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WPI Recreation Center:
Construction Management and Alternative Design Analysis

A Major Qualifying Project
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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Abstract

This project provided an alternative design for the structural supports of the fourth floor of the new WPI Recreation and Sports Center. Using the information developed, a comparative analysis of the alternative design versus the current design was completed based on cost, feasibility, and dynamic response. Also, with information provided by Gilbane Building Co. and Cannon Design, two 4-D models of the project were completed. These models provided a platform to track and compare construction progress. In addition to the models, an earned value analysis was completed to further track construction progress and costs.

Acknowledgements

We would like to thank all the parties involved in the development and construction of the new WPI Recreation Center. Without all of you, our project would not have been possible. We would also like to thank the WPI representatives to the project for giving us insight and information that we could not have obtained elsewhere. Special thanks go to:

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Representatives from WPI

Jeffrey Solomon

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Authorship Page

The work distribution for this project was evenly divided. Stephanie Munion was responsible for the project management sections of the report and the Earned Value Analysis, Chapter 2.1, portions of Chapter 3, and Chapters 5.2 and 5.4. Kristopher Fournier was responsible for the BIM modeling and analysis, Chapter 2.2, portions of Chapter 3, and Chapter 5.1. Joel Stella was responsible for the Structural Analysis, Chapter 2.3, Chapter 4, and Chapter 5.3. The other portions of the report were developed in a collaborative fashion by all members of the group.

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Capstone Design Statement

The capstone design requirement was met for this project by analyzing the current construction of the Recreation Center through the proposed schedule as well as the actual progress and by creating an alternative design to the support system for the fourth floor gymnasium. A 4-D model was created in order to compare and contrast the proposed construction schedule versus the actual construction progress and to perform a cost analysis. The alternative design explored the effects of an increased vibration frequency for both the current support system as well as an alternative support system for the 4^{th} floor gymnasium. The alternative system was incorporated into the design to replace the precast arches in the current design. Then, a cost analysis encompassing material expenses was presented to compare and contrast the two designs. In keeping with the requirements set forth by the ASCE, the following six realistic constraints were addressed during completion of this project: economic, manufacturability, ethical, health and safety, social, and sustainability.

The first constraint addressed was the economic impact that the project will have. Cost estimates were completed during each month of construction, and proposed and actual versions of the schedule were compared through the use of BIM. The prices of materials as well as any delays due to scheduling were examined and used to create an Earned Value Analysis for the project. In the alternative design, the material and labor and equipment costs for both the current and alternative support systems were compared to determine the more cost effective strategy.

The next constraint examined was the manufacturability of the project. The dynamic response of the current concrete arch system was determined for two different forcing frequencies. An alternative design was then created to try and find a more cost effective approach to supporting the 4^{th} floor gymnasium while still adhering to the dynamic response of the two forcing frequencies. Also, the ease of construction was important to account for. There are nine precast arches supporting the fourth floor gymnasium and to replace those with an alternative could be difficult. Fortunately, to replace the arches with a truss system using the same spacing and footings for the arches would be adequate and easily installed.

Ethical considerations needed to be addressed, and were during all portions of the project. When completing the alternative design, all established standards of practice for construction were considered based on those used by Cannon Design that were listed in the drawings.

The next constraint was the health and safety of the project. During any construction project**,** health and safety for the workers, pedestrians, and future inhabitants is always a primary concern. Occupational Safety and Health Administration (OSHA) standards, contractor safety, and building code provisions are a few of the methods used to ensure the safety of everyone involved in a project, from start to finish and occupancy. Gilbane Building Co., the construction firm, accounted for these health and safety standards on the site and in our design we followed the same Massachusetts building codes that were followed in the current design of the building.

The social impact of the project on campus life and the local environment was examined through attendance at the Owner's Meetings. These meetings discussed topics related to campus operation, including student safety and events that were displaced due to construction, as well as public relations opportunities, such as having Santa take pictures in the mock-up on the Quad. Some important impacts that needed to be considered were how the quad would be affected and public safety surrounding the site. Students spend much of their leisure time on the Quad and now that there is a building overlooking a large opening that was once there, students may have been displaced. Attendance at the Owner's Meetings provided insight into how the parties involved coordinate their efforts and resources to create a safe and functional environment for both the WPI and Worcester communities.

The final constraint analyzed was the sustainability of such an expensive and large-scale project on the WPI campus. Who endorses, pays for, and approves the altering of the campus had to be taken into account and also who would be taking care of this building's day to day operations. Finding out information through the Owner's Meetings about how the financiers and the trustees feel about the progress of the project and whether the project was worth the price that will have to be paid were all important realistic considerations. Attendance at the Owner's Meetings emphasized that WPI is aware of the lasting effects that the decisions made during the construction of this project will have on the community, especially those decisions that affect sustainability.

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1.0 Introduction

The world of construction management is constantly changing, with new technologies being created to help simplify and expand the flow of information to simplify the design and construction of large-scale projects. These technologies can be used to create and manipulate three-dimensional models and schedules quickly and efficiently to help keep with the increased pace of these projects. At the center of these advances is the notion that projects can become easier to manage as well as more informative to those looking in. The visual representation of a building being created through the use of 3-D modeling gives the parties involved a way of seeing the project without being on site. The combination of this model with the construction schedule enables advanced and simpler tracking of the progress of the project throughout the construction process. The integration of owners, architects, and engineers through new technologies facilitates the resolution of the many difficulties involved in a project from start to finish and ideally creates the best result for all parties.

