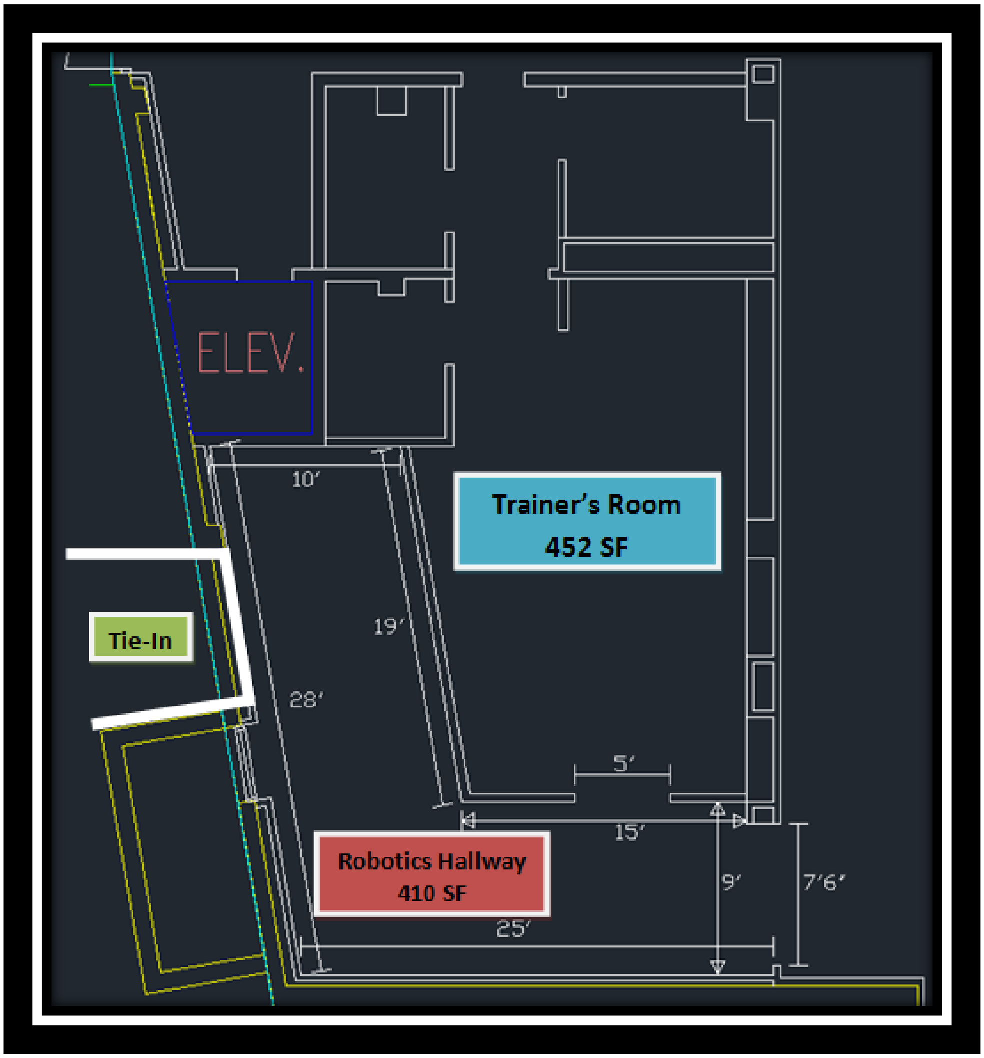


Figure 50: Final Design Configuration for Robotics Hallway & Trainer's Room

5.0 CONCLUSIONS & RECOMMENDATIONS:

This section includes a summary of the results we obtained from the BIM portion of our project, as well as the results of design we developed for the different aspects of the Harrington Auditorium and Recreation Center connection. Also, we provide final conclusions and recommendations for both aspects of the project.

5.1 BIM/4D/5D Conclusions & Recommendations

This major qualifying project used a variety of methods to examine the effectiveness of Building Information Modeling as a tool in Construction Management. A key development that came as a result of the project was the creation of a methodology for linking multiple BIM models and schedules together. By combining multiple modeling tools we were able to show the usefulness of a complete BIM model to all parties involved in a construction project. As an architect, BIM provides others with a better understanding of your building design, and a better final product can be produced with a clearer understanding of the project and all its implications. For a construction manager, BIM provides a better visualization of the project, a more accurate depiction of the materials needed, and provides an integrated method to show how the project will be built and where construction issues could be expected. As a tool for a building owner, BIM can be used to communicate needs to the architect, to understand the construction managers' schedule, to understand the progress of the project more fully, and to prepare budgets far more accurately. Building Information Modeling has great potential, and our project tapped into just some of the features offered by the system.

5.1.1 BIM as a Project-Tracking Tool

A major conclusion of this project was the establishment of BIM as a project-tracking tool. Due to the linking of the schedule and multiple 3D models, we were able to visually model the progress of the construction project. Further, with the addition of the material takeoffs, we were able to clearly model the cost of the project as it was constructed. In essence, we demonstrated the procedures that a project owner could follow to visually track the progress of a project in terms of schedule, materials, and cost. Understanding that this information provides the user with an accurate idea of schedule and cost performances, this tool can be used to evaluate contractors, construction managers, and owners' representatives.

5.1.2 BIM's Increasing in Necessity

It is also important to highlight the increasing necessity of BIM, and its overall cost-effectiveness. When it comes to the decision-making process, no tool outperforms BIM in clarity of purpose and scope. Each week in the owner's meeting, we observed a communication process that was primarily dependent on oral exchange among meeting participants supported by 2D text and graphics. When the digital drawings are brought out though, a decision is often made in only minutes. As projects become increasingly complex, BIM becomes more and more necessary for all participants to understand what is taking place. It could also be argued that the financial savings of efficient decision-making and fewer project changes will cover the cost of maintaining an accurate model. It is likely that complete BIM services will pay for itself over the life of a project. It is for these reasons that this major qualifying project recommends a gradual investment in BIM technology for all applications in Construction Project Management.

5.1.3 Future BIM Research

As this project was completed we recognized one area that further research can be focused on. We suggest that further research be conducted on determining BIM's cost effectiveness as a construction management tool. We found that there was no simple method to measure the potential cost savings that could be realized over the life of a construction project that used BIM versus a project that did not. Although these savings were not readily quantifiable, it was clear that when the 3D model was used (like in the case of verification of floor-to-ceiling height in the Robotic pits area) potentially costly modifications during construction were avoided. The 3D MEP coordination process was another example of how BIM tools improved communication and understanding of complex spatially related issues. Further consideration should be provided here to determine the exact cost benefits of the use of BIM in these cases, because this argument is essential in convincing Construction Management firms the financial and scheduling advantages of incorporating BIM into their projects.

5.2 Harrington Auditorium Connection: Conclusions & Recommendations

Based on our review and analysis of the connection between Harrington Auditorium and the new Sports & Recreation Center, we were able to offer alternative design recommendations for the three main components of the connection: geotechnical, structural, and architectural/functional. The benefits of our proposed solution cannot be verified or properly assessed until the actual work takes place (beside the underpinning design which has already occurred) however we made educated assumptions to determine a design that we found most appropriate given the constraints and conditions of the entire connection.

5.2.1 Geotechnical Design

The geotechnical component of our design consisted of analyzing the underpinning layout beneath the foundation of the west side of Harrington Auditorium and developing an alternative design. This location was directly impacted by the excavation during construction and required geotechnical support to ensure its continuous stability. We created a layout that met all safety requirements to properly secure the footing. The design consisted of eight micropiles evenly spaced over the length of the footing, embedded nine feet into the soil at a 40^{o} effective angle, and a 6” cross-sectional surface diameter reinforced with a #7 Grade 75 steel core bar. Our final design recommendation can be seen in Figure 51.

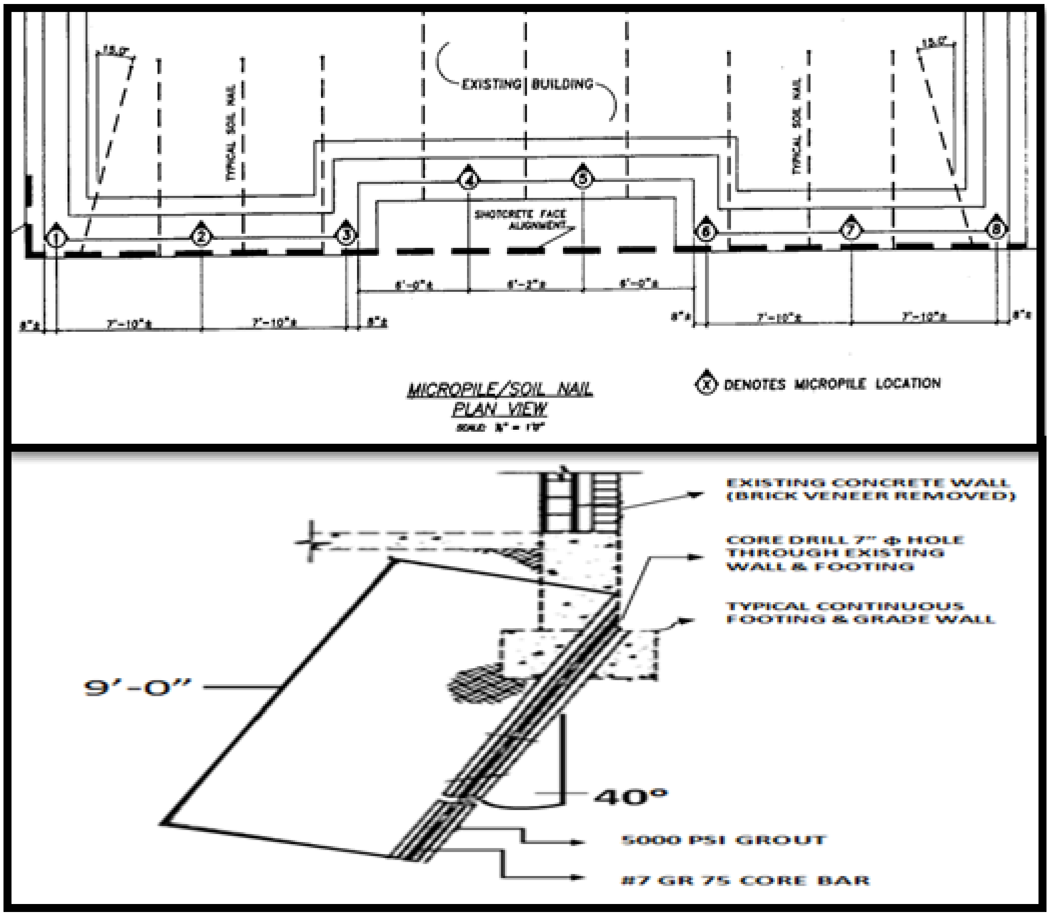


Figure 51: Geotechnical Design Proposal (Plan View Above, Cross-Section Below)

Our design reduced the amount of steel by 31.6% when compared to the actual design used on the Recreation Center. We found other potential design sizes that could have reduced the quantity of steel even more and still meet safety criteria. However, structural capacity is greatly lessened with the reduction of steel, so we settled on our design because it had over twice the necessary capacity while still reducing the quantity of steel by 31.6%. In conclusion, there were many alternatives that could have been used for underpinning, but we created design that satisfied the safety requirements while remaining economical.

If a group were to expand upon our work, we would suggest trying different types of materials. We explored only 5000 psi grout and simple 75000psi steel rebar, since they are the standard used in the industry, however there are many different steel and grout property variations available in the world. An exploration of underpinning using steel and grout with different properties, or even completely different materials altogether such as composite materials, could be interesting and potentially produce a design that is more cost-effective.

5.2.2 Structural Tie-In Design

The structural aspect of our design included developing a support system for the connection between the Sports & Recreation Center with Harrington Auditorium while considering the constructability and practicality of the design. The two buildings will be "tied-in" through the exterior wall of the trainer's room in Harrington Auditorium, which is comprised of brick and CMU. We devised a simple but practical approach that would address the brick and CMU separately, and then combine the individual designs into a smooth transition between the buildings.

We chose to support the brick veneer with an L-4x4x1/2 lintel. We tested over ten different lintel sizes and calculated if they could effectively withstand the applied loading conditions (weight of the brick above the opening). Nearly all of them passed, however we chose a size that would also be economical and practical. The 4x4x1/2 lintel would easily support the load above the span and it was also a size that was not too small or too large, making it the most practical choice.

As for the CMU, we decided to completely eliminate all of the units up to the height of the ceiling. The CMU units in Harrington Auditorium are stacked from floor-to-floor, as opposed to the brick which runs the height of the building. So instead of installing a lintel to support only one CMU unit, we decided to demolish all CMU units from the width of the tie-in up to the height of the ceiling. This approach requires far less construction efforts and material than installing a lintel for the CMU.

If a group were to expand upon our design, we would recommend they research the cost difference of construction between using lintels to support the CMU instead of complete demolition. Also, they could explore different types of supports, more specifically one that would span the brick veneer and CMU simultaneously. From there they could compare the cost and constructability of that type of design with ours to see which would be most feasible.

5.2.3 Functional/Architectural Design

In addition to the geotechnical and structural design we developed, we also explored design solutions for the reconfiguration of the trainer's room in Harrington Auditorium. The trainer's room will have to be reconfigured to accommodate the tie-in and resulting hallway that will be used for travel between the buildings during robotics competitions. We developed three potential configurations of the room and hallway and chose one as the best possible solution based on the dimensional requirements of the hallway, the maximization of the trainer's space, and the constructability of the design. Figure 52 shows a 2D plan view of the design we proposed (the yellow arrows indicate the flow of traffic).

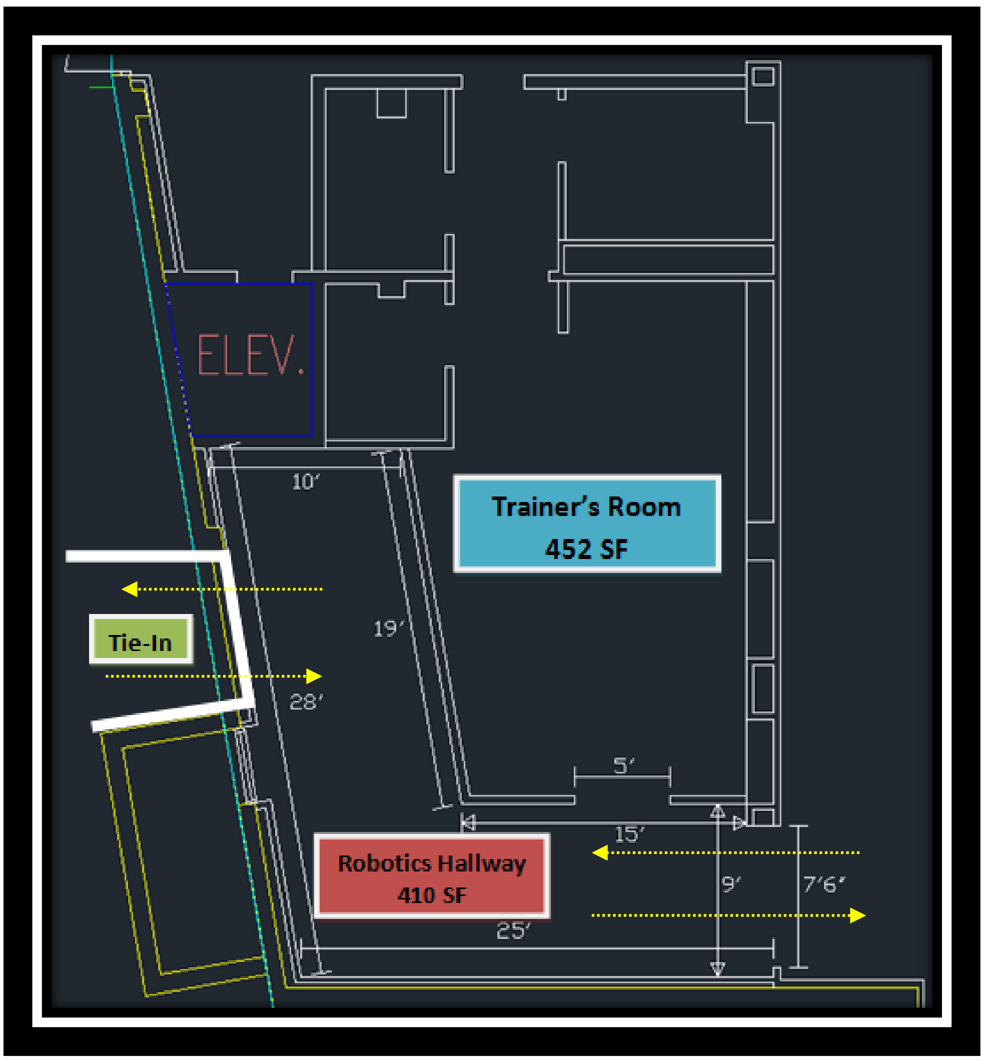


Figure 52: Plan View of Proposed Configuration of the Trainer's Room

We suggest for future research to determine the cost estimate of each design. Although we determined which design appeared to have the easiest constructability, which can also be an indication of cost, we did not perform actual quantity and cost estimates. If each design had a corresponding overall cost, it would likely play a very large role in choosing which design to use. Another way to expand on this portion of our project would be to develop 3D models of each design in Revit. This would allow the user to better analyze the functionality of the design and predict any issues or flaws that would otherwise be difficult to assume from a 2D drawing.

5.3 Overall Conclusion from Project Work

Through this project we have used Building Information Modeling to transform a 3D model of WPI's new Sports and Recreation Center into a 4D model, tracking the concrete, façade, roofing and steel packages. We then used these models to do an earned value analysis of the Recreation Center's construction; finding planned and projected cost of the project in monthly increments. This project also looked at the social impacts of BIM, particularly the implementation of BIM introduced into owners meetings. From this we determined that using visualizations in meetings diminishes confusion between parties, thus speeding up the decision making process.

This project also addressed the geotechnical, structural, and architectural designs of the Recreation Center and Harrington Auditorium connection. We performed the necessary calculations to determine an alternative geotechnical design which consisted of micropiles and a total steel quantity reduction of 31.6%. For the structural aspect of the connection we determined a lintel that could be used to carry the load of the brick veneer, and decided that the CMU wall be completely removed. Finally for the architectural aspect of the connection we determined a suitable reconfiguration of the trainer's room in Harrington Auditorium that would minimize construction necessary and meet the design requirements for a Robotics Hallway.

This project would not have been possible to accomplish without the 3D models that we received from Cannon Design, and schedules, work packages, geotechnical documents and various other information that we receive from Gilbane, and the help of numerous others. We would like to thank everybody involved in this project, its completion would not have been possible without them.

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APPENDIX A: Project Group Contractual Agreement

Project Group Contractual Agreement

Major Qualifying Project

WPI Recreation Center 4

Revised: October 3, 2011

The WPI Recreational Center 4 MQP project team will review both the scope and the nature of all assigned work during their project. Each team member must be motivated, working hard, and fully committed to the project at all times. Each member must be efficient, reliable and available. We believe that each team member should be working at a rate of 100% at all times, with an attitude that is constantly seeking more work. Before assigning tasks to each group member we will go over the allotted work together and determine who is most qualified to complete the tasks at hand. The tasks will be equally distributed and upon distribution we will create a chart of the tasks each team member will be assigned. We will also determine an end date and time in which each task needs to be completed to its entirety. These dates will also be tracked in the chart of tasks.

We have distributed roles to each member of the group. In addition, we have established that in order to complete this project on time and to a high standard, we must help each other with these roles and hold each other accountable. Christopher Baker will be in charge of creating the projected schedule as well as the actual schedule. Andrew Beliveau and Machell Williams will be in charge of creating the three dimensional models from the schedules given to them. Nica Sylvia will be in charge of the analysis between the scheduling and the modeling, and therefore will assist the other group members with their responsibilities. We have chosen to overlap all the major tasks with at least one group member to safeguard the implementation of the schedules to the model and to ensure that necessary information properly managed.

In order to communicate efficiently throughout the duration of the project we will hold a minimum of three group meetings each week. One meeting each week will include our Faculty Advisor, Professor Salazar. This meeting will consist of updating Prof. Salazar on our recent accomplishments, our ongoing challenges, and goals for the upcoming week. The responsibilities of the weekly meetings, which include facilitating, and recording and distributing the details of the meeting, will be shared equally among all members of the group in a determined rotation. The other two weekly meetings will be utilized to distribute and collaborate on work, and to assist each other with recent challenges pertaining to project tasks. We will also hold two group meetings each term in which we will discuss our group dynamics, which will include, but may not be limited to; the efficiency of our group, desired outcomes of our project, and discussing methods to achieve our goals.

We hold that it is each member's responsibility to attend all meetings. Therefore, each meeting is expected to have 100% attendance. If a team member cannot make the meeting then that team member must contact the group at least 24 hours prior to the meeting with a valid excuse. All members are expected to equally contribute to the project by way of meetings in person, email submissions and individual work.

If an occasion arises in which a team member feels that the work distribution is unfairly assigned or that any team member is not fulfilling their responsibilities with respect to group objectives, then the group will discuss the problem and determine a proper solution.

By signing this Contractual Agreement, I hereby agree to the previous statements. I will be hardworking, motivated, and fully committed to the project at hand. I will be efficient, reliable, and available. I will meet all my deadlines, and I will work at 100% at all times with an ambitious attitude towards the project.

Signature: ____________________ Date: 10/3/2011
Christopher Baker

Signature: ____________________ Date: 10/3/2011
Andrew Beliveau

Signature: ____________________ Date: 10/3/2011
Nica Sylvia

Signature: ____________________ Date: 10/3/2011
Machell Williams

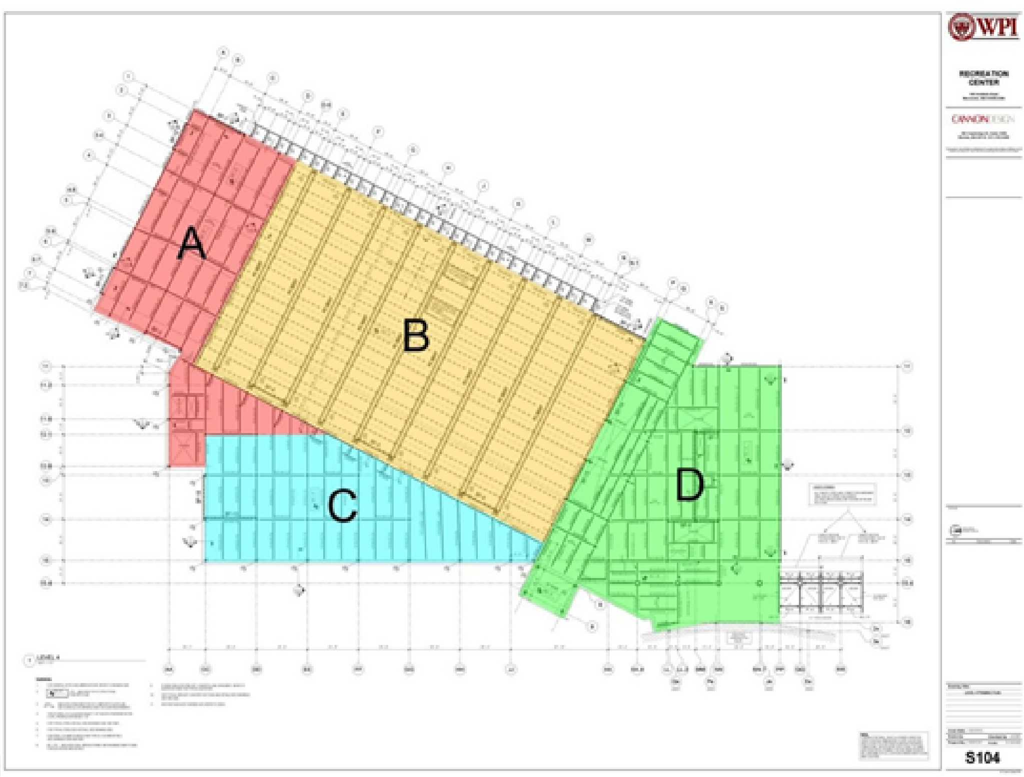
APPENDIX B: Activity Identification Coding System

Project Phases	ID	Divisions (CSI	ID	Level	ID	Area	ID	Structural Element	ID
Concept	CP	General Requirements	01	Foundation	00	Area A	A	Slab	00100
Design	DS	Site Work	02	Level 1	01	Area B	B	Column	00200
Site Work	SW	Concrete	03	Level 2	02	Area C	C	Footings	00300
Construction	CO	Masonry	04	Level 3	03	Area D	D	Retaining Wall	00400
M&O	MO	Metals	05	Level 4	04	Area S	S	Foundation	00500
Demolition	DM	Woods and Plastics	06	Level 5	05	Area X	X	Wall	00600
		Thermal and Moisture	07	Roof	06			CMU	00700
		Doors and Windows	08	All	07			Frames CMU	00800
		Finishes	09	Pool Area	08			Bricks	00900
		Specialties	10					Precast Base	01000
		Equipment	11					Windows/Doors	01100
		Furnishings	12					Curtain Wall	01200
		Special Construction	13					Hangers	01300
		Conveying Systems	14					Metal Panels	01400
		Maechanical	15					Beam	01500
		Electrical	16					Decking	01600
								Misc.	01700
								Misc.	01800

Example: Concrete slab, third floor, area A

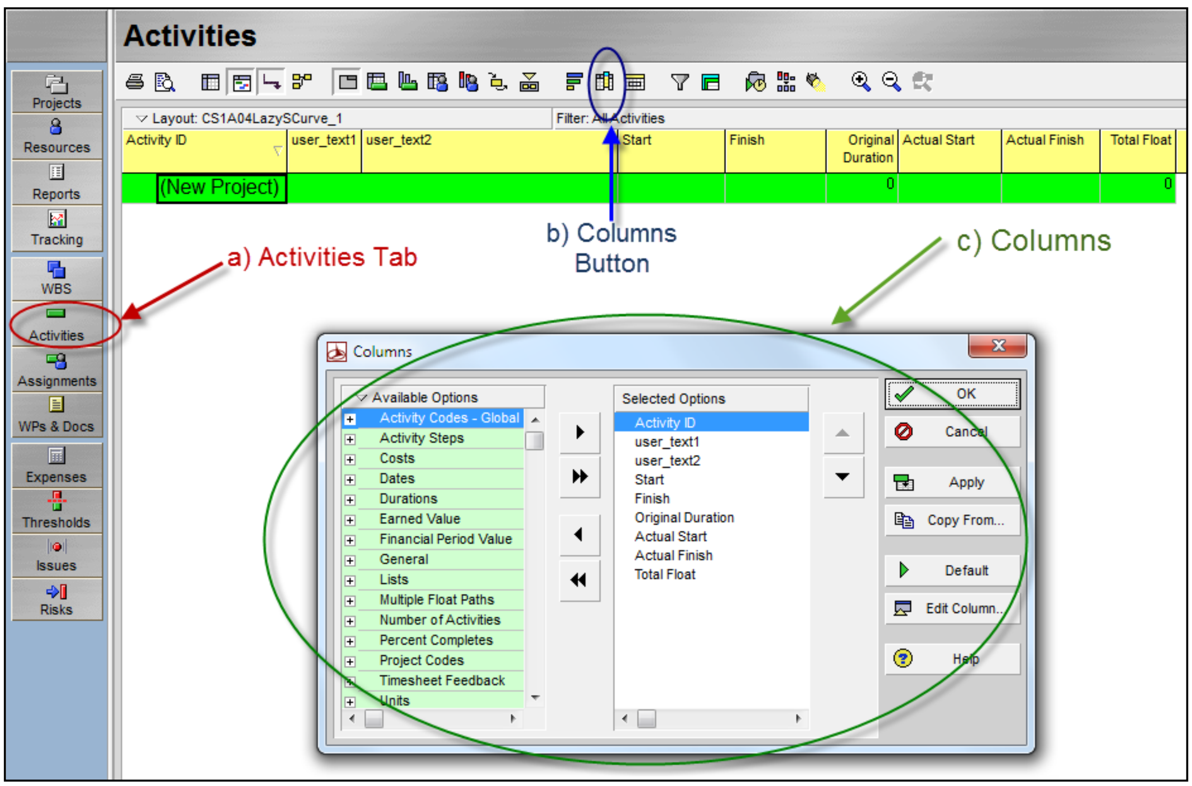
	CO		03		03		A		00100

Activity ID: CO0303A00200



APPENDIX C: Primavera-and Excel Scheduling Process

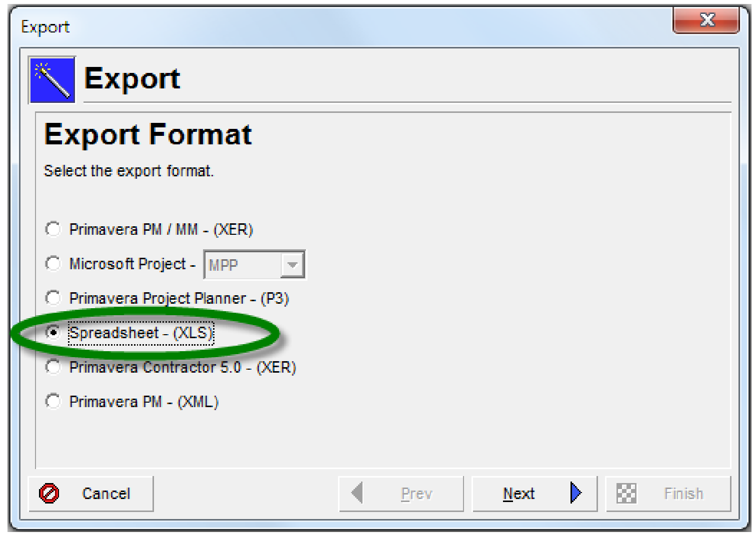
- Create the Columns
  - Activities Tab – Click the "Activities Tab" on the left side of the screen. This will bring you to the page where you can view/adjust all information related to individual activities (Activity ID, Actual and Planned Start/Finish, Duration, Float, WBS, etc.).
  - Columns Button – To adjust the scheduling information that will appear when viewing activities, click the "Columns Button" which is located at the top, center of the page. A "Columns" interface will then appear.
  - Columns – Within the "Columns" interface you can choose all of the information you wish to include to describe each activity from a large variety of available options. You can arrange them in whichever order you prefer. NOTE: For options not included in the "Available Options" then select "user_text" which you can adjust later to the preferred name.



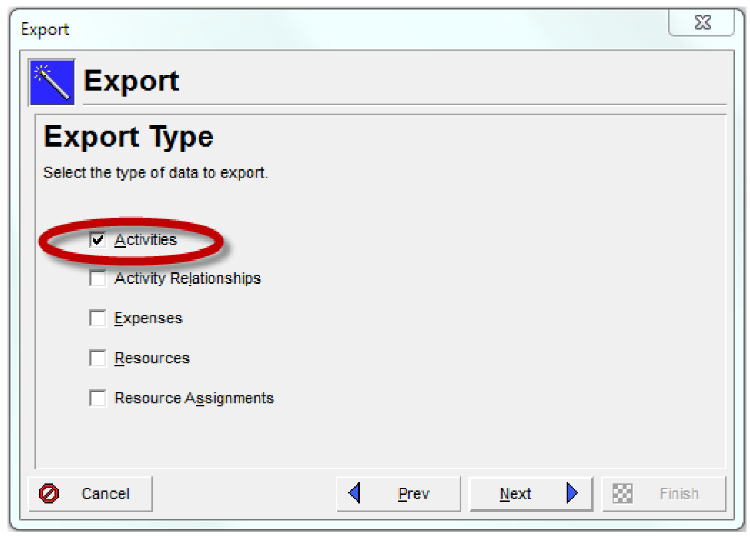
- Example of Activity Heading after choosing Columns

Activity ID	user_text1	user_text2	Start	Finish	Original Duration	Actual Start	Actual Finish	Total Float
RCMQP4			23-May-11	06-Jan-12	165			0

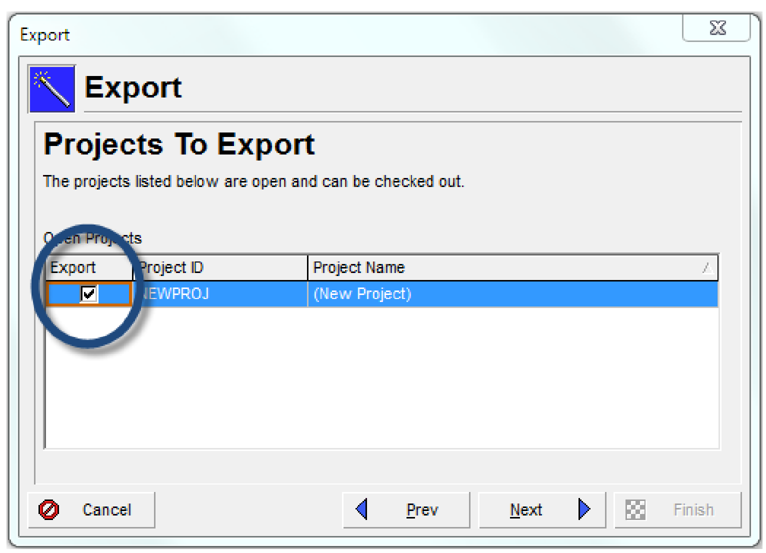
- Export Primavera Columns into Excel
    - Click the “File” tab at the top left of the screen.
    - Under the drop down menu, choose “Export” and the “Export Format” menu will appear. Choose the “Spreadsheet – (XLS)” option, then click “Next.”



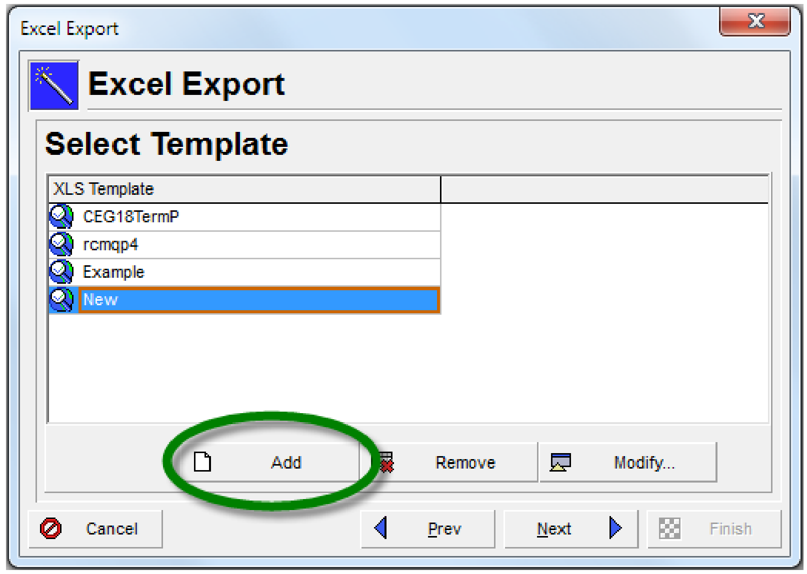
- An “Export Type” menu will appear. Choose the “Activities” option, then click “Next.”



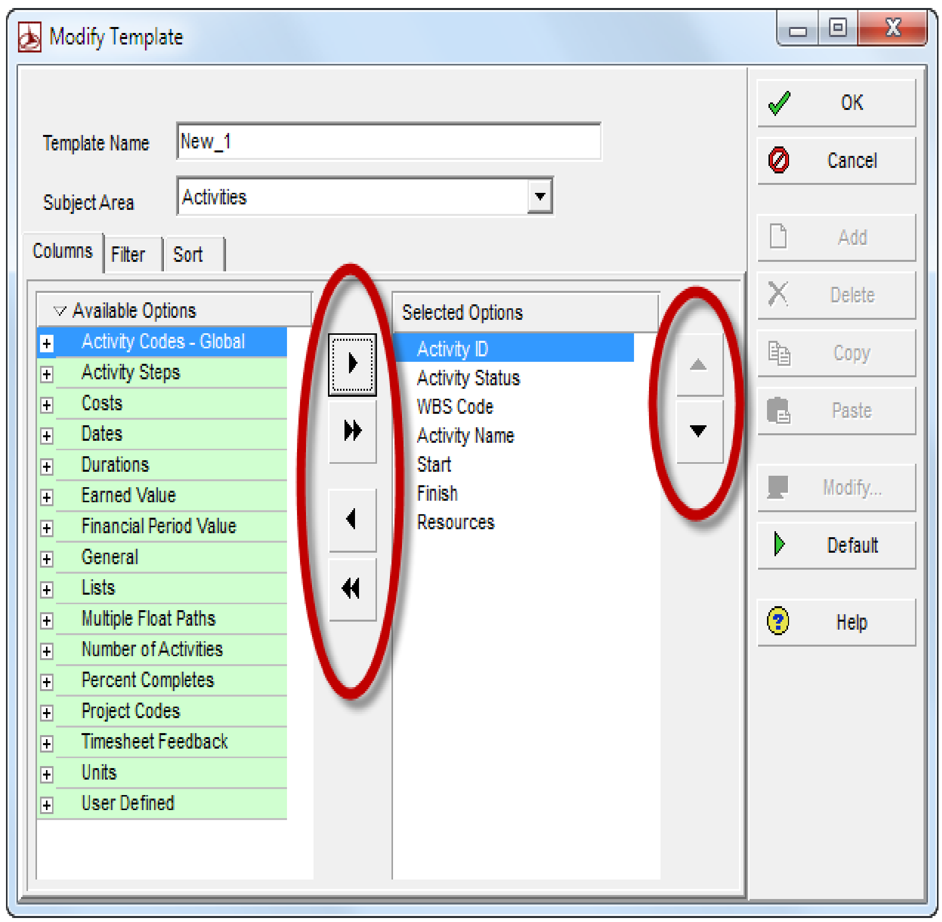
- A “Projects To Export” menu will appear. Choose the Primavera project that you would like to export. Click the empty box under the “Export” heading. A check mark should appear. Click “Next”.
    - NOTE: You can only export projects that were already open when starting the export process.



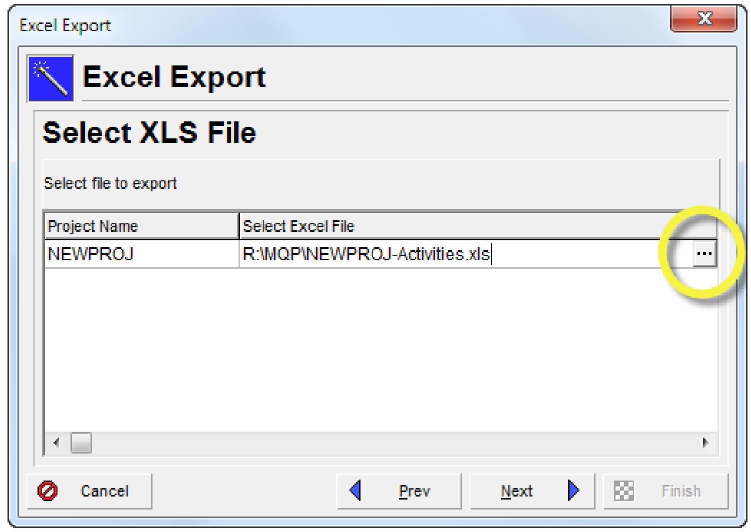
- An “Excel Export” menu will appear. It will contain templates from previous projects, however, if you are creating a new template, click “Add”

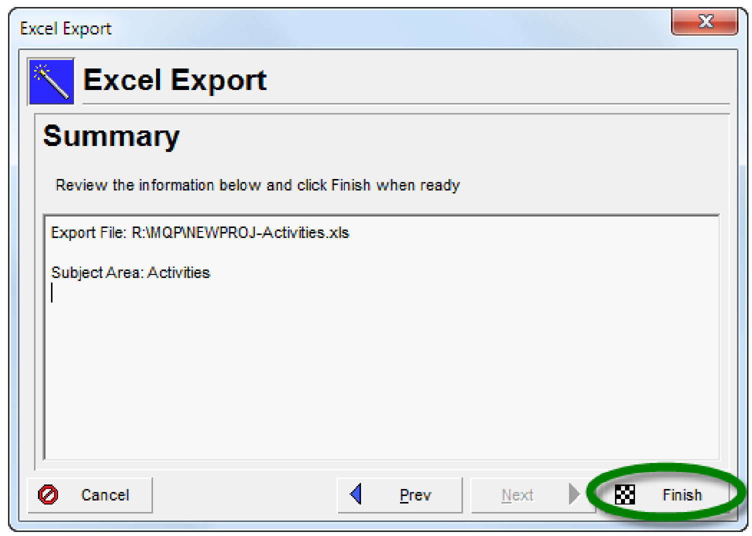


- A “Modify Template” menu will appear. Within this menu you can rename the template and customize the column settings that will appear when exported to Excel. Using the arrows (circled in red on the image below) you can choose which options to include/exclude and rearrange them into whichever order preferred. Once you have organized the “Selected Options”, click “OK” at the top right of the screen.