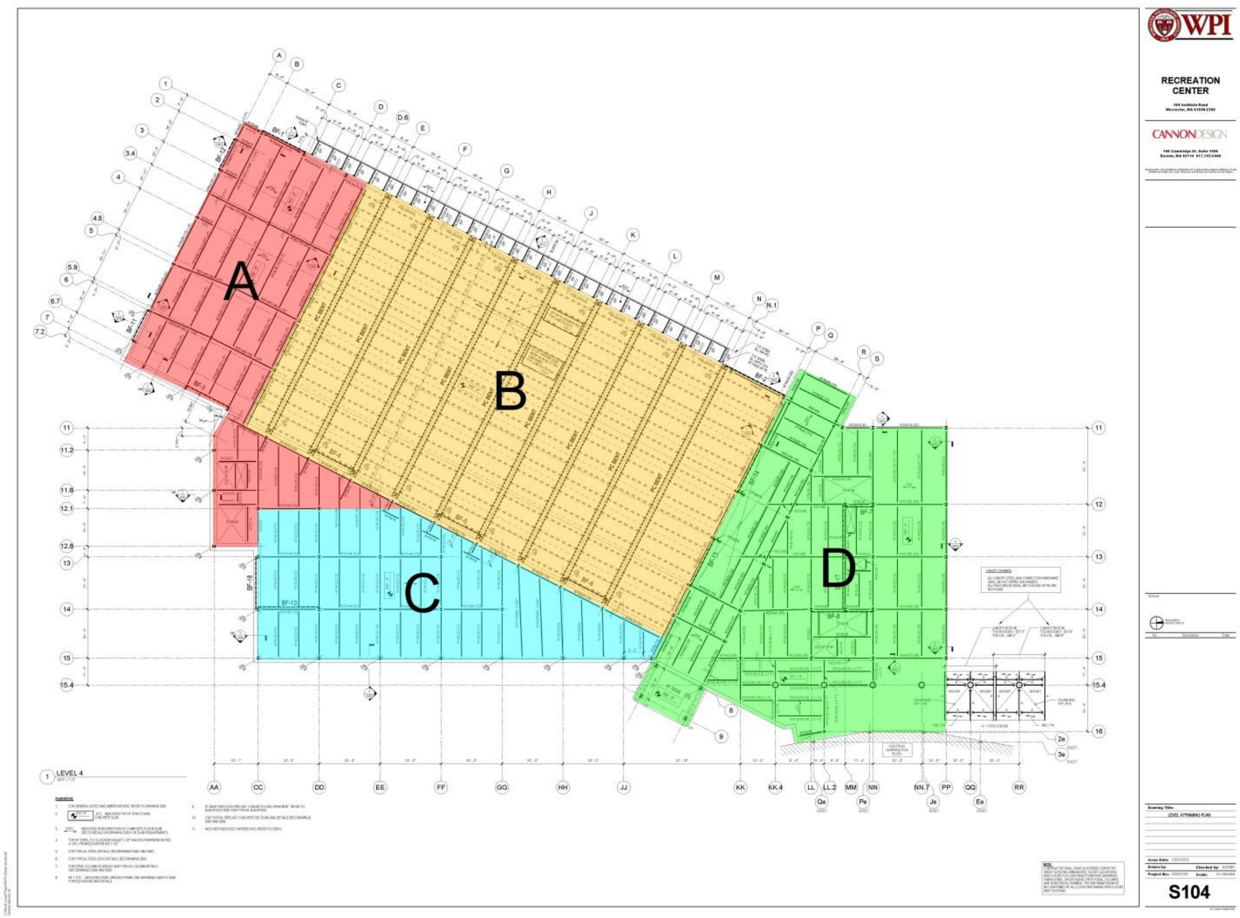
Of the many tasks faced by project managers during the construction of a building, cost analysis and updated scheduling are necessary to ensure the project's completion on time and within budget. Using tools such as earned value analysis, a project manager can monitor the development of the project, as well as identify weaknesses in the current situation. Armed with this the Project Manager can identify the best contractors to complete the work and provide the owner with up-to-date budget reports..

Worcester Polytechnic Institute (WPI) began construction on a new Recreation Center in May of 2010. The project, being managed by Gilbane Building Co., is scheduled for completion in August of 2012. This new Recreation Center will provide WPI with a competition length swimming pool, racquet ball and squash courts, 14,000 square feet of fitness space, a four-court gymnasium, indoor rowing tanks, and an extended three-lane track (WPI Sports and Recreation). The new Recreation Center is the focus of this project because it provides a real world laboratory to study the use of BIM, EVA, and scheduling coordination as the design changes.

Given a 3-D model of the completed construction, two different four-dimensional models were developed to contrast the projected and actual progress of the project. In addition to studying the construction schedule for the Recreation Center, an earned value analysis was performed to compare the value of the work completed in each projected phase versus the amount of work completed in the actual phases. An alternative design of the gymnasium, located on the structure's fourth floor, was created to explore the differences in frequency and provide a better understanding of structural dynamics.

The 4th floor of the new Recreation Center is supported by precast concrete arches spanning the width of the building. An alternative design explored increases in the vibration frequency accounted for in the current design to determine if the open space of the 4th floor could be used for more intensive activities, such as dancing or aerobics. A proposed design using a system of steel trusses in place of the concrete arches was explored. The benefits and cons of each design were weighed, including factors such as cost, ease of fabrication and scheduling differences, to provide WPI with information for any future projects they may pursue.