- This will bring you back to the "Excel Export" screen. Click "Next"
- A "Select XLS File" menu will appear. Select the Excel file (.xls) you will be exporting the column selection into. Click on the box with three dots (see image) to find and select the Excel file you will be using. Once you have chosen the file, click "Next".
  - NOTE: If you didn't create the .xls file previous to this step, simple open a new excel sheet and save it.

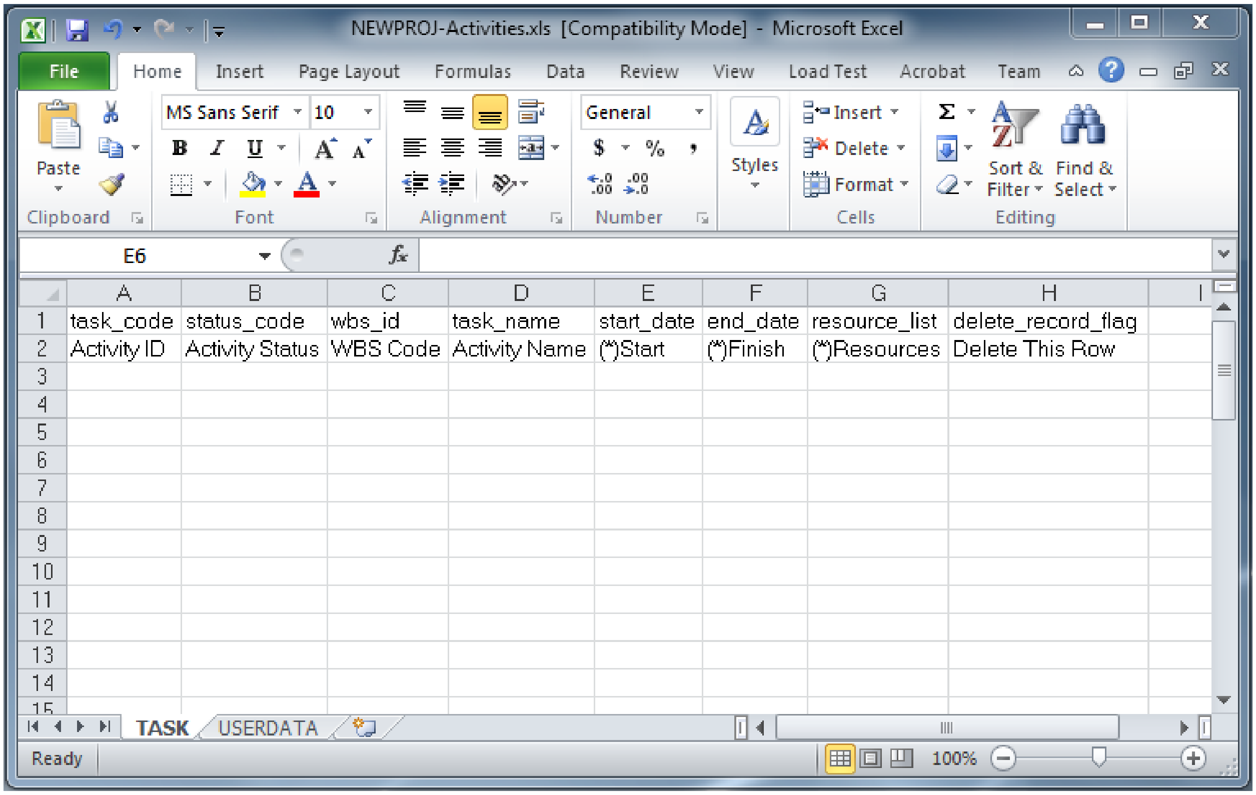




- A "Summary" menu will appear. This menu displays the actions of the export about to take place. After reviewing the information, click "Finish"

- The "The export was successful." box should appear after this process, in which case you are finished. If an "Error" box appears then retry the process.

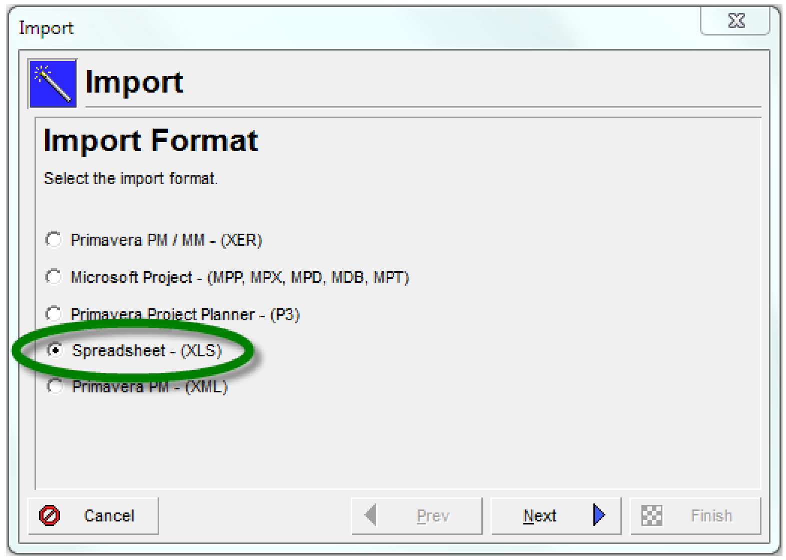
- Fill in the Excel sheet
  - Open the Excel file that you chose to export the Primavera file into. It should now contain the column headings.



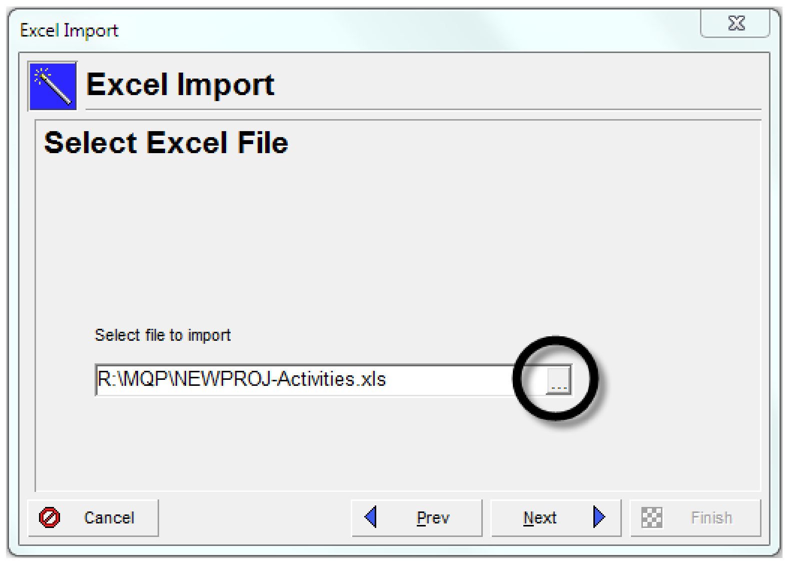
- Fill in the sheet with all activity information. Make sure that you use a uniform format for dates and remain consistent on Identifying activities.
- Format the Excel sheet as wanted (change names of column headings, create filters, color code, etc.) See example below.
- Save the file once you have the completed filling it in.

	A	B	C	D	E	F	G	H	I	J
1		GILBANE	ActivityID	Activity Description	Early Start	Early Finish	Actual Start	Actual Finish	Area	Schedules
2	Structural Precast	4042	CO0301B01800	Erect Precast Structure And TS	11/1/2010	12/14/2010	11/5/2010	11/23/2010	B	32
3	Structural Precast	4044	CO0301B01801	Compete Erect Precast Structure And TS	12/15/2010	12/29/2010	2/8/2011	2/9/2011	B	11
4	Concrete Foundations	5095	CO0300A00501	Conc Deep Founds & Cantel Ret Wall A,B	8/16/2010	9/16/2010			A/B	24
5	Concrete Foundations	5131	CO0300A00302	FRP FTGS/Found Walls Load Dock	11/24/2010	12/8/2010	11/12/2010	12/27/2010	A	11
6	Concrete Foundations	5134	CO0300A00300	FRF Footings Area A & Retaining Wall	8/23/2010	8/26/2010	8/23/2010	8/26/2010	A	4
7	Concrete Foundations	5135	CO0300A00500	FRP Conc Found & Retaining Walls A Line	8/25/2010	9/1/2010	9/2/2010	9/22/2010	A	6
8	Concrete Foundations	5140	CO0300B00301	FRP Conc FTGS 1 Line - Area B	8/19/2010	9/3/2010	8/16/2010	8/23/2010	B	12
9	Concrete Foundations	5141	CO0300B00500	FRP Conc Foundation Falls 1 Line - Area B	8/23/2010	9/13/2010	8/23/2010	9/15/2010	B	16
10	Concrete Foundations	5146	CO0300A00301	FRP Footings Area A.7 to FF .7 Line	8/27/2010	9/17/2010	8/30/2010	10/4/2010	A	16
11	Concrete Foundations	5147	CO0300A00502	FRP Conc Found Walls A.7 to FF.7	9/3/2010	9/24/2010	9/27/2010	10/14/2010	A	16
12	Concrete Foundations	5151	CO0300C00300	FRP Footings Area FF.7 to MM Line	9/20/2010	10/1/2010	9/15/2010	9/29/2010	C	10
13	Concrete Foundations	5152	CO0300C00500	FRP Conc Found Walls FF.7 to MM Line	9/27/2010	10/9/2010	10/12/2010	10/27/2010	C	10
14	Structural Steel/Decking	5155	CO0507A02001	Erect Area A Steel	10/19/2010	10/25/2010	10/28/2010	11/3/2011	A	5

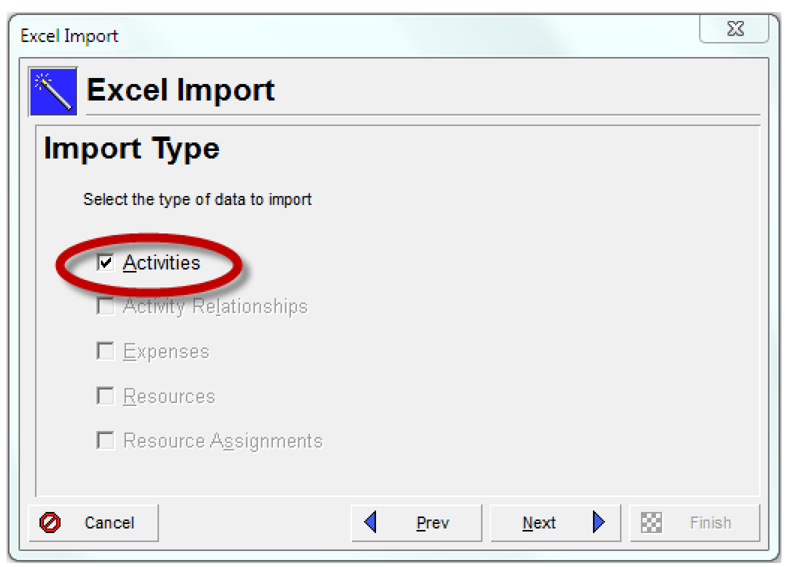
- Import the Excel file into Primavera
  - Open Primavera and click the "File" tab at the top left of the screen.
  - Under the drop down menu, choose "Import" and the "Import Format" menu will appear. Choose the "Spreadsheet – (XLS)" option, then click "Next."



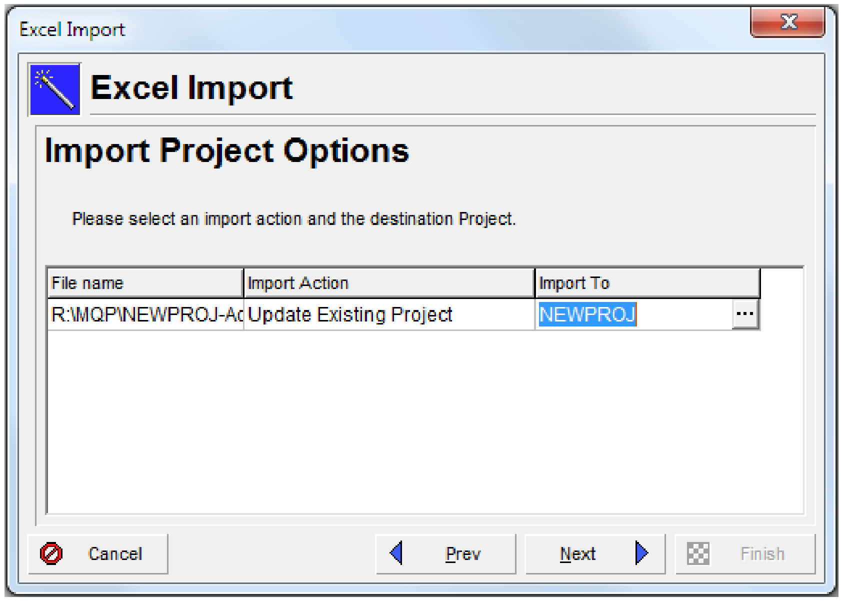
- A "Select Excel File" menu will appear. Choose the excel file you will be importing by clicking box with 3 dots (see image below). Then click "Next"

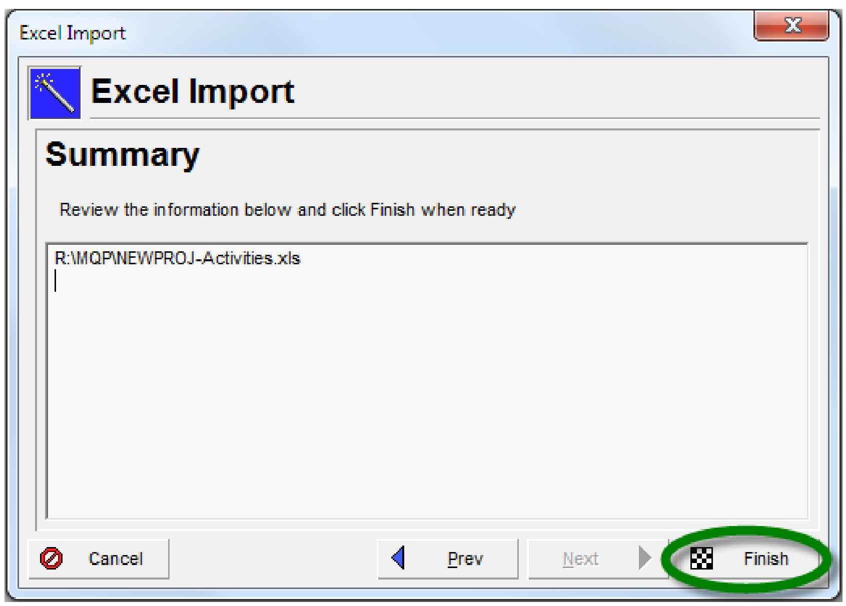


- An "Import Type" menu should appear. Click the box next to "Activities". A check should appear. Click "Next"



- An “Import Project Options” menu should appear. Select the Primavera file that you will be importing the Excel file into by clicking on the “Import To” button. Once chosen, click “Next”





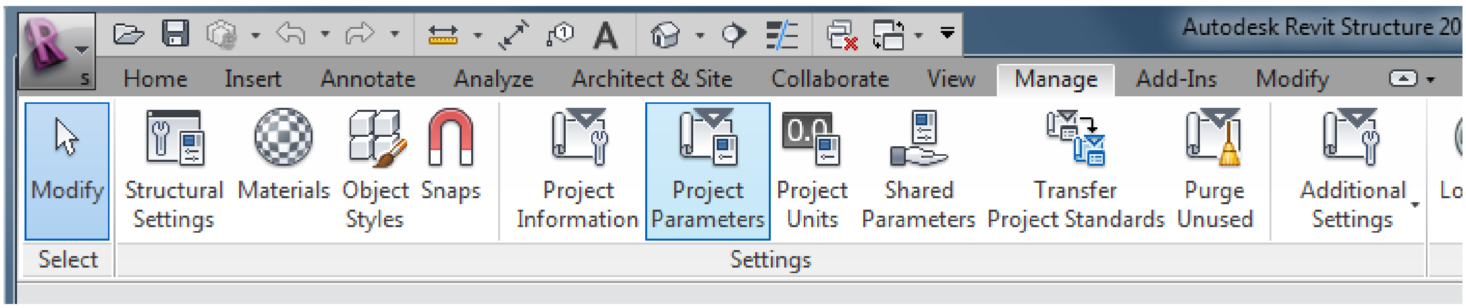
- A “Summary” menu should appear. Review the import information and click “Finish”
  - A box that says “The import was successful” should appear. If so, then the import is complete.

APPENDIX D: Revit Element Identification Process

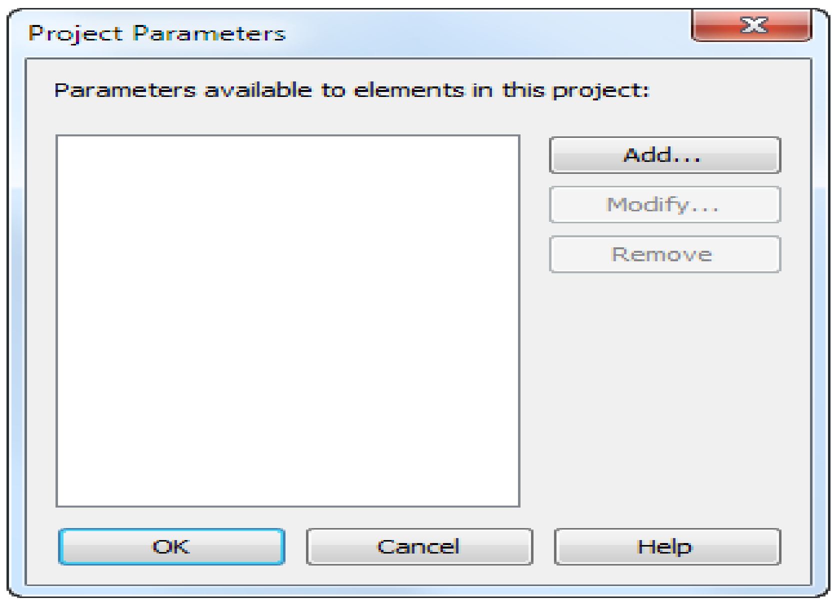
The following steps teach you how to attach and activity ID to each object in the Revit model

To Add an Activity ID to different objects in the Revit model you must make a Project Parameter to store the information for the ID.

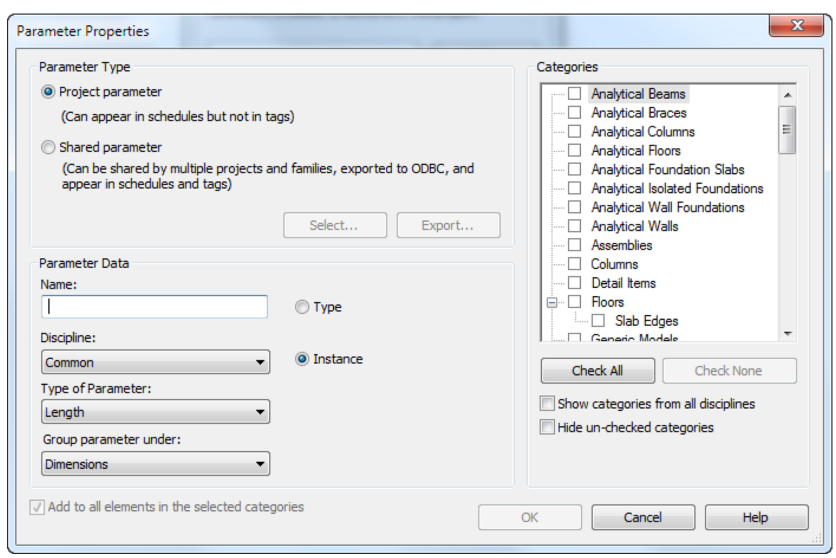
- Select the "Manage" Tab
  - Select the "Project Parameters" Tab



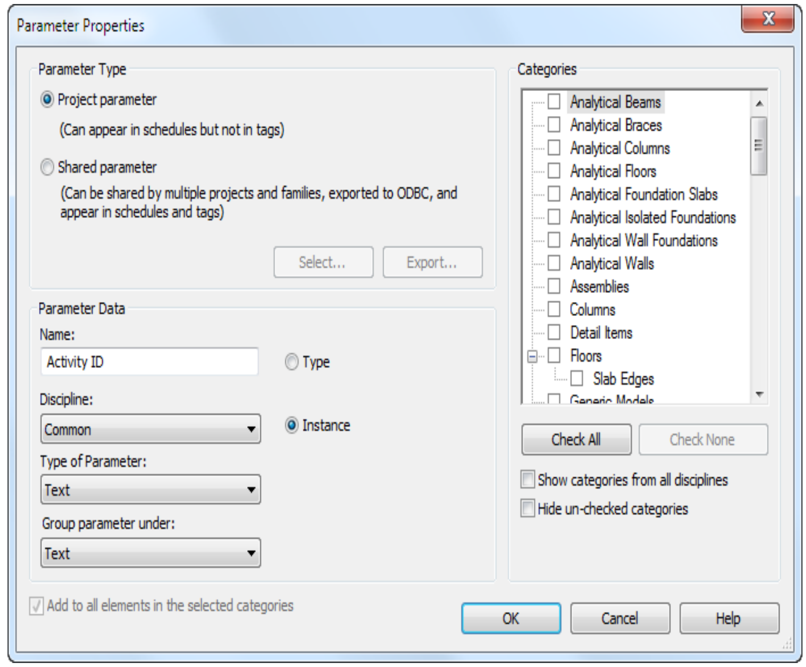
- Select "Add…"



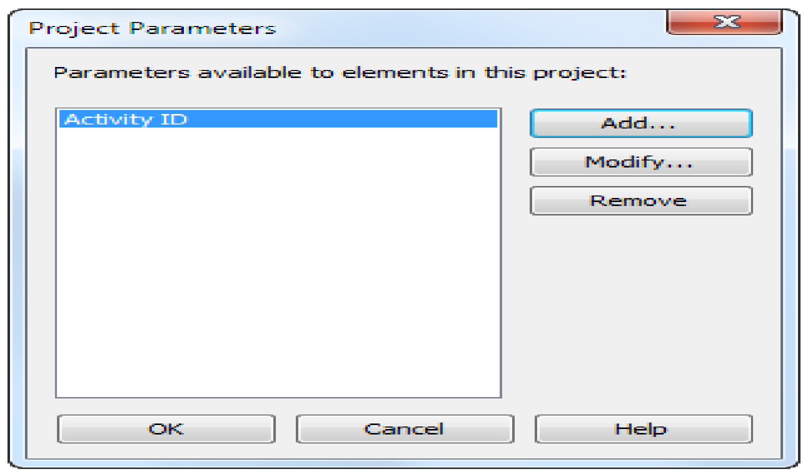
- Under "Parameter Type" select "Project parameter"



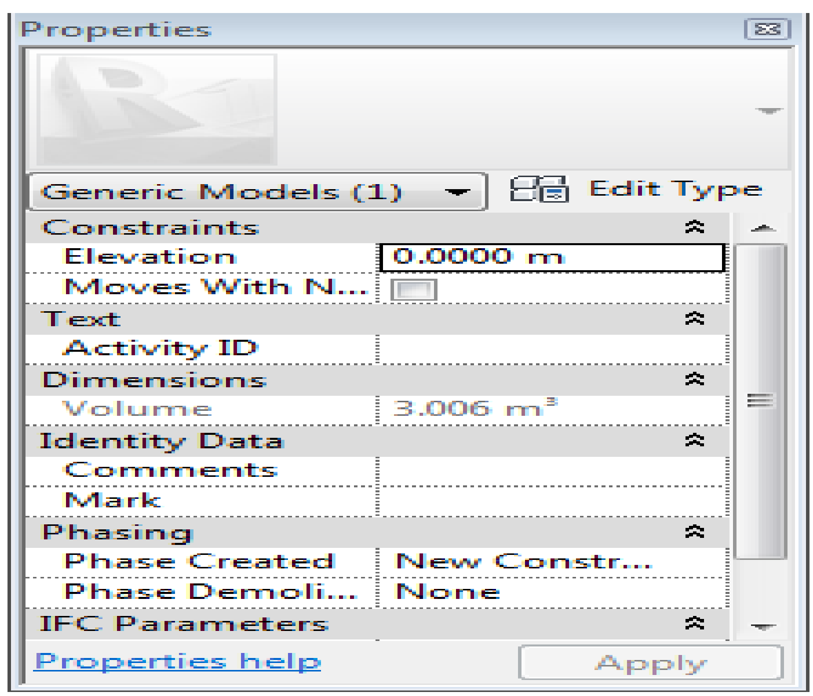
- Under “Parameter Data”
  - In the “Name” field enter “Activity ID”
  - In the “Type of Parameter:” menu select “Text”
  - In the “Group Parameter under:” menu select “Text”
- All other defaults can be left in place.
- Click “OK”



- Click “OK”

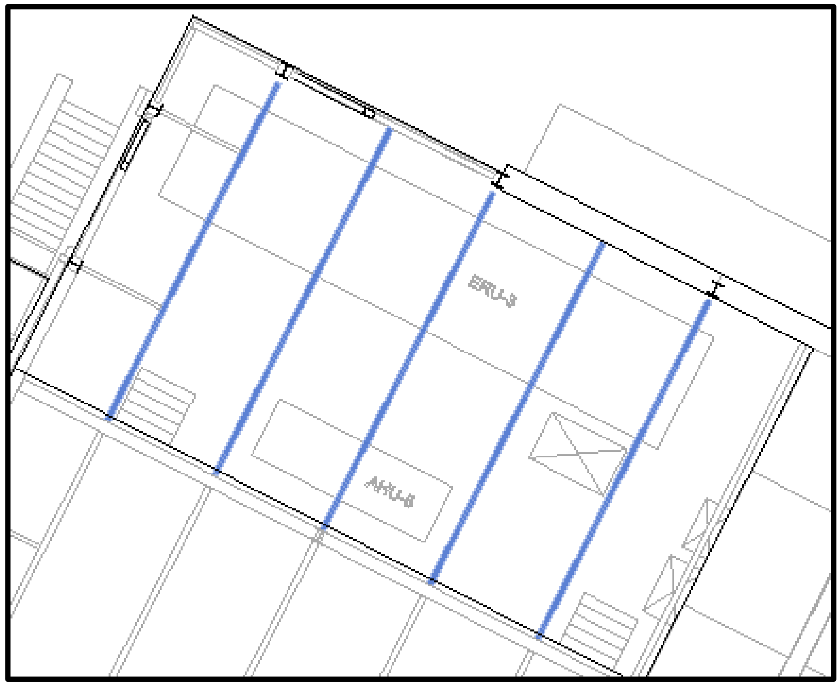


Now the Activity ID Parameter has been created to accept the data to ID the objects in the Model. The new Parameter can be found in the “Properties” sidebar to the left of the screen as shown to the right

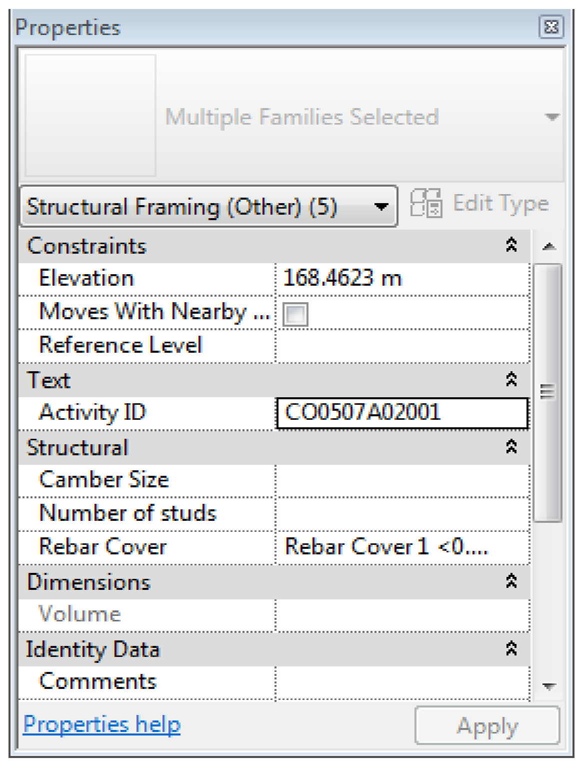


In order to ID the objects one needs to select the objects pertaining to the ID needed and enter the ID.

- Highlight the Objects to be identified



- Input the Activity ID corresponding with the objects selected in the "Activity ID" field under the "Text" section.
- Click "Apply"



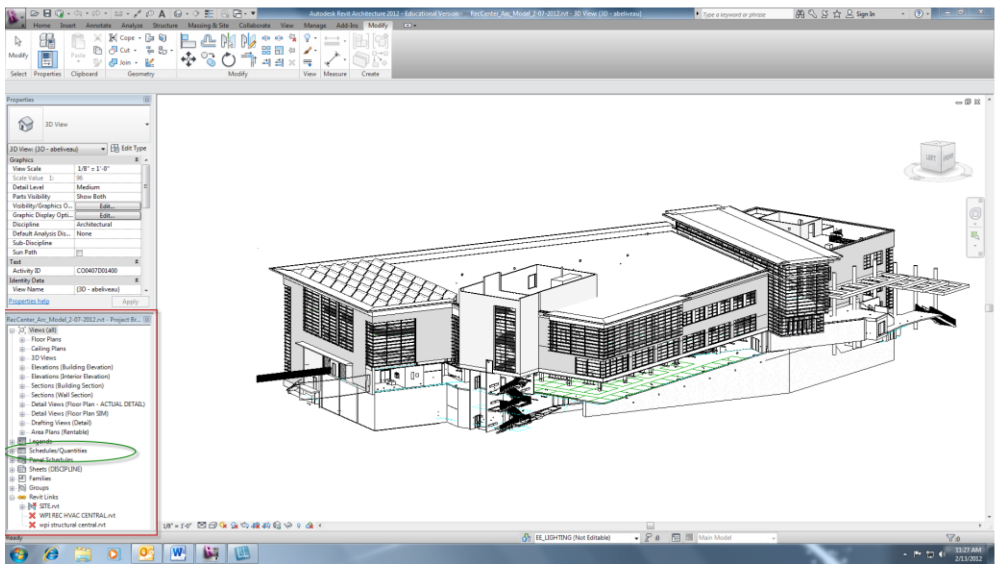
Once this is completed for each object in the model based on their corresponding Activity ID you are able to import the model with the Activity ID's into Navisworks.

APPENDIX E: Material Quantity Takeoff Process

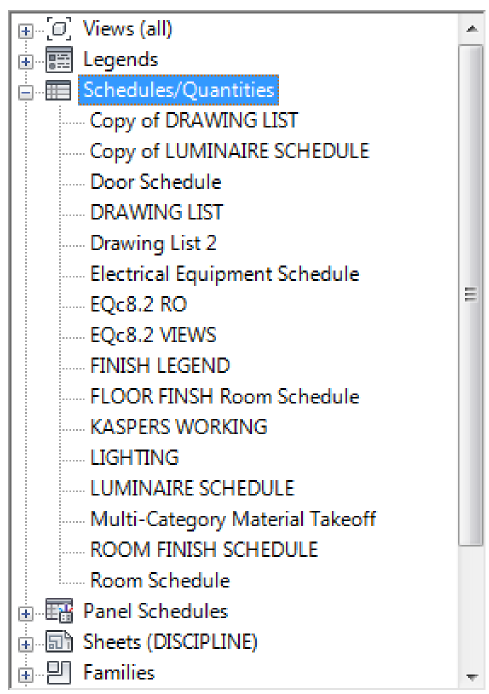
Following this process outlines the necessary steps to take when creating a materials quantity take off in Revit.

First, open the Autodesk Revit file that you wish to examine. Be sure that this file is saved somewhere that you can access – not all steps in this tutorial will work if the file is not saved prior to conducting the material takeoff.

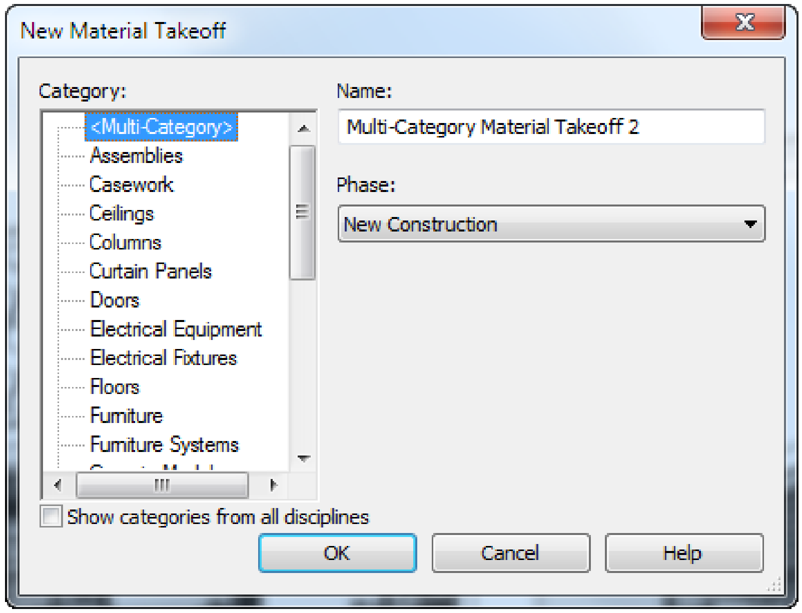
In the lower left of the main screen in Revit, notice the Project Browser. All views and sheets can be sorted in the Project Browser. For a Material Takeoff, expand the Schedules/Quantities menu.



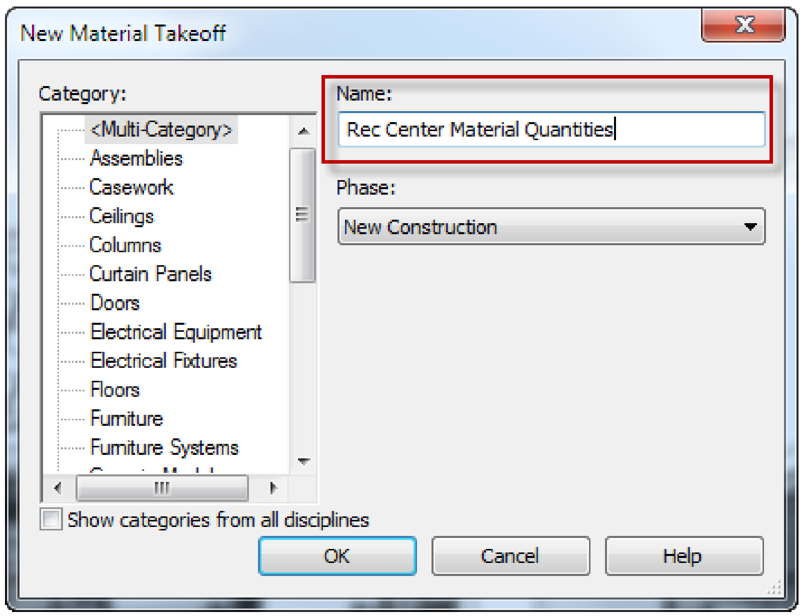
Once expanded, right-click on the Schedules/Quantities header in the Project Browser. In this right-click menu, choose "New Material Takeoff".



Next, you will be prompted with the New Material Takeoff dialog box.

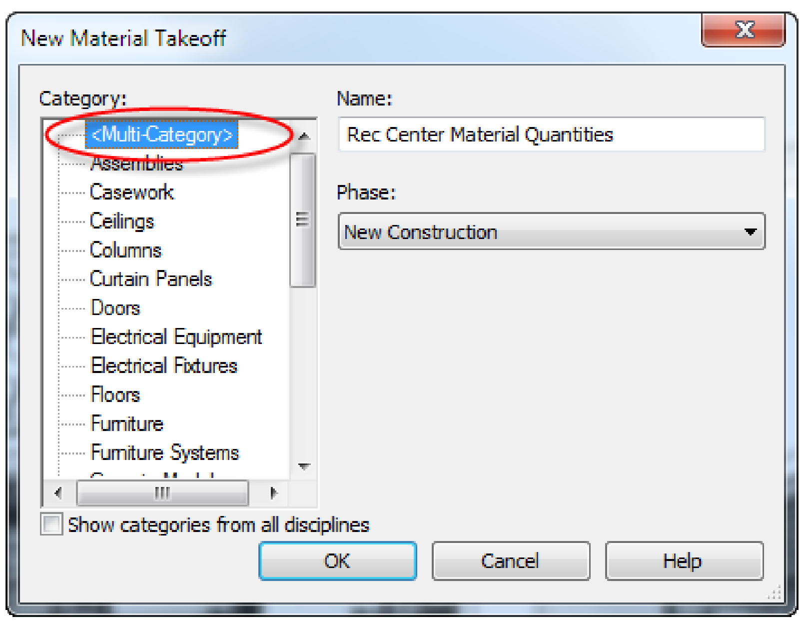


Now you must name the Material Takeoff – create a name you will remember and that makes sense.

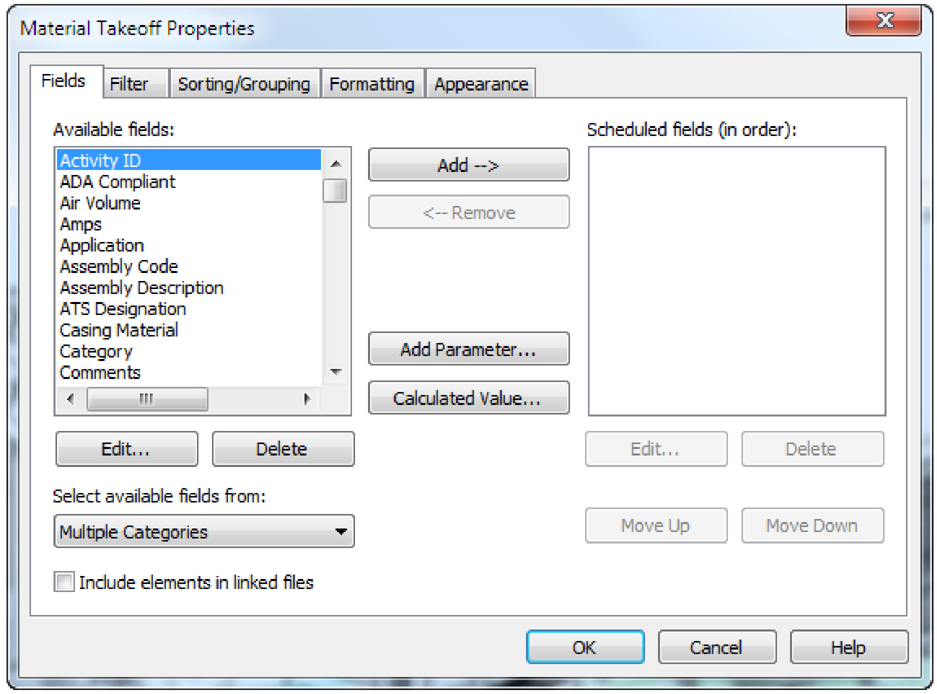


Next, ensure that the "Category" is set to "Multi-Category". This will ensure that you can run one takeoff and receive data about more than one type of materials.

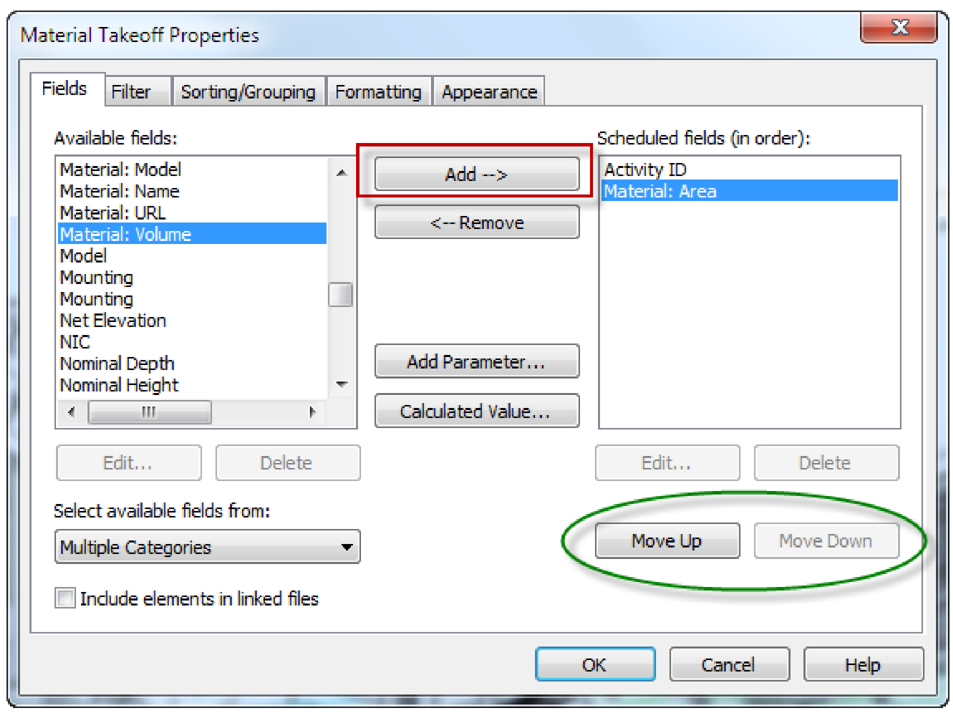
Now, move to the next step by selecting OK.



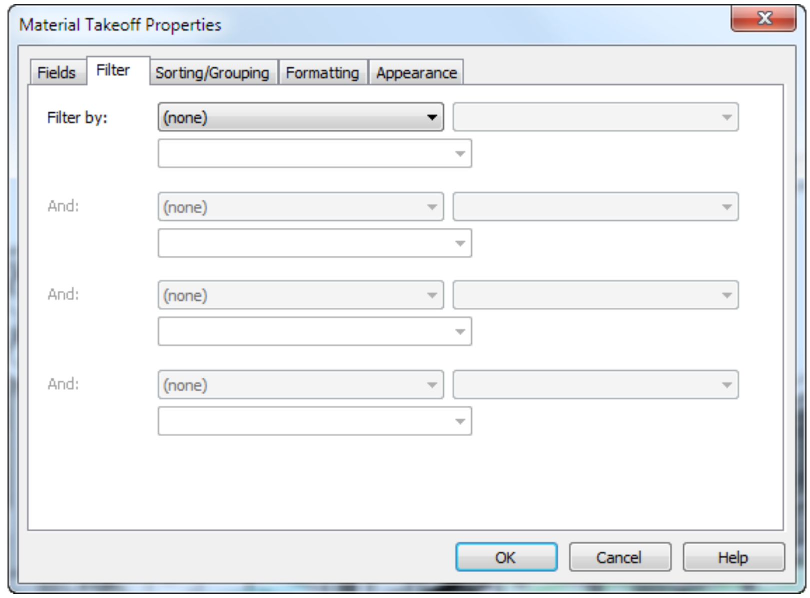
You will now be prompted with the Material Takeoff Properties dialog box. This dialog box will establish what you want information for in the project, and how to display that information.



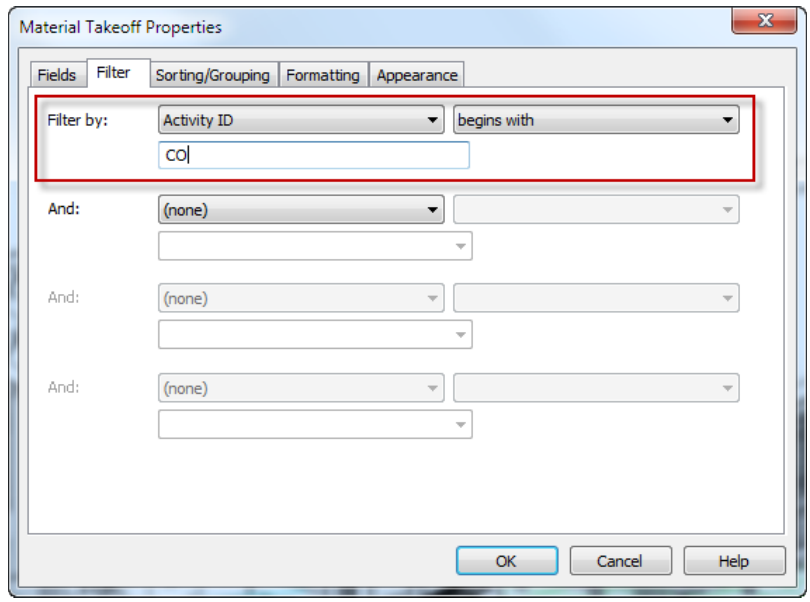
The first thing to take care of is to establish the scheduled fields you wish to have displayed in the takeoff. Browse through the options seen in the "Available Fields" menu on the left of the dialog box. When you are prepared to add a field, highlight the field, then click the "Add" button. This will populate the "Scheduled Fields" menu. Note that the Schedule Fields will appear in order from left to right, starting with the top in this menu, and ending with the bottom. This order can be changed by using the Move Up/Move Down options.



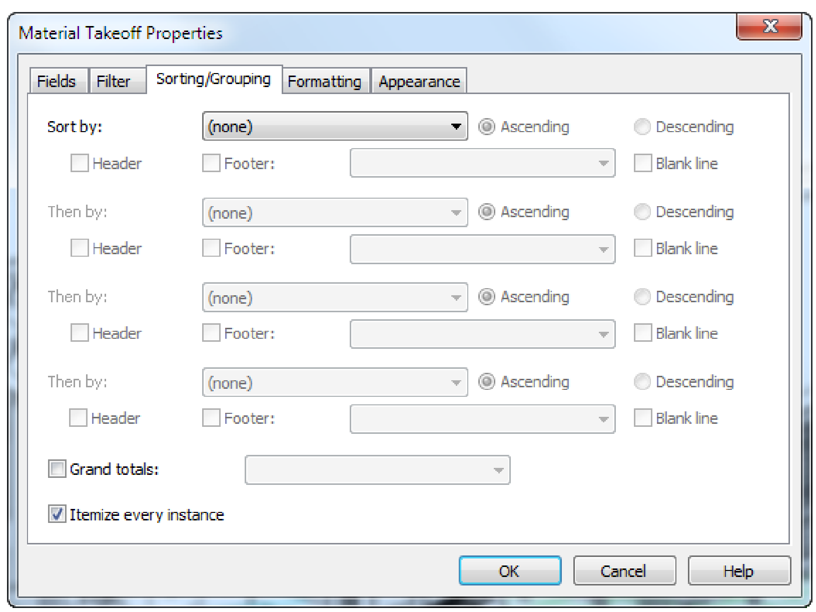
Next, move the dialog box tab over to "Filter".



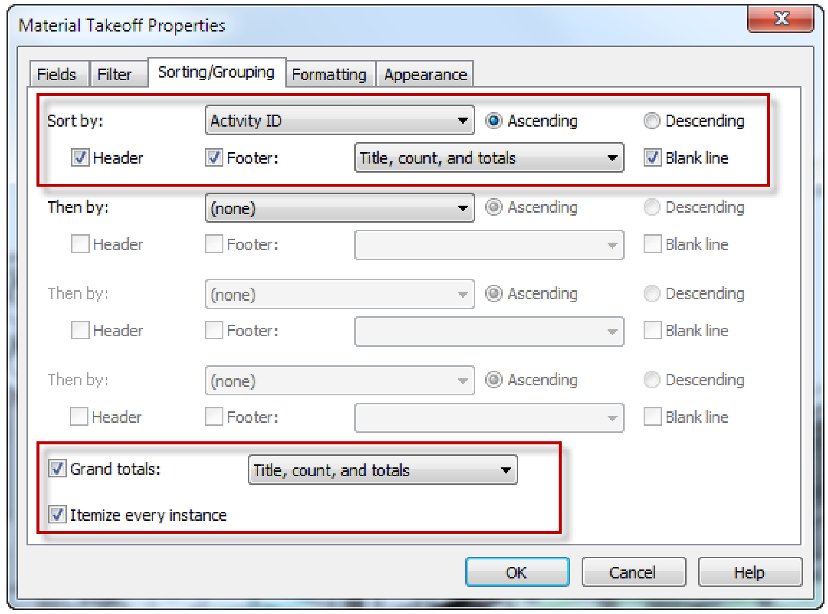
If you would like to restrict which elements are displayed, for instance if you wish to only see materials from particular trades that you have previously identified, you can do so by filtering the display. In this example, we choose to filter by a data set called "Activity ID", sorting by ID's that begin with "CO". This process is similar to establishing rules for an email inbox or other restrictive process.



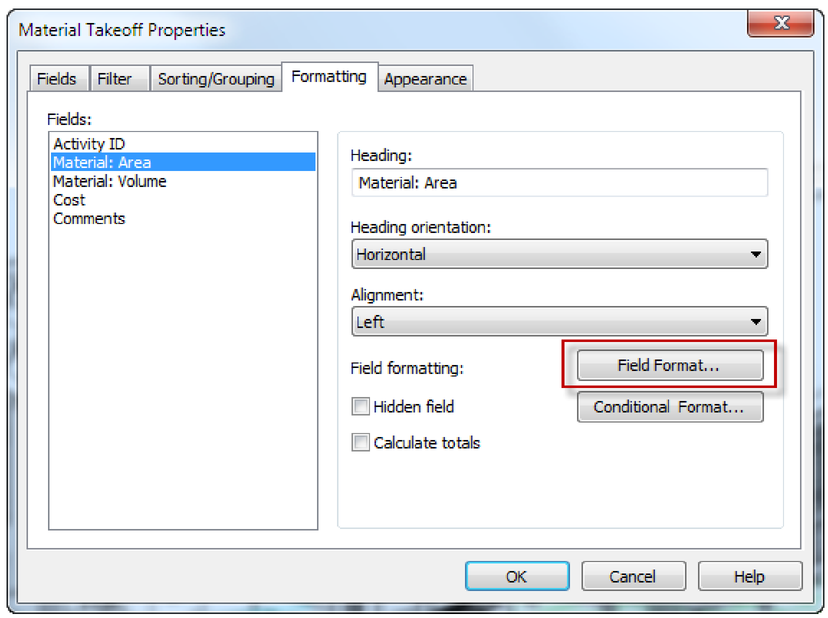
Next, move the dialog box tab to "Sorting/Grouping".



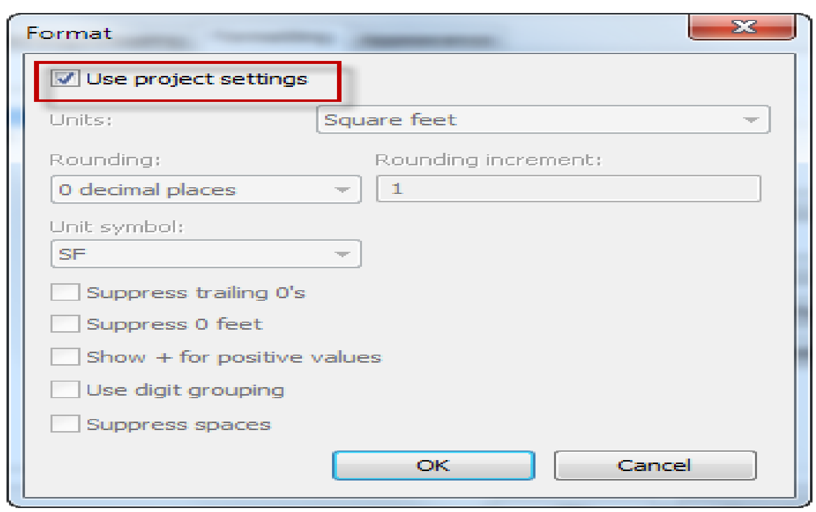
Sorting your results will enable you to display them graphically in a manner that helps you best. In this case, I choose to display this material takeoff with a sort by Activity ID, but a Family/Type sort is very common as well. Be sure to select the "Header", "Footer", and "Blank line" option boxes. For ease of reading, I suggest leaving the "Footer" set to display "Title, Count, and totals". You may also wish to select the "Grand totals" option box, as this will total all materials for you at the bottom of your takeoff. Again, set this to display "Title, Count, and totals". Lastly, I suggest leaving the option box titled "Itemized every instance" selected.



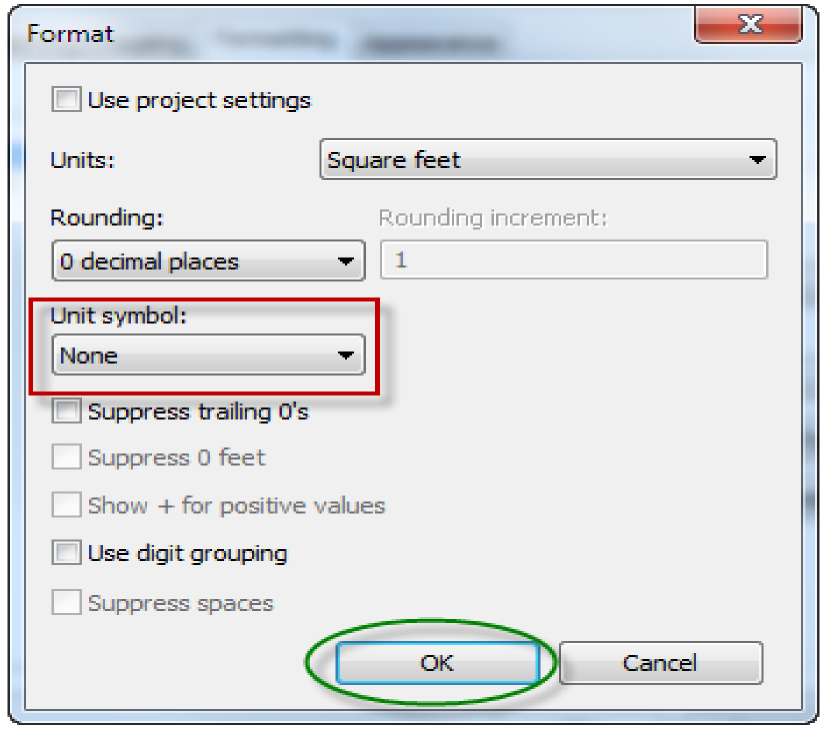
Next, move the dialog box tab to "Formatting". Here you can choose how each item will be displayed in your takeoff. You may choose to have each value labeled with it's units, or you can have the value displayed as a number only. To change this setting, select a Field, then choose Field Format.



You will then be prompted by the Format sub-dialog box. To change these settings, deselect Use project settings.

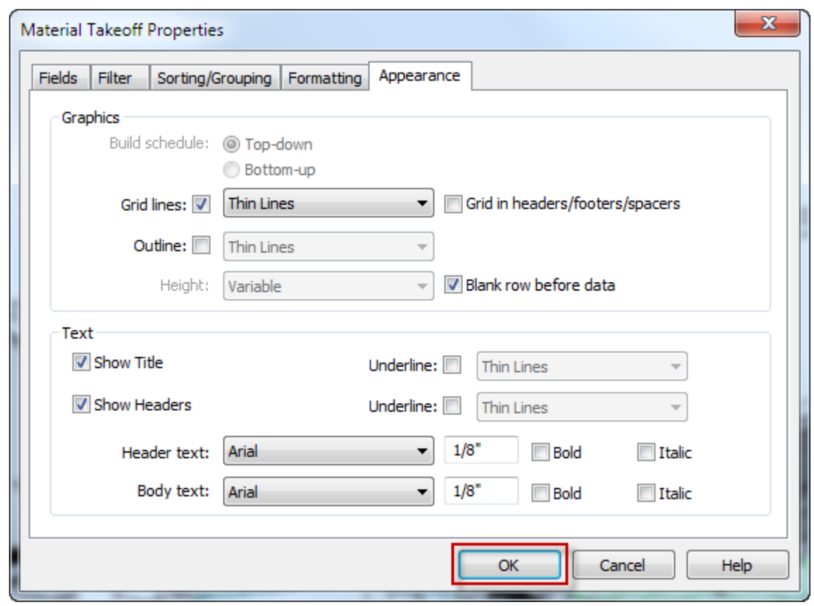


Once this is no longer selected, the other options will appear editable. Make changes as necessary, including the Unit Symbol display. Click OK when done.

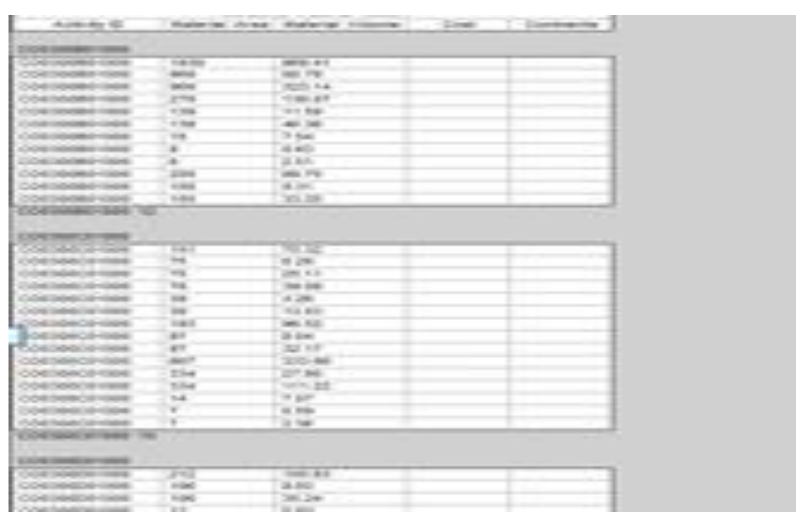


Move the dialog box tab to “Appearance”. Confirm that the preset settings are correct, and make changes as desired.

Click OK.

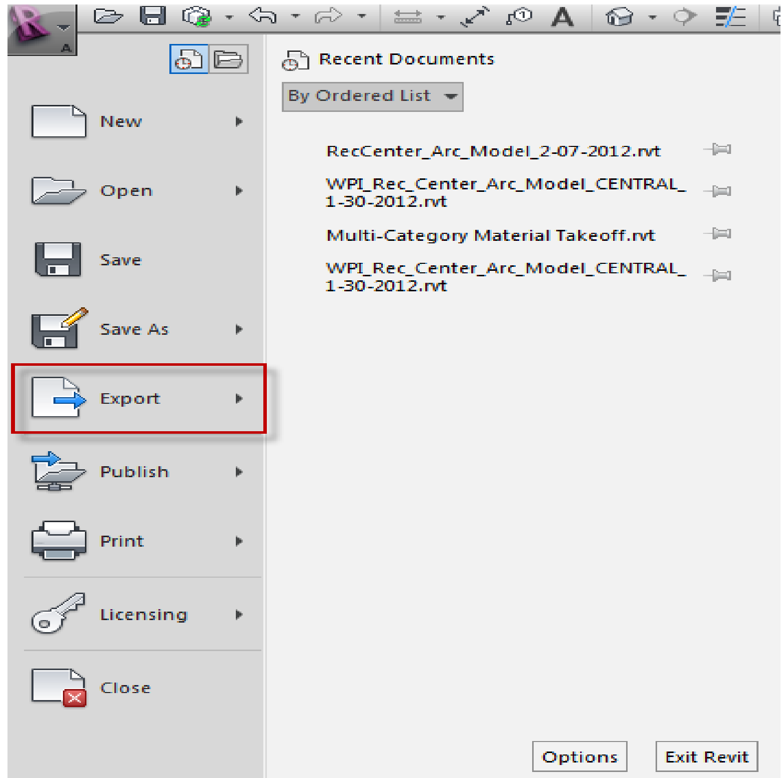


By clicking OK, you advance to the material takeoff report that Revit produces. It appears as a new Schedule in the Schedule/Quantities menu in the Project Browser, and it named what you originally named the takeoff.

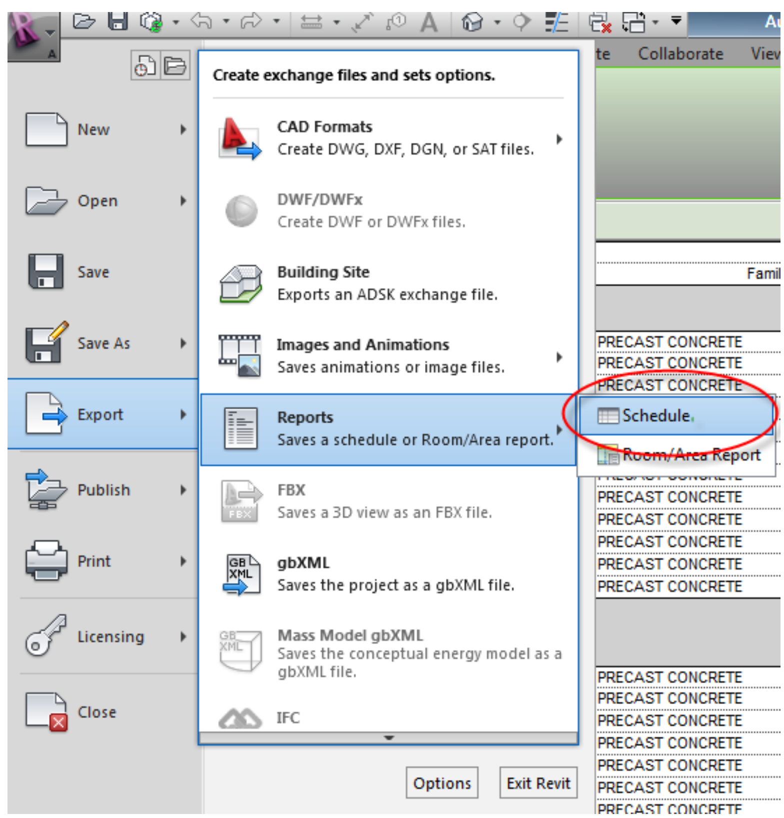


By clicking OK, you advance to the material takeoff report that Revit produces. It appears as a new Schedule in the Schedule/Quantities menu in the Project Browser, and it named what you originally named the takeoff.

You may also choose to export this material takeoff so that you can manipulate the values in Microsoft Excel or other tabulation software. The first step in exporting the data set we just created is to save the file. It is essential to exporting that your file is saved.

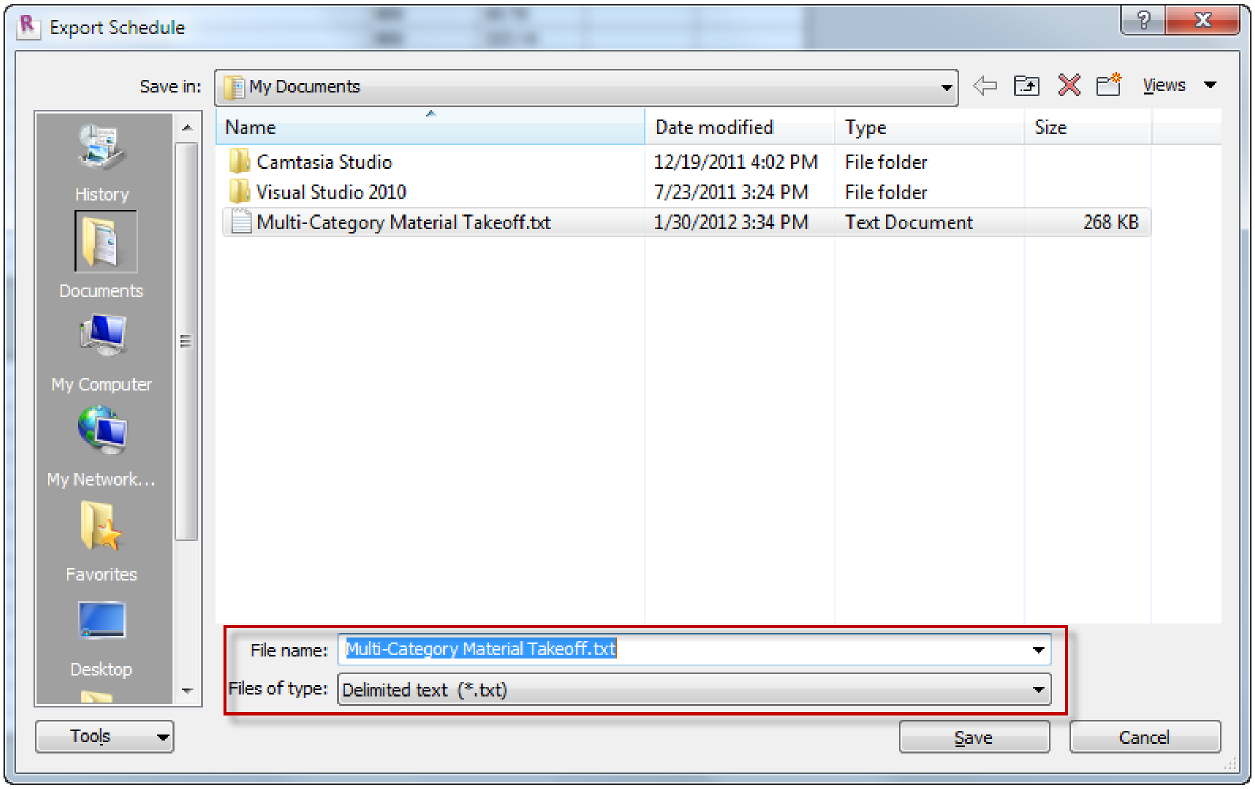


Next, to export the material takeoff, click the "R" icon, also known as the main menu in Revit. Once open, select Export.

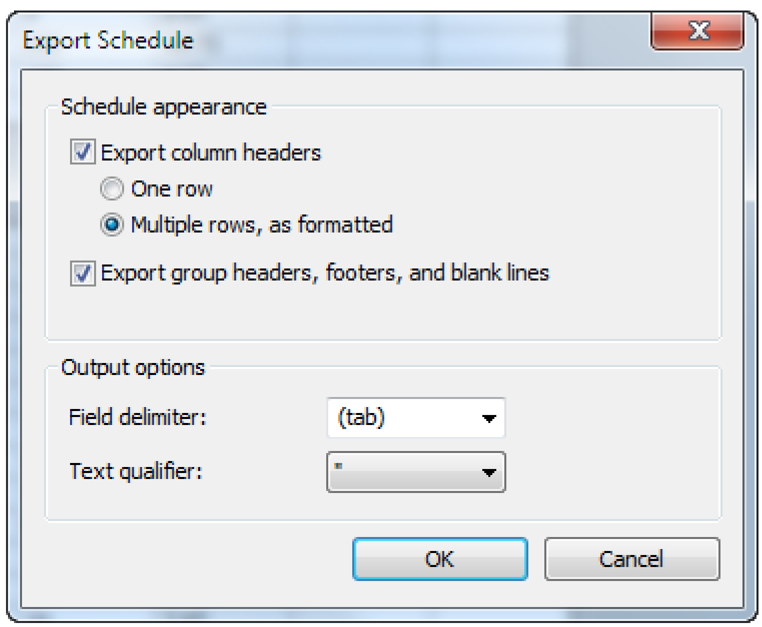


After selecting Export, choose Reports. From reports, click on Schedule.

Next, you will be brought to the Export Schedule dialog box. Set the destination and name of your exported file. Be sure to leave the file type set as Delimited Text (*txt).



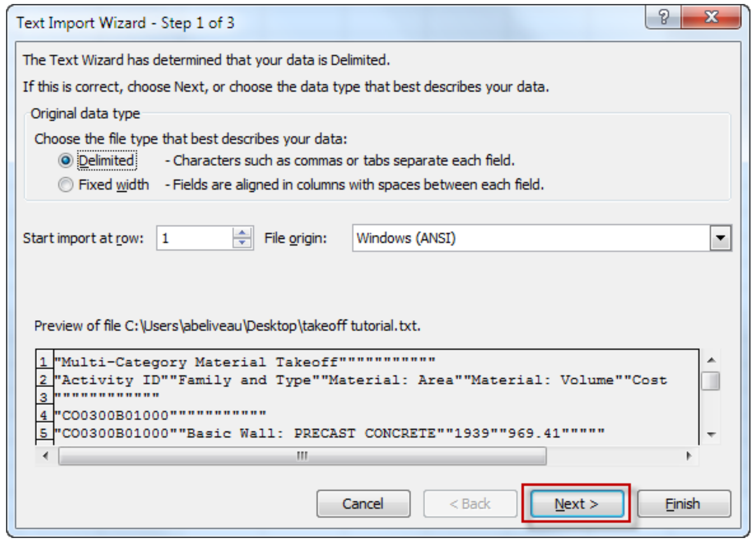
Choose Save.



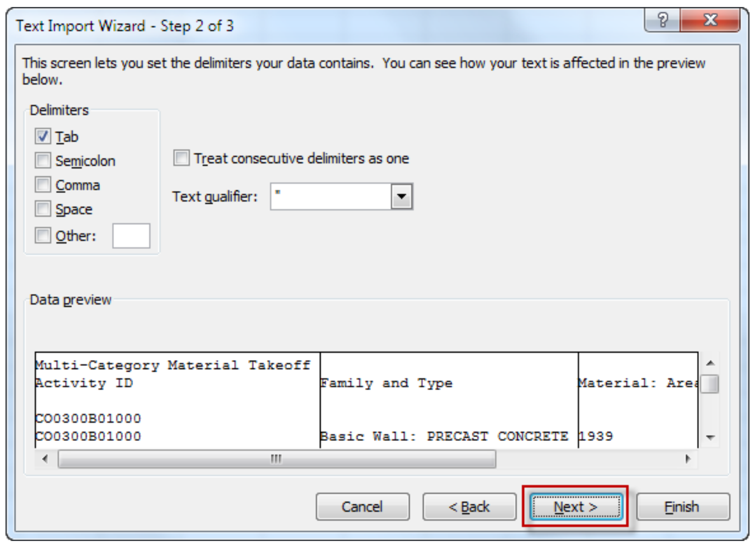
Next, the Export Schedule dialog box will reappear. Be sure to leave the settings as they are. They should appear like this:

You have just exported your Material Quantity Takeoff from Revit.

To open this file in Excel, first open the Excel application. Next, choose open new file. Navigate to the file that you just exported, and click open. (You may need to change the file type settings, as the export was a *.txt file)

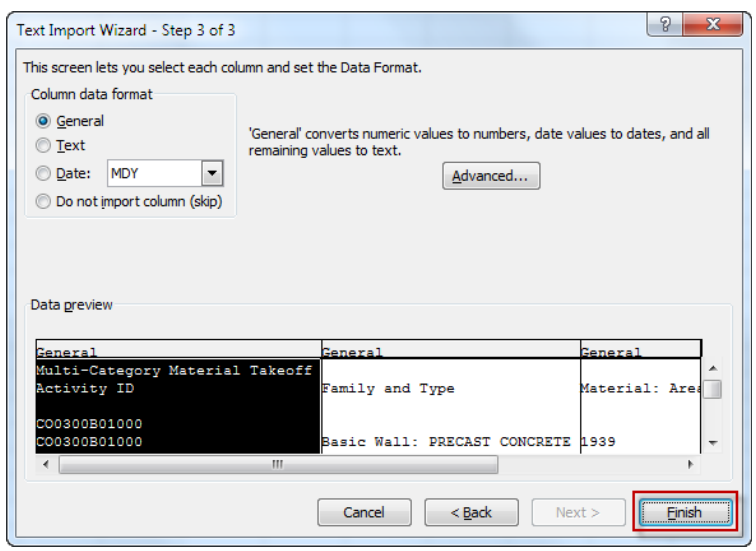


The Text Import Wizard will then open. For the next steps, change nothing to the settings in the wizard, just click Next >.



Next, click on Finish.

You have just completed the Material Quantity Takeoff process from start to finish



You may now edit the results however you may need.

	A	B	C	D	E	F	G	H
1		Multi-Category Material Takeoff						
2	**Activity ID**	**Family and Type**	**Material: Area**	**Material: Volume**	**Cost**	**Comments**		
3								
4	**CO0300B01000**							
5	CO0300B01000	Basic Wall: PRECAST CONCRETE	1939	969.41				
6	CO0300B01000	Basic Wall: PRECAST CONCRETE	969	80.78				
7	CO0300B01000	Basic Wall: PRECAST CONCRETE	969	323.14				
8	CO0300B01000	Basic Wall: PRECAST CONCRETE	278	139.07				
9	CO0300B01000	Basic Wall: PRECAST CONCRETE	139	11.59				
10	CO0300B01000	Basic Wall: PRECAST CONCRETE	139	46.36				
11	CO0300B01000	Basic Wall: PRECAST CONCRETE	15	7.54				
12	CO0300B01000	Basic Wall: PRECAST CONCRETE	8	0.63				
13	CO0300B01000	Basic Wall: PRECAST CONCRETE	8	2.51				
14	CO0300B01000	Basic Wall: PRECAST CONCRETE	200	99.75				
15	CO0300B01000	Basic Wall: PRECAST CONCRETE	100	8.31				
16	CO0300B01000	Basic Wall: PRECAST CONCRETE	100	33.25				
17	**CO0300B01000: 12**		4863	1722.34				
18								
19	**CO0300C01000**							
20	CO0300C01000	Basic Wall: PRECAST CONCRETE	151	75.32				
21	CO0300C01000	Basic Wall: PRECAST CONCRETE	75	6.28				
22	CO0300C01000	Basic Wall: PRECAST CONCRETE	75	25.11				
23	CO0300C01000	Basic Wall: PRECAST CONCRETE	78	39.08				
24	CO0300C01000	Basic Wall: PRECAST CONCRETE	39	3.26				
25	CO0300C01000	Basic Wall: PRECAST CONCRETE	39	13.03				
26	CO0300C01000	Basic Wall: PRECAST CONCRETE	193	96.52				
27	CO0300C01000	Basic Wall: PRECAST CONCRETE	97	8.04				
28	CO0300C01000	Basic Wall: PRECAST CONCRETE	97	32.17				
29	CO0300C01000	Basic Wall: PRECAST CONCRETE	667	333.66				
30	CO0300C01000	Basic Wall: PRECAST CONCRETE	334	27.8				
31	CO0300C01000	Basic Wall: PRECAST CONCRETE	334	111.22				
32	CO0300C01000	Basic Wall: PRECAST CONCRETE	14	7.07				
33	CO0300C01000	Basic Wall: PRECAST CONCRETE	7	0.59				
34	CO0300C01000	Basic Wall: PRECAST CONCRETE	7	2.36				
35	**CO0300C01000: 15**		2207	781.51				
36								
37	**CO0300D01000**							
38	CO0300D01000	Basic Wall: PRECAST CONCRETE	212	105.63				
39	CO0300D01000	Basic Wall: PRECAST CONCRETE	106	8.83				
40	CO0300D01000	Basic Wall: PRECAST CONCRETE	106	35.24				

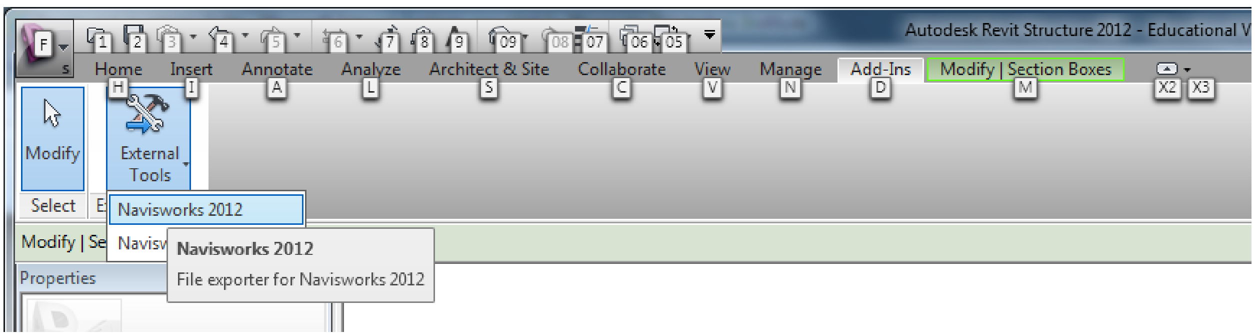
APPENDIX F: NavisWorks Simulation Process

The following process outlines the steps necessary to link Revit and Primavera files within NavisWorks and create a 4D simulation.

Revit Export into NavisWorks:

In order to have a successful Revit export, make sure that you are in the 3D-view with no elements selected and have the entire model displayed.

- Select the "Add-In's" tab
    - Select the "External Tools" tab
        - Select "Navisworks 2012"
            - Save the file

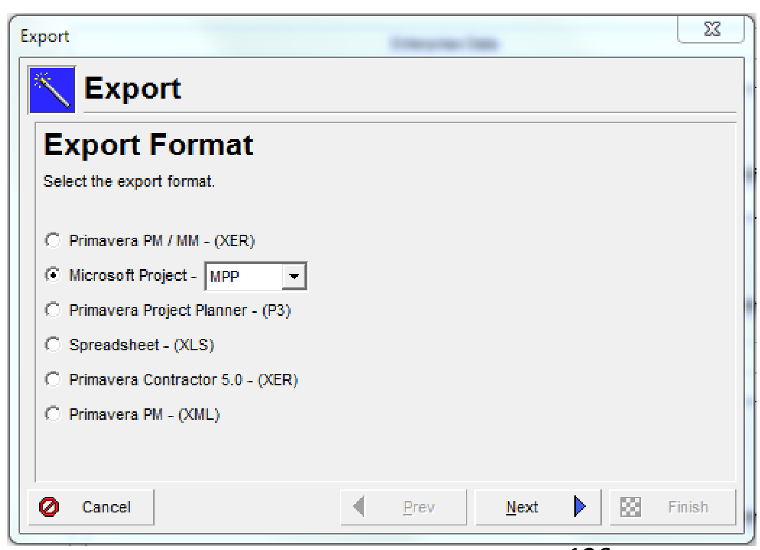


- After following these steps the Revit model will export to a NavisWorks file

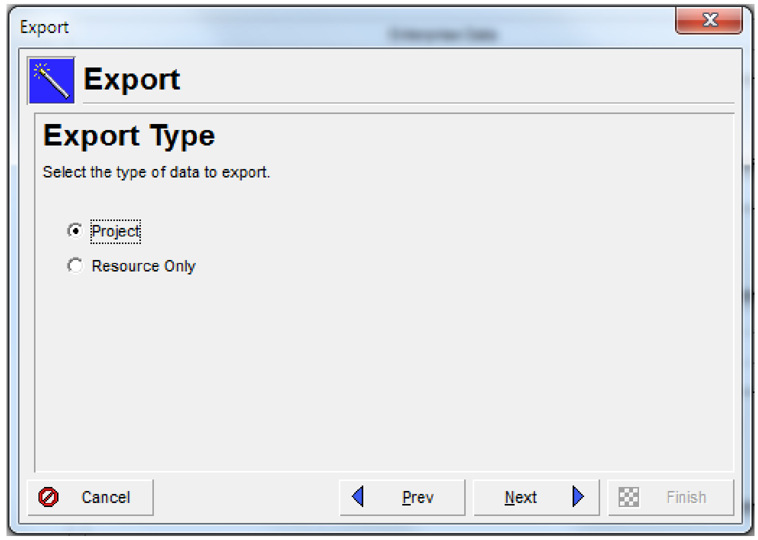
Primavera:

Once the Revit model is exported to NavisWorks, the corresponding Primavera schedule should be exported next.