As with any project there is an order of operations to how aspects must be completed. On the following page there is a photo of the order of construction starting with Area A and concluding with Area D. This project is no different; there were three main pieces that needed to be completed. First the four-dimensional models needed to be developed and the transition from the 3-D to the 4-D models are examined. Second, the earned value analysis needed to be completed, this was dependent on values from the 4-D model, and was also incorporated into it. Then, the alternative design needed to be completed as it was an independent analysis done partly by hand and partly on a computer, and then compared with the values obtained from the 4-D model and costs associated with the EVA. These three tasks were completed and the processes were analyzed and studied based on the new Recreation Center being built at WPI.



2.0 Background

2.1 Project Management

Project management is the "the art and science of coordinating people, equipment, materials, money, and schedules to complete a specified project on time and within approved cost" (Oberlender, 2000). Since each construction project is different, involving a unique location, plan, budget, and/or scope, the owner of the project may find it challenging to remain both knowledgeable and insightful on the various aspects of the project. Project managers are enlisted to guide the owner through the design and building phases and provide expertise from their past experiences. Project managers work closely with people from many different areas, providing them with resources and contacts that may otherwise be unavailable to the owner. By involving the project manager from the beginning of the process, the owner is able to vary their level of involvement, while also receiving the benefits of the project manager's experience.

2.1.1 Contractual Agreements

Each construction project begins with identifying the purpose of the project, and then this purpose becomes the owner's scope. The owner must first determine exactly why they want the facility and what its proposed uses are, before they begin the project. Once the owned knows what they want out of their building, the owner would need to hire a designer. The first stage of the design process is called the schematic design, which provides information about the building elevations, layouts of floors, room arrangements, and other overall features of the project (Oberlender, 2000). The owner would then be able to conduct schedule and cost estimations and determine if they want to move forward with the project as currently proposed. If so, a team of designers would be assembled and a more in depth design would be developed.

Design development includes all the uses defined by the owner, including the systems within the project, and it enables the designer to produce contract documents. The design process has slight variations depending on the parties involved; however, if the owner is using a project manager as their representative, they will want to hire them prior to confirming their maximum budget and desired schedule. By doing this, the owner expects the project manager to completely understand the project and offer their experience in the initial phases, and offer their experience to the design team. The relationships among all the parties involved are specifically defined in a contractual agreement.

The three main contractual agreements for construction projects are design/bid/build (D/B/B), design/build (D/B), and construction manager (CM) contracts. Contractual agreements often integrate portions of a variety of these contracts in order to fit the individual needs of the project. As long as the responsibilities of each party involved are well defined, this practice is beneficial to the project because it provides the owner with more flexibility.

D/B/B contracts are considered the traditional delivery system and are used for buildings with a well-defined scope (Oberlender, 2000). D/B/B contracts involve three parties: the owner, the designer, and the builder. In D/B/B contracts, the owner has one contract with the designer and another with the general contractors, as seen in Figure 1 below.

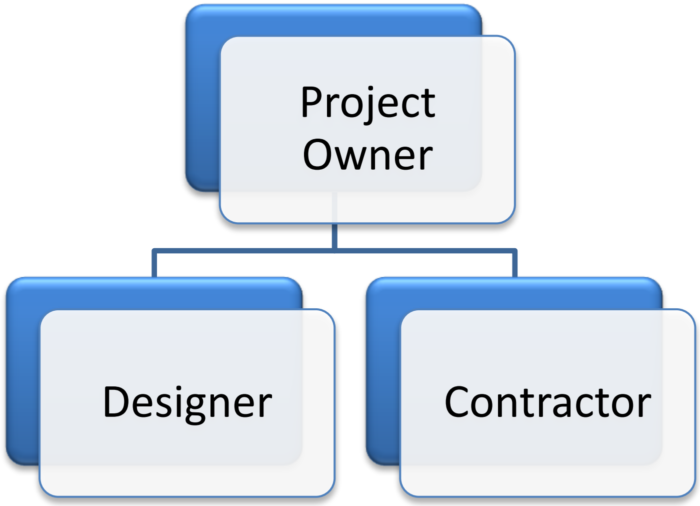


Figure 1: Design/Bid/Build Arrangement

D/B/B contracts involve three steps: completion of design, solicitation of bids, and finally, awarding the work contracts, thus beginning construction. Each of these steps is completed before the next begins, which provides structure to the project, but also extends the scheduled completion time, which can be an issue for a project that needs to be completed rapidly. Owners who choose D/B/B contracts have the ability to fully understand the project's configuration, the effect the construction will have on its surroundings and the estimated cost of the project because the design is completed before construction begins. This often results in a reduction in unexpected costs during construction and fabrication. With D/B/B contracts, cost is primary and the schedule is secondary. Because the schedule is secondary, D/B/B projects can take longer from start to completion if the design work is being reviewed and altered multiple times or if the bidding of the project takes longer than expected. The owner has a relatively high involvement during design and can have lower involvement during construction.

With D/B contracts, the owner has the ability to fast-track the project. Fast tracking is beneficial for projects with time constraints because in a fast-tracked project, construction begins before the design is finished and all of the bids are procured. D/B contracts involve two parties: the owner and a design/build firm. The organization can be seen in Figure 2 below (Oberlender, 2000).