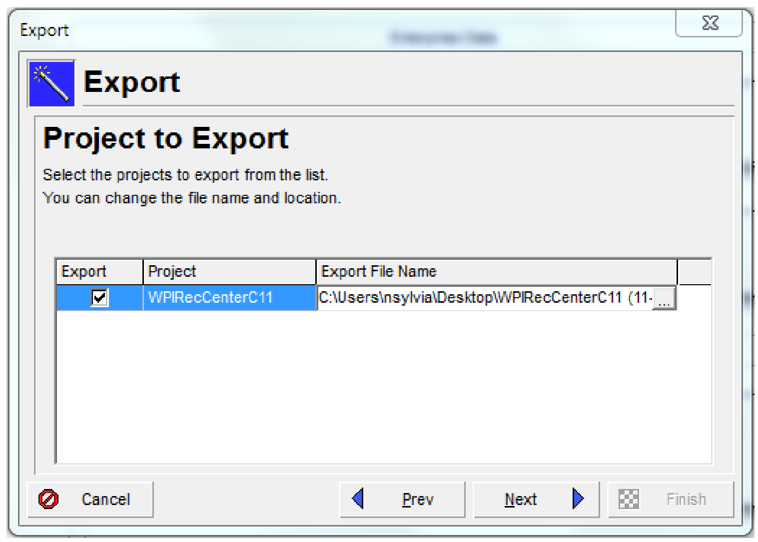
- Click "file"
    - Export
        - An export box appear on the computer screen
- Export Format
    - In the export box chose Microsoft Project (MPP)
    - Click "Next"



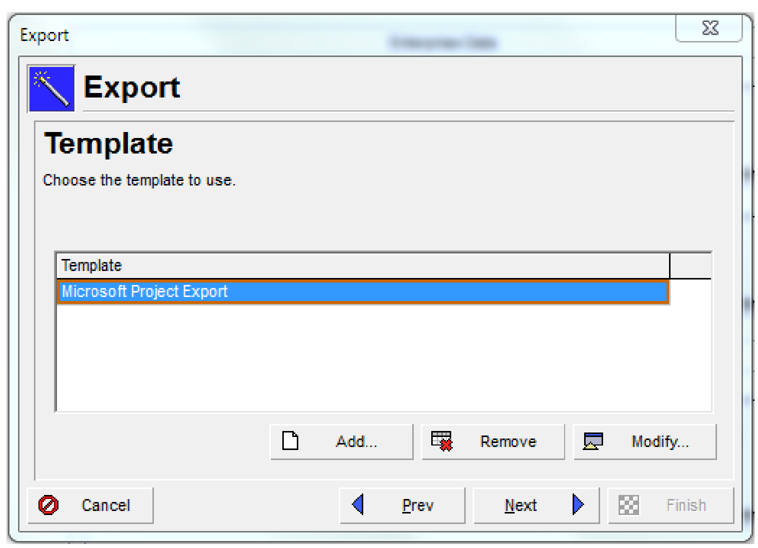
- Export Type
    - Select “Project”
    - Click “Next”



- Project to Export
    - Check the export box
    - Under “Export File Name” select where you would like to export the project to
    - Click “Next”

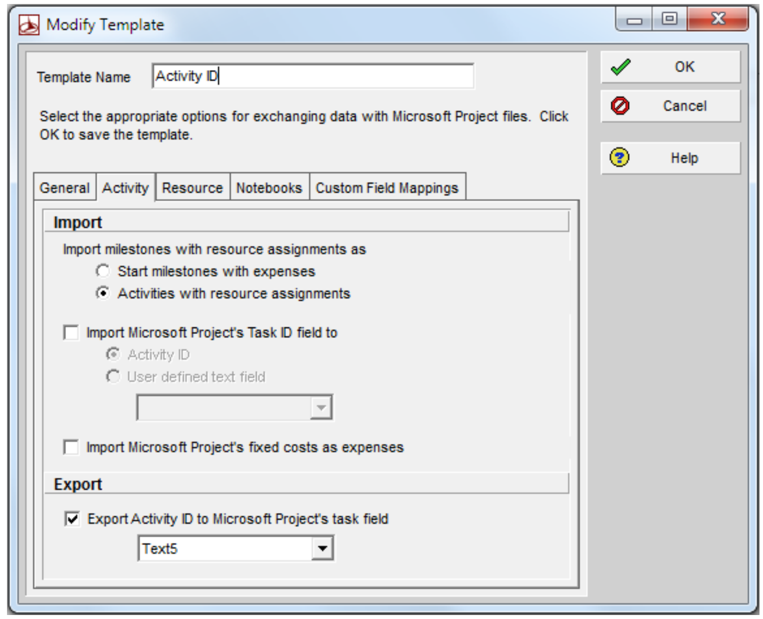


- Template
    - Click “Add…”

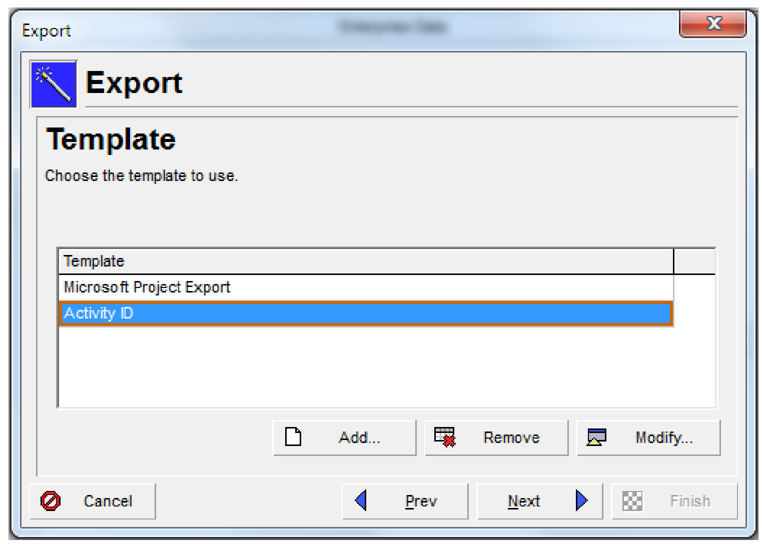


A “Modify Template” box will pop up

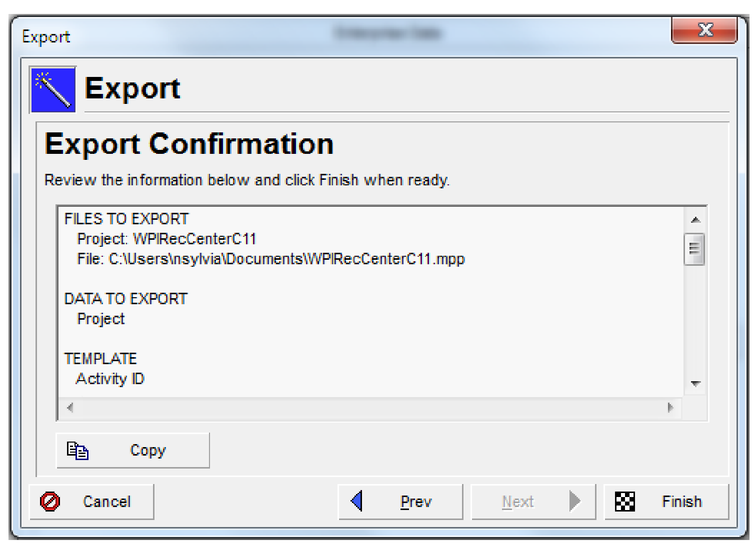
- Create a template name
- Click the activity tab
- Under “Export” check the box “Export Activity ID to Microsoft Project’s Task Field”
- In the drop down box chose “Text 5”
- Click “OK”



- Template
  - Select “Activity ID” (This is the Activity Id that has just been created in the Modify Template)
  - Click “Next”



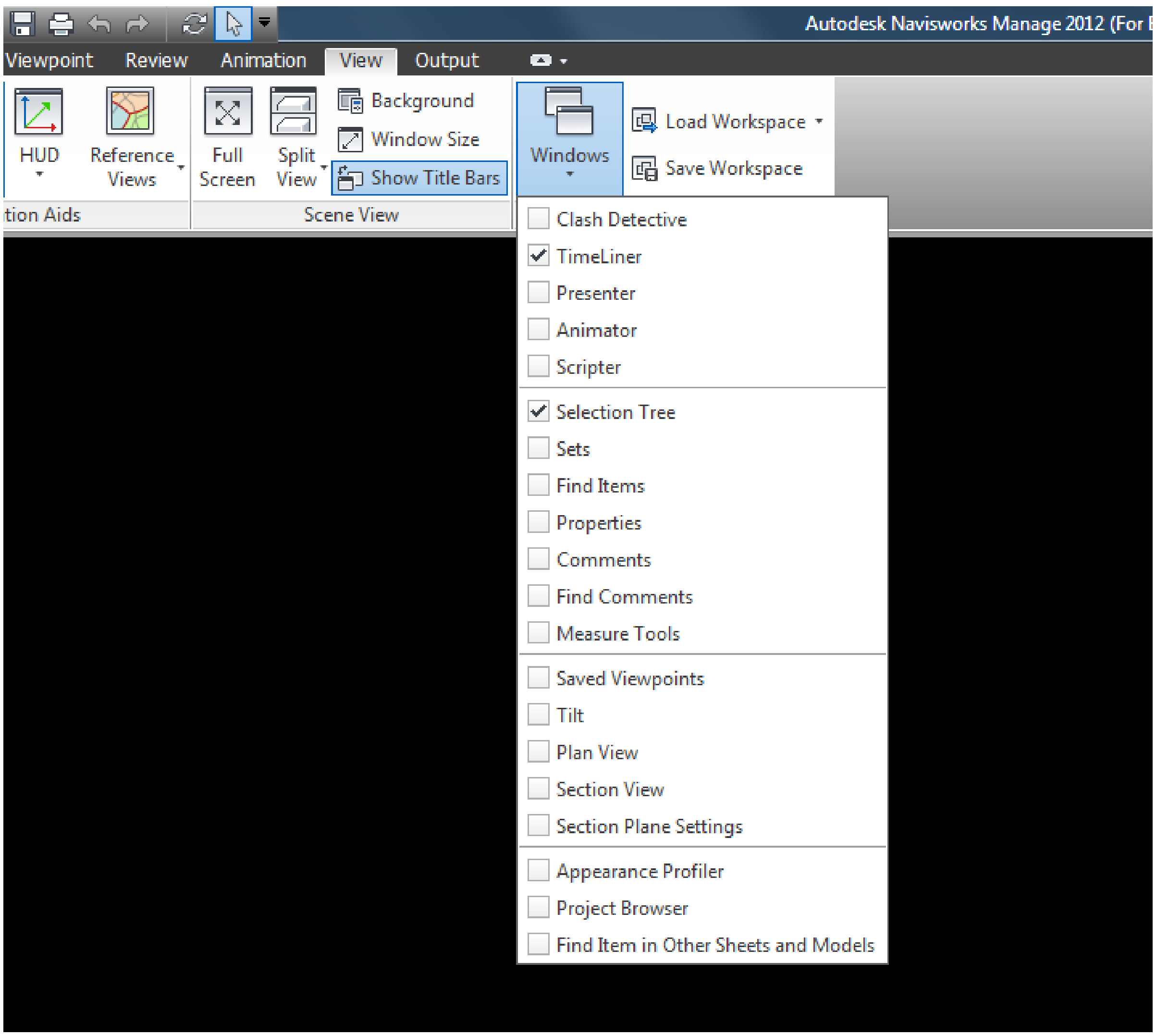
- Export Confirmation
  - Click Finish



NavisWorks:

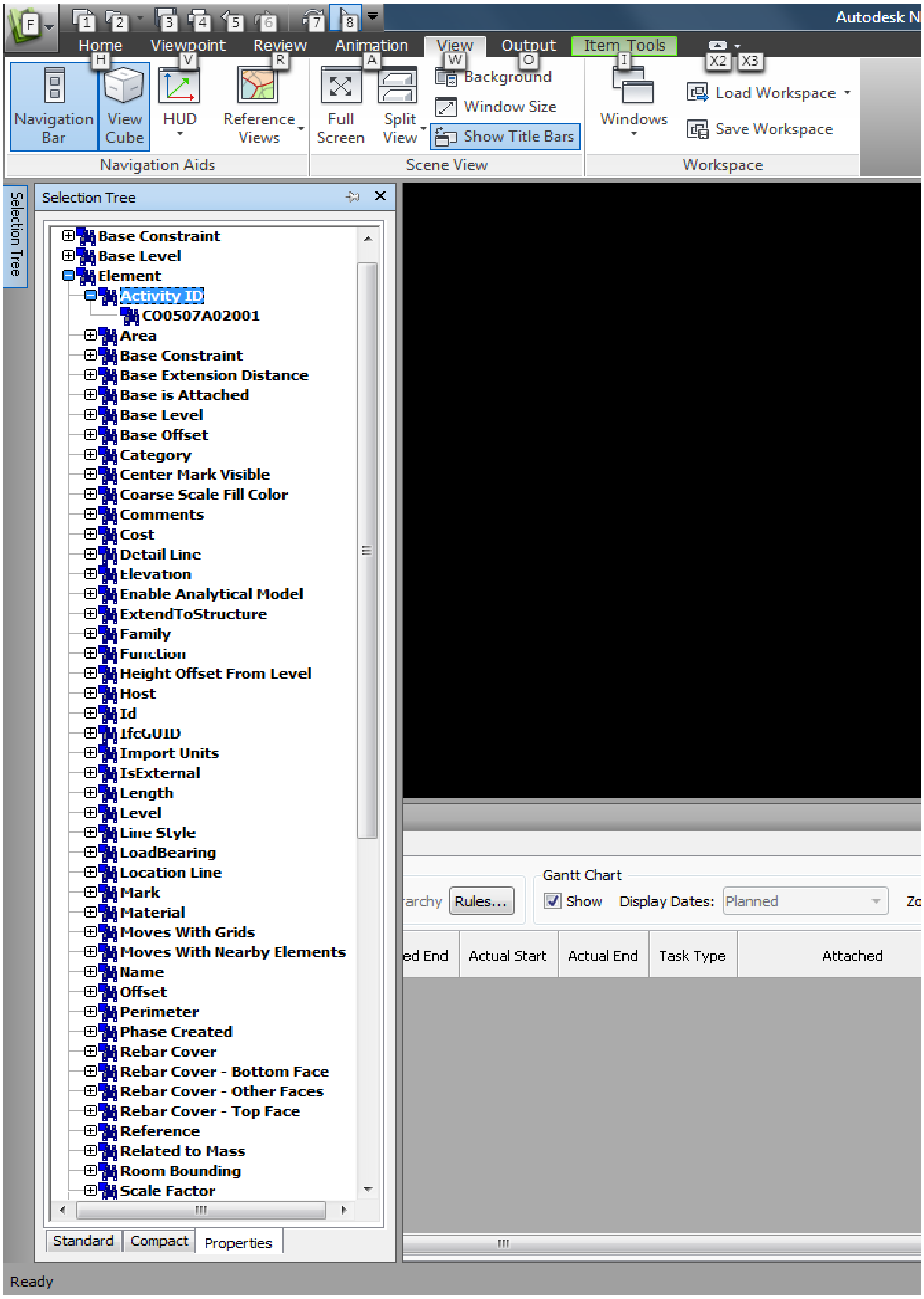
Once both the Primavera and Revit files are exported to NavisWorks, open the exported Revit file.

- Click on the "View" tab
  - Click on the "Windows" tab
    - Select "Timeliner" and "Selection Tree

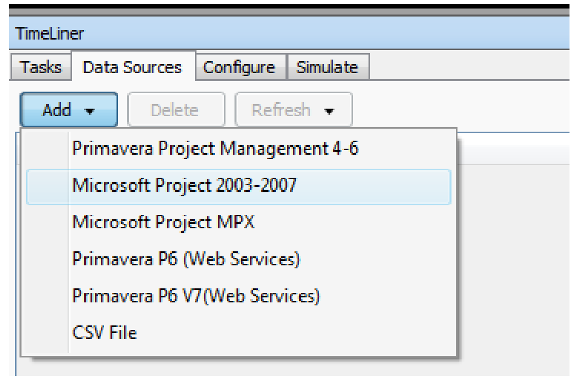


In the “Selection Tree” tab

- Click the “Properties” tab (on the bottom of the screen)
  - Double Click “Element” to open the element
    - Double Click “Activity ID” to open the Activity ID

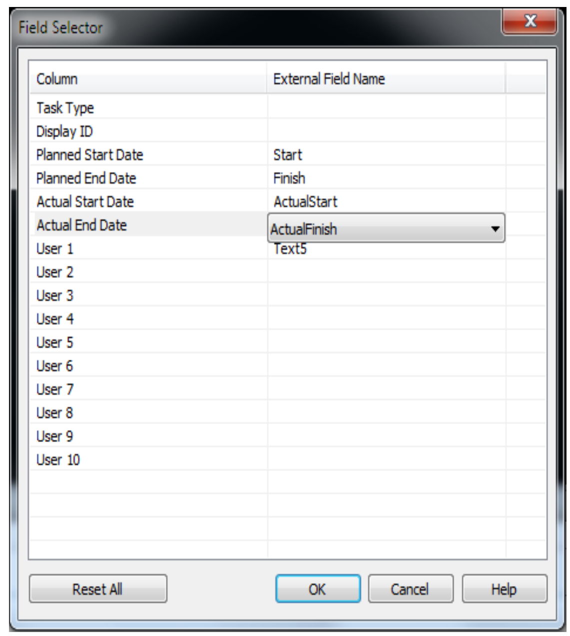


- In the “TimeLiner” tab
    - Select the “Data Source” tab
        - Click “add”
            - Choose Microsoft Project (2003-2007)



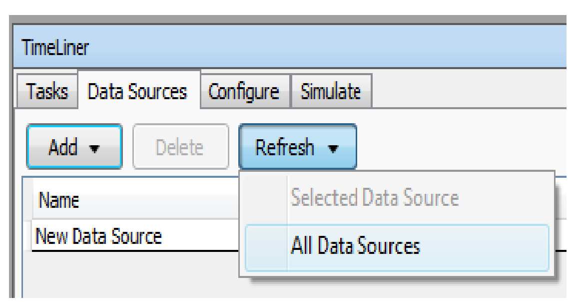
It will open a browser window. In that window open the file that has just been exported from Primavera.

- A “Field Selector” Window will open
    - Under the “External Field Name” column set up the following, using the drop down boxes
        - For “Planned Start Date” chose “start”
        - For “Planned End Date” chose “Finish”
        - For “Actual Start Date” chose “ActualFinish”
        - For “Actual End Date” chose “ActualFinish”
        - For “User 1” chose “Text5”
            - This is the text5 that was used for exporting your activity ID’s during the Primavera export
        - Click “ok”

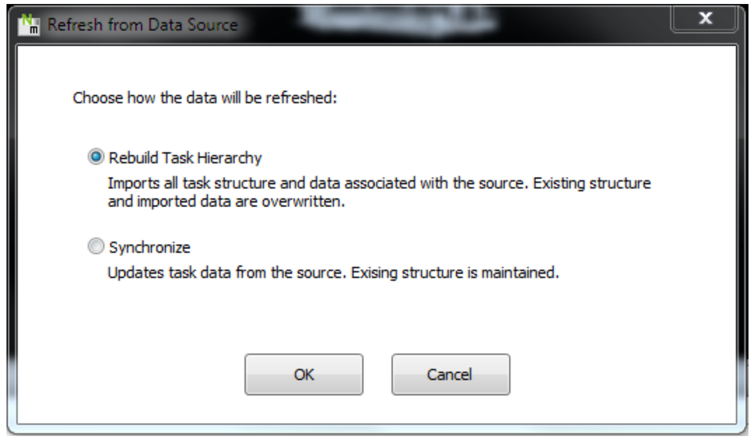


Under “name” in the timeline a “New Data Source” tab will appear

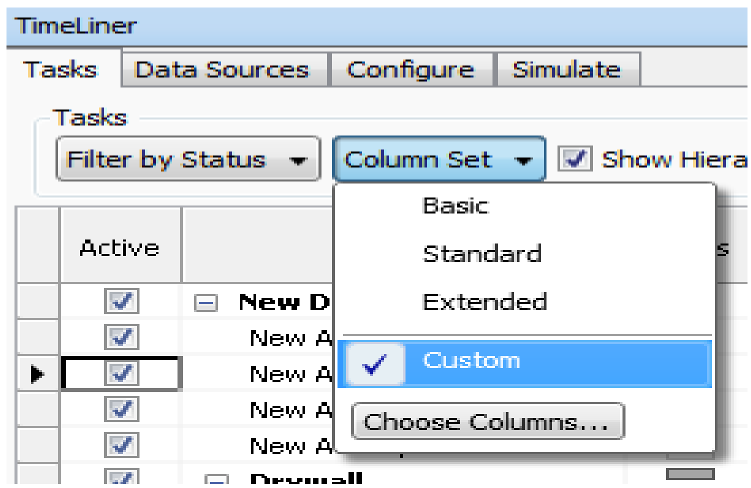
- Click the “refresh” tab
    - Select “All Data Sources”



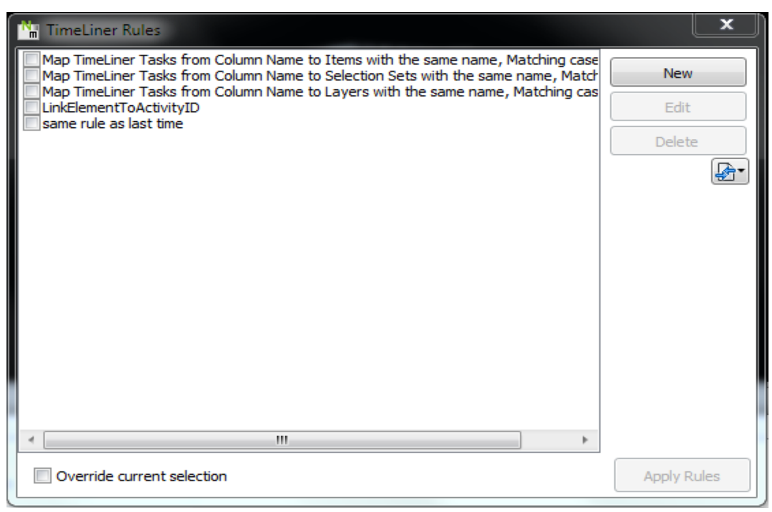
- A “Refresh for Data Sources” window will appear
    - Select “Rebuild Task Herarchy”
    - Select “OK”



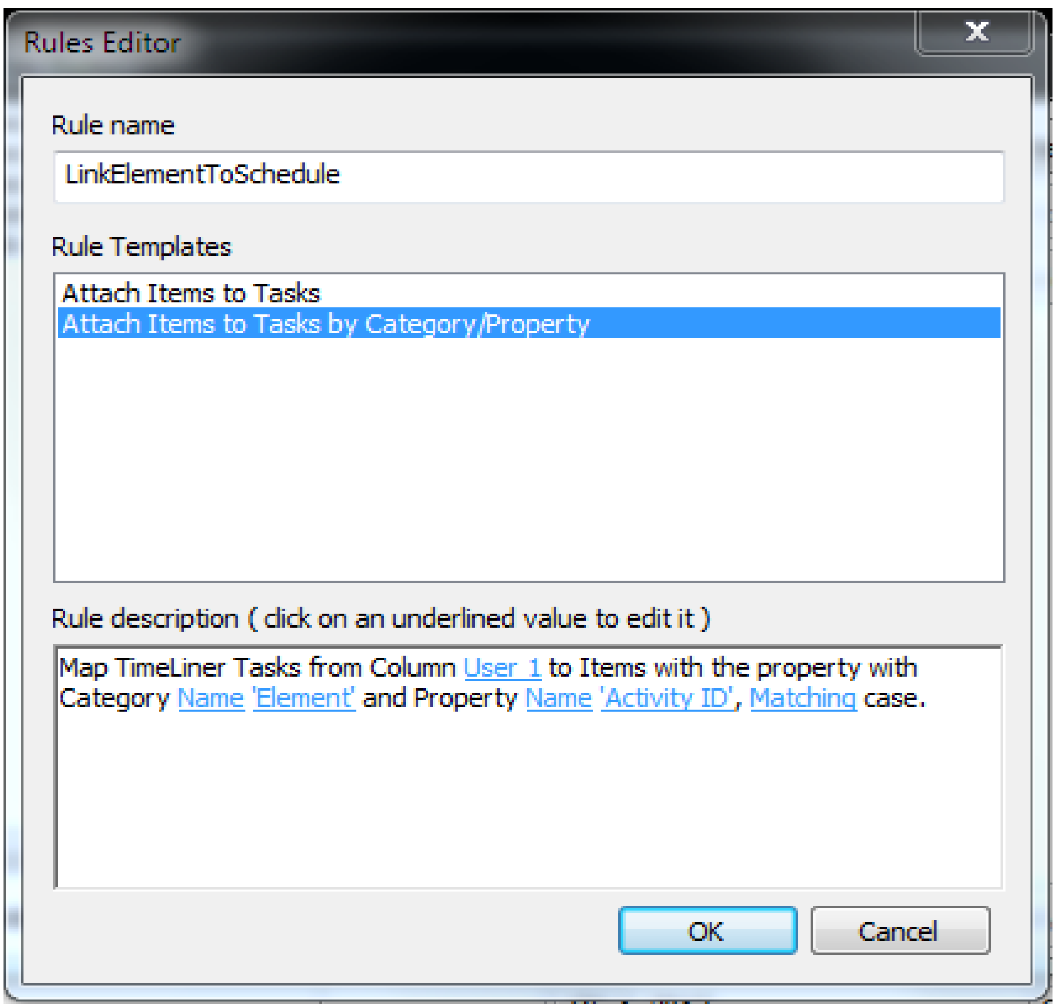
- In the “Timeliner” tab
    - Select the “Tasks” tab
        - Click the “Column Set” tab
        - Chose “Custom”



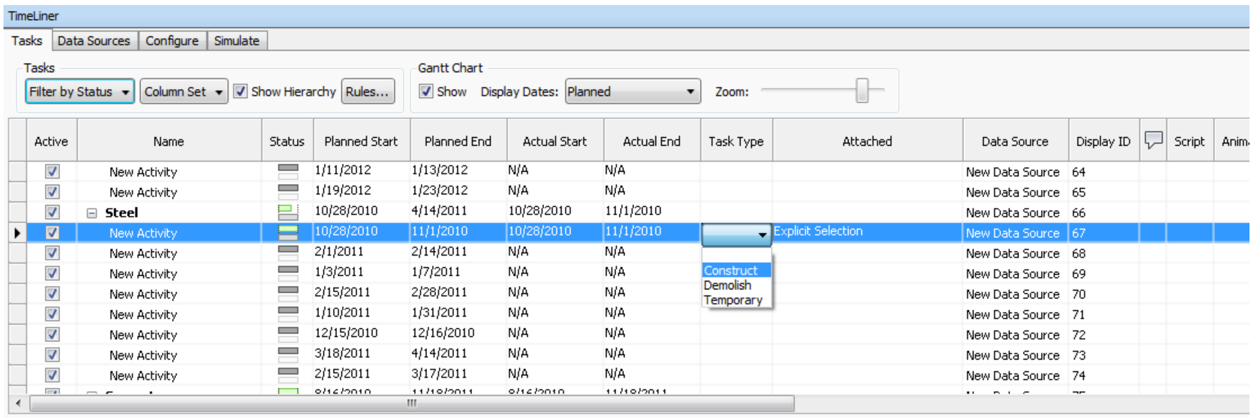
- Select the “Rules” tab
    - A “TimeLiner Rules” window will appear
        - Select “new”



- A “Rules Editor” window will appear
    - Under “Name Rule” type in “LinkElementToSchedule”
    - Under “Rule Templates” chose “Attach Items to Task by Category/Property”
    - Under “Rule Description” do the following:
        - Change “Column Name” to “User 1”
        - Change “Category Name” to “Name”
        - Change “<Category>” to “’Element’”
        - Change “Property Name” to “Name”
        - Change “<Property>“ to “’Activity ID’”
        - Change “Ignoring” to “Matching”
    - Select “OK” at the bottom of the box
            - Check the “LinkElementToActivityID” box
            - Click the “Apply Rules” tab



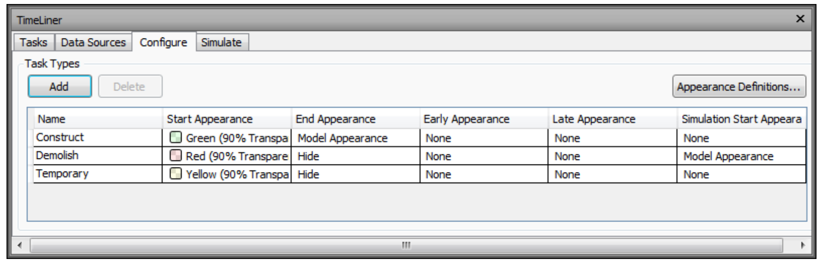
- In the “TimeLiner” tab
    - Select the “Tasks” tab
        - Under the “Task Type” column select each box to say “Construction”
    - Select the “Simulate” tabe
    - Press the “Play” button



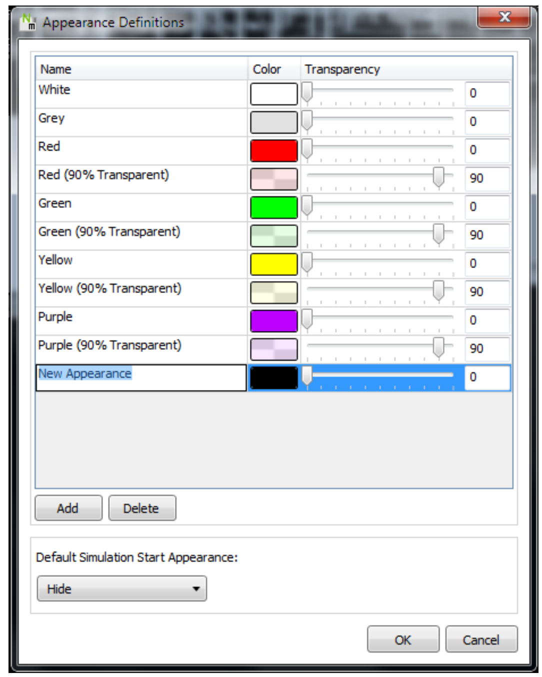
APPENDIX G: NavisWorks Transparency and Color Change

The following steps teach you how to change the color and transparency of different activities in your NavisWorks simulation.

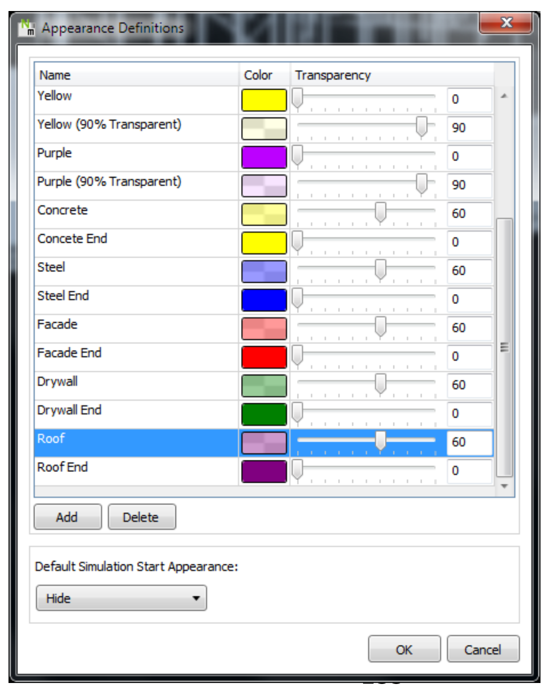
Open your NavisWorks model



- In the "Timeliner" tab
    - Select Configure

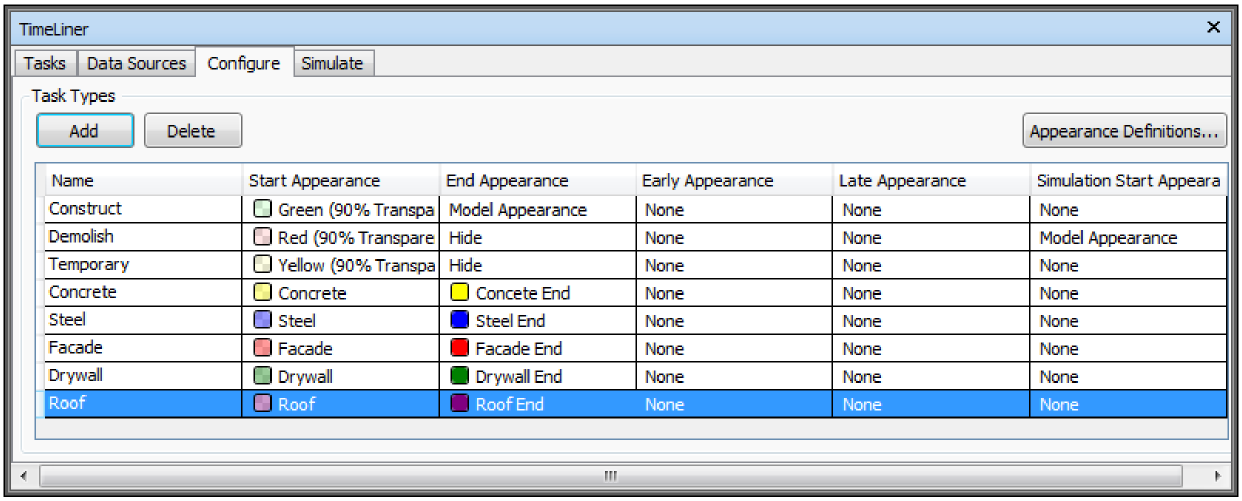


- Click the "Appearance Definitions…" tab on the right side
    - A new window will pop up
        - Click "Add"
            - A new bar will pop up



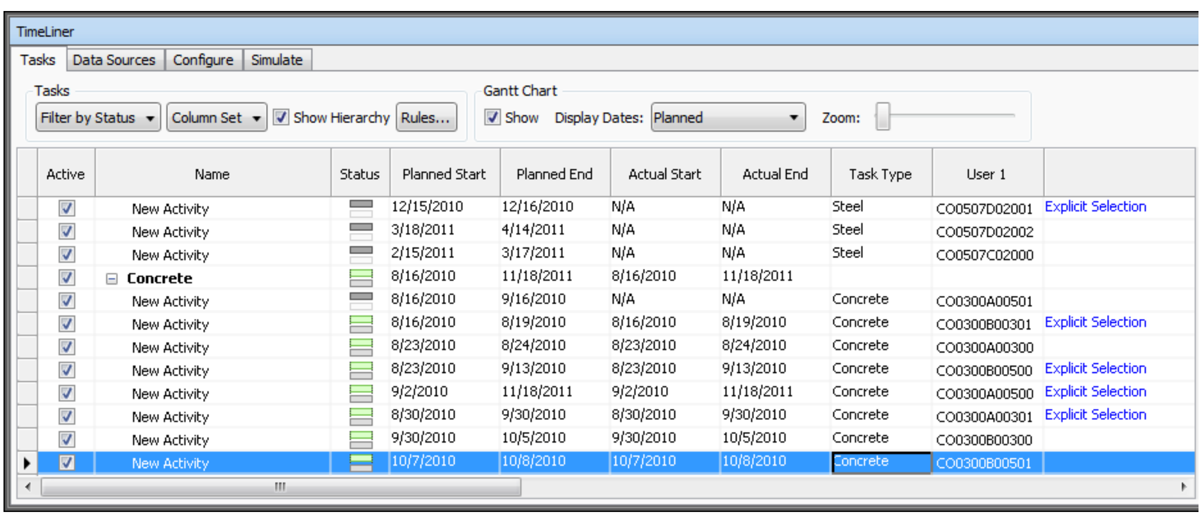
- In the box the says "New Appearance" change it to say "Concrete"
- Change the color to yellow by double clicking the black box
- Change the transparence to 60%
- Under the "Default Simulation Start Appearance:" select "Hide"
- Add another box and repeat these steps making the "Name Appearance" "Concrete End" and the transparency 0%
- Create the above following boxed for each section of the work breakdown schedule (steel, drywall, façade, and roof) selecting a color for each different section
    - Click "OK"

- Under “Task Type” click the “Add” tab
    - Under “Name” change from “New Task Type” to “Concrete”
    - Under “Start Appearance” Change the dropdown menu from “None” to “Concrete”
    - Under “End Appearance” change the dropdown menu from “None” to “Concrete End”
    - Do this for each of the five sections of the work breakdown schedule



Name	Start Appearance	End Appearance	Early Appearance	Late Appearance	Simulation Start Appeara
Construct	Green (90% Transpa	Model Appearance	None	None	None
Demolish	Red (90% Transpare	Hide	None	None	Model Appearance
Temporary	Yellow (90% Transpa	Hide	None	None	None
Concrete	Concrete	Concete End	None	None	None
Steel	Steel	Steel End	None	None	None
Facade	Facade	Facade End	None	None	None
Drywall	Drywall	Drywall End	None	None	None
Roof	Roof	Roof End	None	None	None

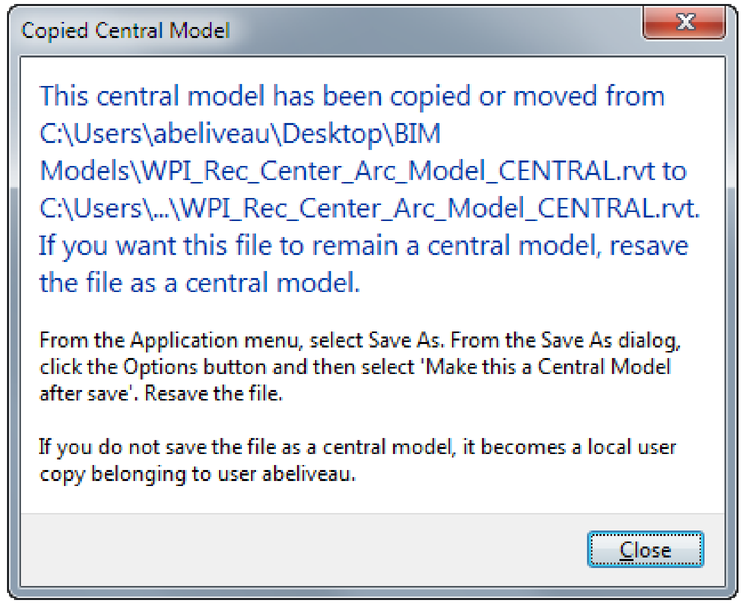
- Select the “Tasks” tab in the Timeliner
    - Under each “Task Type” click each activities drop down menu and select its perspective section in the work breakdown structure



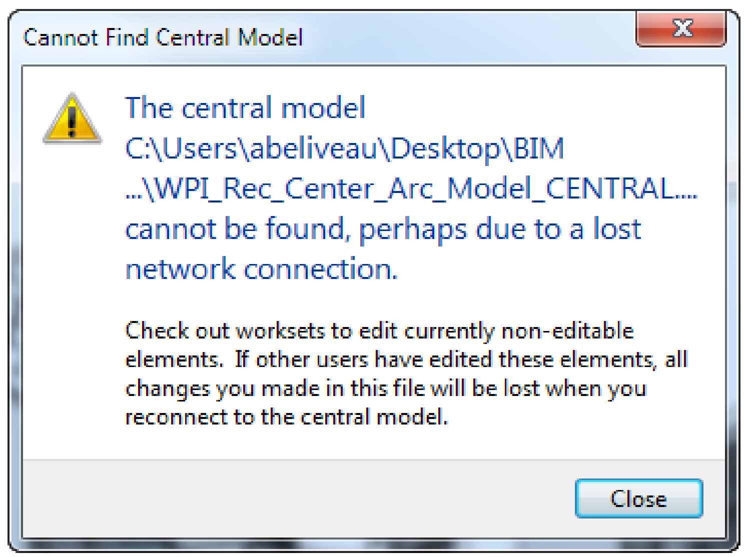
Active	Name	Status	Planned Start	Planned End	Actual Start	Actual End	Task Type	User 1	
☑	New Activity		12/15/2010	12/16/2010	N/A	N/A	Steel	CO0507D02001	Explicit Selection
☑	New Activity		3/18/2011	4/14/2011	N/A	N/A	Steel	CO0507D02002	
☑	New Activity		2/15/2011	3/17/2011	N/A	N/A	Steel	CO0507C02000	
☑	Concrete		8/16/2010	11/18/2011	8/16/2010	11/18/2011			
☑	New Activity		8/16/2010	9/16/2010	N/A	N/A	Concrete	CO0300A00501	
☑	New Activity		8/16/2010	8/19/2010	8/16/2010	8/19/2010	Concrete	CO0300B00301	Explicit Selection
☑	New Activity		8/23/2010	8/24/2010	8/23/2010	8/24/2010	Concrete	CO0300A00300	
☑	New Activity		8/23/2010	9/13/2010	8/23/2010	9/13/2010	Concrete	CO0300B00500	Explicit Selection
☑	New Activity		9/2/2010	11/18/2011	9/2/2010	11/18/2011	Concrete	CO0300A00500	Explicit Selection
☑	New Activity		8/30/2010	9/30/2010	8/30/2010	9/30/2010	Concrete	CO0300A00301	Explicit Selection
☑	New Activity		9/30/2010	10/5/2010	9/30/2010	10/5/2010	Concrete	CO0300B00300	
☑	New Activity		10/7/2010	10/8/2010	10/7/2010	10/8/2010	Concrete	CO0300B00501	

Once this process has been complete when you simulate the model it will build with the color coordination you chose for each work breakdown section. At the start of construction for each activity that activity will show up with a transparency of 60% and when the construction is complete for each activity the activities transparency will switch to 0% transparent.

APPENDIX H: Step Solve Shared Project Errors



- First, open Revit Architecture and select the file you wish to open.
- When your file opens, if it is a former Central file from another user that they have shared to you, you may see an error such as this:

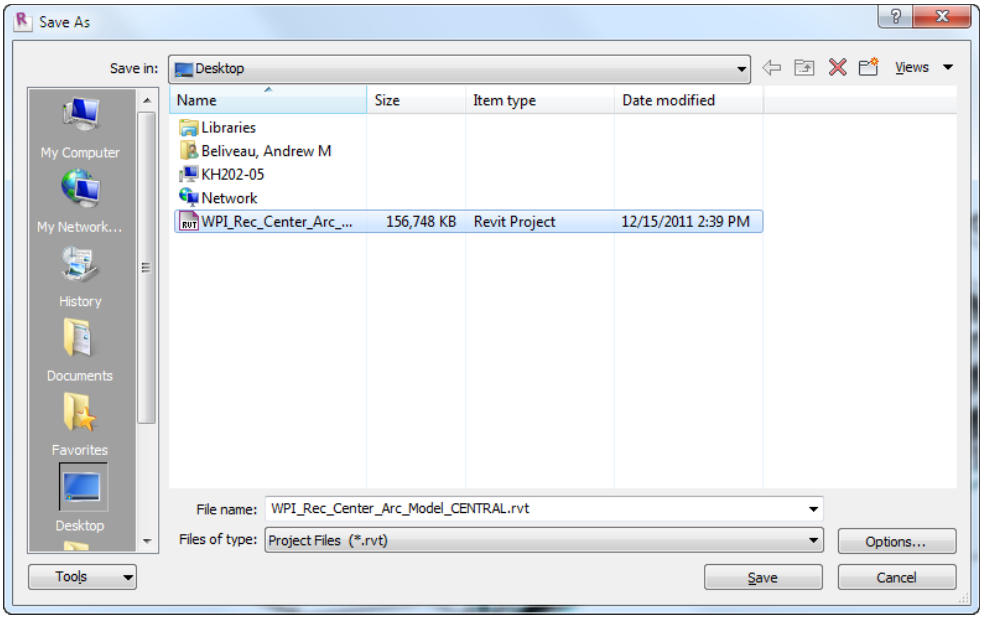


- If you do see this error, select Close and continue with the steps below.
- The Revit project will now open.
- After the file loads, you will receive the following message:

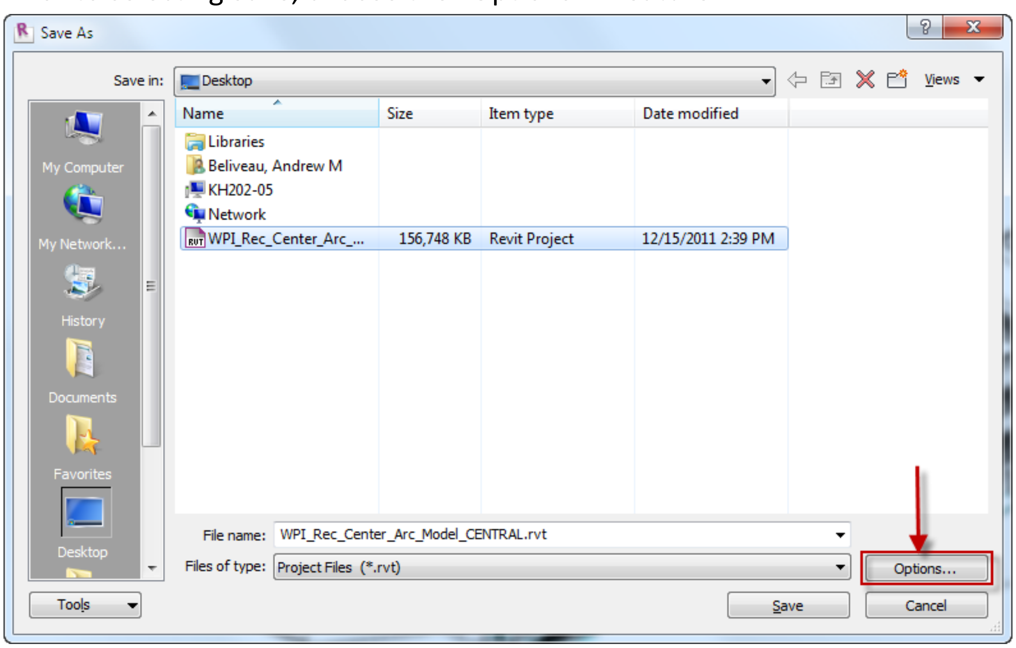
- This message informs you that the Workset that you've opened is not editable, and therefore can only be viewed and not manipulated.
- Select Close to continue.

- The project will now open in its non-editable form. Note via the box at the bottom of the screen (seen below) that the Worksets are not editable.

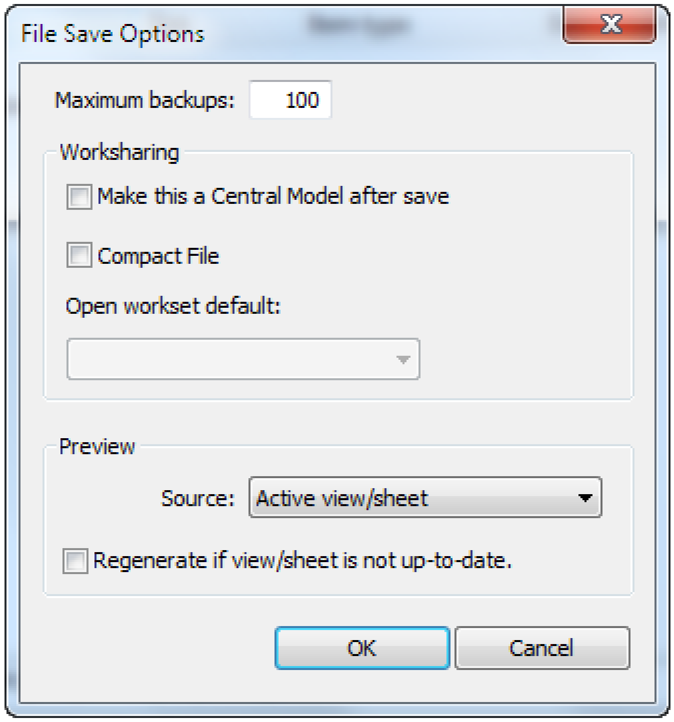
- To fix this issue, first you must select File > Save As > Project. This will save the project as a new file, which you will use to make your manipulations.
- You will then be prompted with the dialog box below. Please name the file and select its directory destination at this time.



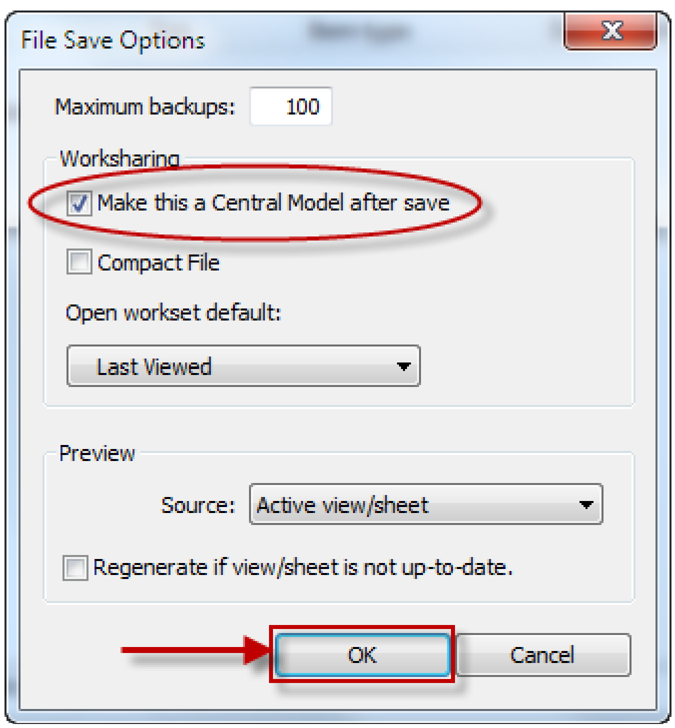
- Prior to selecting Save, choose the "Options…" feature



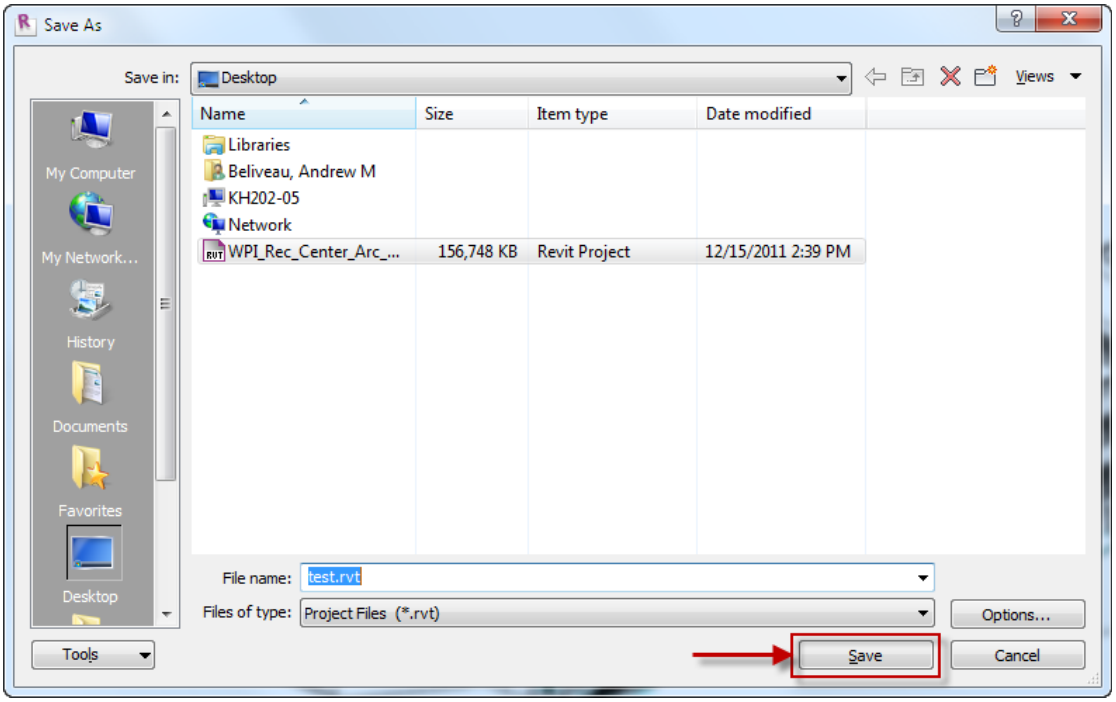
- You will then be prompted by the File Save Options dialog box.



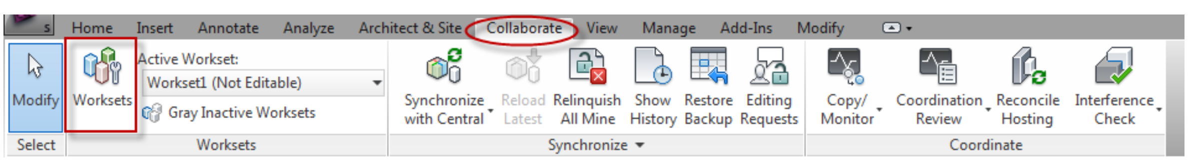
- You must select "Make this a Central Model after save"
- Once this box is checked, please select OK.



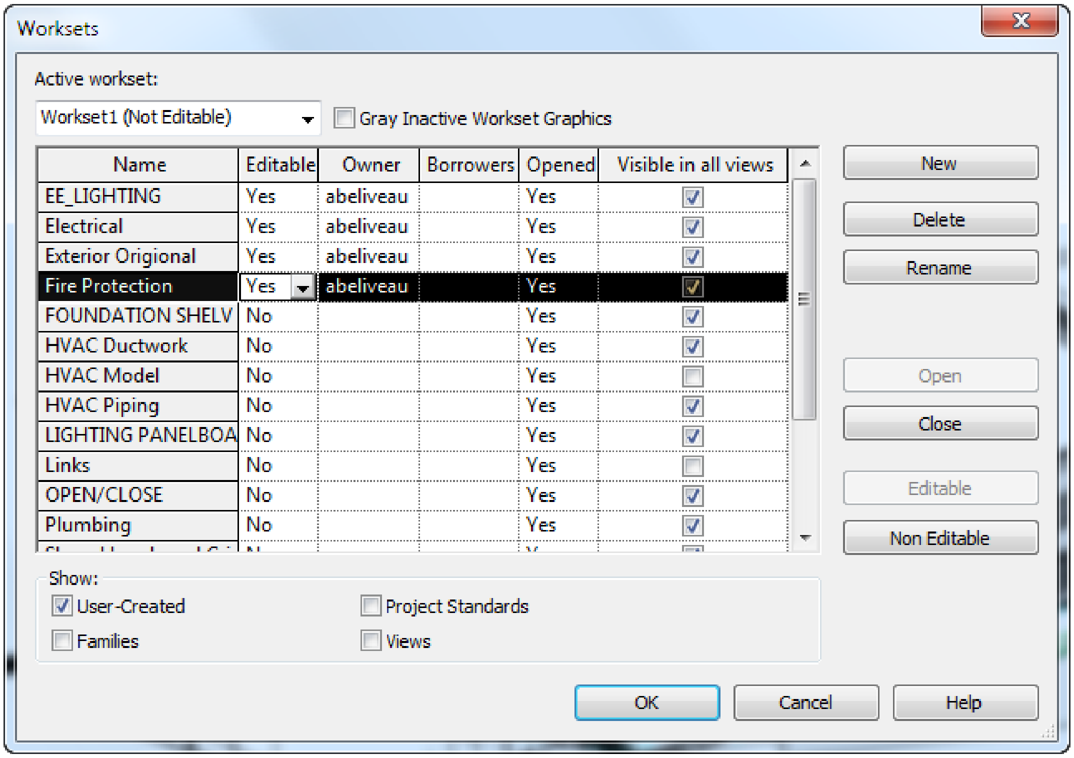
- Next, select Save in the Save As dialog box.



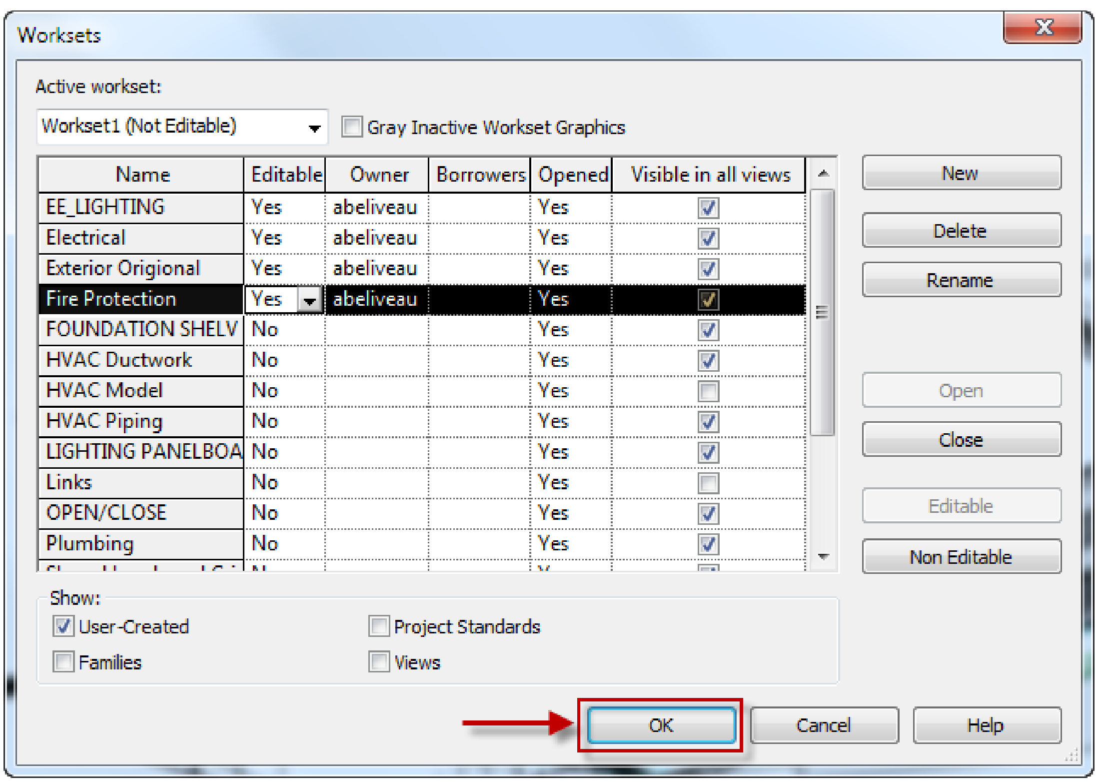
- Note: This process may take a few minutes depending on file size and processor capabilities.
- Now that ownership of the project has been transferred to you, you can now make all worksets editable for your manipulations.
- Under the Collaborate tab, select Worksets



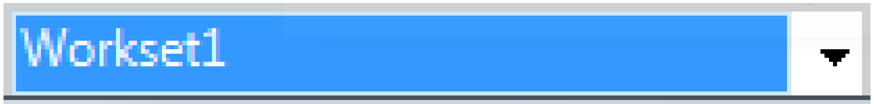
- In the Worksets dialog box, change the Editable property for each Workset to Yes using the dropdown menu.



- Then Select OK

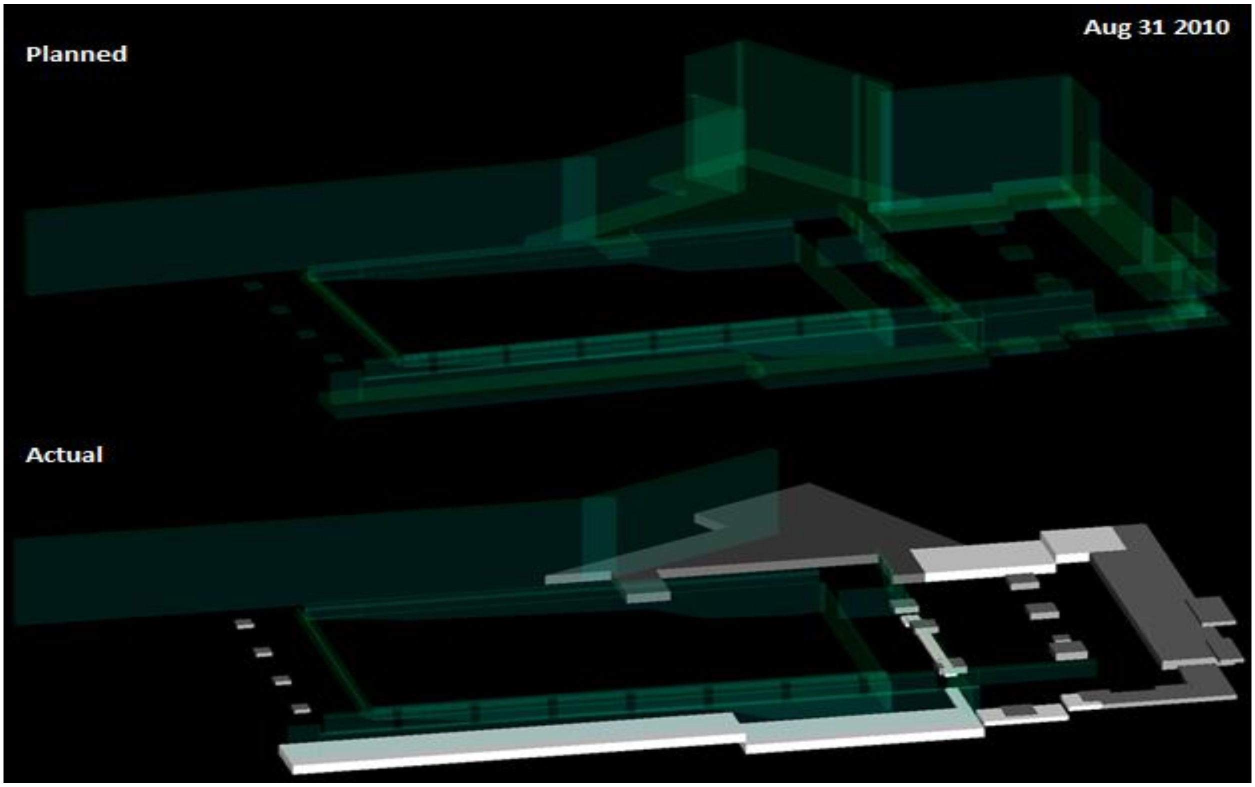


- Note: This process may take a few minutes depending on file size and processor capabilities.
- Note now that all Worksets are editable and can be manipulated as desired.



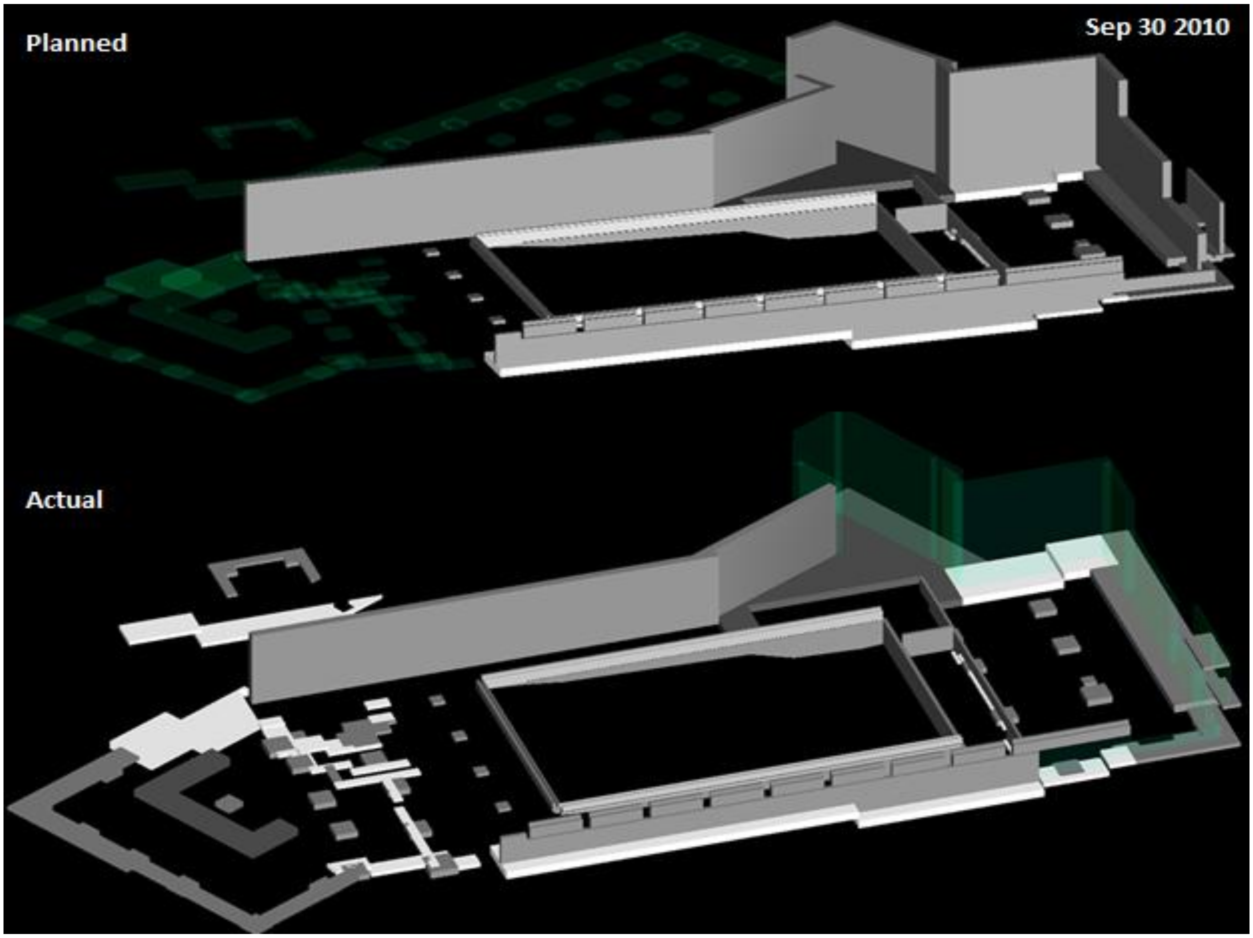
- Save the file, and you may move on with your work.

APPENDIX I: Monthly Construction Phases with Corresponding Material Quantities



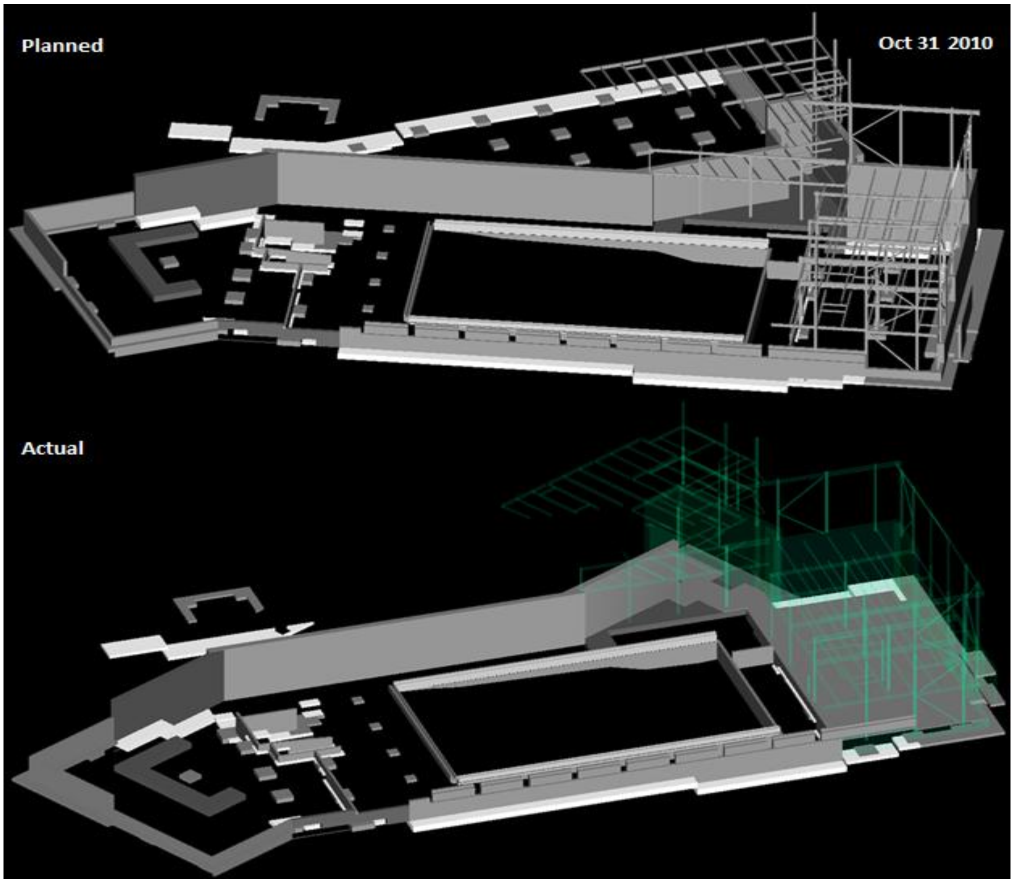
August 31st 2010		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	22.33	17.26
Façade	0.00	0.00
Roofing	0.00	0.00
Steel	0.00	0.00

August 31st 2010				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	0.00	0.00	0.00	0.00
Roofing	0.00	0.00	0.00	0.00
Steel	0.00	0.00	0.00	0.00
Concrete	23.20	17.93	646267.38	499398.64
Precast Concrete	0.00	0.00	0.00	0.00
Brick & Precast	0.00	0.00	0.00	0.00
Glass & Glazing	0.00	0.00	0.00	0.00



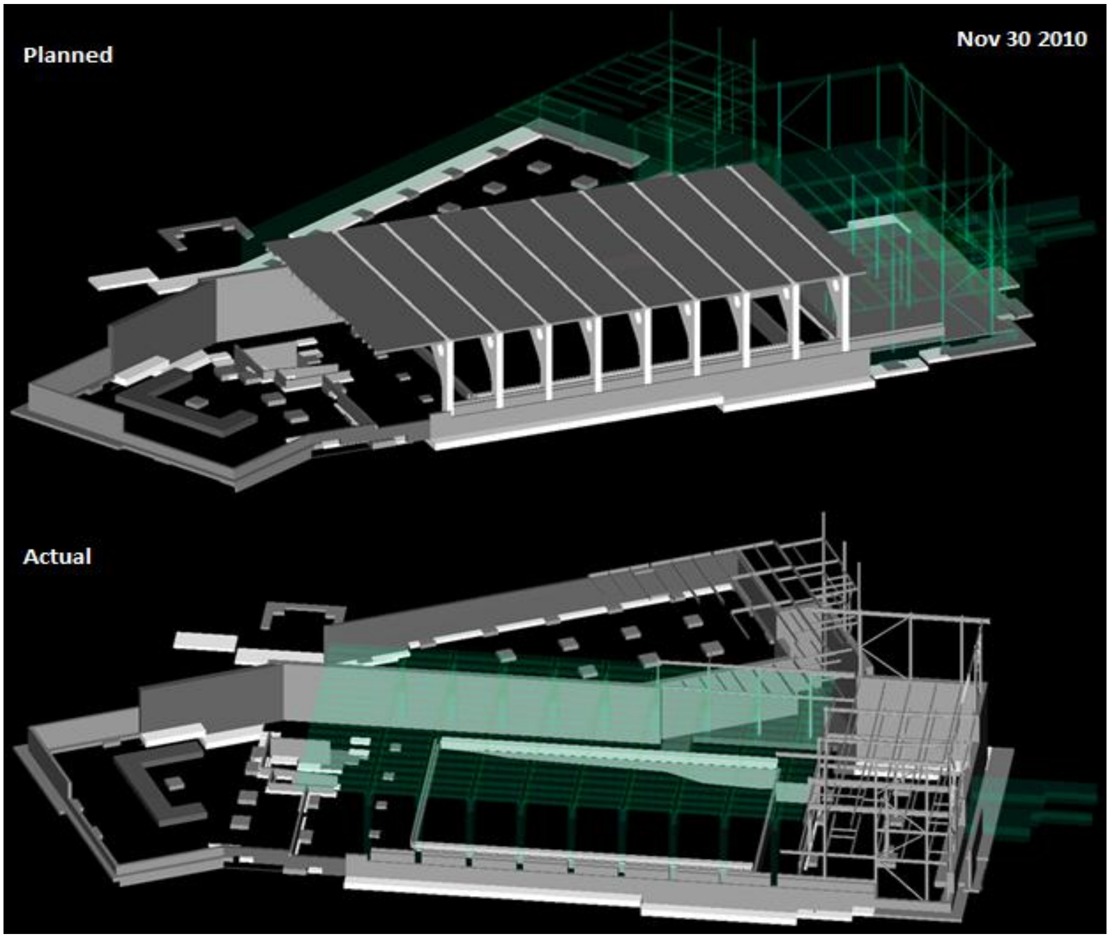
September 30th 2010		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	43.89	39.10
Façade	0.00	0.00
Roofing	0.00	0.00
Steel	0.00	0.00

September 30th 2010				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	0.00	0.00	0.00	0.00
Roofing	0.00	0.00	0.00	0.00
Steel	0.00	0.00	0.00	0.00
Concrete	45.60	40.63	623970.78	632202.68
Precast Concrete	0.00	0.00	0.00	0.00
Brick & Precast	0.00	0.00	0.00	0.00
Glass & Glazing	0.00	0.00	0.00	0.00



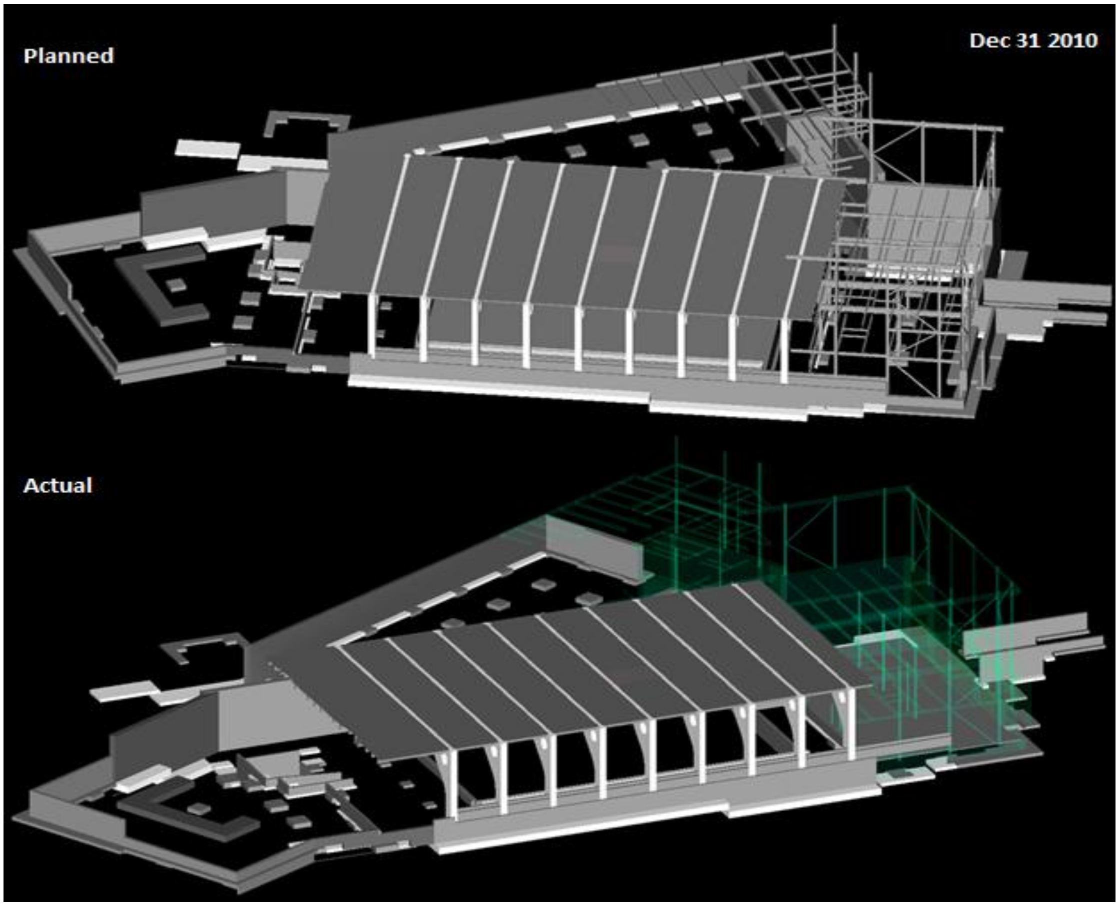
October 31st 2010		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	46.98	47.59
Façade	0.00	0.00
Roofing	0.00	0.00
Steel	16.82	0.93

October 31st 2010				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	0.00	0.00	0.00	0.00
Roofing	0.00	0.00	0.00	0.00
Steel	16.82	0.93	588416.47	32689.80
Concrete	48.81	49.44	89252.37	245634.74
Precast Concrete	0.00	0.00	0.00	0.00
Brick & Precast	0.00	0.00	0.00	0.00
Glass & Glazing	0.00	0.00	0.00	0.00



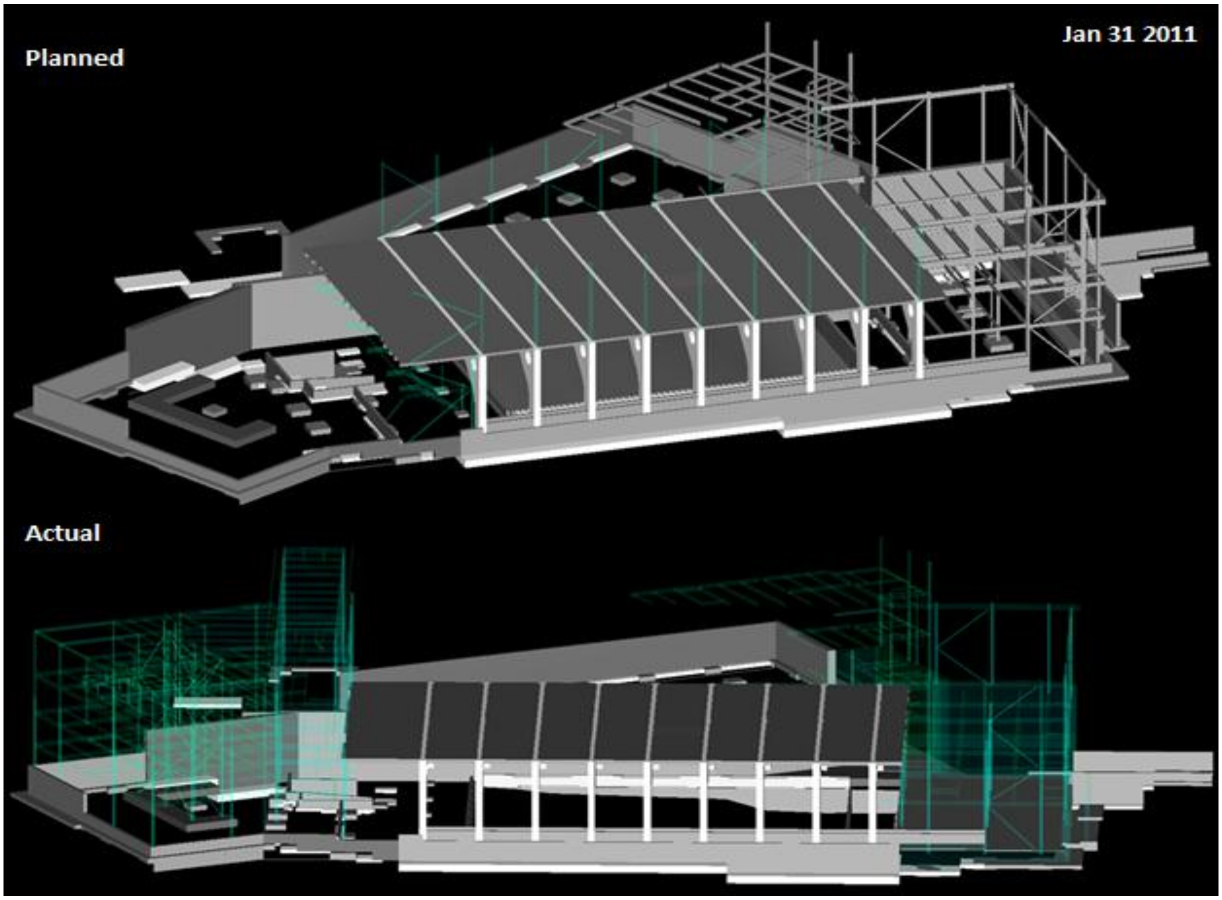
November 30th 2010		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	50.95	53.03
Façade	0.00	0.00
Roofing	0.00	0.00
Steel	16.82	5.05