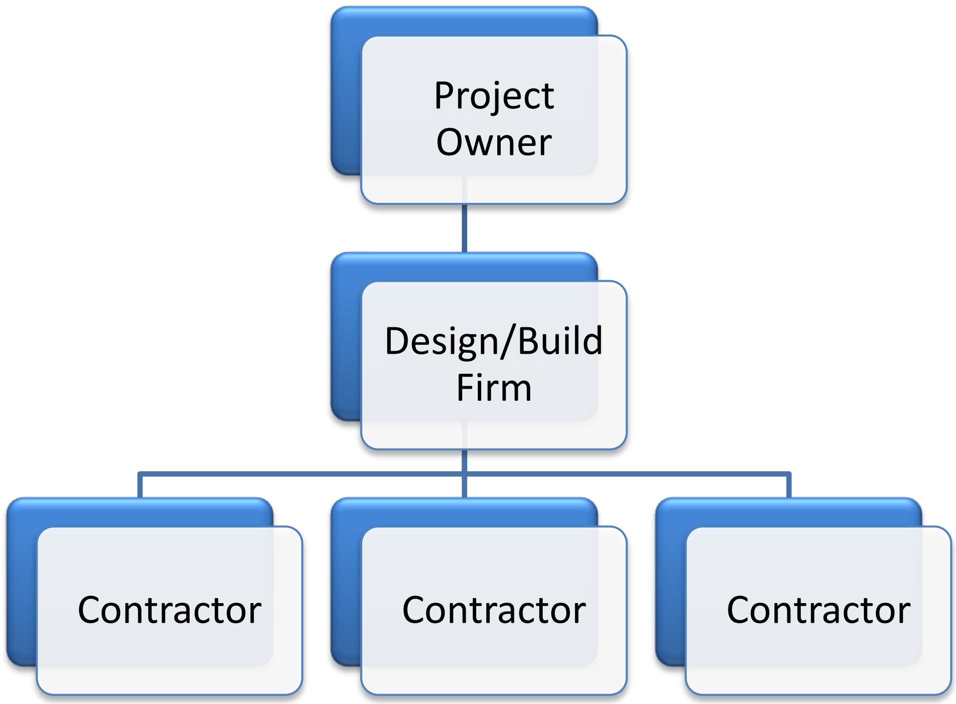


Figure 2: Design/Build Contractual Arrangement

The owner is highly involved in D/B contracts including everything from design alternative decisions, to monitoring cost and schedules. Projects that involve D/B contracts generally have less subcontracting because the design is completed in-house with the design/build firm. With D/B contracts the owner generally only has one contract with the design/build firm and thus assumes less risk because the design/build firm is responsible for all the contractors that are hired.

With CM contracts, the owner has control over their level of involvement during all phases of the project because they have the ability to give responsibilities to the CM

(Oberlender, 2000). CM contracts involve contractual agreements between four parties: the owner, the CM, the designer, and the subcontractors. There are a number of variations in the CM contract, each of which results in varying contractual relationships among the parties involved. However, the premise for all CM contracts is that the owner contracts a knowledgeable CM firm to coordinate all aspects of the project and complete the project according to the owner's specifications. All CM contracts should involve the CM early in the project to ensure integration among all the parties involved. Figure 3 below shows one possible relationship for CM, "CM at risk".

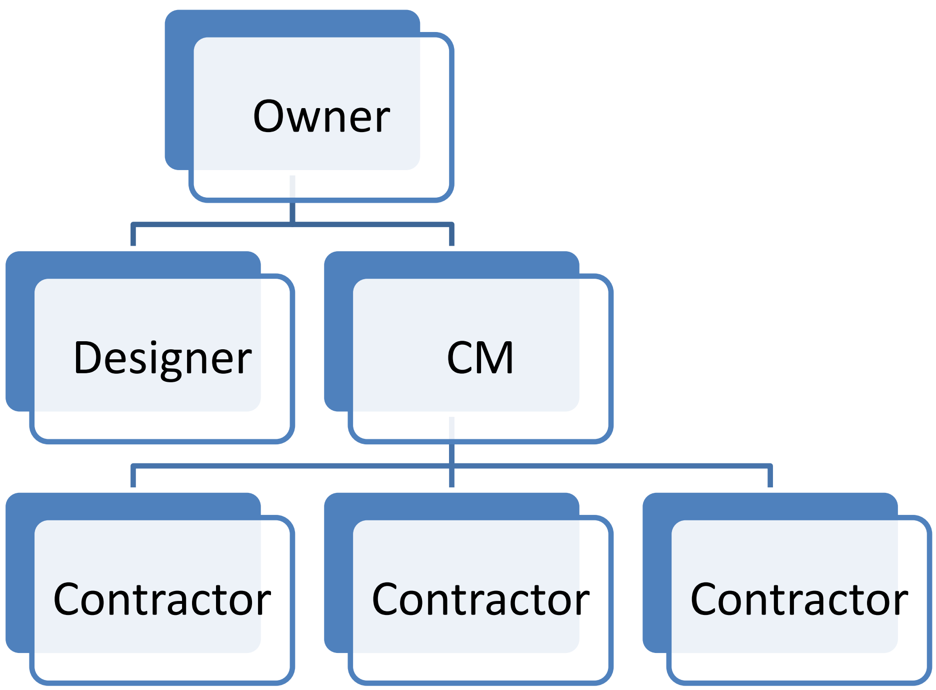


Figure 3: Construction Manager Contractual Arrangement

Typically for "CM at Risk" contracts, the CM firm would self-perform any design or construction work their firm can support, and then subcontract the rest of the work, depending on the capabilities of the CM firm. In Figure 3 above, the Owner hired the CM and designer separately, and therefore the owner would assume the risk associated with the design, and the CM would assume the risk associated with the contractors or subcontractors.