November 30th 2010				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	0.00	0.00	0.00	0.00
Roofing	0.00	0.00	0.00	0.00
Steel	16.82	5.05	0.00	143835.14
Concrete	50.25	51.20	40317.88	48869.80
Precast Concrete	68.75	100.00	1097921.13	1597000.00
Brick & Precast	0.00	0.00	0.00	0.00
Glass & Glazing	0.00	0.00	0.00	0.00



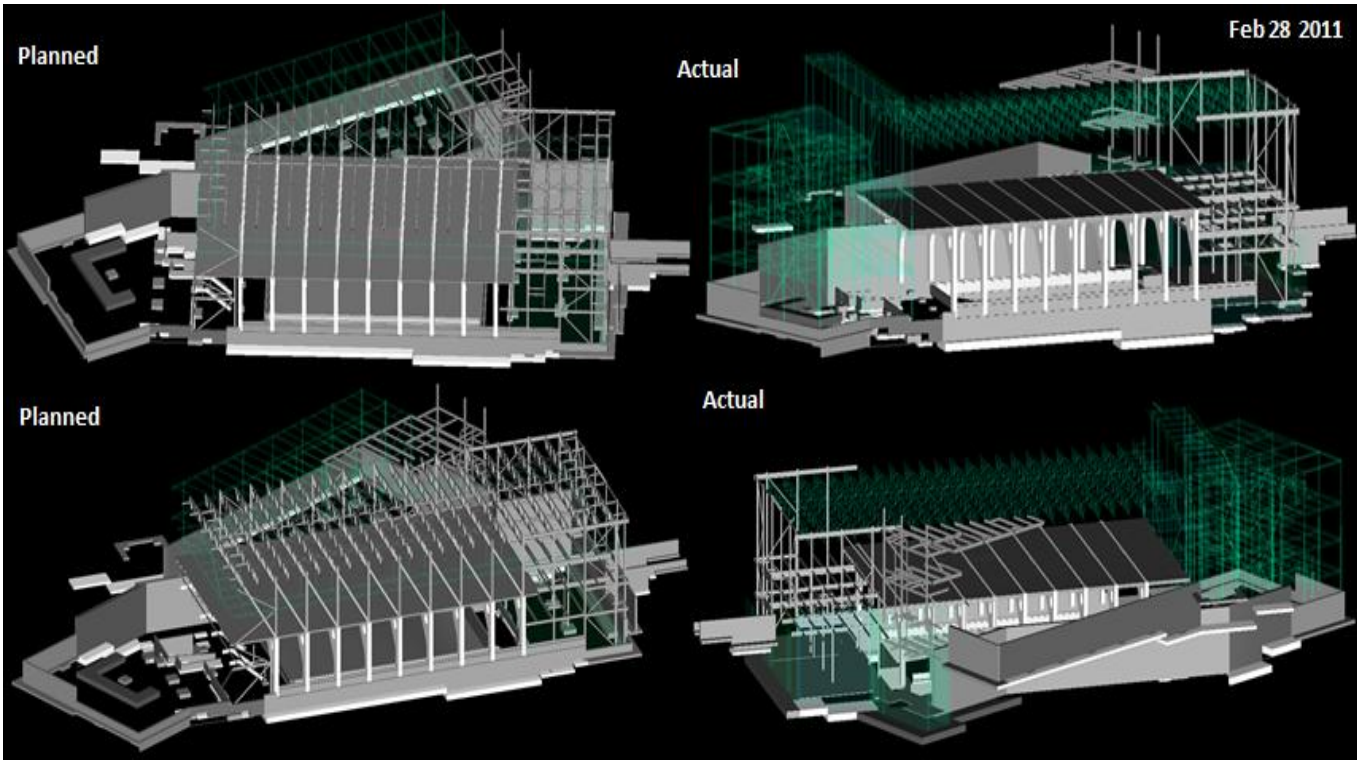
December 31st 2010		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	60.01	54.31
Façade	0.00	0.00
Roofing	0.00	0.00
Steel	16.82	9.35

December 31st 2010				
	Percent Planned	**Cost Planned**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	0.00	0.00	0.00	0.00
Roofing	0.00	0.00	0.00	0.00
Steel	16.82	9.35	0.00	150373.10
Concrete	58.46	52.53	228470.76	37138.20
Precast Concrete	100.00	100.00	499078.87	0.00
Brick & Precast	0.00	0.00	0.00	0.00
Glass & Glazing	0.00	0.00	0.00	0.00



January 31st 2011		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	60.01	54.31
Façade	0.00	0.00
Roofing	0.00	0.00
Steel	23.50	20.22

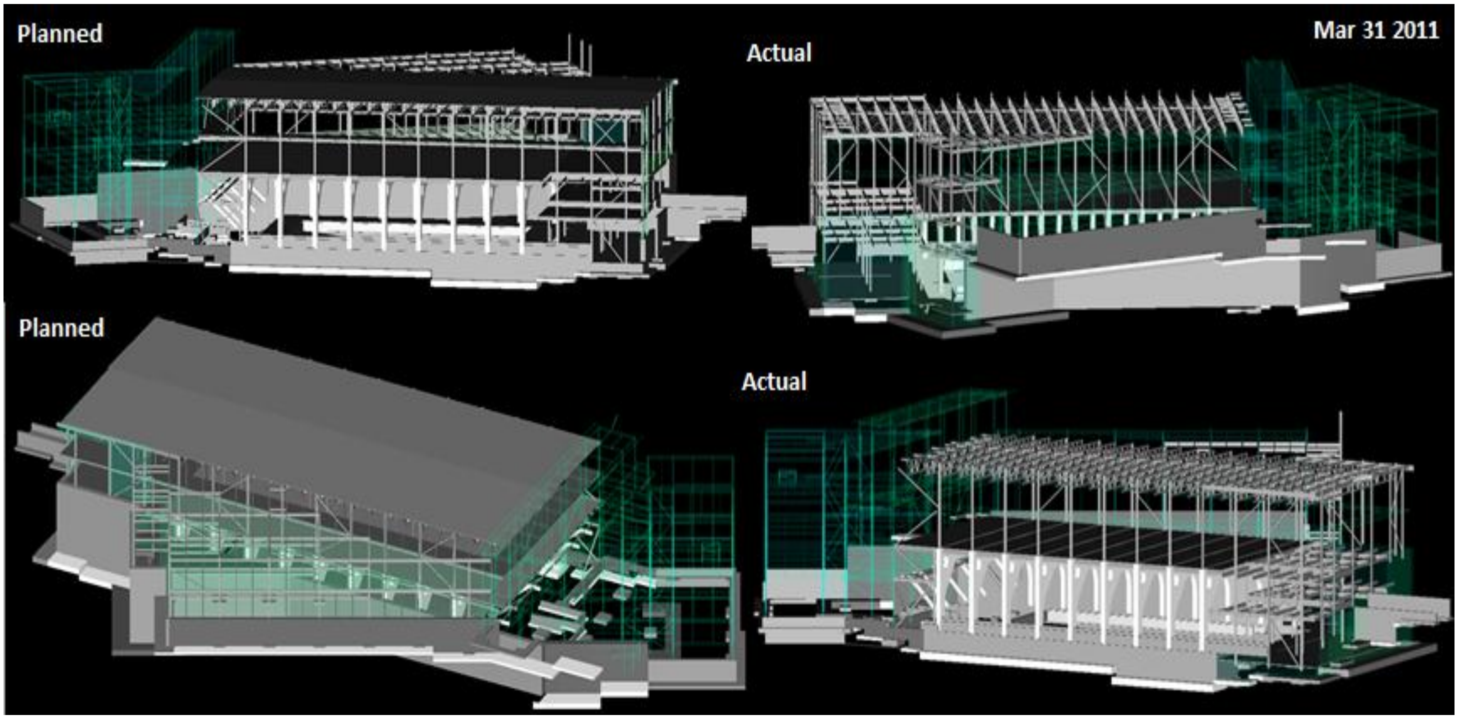
January 31st 2011				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	0.00	0.00	0.00	0.00
Roofing	0.00	0.00	0.00	0.00
Steel	23.50	20.22	233623.13	380509.32
Concrete	58.46	52.53	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	0.00	0.00	0.00	0.00
Glass & Glazing	0.00	0.00	0.00	0.00



February 28th 2011		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	61.03	54.31
Façade	0.00	0.00
Roofing	0.00	0.00
Steel	55.96	37.62

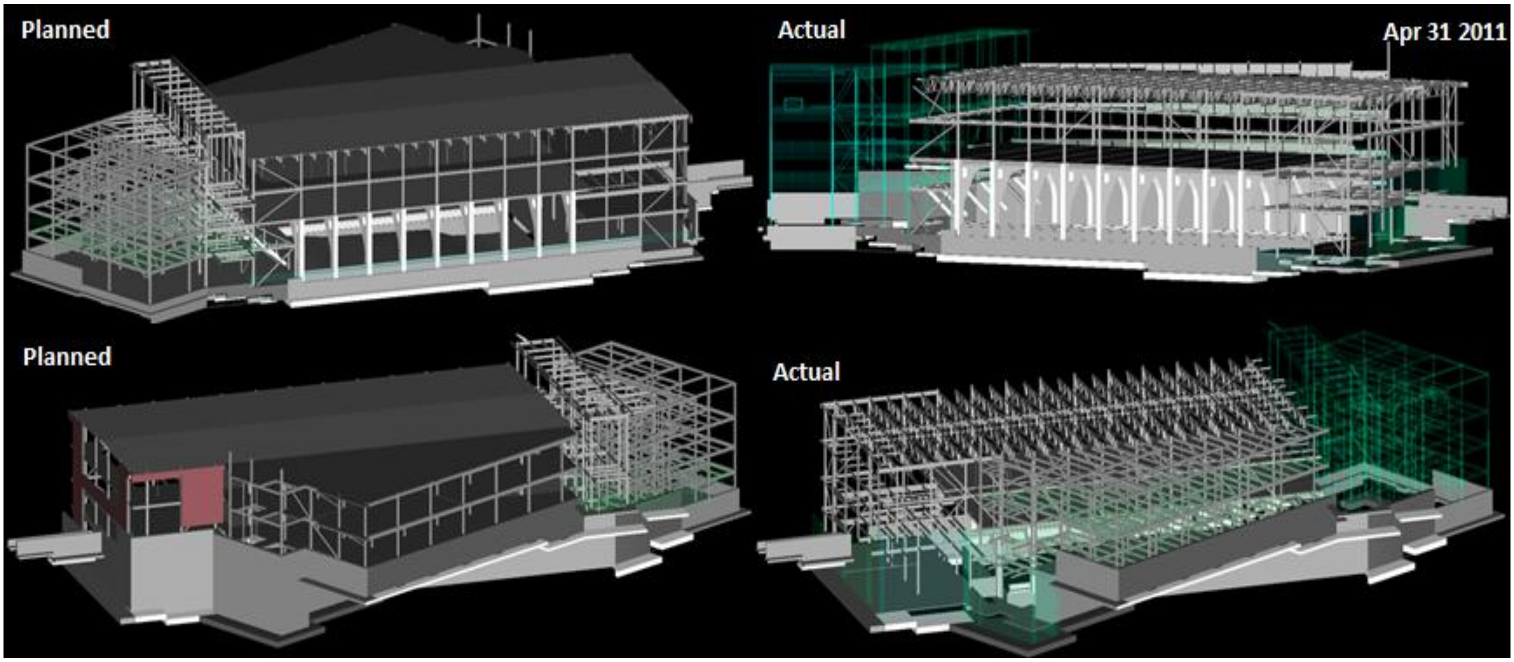
February 28th 2011				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	0.00	0.00	0.00	0.00
Roofing	0.00	0.00	0.00	0.00
Steel	55.96	37.62	1135425.85	608466.21
Concrete	59.51	52.53	29355.30	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	0.00	0.00	0.00	0.00
Glass & Glazing	0.00	0.00	0.00	0.00

APPENDIX J: Monthly Construction Phases with Percent Complete and Cost



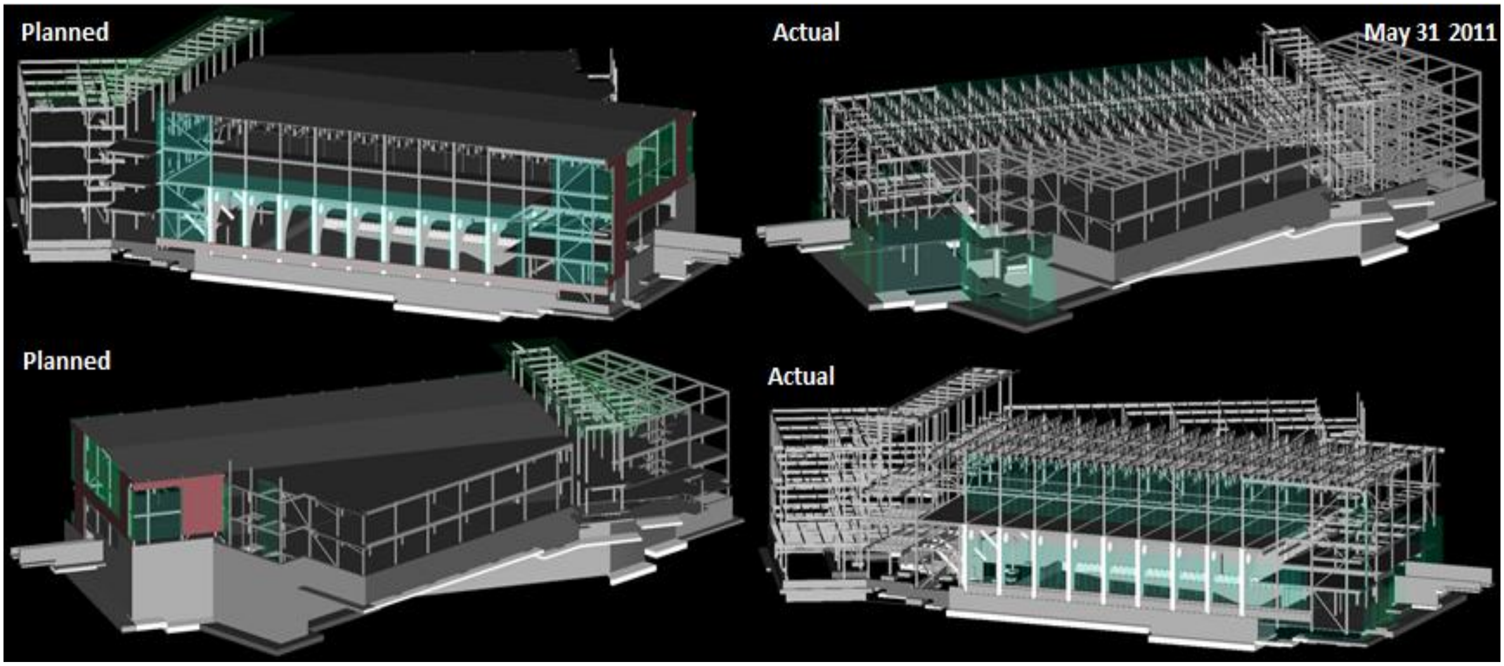
March 31st 2011		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	84.20	56.17
Façade	1.77	0.00
Roofing	55.38	0.00
Steel	81.53	75.00

March 31st 2011				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	0.00	0.00	0.00	0.00
Roofing	55.38	0.00	68120.78	0.00
Steel	81.53	75.00	894393.03	1307592.15
Concrete	83.59	54.46	670650.08	53716.49
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	2.76	0.00	34094.92	0.00
Glass & Glazing	0.00	0.00	0.00	0.00



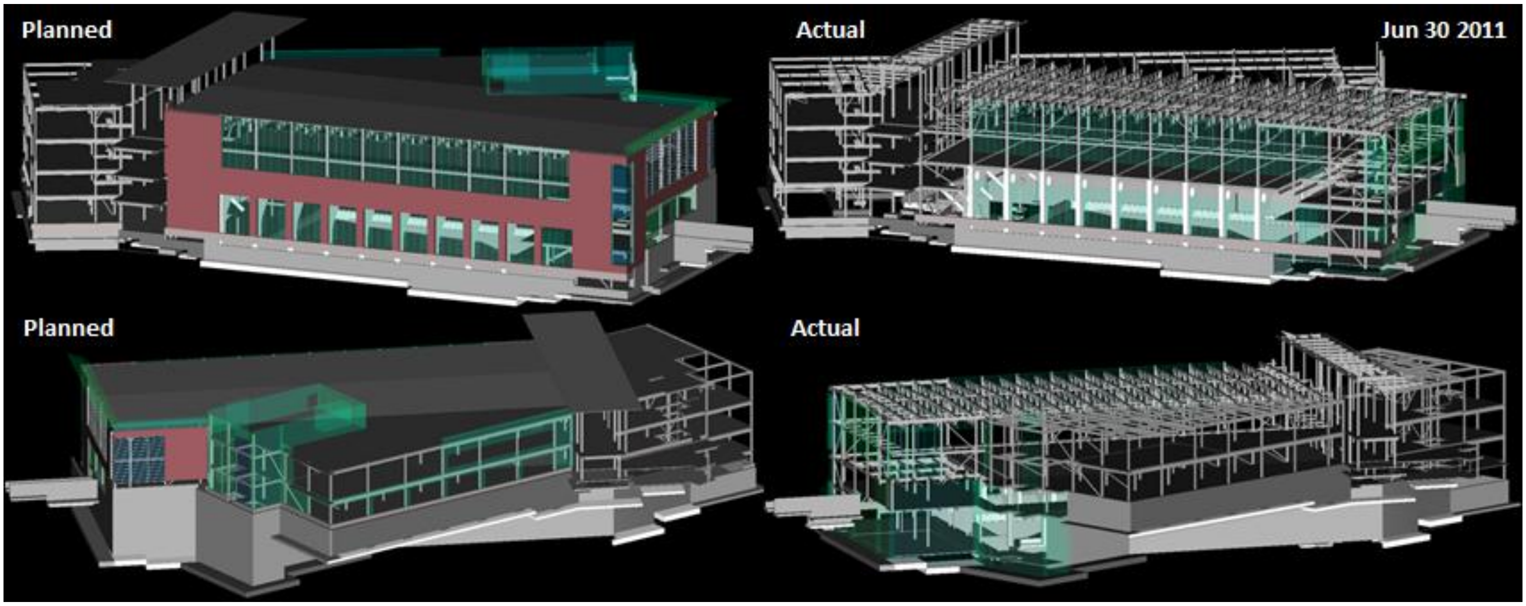
April 30th 2011		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	88.16	63.75
Façade	10.50	0.00
Roofing	75.37	0.00
Steel	100.00	96.09

April 30th 2011				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	0.00	0.00	0.00	0.00
Roofing	75.37	0.00	24586.90	0.00
Steel	100.00	96.09	645950.52	737481.97
Concrete	87.70	62.33	114555.84	219315.67
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	16.36	0.00	168179.82	0.00
Glass & Glazing	0.00	0.00	0.00	0.00



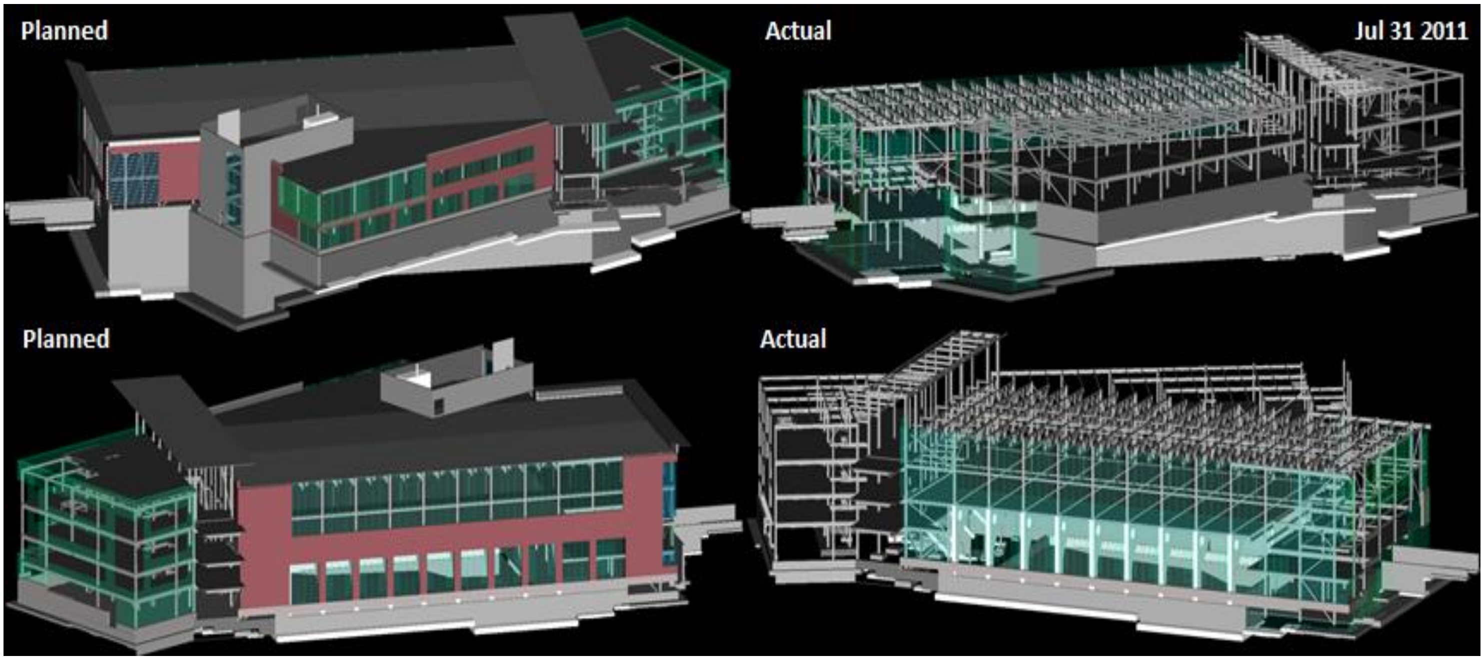
May 31st 2011		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	100.00	73.13
Façade	25.10	0.52
Roofing	97.76	0.00
Steel	100.00	100.00

May 31st 2011				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	0.00	0.00	0.00	0.00
Roofing	97.76	0.00	27538.47	0.00
Steel	100.00	100.00	0.00	136861.31
Concrete	100.00	72.09	342580.62	271704.95
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	38.57	0.00	274605.51	0.00
Glass & Glazing	3.20	4.76	95385.05	142009.50



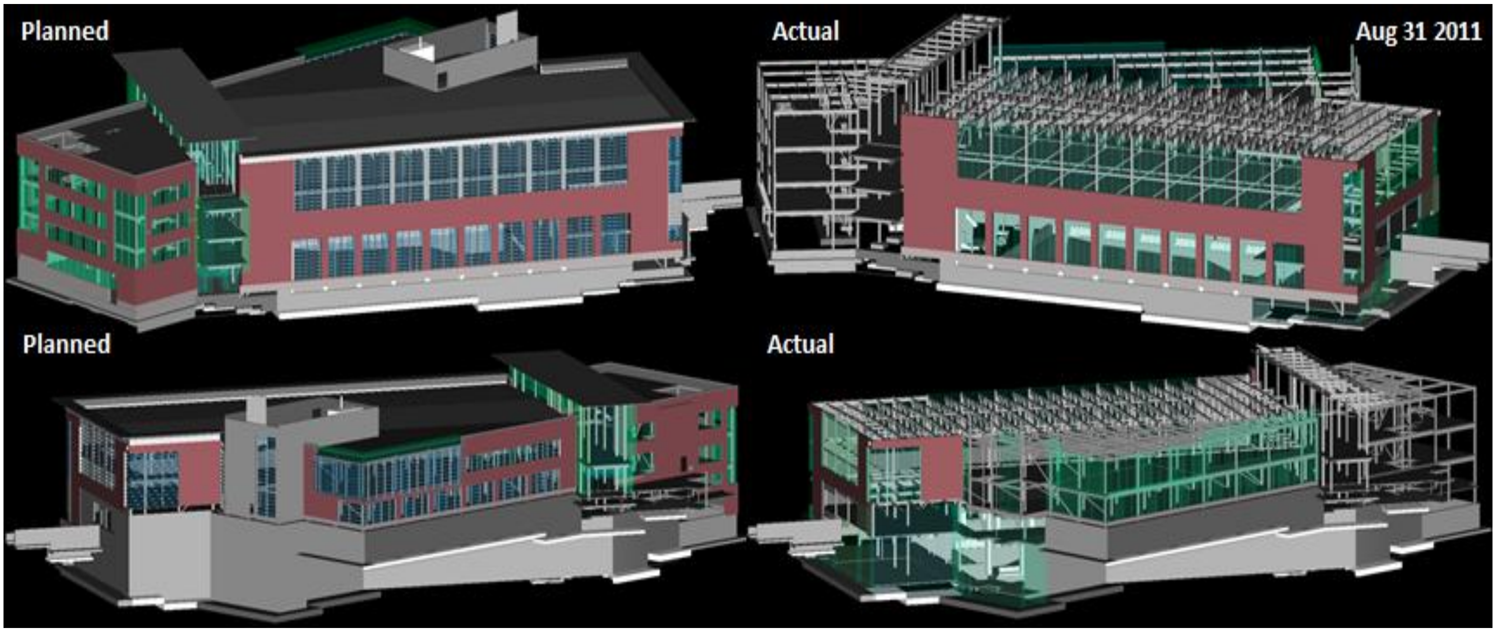
June 30th 2011		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	100.00	83.51
Façade	47.76	3.33
Roofing	100.00	0.00
Steel	100.00	100.00

June 30th 2011				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	37.92	0.00	259824.19	0.00
Roofing	100.00	0.00	2753.85	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	82.87	0.00	300394.03
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	56.60	3.21	223002.12	39750.17
Glass & Glazing	18.27	11.62	449863.91	204830.43



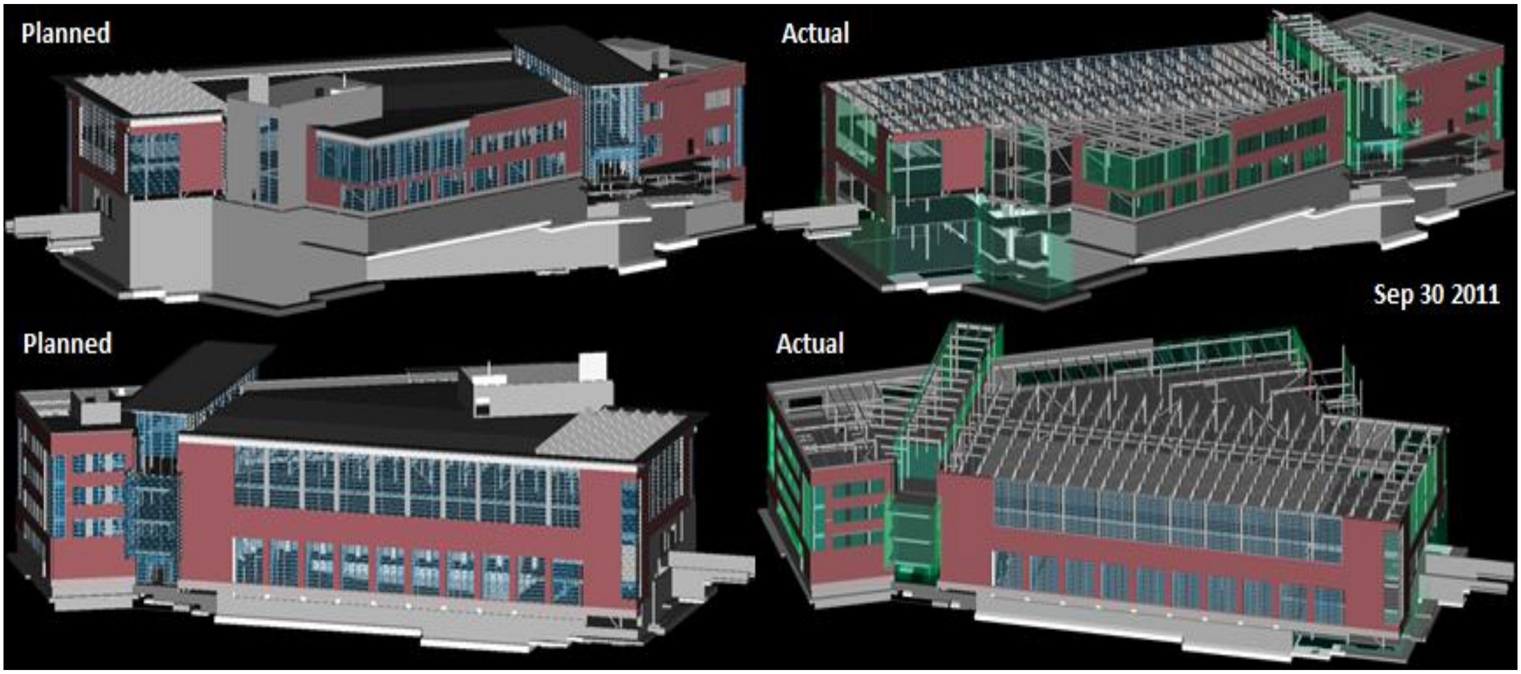
July 31st 2011		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	100.00	84.37
Façade	78.81	17.78
Roofing	100.00	0.00
Steel	100.00	100.00

July 31st 2011				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	59.58	0.00	148470.97	0.00
Roofing	100.00	0.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	83.76	0.00	24618.58
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	92.88	24.29	448613.09	260640.73
Glass & Glazing	39.96	20.04	647724.41	251220.74



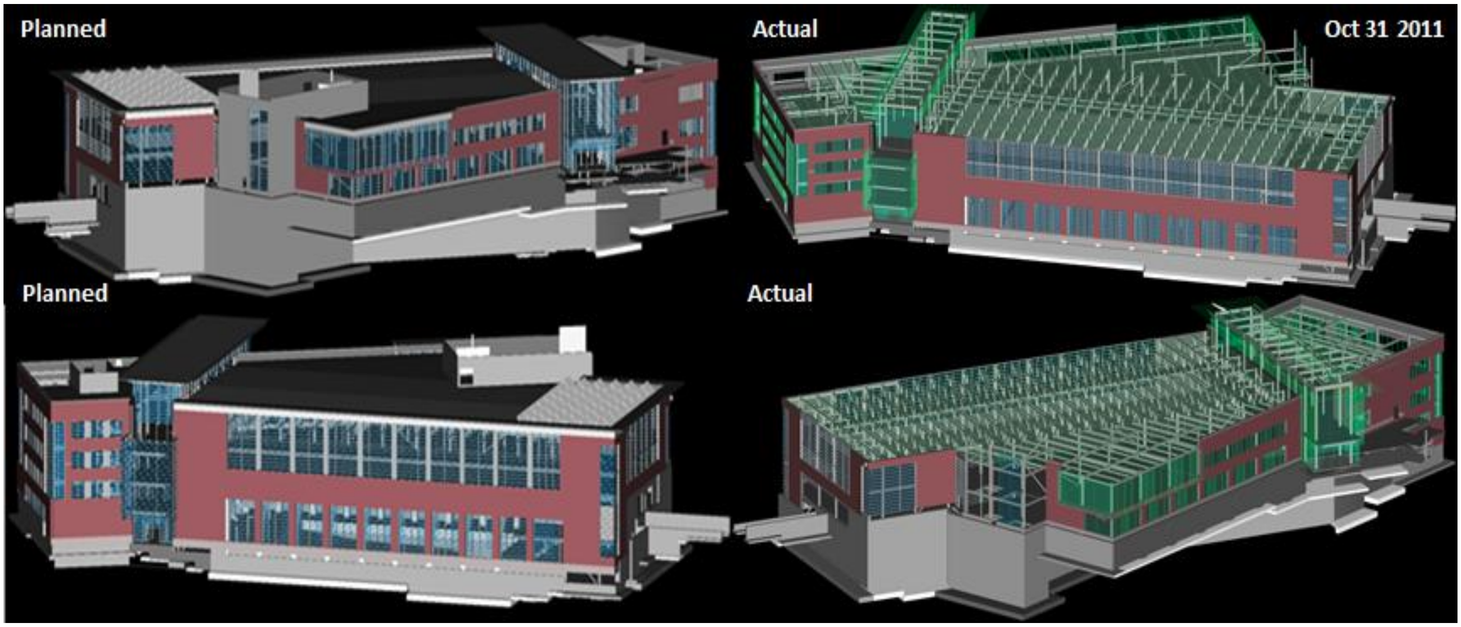
August 31st 2011		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	100.00	84.37
Façade	93.57	40.09
Roofing	100.00	0.00
Steel	100.00	100.00

August 31st 2011				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	74.18	0.00	99998.19	0.00
Roofing	100.00	0.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	83.76	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	56.85	88017.53	402515.32
Glass & Glazing	100.00	33.02	1792092.63	387701.47



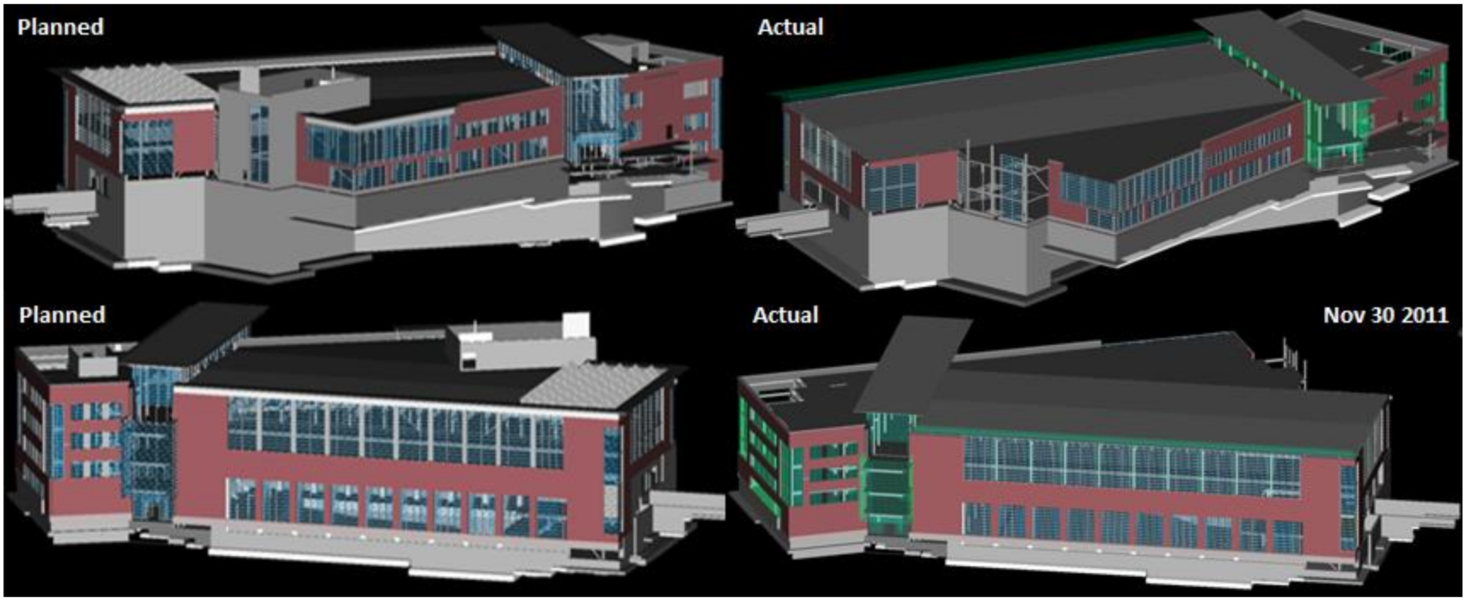
September 30th 2011		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	100.00	97.74
Façade	100.00	69.72
Roofing	100.00	0.00
Steel	100.00	100.00

September 30th 2011				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	100.00	0.00	176946.65	0.00
Roofing	100.00	0.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	97.65	0.00	387095.27
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	533606.78
Glass & Glazing	100.00	50.73	0.00	528452.18



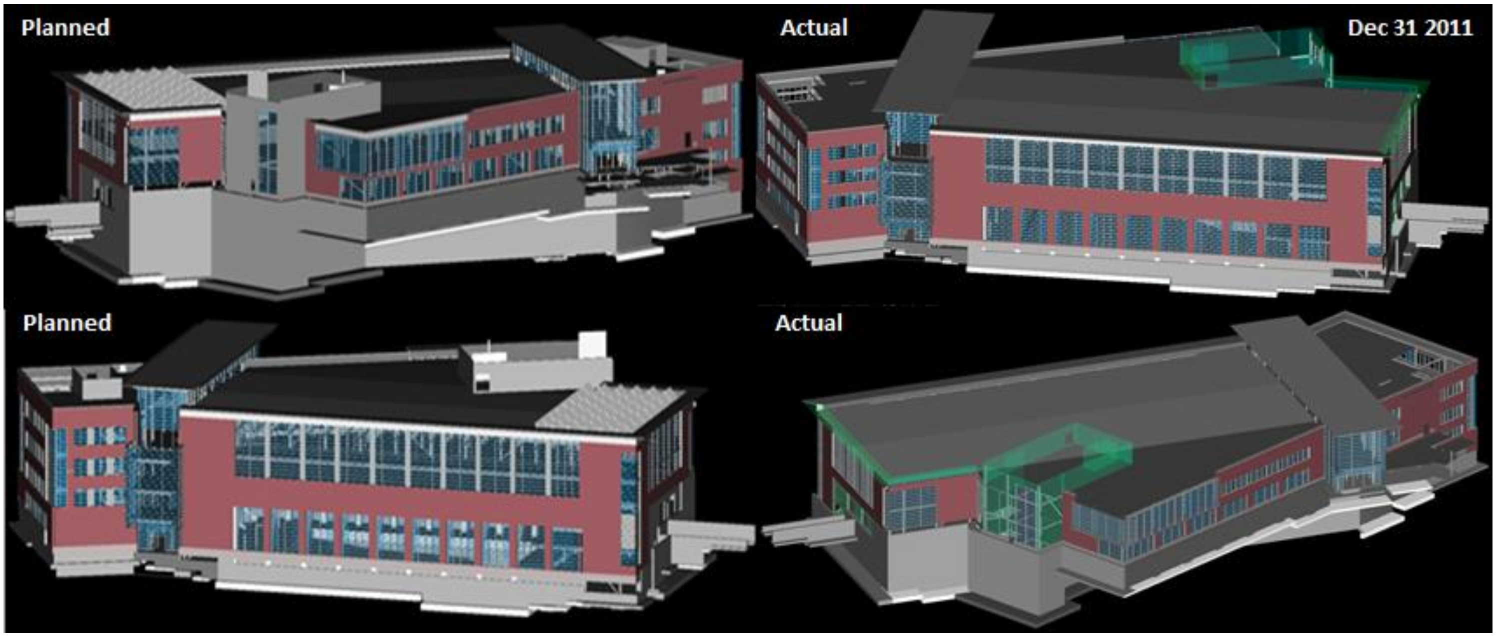
October 31st 2011		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	100.00	100.00
Façade	100.00	72.05
Roofing	100.00	55.56
Steel	100.00	100.00

October 31st 2011				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	100.00	0.00	0.00	0.00
Roofing	100.00	55.56	0.00	68333.42
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	100.00	0.00	65331.95
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	0.00
Glass & Glazing	100.00	72.02	0.00	635587.83



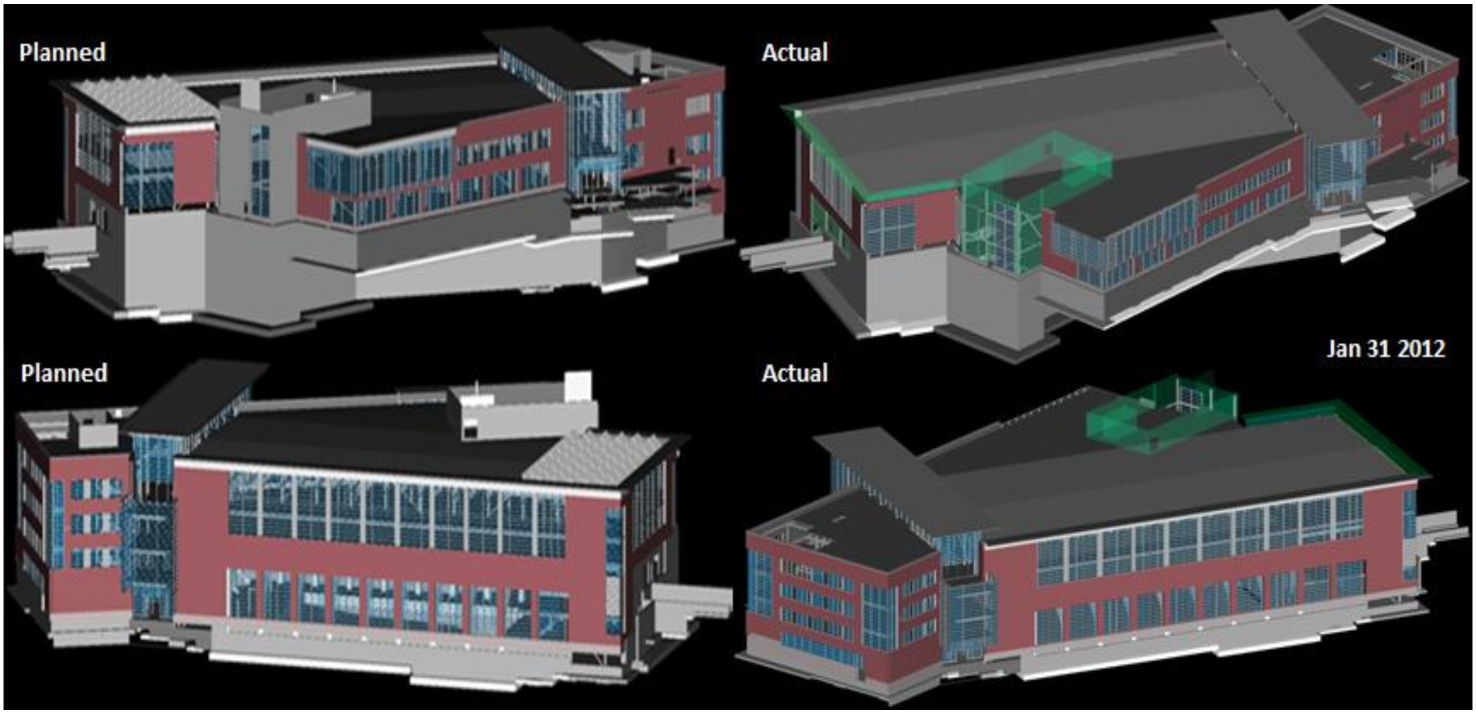
November 30th 2011		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	100.00	100.00
Façade	100.00	75.99
Roofing	100.00	100.00
Steel	100.00	100.00

November 30th 2011				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	100.00	7.31	0.00	50101.43
Roofing	100.00	100.00	0.00	54666.57
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	100.00	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	0.00
Glass & Glazing	100.00	91.44	0.00	579679.80



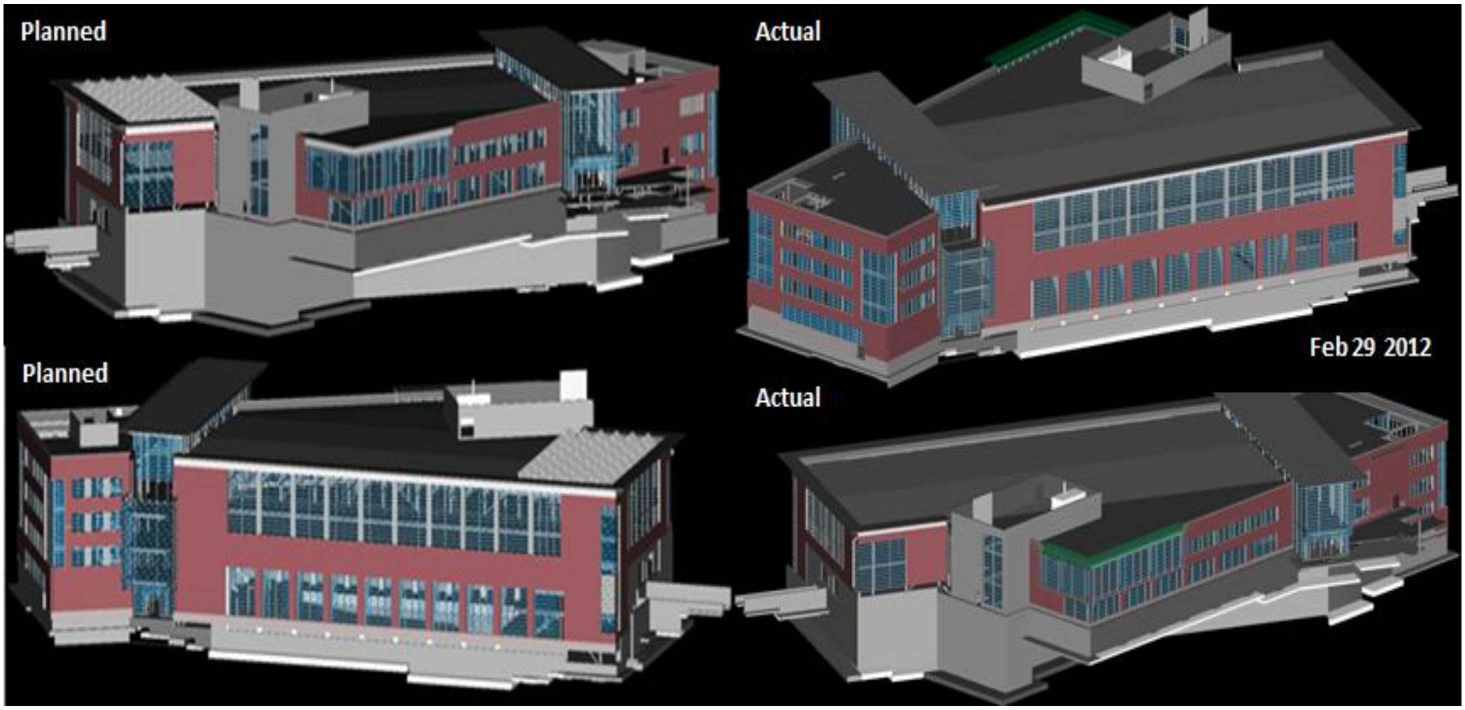
December 31st 2011		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	100.00	100.00
Façade	100.00	80.45
Roofing	100.00	100.00
Steel	100.00	100.00

December 31st 2011				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	100.00	21.47	0.00	97042.62
Roofing	100.00	100.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	100.00	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	0.00
Glass & Glazing	100.00	100.00	0.00	255584.05



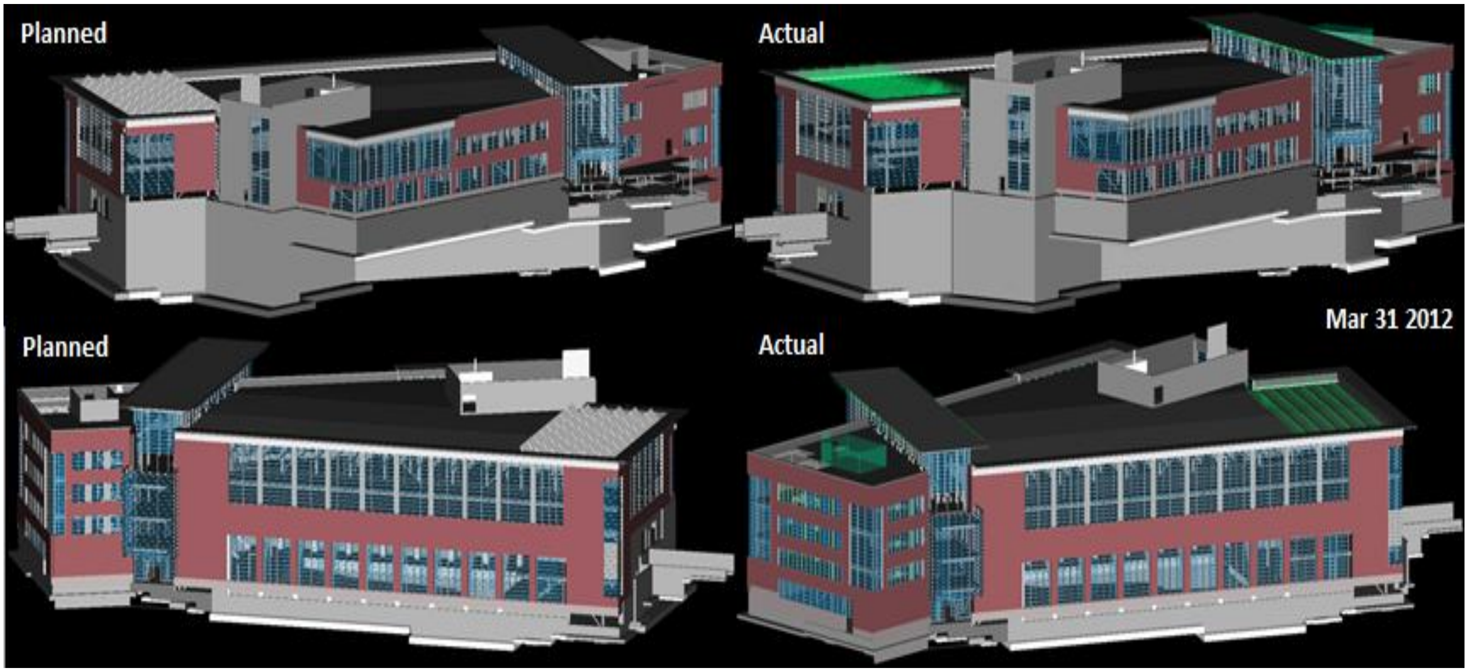
January 31st 2012		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	100.00	100.00
Façade	100.00	89.78
Roofing	100.00	100.00
Steel	100.00	100.00

January 31st 2012				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	100.00	58.93	0.00	256642.67
Roofing	100.00	100.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	100.00	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	0.00
Glass & Glazing	100.00	100.00	0.00	0.00



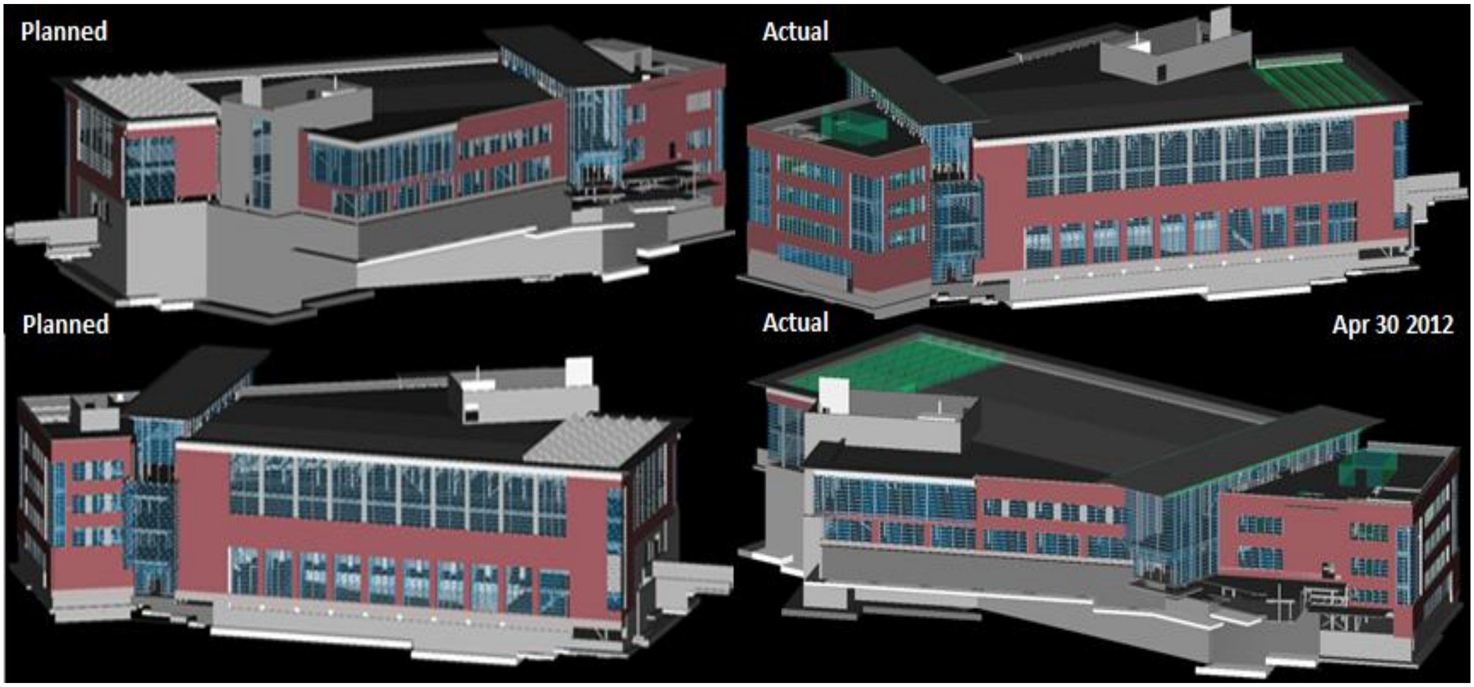
February 29th 2012		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	100.00	100.00
Façade	100.00	93.55
Roofing	100.00	100.00
Steel	100.00	100.00

February 29th 2012				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	100.00	74.10	0.00	103984.80
Roofing	100.00	100.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	100.00	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	0.00
Glass & Glazing	100.00	100.00	0.00	0.00



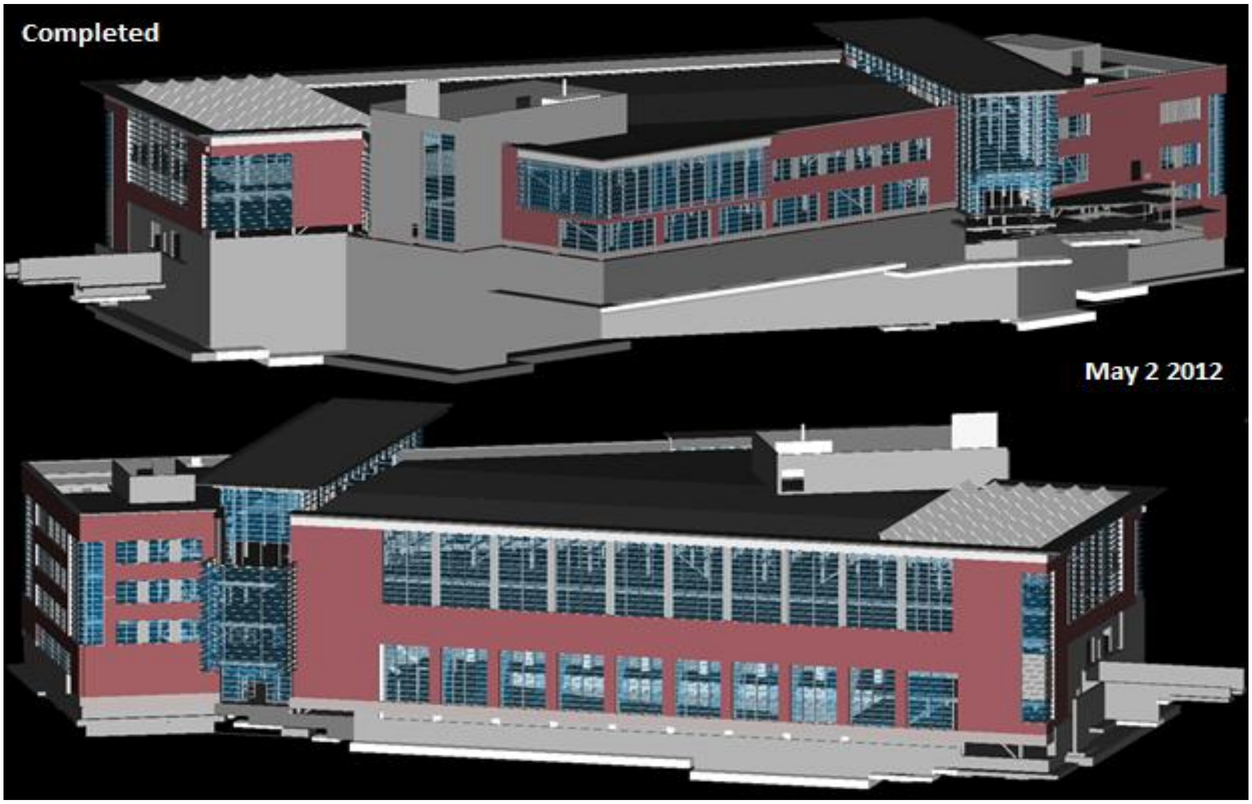
March 31st 2012		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	100.00	100.00
Façade	100.00	95.05
Roofing	100.00	100.00
Steel	100.00	100.00

March 31st 2012				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	100.00	80.11	0.00	41194.96
Roofing	100.00	100.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	100.00	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	0.00
Glass & Glazing	100.00	100.00	0.00	0.00



April 30th 2012		
	Planned Cumulative Percentage	Actual Cumulative Percentage
Concrete	100.00	100.00
Façade	100.00	99.21
Roofing	100.00	100.00
Steel	100.00	100.00

April 30th 2012				
	Percent Planned	Percent Complete	Monthly Cost Planned	Monthly Cost Complete
Metal Panels	100.00	96.82	0.00	114469.76
Roofing	100.00	100.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	100.00	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	0.00
Glass & Glazing	100.00	100.00	0.00	0.00



May 2nd 2012		
	Planned Cumulative Percentage	**Actual Cumulative Percentage**
Concrete	100.00	100.00
Façade	100.00	100.00
Roofing	100.00	100.00
Steel	100.00	100.00

May 2nd 2012				
	Percent Planned	**Percent Complete**	**Monthly Cost Planned**	**Monthly Cost Complete**
Metal Panels	100.00	100.00	0.00	21803.76
Roofing	100.00	100.00	0.00	0.00
Steel	100.00	100.00	0.00	0.00
Concrete	100.00	100.00	0.00	0.00
Precast Concrete	100.00	100.00	0.00	0.00
Brick & Precast	100.00	100.00	0.00	0.00
Glass & Glazing	100.00	100.00	0.00	0.00

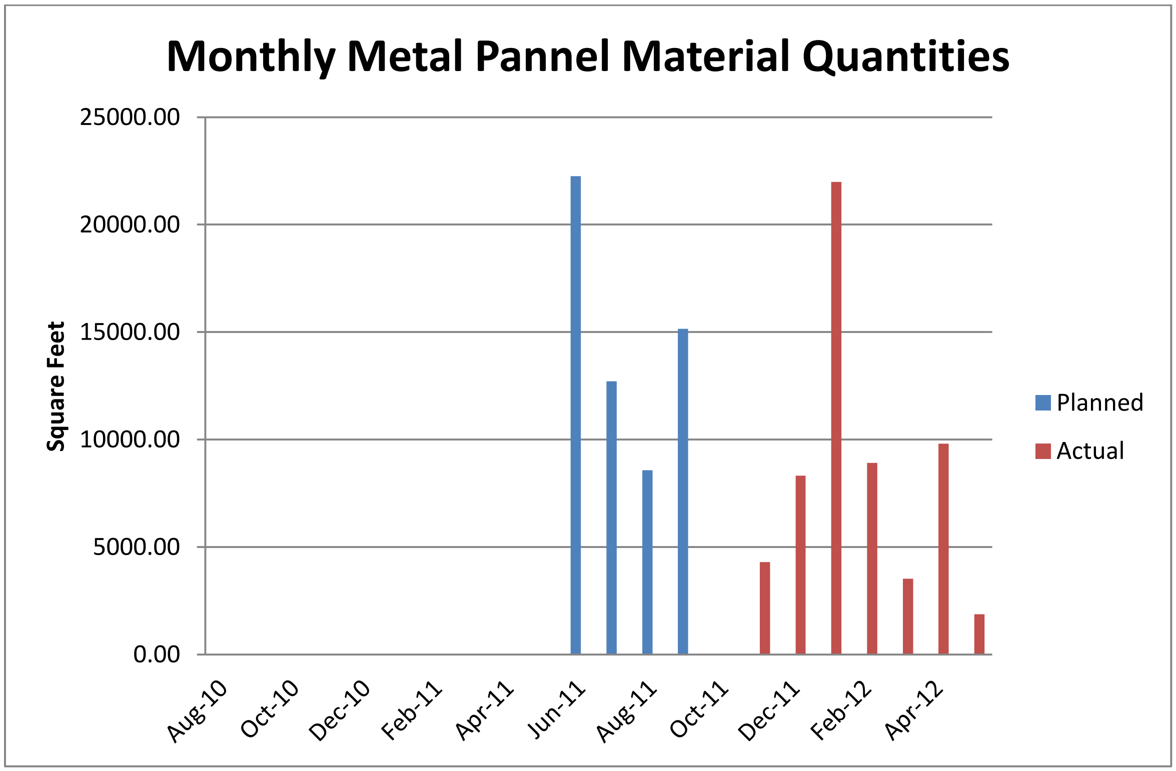
APPENDIX K: Planned vs. Actual Material Quantities By Month and Trade

Metal Panels

Earned Value Analysis (Schedule Varience Only)

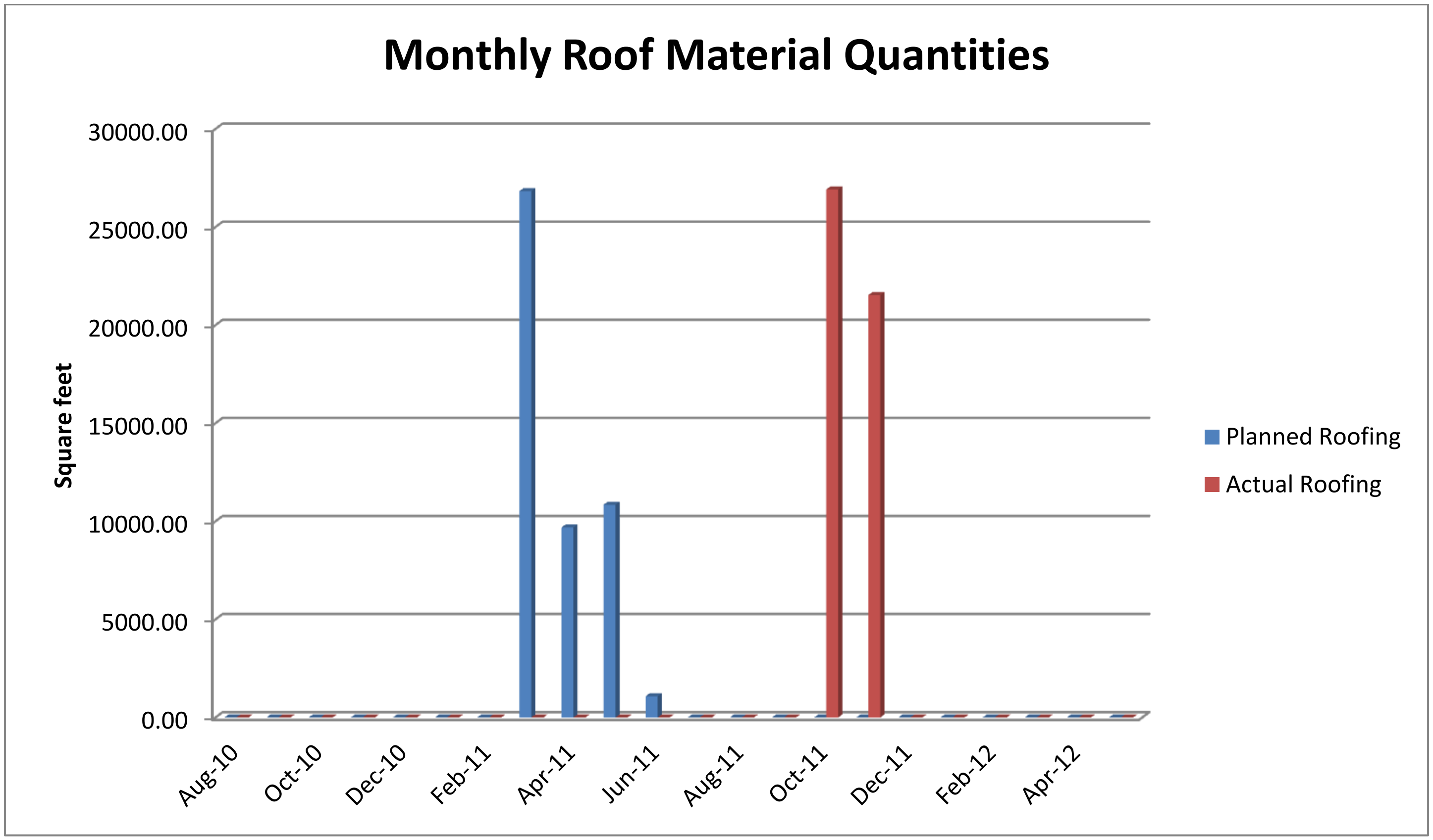
	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11
BCWP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BCWS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SPI										

	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12
BCWP	0.00	0.00	0.00	0.00	0.00	50101.43	147144.04	403786.71	507771.52	548966.48	663436.24	685240.00
BCWS	259824.19	408295.16	508293.35	685240.00	685240.00	685240.00	685240.00	685240.00	685240.00	685240.00	685240.00	685240.00
SV	-259824.19	-408295.16	-508293.35	-685240.00	-685240.00	-635138.57	-538095.96	-281453.29	-177468.48	-136273.52	-21803.76	0.00
SPI	0.00	0.00	0.00	0.00	0.00	0.07	0.21	0.59	0.74	0.80	0.97	1.00



Roofing

Earned Value Analysis (Schedule Varience Only)																						
	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12
BCWP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	68333.42	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00
BCWS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	68120.78	92707.69	120246.15	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00	123000.00
SV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-68120.78	-92707.69	-120246.15	-123000.00	-123000.00	-123000.00	-123000.00	-54666.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SPI								0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	1.00	1.00	1.00	1.00	1.00	1.00	1.00

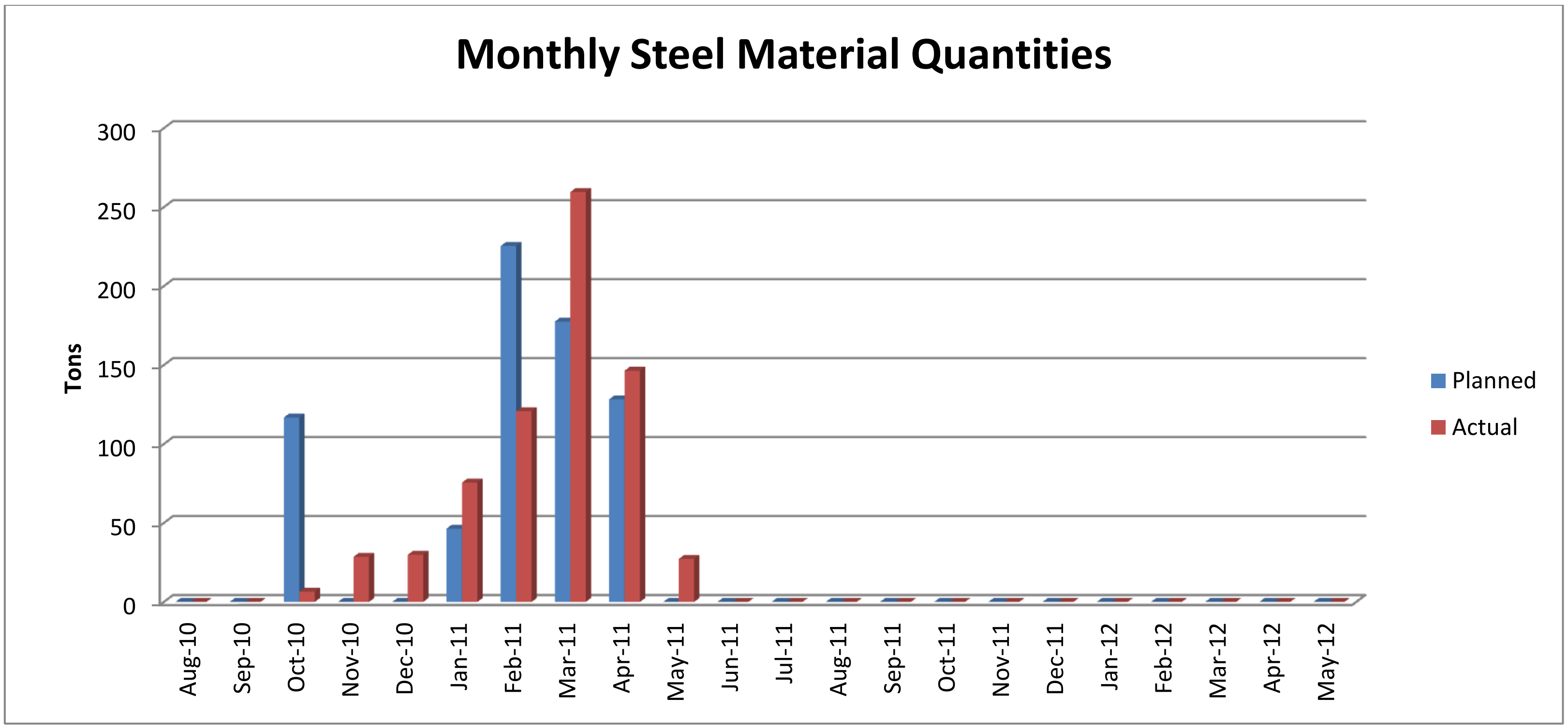


Steel

Earned Value Analysis (Schedule Varience Only)

	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11
BCWP	0.00	0.00	32689.80	176524.94	326898.04	707407.35	1315873.57	2623465.72	3360947.69	3497809.00	3497809.00
BCWS	0.00	0.00	588416.47	588416.47	588416.47	822039.60	1957465.45	2851858.48	3497809.00	3497809.00	3497809.00
SV	0.00	0.00	-555726.66	-411891.53	-261518.43	-114632.25	-641591.88	-228392.76	-136861.31	0.00	0.00
SPI			0.06	0.30	0.56	0.86	0.67	0.92	0.96	1.00	1.00

	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12
BCWP	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00
BCWS	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00	3497809.00
SV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SPI	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

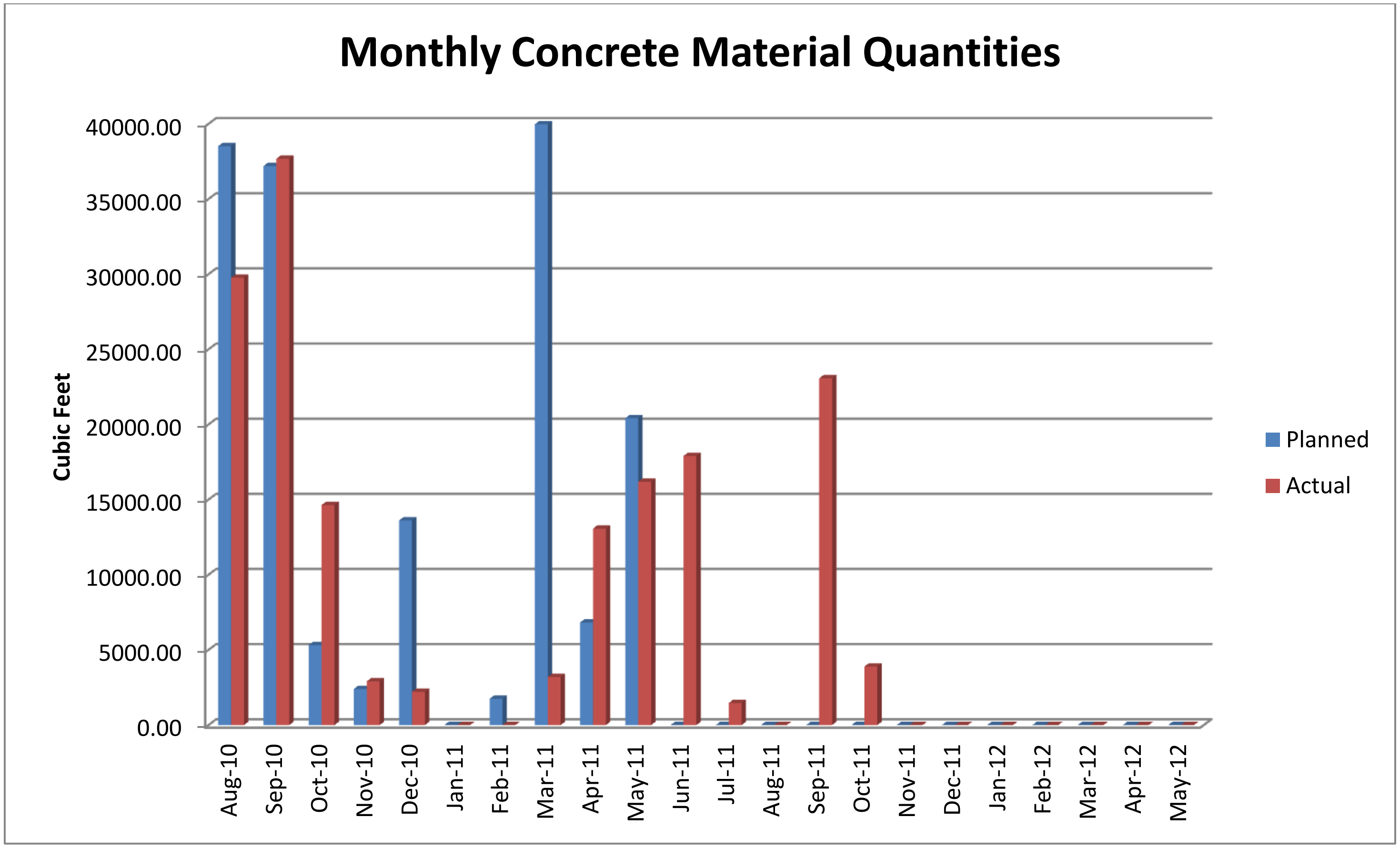


Concrete

Earned Value Analysis (Schedule Varience Only)

	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11
BCWP	499398.64	1131601.31	1377236.05	1426105.85	1463244.05	1463244.05	1463244.05	1516960.54	1736276.22	2007981.16	2308375.20
BCWS	646267.38	1270238.16	1359490.53	1399808.41	1628279.17	1628279.17	1657634.47	2328284.55	2442840.38	2785421.00	2785421.00
SV	-146868.74	-138636.85	17745.52	26297.44	-165035.12	-165035.12	-194390.41	-811324.00	-706564.17	-777439.84	-477045.80
SPI	0.77	0.89	1.01	1.02	0.90	0.90	0.88	0.65	0.71	0.72	0.83

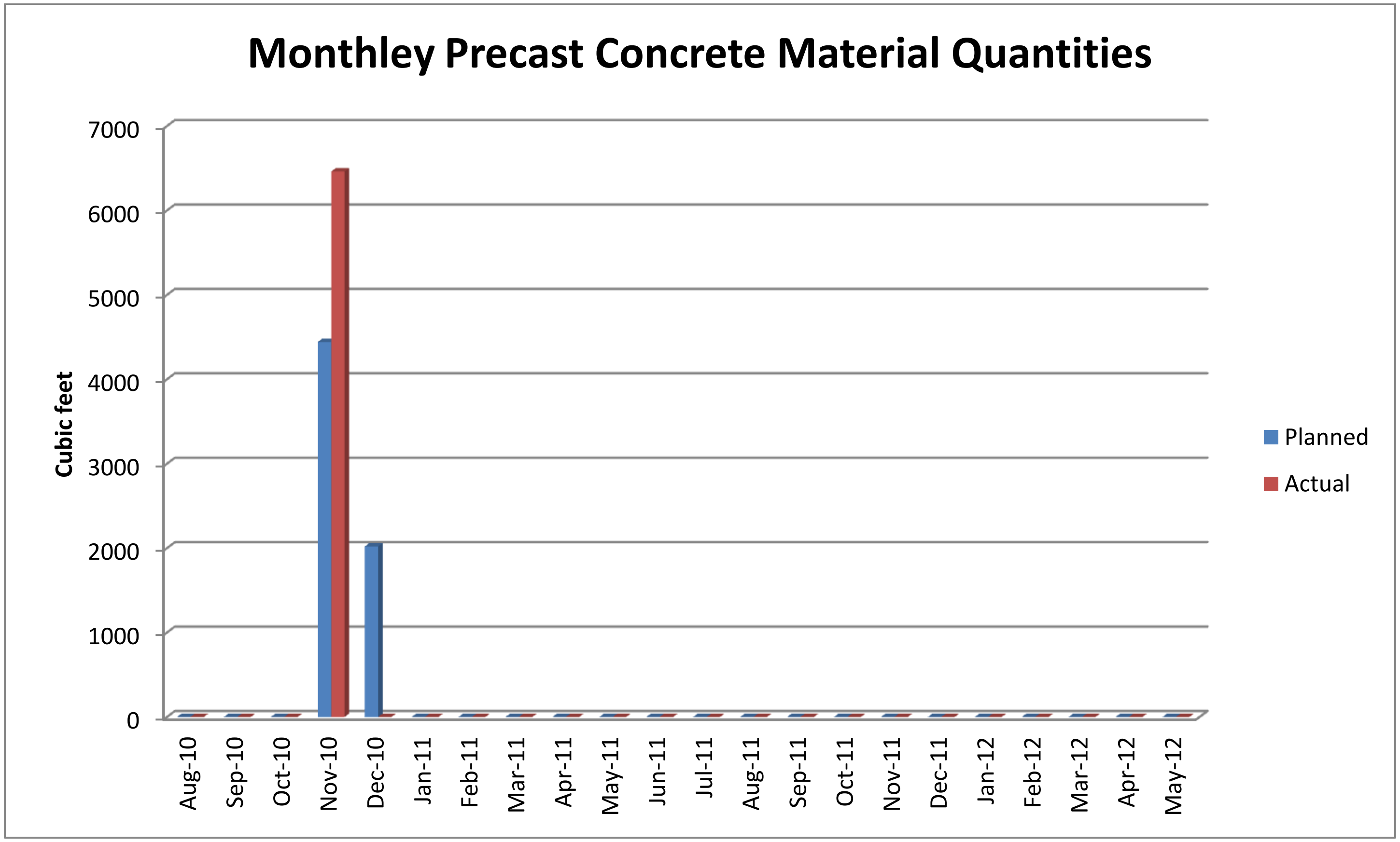
	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12
BCWP	2332993.78	2332993.78	2720089.05	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00
BCWS	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00	2785421.00
SV	-452427.22	-452427.22	-65331.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SPI	0.84	0.84	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00