2.1.2 Project Financing

The project financing is another essential component of project management. This includes setting the budget, which dictates the outcome of the entire project, and arranging the appropriate terms of payment, which ensures all parties involved understand how payment will be processed. These critical factors require open communication and are essential to the success of the project.

When the project begins, the owner must identify the maximum amount they are willing to spend, or are capable of spending. The early stages of estimating are not very accurate because the materials that will be used and the complexities of the design are unknown, but early estimates are still important because it adds limits for the project team to follow (Oberlender, 2000). By comparing these initial estimates with the final cost, the project team can determine how successful they were and identify areas of improvement that can be applied to future projects. Once the owner has identified their budget, the other parties involved must base their budgets on it. For some parties, this might mean variations in material selection, while for others, it might require a reduction in profits. For both cases, the party must consider the risk associated with these changes (Oberlender, 2000).

Another critical factor affecting the financing of a project is the terms of payment. The terms of payment are defined in the contractual agreements and critically affect the risk that each party assumes in the project. Some options for the terms of payment include a lump-sum arrangement; this is when the owner pays a fixed price for the work (Oberlender, 2000). Since this fixed price does not vary with changes in the actual cost of the materials or labor, the CM would assume the contingency risks that exceed their projected estimates. Another option is a unit-price arrangement, where the contractors charges per unit of work rather than for the entire project.

Unit-price arrangements are ideal for projects with excessive excavation or other areas of work with significant uncertainty. This arrangement protects the CM from possibly exceeding the construction contingencies and protects the owner from inflated bids that would have covered these high risk cases. The final option is a cost-plus contract, which requires the owner to pay the cost of materials and labor plus an additional fee (Oberlender, 2000). Cost-plus contracts may also use a Guaranteed Maximum Price (GMP). GMP contracts ensure that the CM will be reimbursed for all monies spent within the GMP budget, but also reduces risk to the owner by obligating the CM to stay within a guaranteed maximum price. If the CM exceeds the GMP, they are responsible for the additional cost, and in turn, their profits will decrease accordingly.

2.1.3 Project Schedule

The project schedule is created by; first determining the method of construction, then determining the sequential order of the work to be completed, then identifying appropriate durations, and finally determining the start and finish dates for the project (Oberlender, 2000). Ensuring that all the activities that need to be completed are identified is the most important predecessor to the project schedule. The owner is responsible for identifying the start and completion dates for the project. Once they are established, the designer and contractor are contracted to work in accordance with these dates.

Using the activities and schedules defined, the project manager can create a visual representation of the schedule. This can be in the form of a Gantt Chart or a Critical Path Method (CPM) network diagram. Gantt charts are bar charts that show each activity as a separate bar plotted against the total duration of the project. A Gantt chart is useful when looking at the schedule day to day because it shows what activities are happening daily. In Figure 4 below, an example of a Gantt chart, the activities that dictate the duration, or critical activities, are identified using a red block, and the lag time for the activity is indicted by the blue arrow.

Activity ID	Original Duration	EST	EFT	LST	LFT	TF
A	2	0	2	0	2	0
B	3	2	5	12	15	10
C	8	2	10	3	11	1
D	6	2	8	2	8	0
E	8	5	13	15	23	10
F	9	10	19	11	20	1
G	12	8	20	8	20	0
H	5	8	13	13	18	5
I	3	13	16	18	21	5
J	2	13	15	23	25	10
K	5	20	25	20	25	0
L	1	20	21	22	23	2
M	2	20	22	21	23	1
N	2	15	17	27	29	12
O	2	21	23	23	25	2
P	4	22	26	23	27	1
Q	2	17	19	29	31	12
R	7	25	32	25	32	0
S	2	26	28	27	29	1
T	1	19	20	31	32	12
U	3	28	31	29	32	1
V	5	32	37	32	37	0

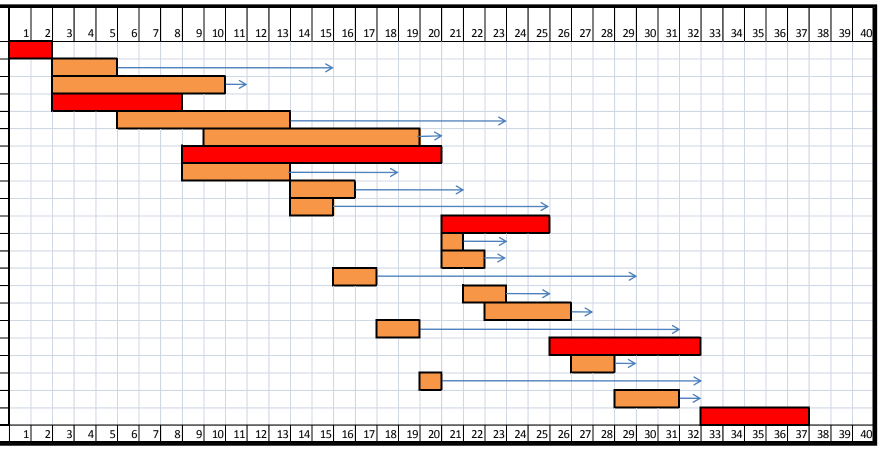


Figure 4: Example of a Gantt chart

Another way to visually represent the project schedule is with a CPM network. The CPM method shows the interrelationships between activities in the project (Oberlender, 2000). Although this method requires more coordination, it provides more details and can help the CM identify conflicts. An example of a CPM diagram for the same project as the Gantt chart above can be seen below in Figure 5 below.

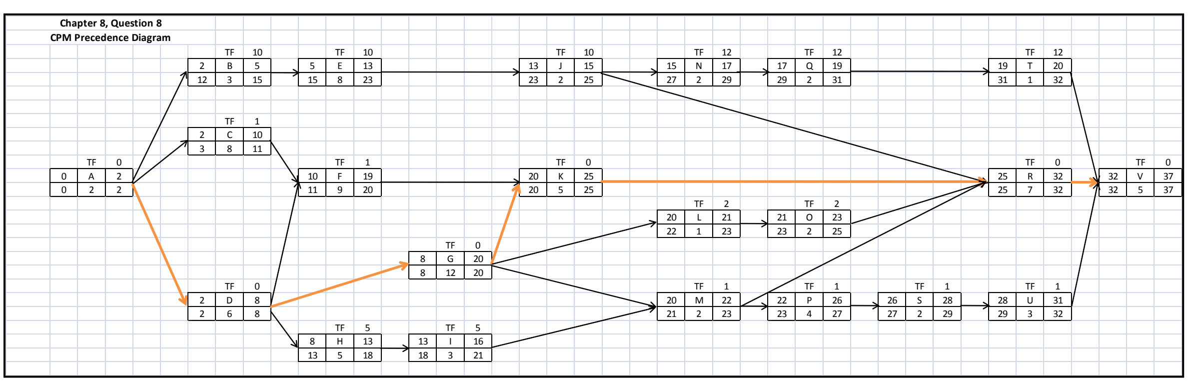


Figure 5: Example of a Critical Path Method

During the planning and construction of a project, the schedule is a key element used in project management. These visual representations of the schedule can be used in coordination meetings and can be understood by the owner. Most importantly, however, these charts visually translate the timeline of the project, which is essential to a timely completion.

2.1.4 Earned Value Analysis

Earned value analyses are used to monitor the progress of work completed as compared to the planned work (Oberlender, 2000). The budgeted cost of work scheduled (BCWS) is the amount of money that was budgeted at each time period. The BCWS can be found by adding the individual costs for each of the activities within a certain phase of the CPM diagram. The curve generated by accumulating the sum of cost within each phase over the duration of the project is known as the Lazy S curve. The actual amount of money spent during each phase is the actual cost of work performed (ACWP). The ACWP is found by referencing the records of the project and totaling the cost of work and materials actually used. The amount of money earned based on the work that has been completed is the budgeted cost of work performed (BCWP). The BCWP is calculated by multiplying the percentage of work completed by the total budgeted cost of the activity. As seen in the equations below from Oberlender (2000), the cost and schedule variances and performance indexes can be calculated using BCWS, ACWP, and BCWP.

$$Cost\ Variance\ (CV) = BCWP - ACWP$$

$$Schedule\ Variance\ (SV) = BCWP - BCWS$$

$$Cost\ Performance\ Index\ (CPI) = \frac{BCWP}{ACWP}$$

$$Schedule\ Performance\ Index\ (SPI) = \frac{BCWP}{BCWS}$$

The cost variance shows whether the work paid for was equivalent to the work actually completed. Therefore, if more money was paid in a period than was budgeted to be completed for that period, there would be a cost overrun. This overrun is signified by a negative value for the cost variance and a cost performance index that is less than one. The schedule variance is similar to the cost variance in that it subtracts the planned cost of work scheduled from the earned cost of work performed. Therefore, if the budgeted work hours are less than the earned work hours, then the project is ahead of schedule, whereas, the reverse would mean the project is behind schedule (Oberlender, 2000).

The cost performance index (CPI) and schedule performance index (SPI) show the magnitude of cost and schedule overrun or under run, respectively. Zero or positive variances and an index of 1.0 is a favorable performance because this indicates that the project is on, or is ahead of schedule and performance. By plotting the CPI and SPI on a graph as seen in Figure 6 below, the project manager can measure how well the planned cost compares to the actual costs incurred and work completed.