Precast Concrete

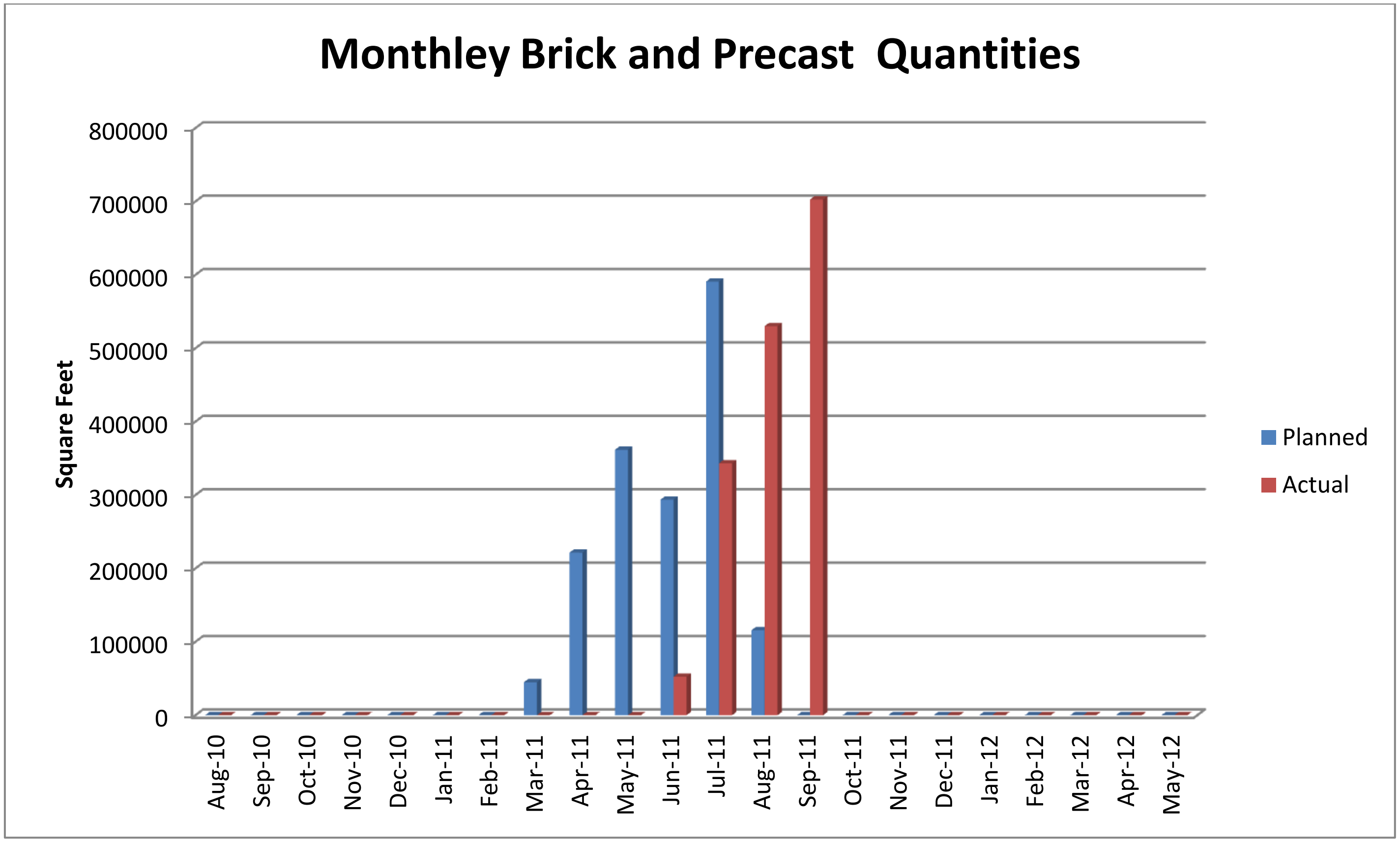
Earned Value Analysis (Schedule Varience Only)											
	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11
BCWP	0.00	0.00	0.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00
BCWS	0.00	0.00	0.00	1097921.13	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00
SV	0.00	0.00	0.00	499078.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SPI				1.45	1.00	1.00	1.00	1.00	1.00	1.00	1.00

	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12
BCWP	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00
BCWS	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00	1597000.00
SV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SPI	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00



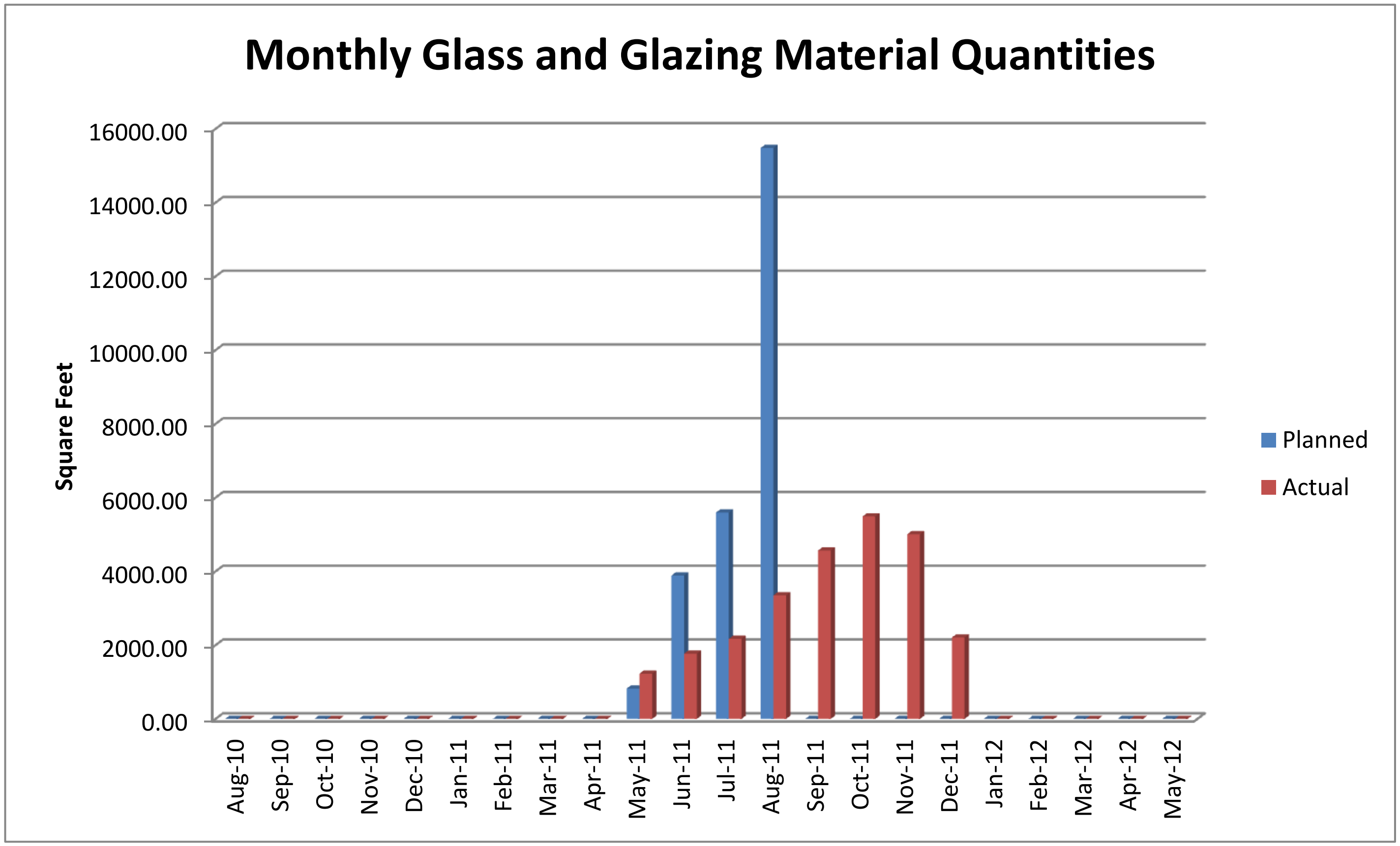
Brick and Precast

Earned Value Analysis (Schedule Varience Only)																						
	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12
BCWP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	39750.17	300390.89	702906.22	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00
BCWS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34094.92	202274.75	476880.25	699882.38	1148495.47	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00	1236513.00
SV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-34094.92	-202274.75	-476880.25	-660132.21	-848104.58	-533606.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SPI								0.00	0.00	0.00	0.06	0.26	0.57	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00



Glass and Glazzing

Earned Value Analysis (Schedule Varience Only)																					
	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12
BCWP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	142009.50	346839.93	598060.67	985762.14	1514214.32	2149802.15	2729481.95	2985066.00	2985066.00	2985066.00	2985066.00	2985066.00	2985066.00
BCWS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	95385.05	545248.96	1192973.37	2985066.00	2985066.00	2985066.00	2985066.00	2985066.00	2985066.00	2985066.00	2985066.00	2985066.00	2985066.00
SV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	46624.45	-198409.03	-594912.70	-1999303.86	-1470851.68	-835263.85	-255584.05	0.00	0.00	0.00	0.00	0.00	0.00
SPI										1.49	0.64	0.50	0.33	0.51	0.72	0.91	1.00	1.00	1.00	1.00	1.00	1.00

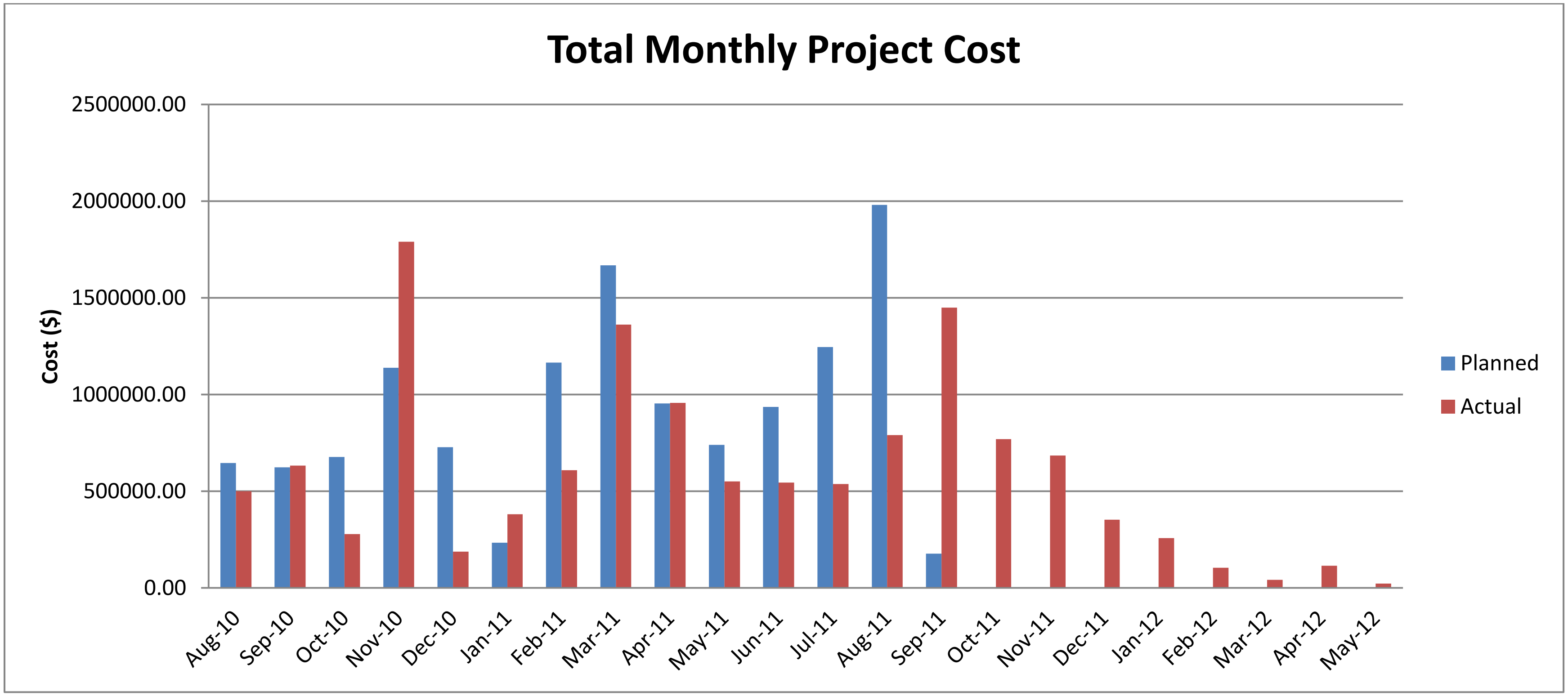


Total Cost

Earned Value Analysis (Schedule Varience Only)

	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11
BCWP	499398.64	1131601.31	1409925.85	3199630.79	3387142.09	3767651.41	4376117.62	5737426.26	6694223.90	7244799.66	7789774.29
BCWS	646267.38	1270238.16	1947907.00	3086146.01	3813695.64	4047318.77	5212099.92	6879358.73	7832631.82	8572741.46	9508185.53
SV	-146868.74	-138636.85	-537981.14	113484.78	-426553.55	-279667.36	-835982.29	-1141932.47	-1138407.91	-1327941.80	-1718411.23
SPI	0.77	0.89	0.72	1.04	0.89	0.93	0.84	0.83	0.85	0.85	0.82

	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12
BCWP	8326254.34	9116471.13	10565625.37	11334878.57	12019326.38	12371953.04	12628595.71	12732580.52	12773775.48	12888245.24	12910049.00
BCWS	10752994.00	12733102.35	12910049.00	12910049.00	12910049.00	12910049.00	12910049.00	12910049.00	12910049.00	12910049.00	12910049.00
SV	-2426739.66	-3616631.21	-2344423.63	-1575170.43	-890722.62	-538095.96	-281453.29	-177468.48	-136273.52	-21803.76	0.00
SPI	0.77	0.72	0.82	0.88	0.93	0.96	0.98	0.99	0.99	1.00	1.00



APPENDIX L: Underpinning Design Calculations & Related Sources

RCMQP4 | HARRINGTON AUD. (pg 1) | 2/13/2012

UNDERPINNING DESIGN

- ESTIMATED FOOTING LOAD

TRIBUTARY ROOF LOAD: 8'

WAFFLE SLAB ~ 0.9 CF/SF → 135 PSF
19×19 – 5" @ 24"
T & G ROOF → 6 PSF
SNOW LOAD → 40 PSF
181 PSF

* SAY 200 PSF

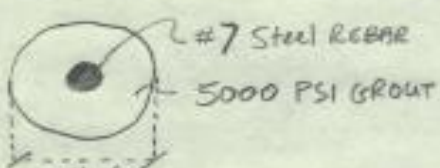
200 PSF × 8ft = 1600 plf = 1.6 KLF
Wall: 14ft (HEIGHT) × 120 PSF = 1700 plf = 1.7 KLF
LIVE LOAD (during construction) = 0.6 KLF
3.9 KLF

- LOADING CAPACITY

MAX PILE SPACING BY CODE: 8'

TOTAL LOAD PER PILE = 8' × 3.9 KLF = 31.2 Kips

- AVAILABLE CAPACITY



	AREA	S.F.	STRENGTH	CAPACITY
STEEL	$0.60\ in^2$	0.40	75 KSI	18 KSI
GROUT	$27.67\ in^2$	0.33	5.0 KSI	45.66 KSI

TOTAL: 63.66 KIPS

(AVAILABLE) 63.66K > 31.20K (ULTIMATE)

OK

CONT. →

- EMBEDMENT / BOND CALCULATIONS

TWO WELL PUBLISHED REFERENCES CONFIRM THE EMBEDMENT/BOND VALUES USED IN THE DESIGN

① NHI / FHWA Pub. 05-040
② FHWA Pub. RD-75-129

BASED ON REF ① THE ALLOWABLE BOND FOR "COMPACT SAND" IS IN THE RANGE OF 5 TO 10 KLF

RANGE OF CALCULATED BOND LENGTH:

$$\frac{31.2 \text{ kips}}{5 \text{ KLF}} = 6.24 \text{ ft} \quad ; \quad \frac{31.2 \text{ kips}}{10 \text{ KLF}} = 3.12 \text{ ft}$$

MINIMUM BOND LENGTH = 6.24 ft

DESIGN BOND LENGTH: 9 ft (OK)

EMBEDMENT CHECK

FOR PILES WITH DIAMETERS IN THE RANGE OF ~ 4"-6" THE EMPIRICAL BOND VALUES ARE PLOTTED & TABULATED

BASED ON REF ② FOR PILES W/ 9 ft EMBEDMENT LENGTH, THE CALCULATED SAFETY FACTOR IS:

$$\frac{105 \text{ kips}}{31.2 \text{ kips}} = 3.37 \rightarrow 3.37 > 1.5 \quad \text{(OK)}$$

GROUT-TO-CONCRETE CONNECTION

REFERENCE: PCI AS PUBLISHED IN FOUNDATIONS IN TENSION BY T.H. HANNA (1982)

FOOTING THICKNESS: 12" (L_F)
CORE HOLE: 7" (D_P)
ULTIMATE BOND STRENGTH (CONCRETE): 200-400 psi (δ)
EFFECTIVE ANGLE: 40° (ϕ)

ULTIMATE CAPACITY, $P_u = [\pi \times D_P \times L_F \times \delta] / \cos\phi = [\pi \times 7" \times 12" \times 200 \text{psi}] / \cos(40°)$

$$SF = \frac{P_u}{P_a} = \frac{68.9 \text{ kips}}{31.2 \text{ kips}} = 2.2 \rightarrow 2.2 > 2.0$$

(OK)

RCMQP4	HARRINGTON AUD (pg. 3)	2/13/2012

UNDERPINNING DESIGN VS. GZA DESIGN

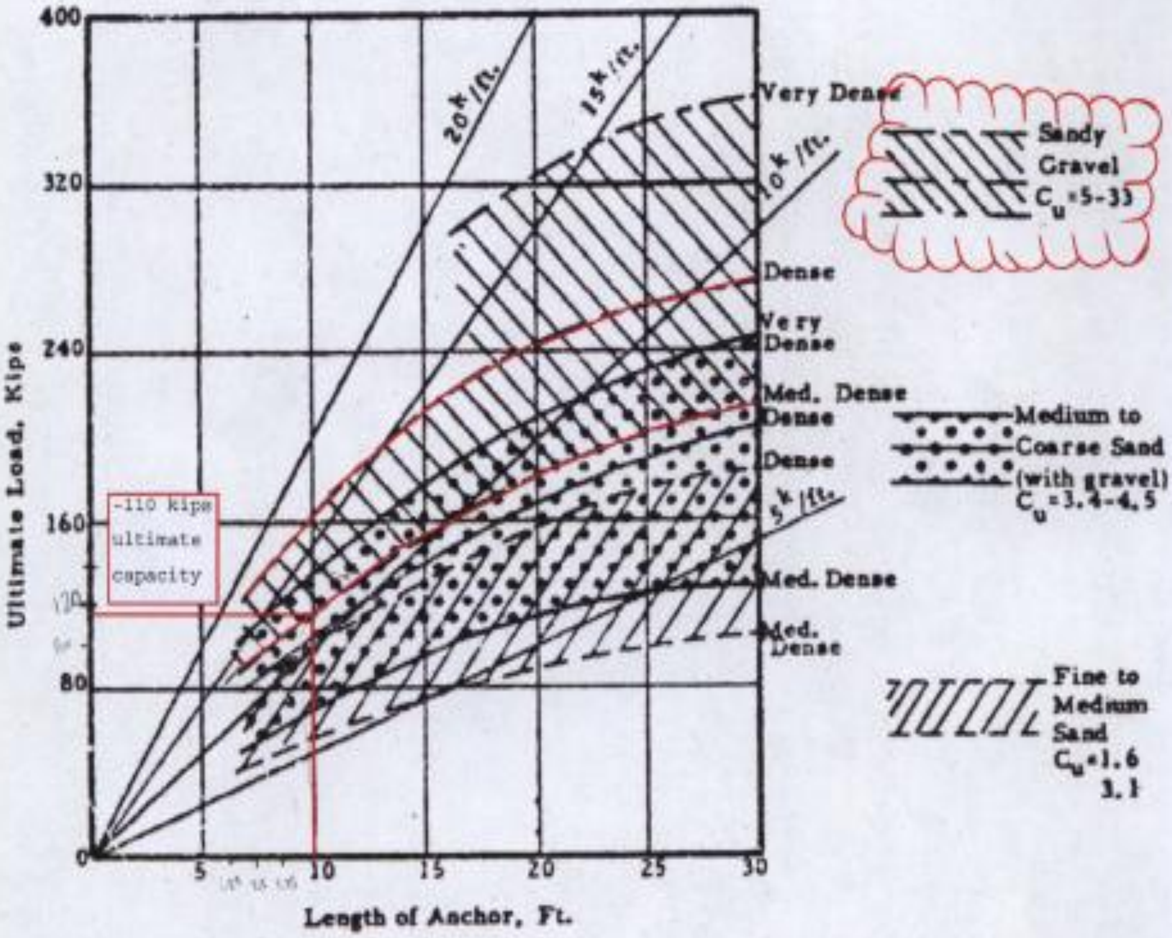
MQP DESIGN	GZA DESIGN
#7 STEEL: 0.60 in^2	#8 STEEL: 0.79 in^2
HOLE DIAMETER: 6"	HOLE DIAMETER: 6"
BOND LENGTH: 9 ft	BOND LENGTH: 10 ft
# of PILES: 8	# of PILES: 8

CALCULATIONS

MQP: $0.60 in^2 \times 9 ft (12 in/ft) \times 8$ piles $= 758.4 in^3$

GZA: $0.79 in^2 \times 10 ft (12 in/ft) \times 8$ piles $= 518.4 in^3$

$$\% \text{ DIFFERENCE} = \frac{758.4 - 518.4}{758.4} = 0.316 \times 100 = \underline{31.6\%}$$



Diameter of Anchor 4"-6"
Depth of Overburden ≥ 13 feet

NOTE: 1ft. = .305 m
1in. = 2.54cm
1k/ft = 14.6 kN/m

Figure 71. Load capacity of anchors in cohesionless soil showing effects of relative density, gradation, uniformity, and anchor length (after Ostermayer, 1974).

Reference: Federal Highway Administration Publication FHWA-RD-75-129
Lateral Support Systems and Underpinning by D.T. Goldberg, et.al
Final Report Published April 1, 1976; DOT Contract DOT-FH-11-8499.

Geotechnical Design – Empirical

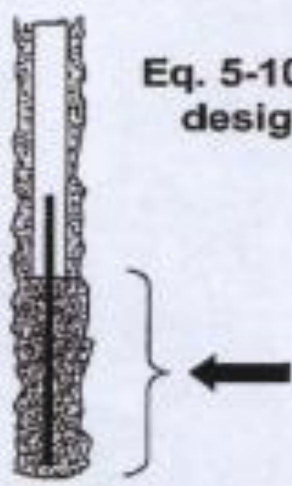
Average Bond Values (allowable loads)

- Clay: 15-30 kN/m (1-2 k/ft)
- Loose sands: 30-60 kN/m (2-4 k/ft)
- Compact sand: 60-120 kN/m (5-10 k/ft)
- Rock: 60-240+ kN/m (5-20+ k/ft)

Typical for approximately 125 – 175 mm diameter micropile

5-29

Calculate Bond Length



Eq. 5-10, with $P_{G\text{-allowable}}$ set equal to design load

$$L_b = \frac{P_{G-allowable} \times FS}{\alpha_{bond} \times \pi \times D_b}$$

5-30

Table 4.2 (a)

Rock/grout bond values which have been recommended for design

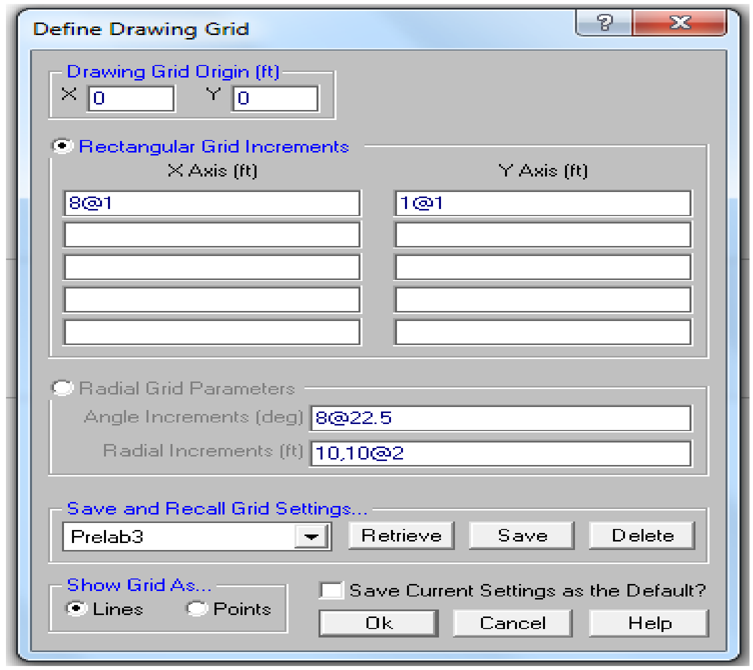
(After Littlejohn and Bruce, 1976)

Rock type	Working bond (N/mm^2)	Ultimate bond (N/mm^2)	Factor of safety	Source
Igneous				
Medium hard basalt		5.73	3—4	India-Rao (1964)
Weathered granite		1.50—2.50 (217–365 psi)		Japan-Suzuki et al. (1972)
Basalt	1.21—1.38	3.86	2.8—3.2	U.K.
Granite	1.38—1.55	4.83	3.1—3.5	U.K.
Serpentine	0.45—0.59	1.55	2.6—3.5	U.K.
Granite & basalt		1.72—3.10	1.5—2.5	USA-PCI (1974)
Metamorphic				
Manhattan schist	0.70	2.80 (400 psi)	4.0	USA-White (1973)*
Slate & hard shale		0.83—1.38	1.5—2.5	USA-PCI (1974)
Calcareous sediments				
Limestone	1.00	2.83	2.8	Switzerland-Losinger (1966)
Chalk-Grades I—III	0.01N (N = S.P.T. in blows/0.3 m)	0.22—1.07	1.5—2.0 (Temporary) 3.0—4.0 (Permanent)	U.K.-Littlejohn (1970)
Tertiary limestone	0.83—0.97	2.76	2.9—3.3	U.K.
Chalk limestone	0.86—1.00	2.76	2.8—3.2	U.K.
Soft limestone		1.03—1.52	1.5—2.5	USA-PCI (1974)
Dolomitic limestone		1.38—2.07	1.5—2.5	USA-PCI (1974)
Arenaceous sediments				
Hard coarse-grained sandstone	2.45		1.75	Canada-Coates (1970)
Weathered sandstone		0.69—0.85	3.0	New Zealand-Irwin (1971)
Well-cemented mudstones		0.69 (100 psi)	2.0—2.5	New Zealand-Irwin (1971)
Bunter sandstone	0.40		3.0	U.K.-Littlejohn (1973)
Bunter sandstone (UCS > 2.0 N/mm^2)	0.60		3.0	U.K.-Littlejohn (1973)
Hard fine sandstone	0.69—0.83	2.24	2.7—3.3	U.K.
Sandstone		0.83—1.73	1.5—2.5	USA-PCI (1974)
Argillaceous sediments				
Keuper marl		0.17—0.25 (0.45 C_u)	3.0	U.K.-Littlejohn (1970) C_u = undrained cohesion
Weak shale		0.35		Canada-Golder Brawner (1973)*
Soft sandstone & shale	0.10—0.14	0.37	2.7—3.7	U.K.
Soft shale		0.21—0.83	1.5—2.5	USA-PCI (1974)
General				
Competent rock (where UCS > 20 N/mm^2)	Uniaxial compressive strength-30 (up to a maximum value of 1.4 N/mm^2)	Uniaxial compressive strength-10 (up to a maximum value of 4.2 N/mm^2)	3	U.K.-Littlejohn (1972)
Weak rock	0.35—0.70 (50–100 psi)			Australia-Koch (1972)
Medium rock	0.70—1.05 (100–150 psi)			
Strong rock	1.05—1.40 (150–200 psi)			
Wide variety of igneous and metamorphic rocks	1.05 (150 psi)		2	Australia-Standard CA35 (1973)
Wide variety of rocks	0.98			France-Fargeot (1972)
	0.50			Switzerland-Walther (1959)
	0.70			Switzerland-Comte (1965)
		1.20—2.50		Switzerland-Comte (1971)
	0.70		2—2.5 (Temporary) 3 (Permanent)	Italy-Mascardi (1973)*
	0.60	2.76	4	Canada-Golder Brawner (1973)*
	1.4	4.2 15—20 % of grout crushing strength	3	USA-White (1973)
Concrete		1.38—2.76 (200–400 psi)	1.5—2.5	USA-PCI (1974)

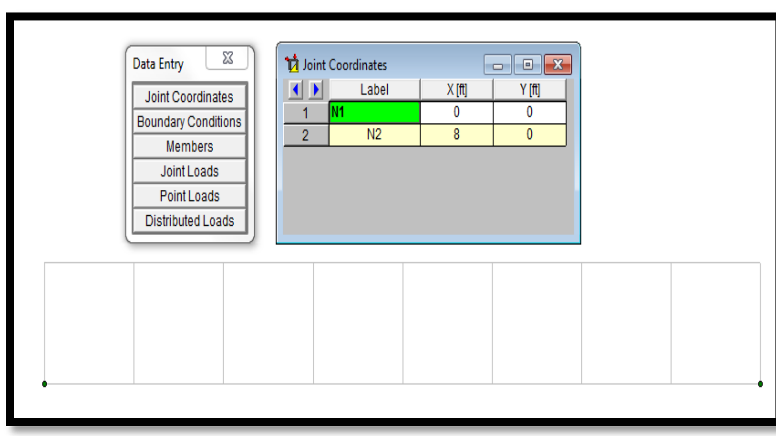
* Replies to a questionnaire on rock anchors by University of Aberdeen 1973.

APPENDIX M: RISA 2D Steps to Create a Beam w/ Loading Conditions

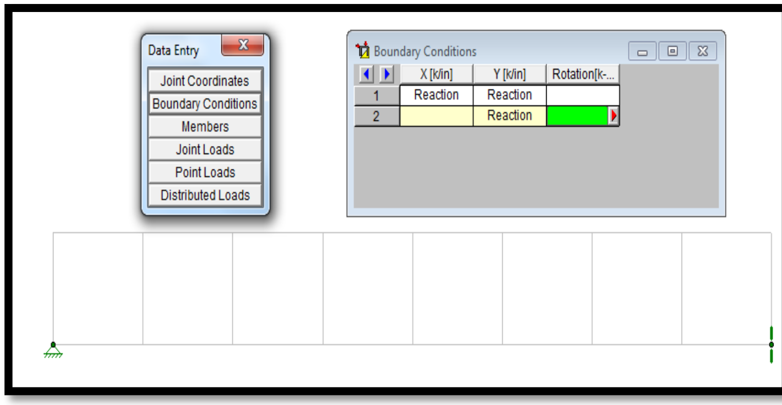
- **Define Drawing Grid**
  - Click the "Insert" Tab
  - Within this tab choose the "Grid"
  - The "Define Drawing Grid" screen will appear
  - Define the width (x-axis) and the height (y-axis)
  - For example: "30@1" means 30 units at 1 foot units, so 30 feet altogether
  - After setting the x- and y-axis, click "OK" and the screen will display the grid described



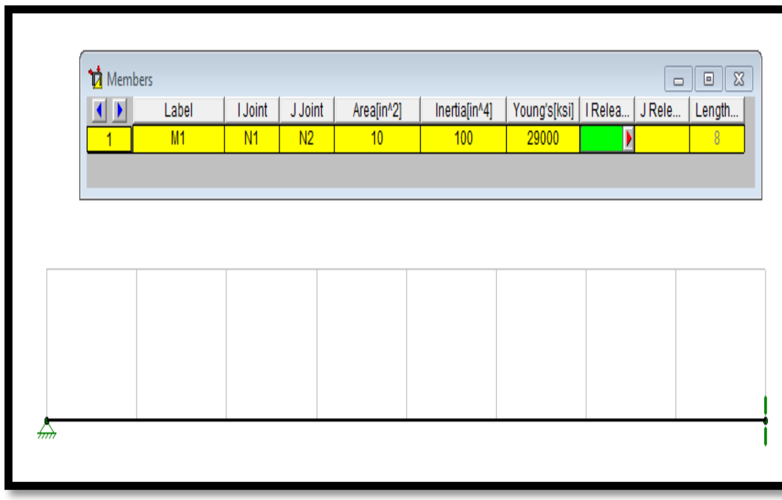
- **Define Joint Coordinates**
  - Click "Joint Coordinates" option in the "Data Entry" menu
  - Choose the location (x, y) of the joints of the structural member (frame, beam, truss, etc.)
  - After choosing the location of each joint, the coordinate will appear on the grid



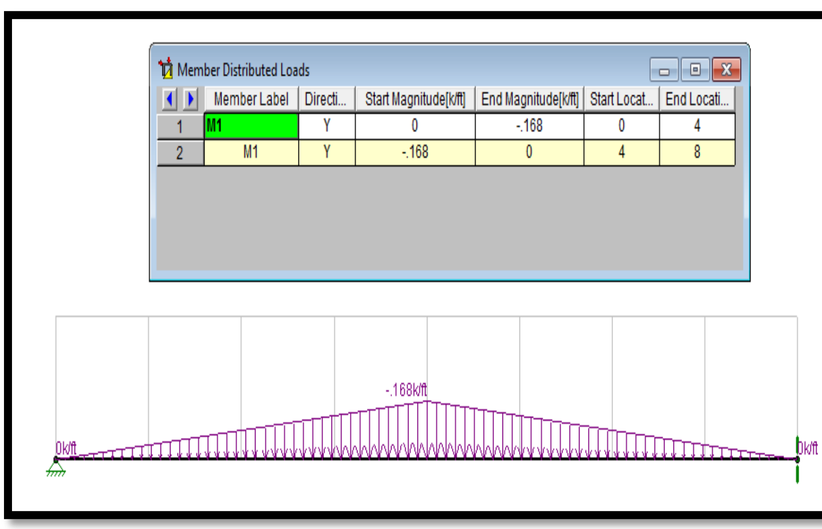
- **Define Boundary Conditions**
  - Click “Boundary Conditions” option in the “Data Entry” menu
  - Choose the reaction in the x- and y-direction for each joint
  - Ex. A pin has a fixed x- and y-reaction and a free rotation



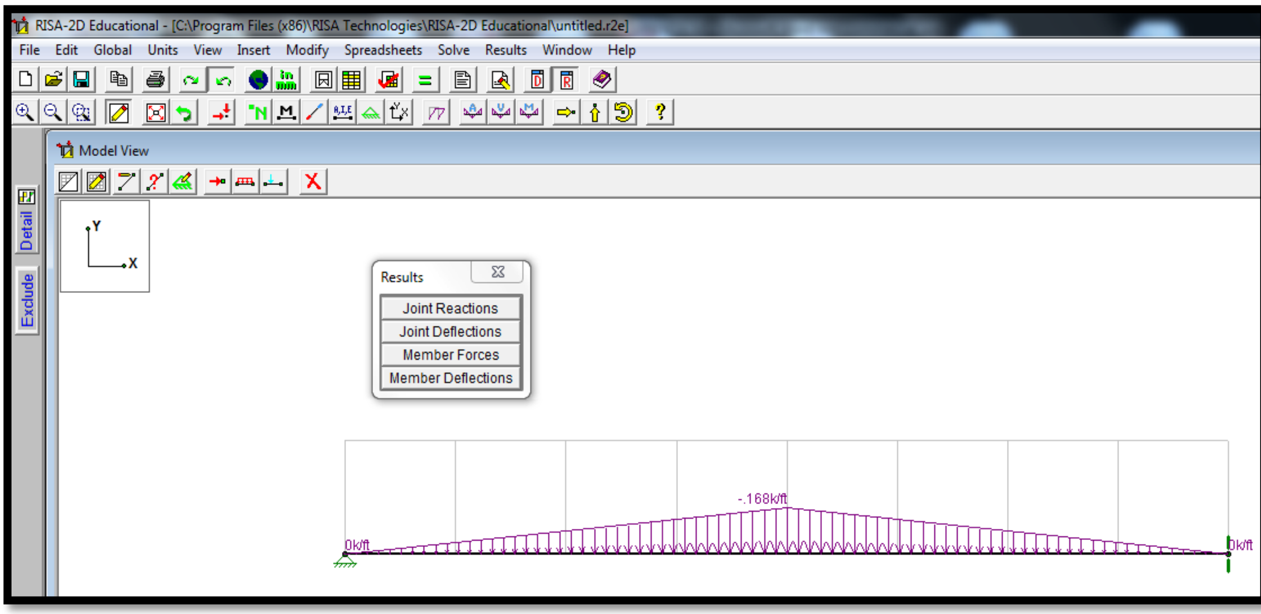
- **Define Members**
  - Choose the parameters for each member including joints, moment of inertia, modulus of elasticity and length
  - The member should appear on the grid once the parameters are chosen



- **Define Loads**
  - Determine the loads that will applied to the structure
  - Choose “Distributed Loads” or “Point Loads” in the “Data Entry” menu
  - Enter in the properties of the load (location, magnitude, direction)



- **Solve**
  - Click the “Solve” tab at the top of the page
  - This will open up a “Results” menu
  - From here you can solve for Joint Reactions/Deflections and Member Forces/Deflections
  - Follow these same steps for different loads or member properties and solve again



APPENDIX N: Interview with Professor Stafford (Robotics Dept.)

ATTENDEES: Chris Baker & Prof. Kenneth Stafford
LOCATION: Higgins Laboratories, Room 011
DATE: February 8, 2012

- Appointed to the architectural advisory staff during conceptual design of the Rec Center to provide input on robotics pits and tie-in with Harrington

- Special design for robotics pits included 10' ceilings, a ramp instead of stairs, electrical drops at each pit

- The ideal transition dimension are 8'x8'
    - Height: Max height of robot is 5 foot collapsed in a 2foot high wagon = 8 feet
    - Width: 3 feet wide wagons and need to allow room for 2 to pass at a time with a buffer: Approx 8 feet

- Ideally the hall should be designed to accommodate traffic of robotics in separate directions simultaneously, to decrease time spent in transition and make it a smoother path

- They would prefer a hallway that accommodates this even if it requires twists and turns and is a longer path

- The robotics can increase in size during conditions to due mechanical failures and loss of ability to collapse so a buffer would be preferred

- Since this is going to be considered a top-notch facility for robotics competitions he believes it should have an adequate transition hallway

- The new robotics pits will allow for WPI to host larger robotics competitions since the pits will be located at a separate location, opening up more room on the competition floor

- The two largest competitions they host will grow from 34 to 52 to teams and 48 to 64 teams respectively

- A typical robot weighs 150 pounds and travels on a 4 wheeled wagon to-and from the competition floor (for maintenance in between rounds)

- Typical robotics pits fixes take 15 to 45 minutes, however when the competitors start to dwindle down, they may not even have time to visit the pits