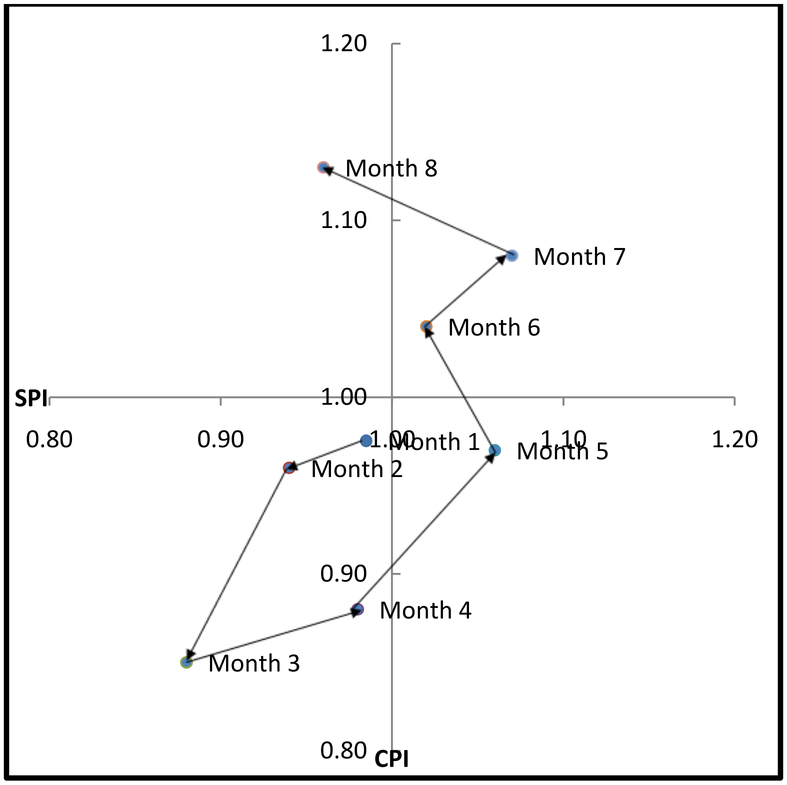


Figure 6: Sample CPI and SPI Graph

When reviewing this graph, the project manager is able to identify that in Month 3 the earned value for schedule and cost were less than the actual cost and schedule. This indicates poor performance and signifies that changes needed to be made. By Month 7, the CPI and SPI were both greater than one. This meant that the schedule performance is progressing better than was planned and more work was completed than was budgeted for. This type of analysis is best used by the project manager because it enables them to monitor the effectiveness of changes they make to the operations of the project. Additionally, it allows the project manager to identify areas for improvement during the course of the project rather than after completion, which can ultimately reduce the risk of incurring liquidated damages or late delivery. Since earned value analyses require detailed information such as quantities, cost per unit or phase, and detailed schedule tracking, the owner most likely would not be completing this analysis.

2.1.5 WPI Recreation Center

The management of the construction of the new WPI Recreation Center displays many project management techniques. The project involves a CM @ Risk contractual agreement, a cost plus compensation with a GMP, and extensive use of scheduling aids. The project also utilizes weekly owner's meetings that serve to update the owner and discuss progress and potential changes of scope as well as a number of other planning meetings, such as coordination meetings. Like every construction project, there are a number of components in this project that involve details that are specific to this project; and it is because of this that project management is essential to any project's success.

The new WPI Recreation Center involves a CM Agent contract with Cardinal Construction and a CM @ Risk contract with Gilbane Building Co. (Gilbane). Cardinal Construction works as the owner's representative on this project, which means they are responsible for ensuring WPI's voice is always represented. Since Cardinal has worked closely with WPI's campus and community on a number of other projects they are able to provide insight from their past experiences. Gilbane was brought into the project in the pre-construction phases as the CM @ Risk. For this project, Gilbane is not self-performing any of the work and is providing the owner, WPI, with a GMP contract, and therefore was assuming financial risk in the project. Additionally, Cannon Design is the designer for the project and is contracted directly to WPI, although they work closely with Gilbane and Cardinal Construction to ensure the success of the project. In Figure 7 below, there is a hierarchy of the contractual agreements between the parties involved in the new WPI Recreation Center.

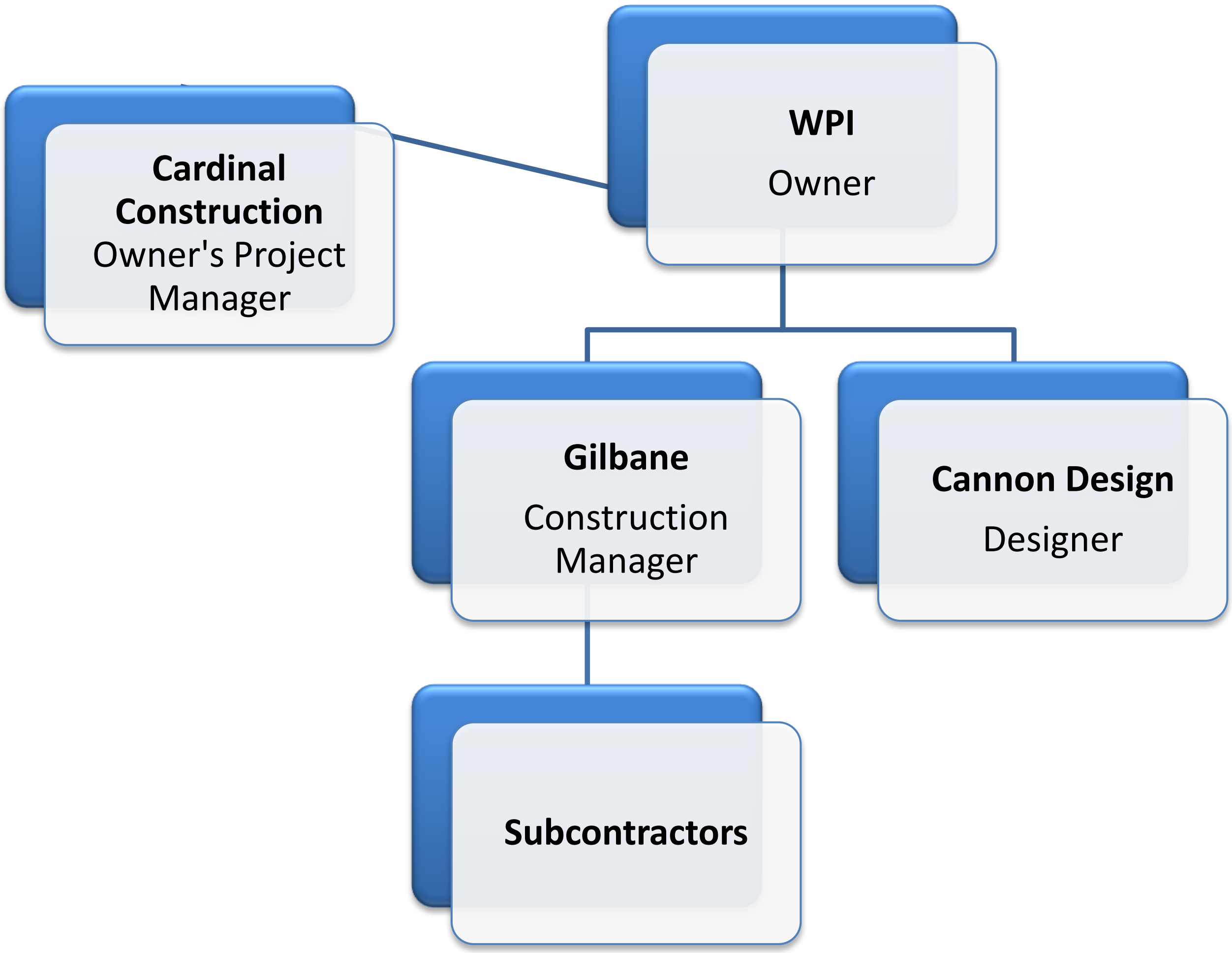


Figure 7: Work Breakdown Structure of WPI Recreation Center

For the new WPI Recreation Center, the early stages of the project were very important. Upon identifying the need for the facility and preparing an early cost estimate, the Board of Trustees delayed the project because of financial uncertainty. After reviewing WPI's spending and the changes in the economy, WPI decided to continue planning in 2006. In May 2010, several years after the need was identified, WPI broke ground on the facility. After working with Cannon Design as the designer, Gilbane as the CM @ Risk, and Cardinal Construction, as the CM Agent, WPI has contracted the project for a cost-plus with GMP compensation. After careful consideration WPI decided to postpone the submittal of the GMP until after all bidding was completed. The finalization of certain specialty items within the facility delayed the bidding and thus the GMP was not officially submitted until late 2010. However, by waiting until after the bidding process Gilbane was able to provide a GMP that contained fewer contingencies because there were fewer unknown costs, which is ultimately a benefit to the owner. As of early 2011, construction is underway and project management techniques continue to be utilized. One essential technique that was used from the beginning of the project is weekly meetings with all those involved in the project.

Owner's Meetings

In many construction projects, after contractual agreements are defined, the project begins and typically, this involves Owner's Meetings, Design Kick-Off Meetings, Coordination Meetings, and a number of other planning meetings. All of these meetings have the common goal of communicating to all parties involved, the evolution of the project from scope to final product. In the case of the new WPI Recreation Center, Owner's Meetings began early on, first with the designer and then with the designer and CM, and continued at weekly intervals throughout the project.

Owner's Meetings are held to ensure the project is remaining true to the scope and within budget, to keep the owner notified of and involved in changes and delays, to anticipate potential changes, to make decisions regarding subcontracts and selection of material, and to address any other topics that the involved parties feel are necessary. WPI, as the owner, has chosen to remain highly involved, and during the Owner's Meetings they are able to approve change orders and consult with Gilbane about the effects of the project on the site and the surrounding area. Representatives from WPI, Gilbane, Cardinal Construction, and Cannon Design attend Owner's Meetings, and a detailed breakdown of the typical participants to these meetings and their titles can be found in Appendix B. Some of those who attend the meetings regularly include Neil Benner, senior project manager from Gilbane, Brent Arthaud, Cardinal Construction, Jeff Solomon, Chief Financial Officer of WPI, Dana Harman, Director of Physical Education, Recreation, and Athletics of WPI, and Alfredo DiMauro, Assistant Vice President for Facilities of WPI. Other parties attend less frequently depending on the topics being discussed. For example, Sean O'Connor from WPI Network Operations attended a meeting that discussed installing a web camera in the pool Area A during construction.

Neil Benner prepares the agenda for the Owner's Meeting, using Prolog Manager Software (Prolog), and chairs the meetings with an agenda generated from Prolog. A sample of these agendas can be seen in Appendix B. Mr. Benner directs the discussion along each of the topics, and Melissa Hinton, Project Engineer, takes notes on updates and changes, and reflects these changes in future agendas. These meetings are run as discussions based on jointly identified issues that need to be addressed. At the meetings, various groups offer their expertise or opinions on topics in which they are knowledgeable and act according to their contractual roles and responsibilities. Some past topics include excess soil usage, decisions on the indoor rowing tank, procurement, and redesigns for areas such as the robot pits. This is just a sample of the many topics discussed in these meetings. Representatives from WPI are able to report conflicts resulting from construction, such as fencing needed for soccer balls and field hockey balls, emergency blue lights, and additional lighting on redirected access routes. WPI's decision to remain highly involved ensures that the project is true to their specific needs and that all parties involved are on schedule and within budget.

Gilbane also utilizes Primavera software to organize the schedule of the project. The Primavera software generates both the Gantt Chart and the CPM diagram using the information input into the system. These schedules have been updated regularly after coordination meetings and there were at least four versions produced as of October 2010. Figures 8 and 9 below show a screenshot of activities input into Primavera software and the Gantt chart and CPM Diagram the software generates using this information.

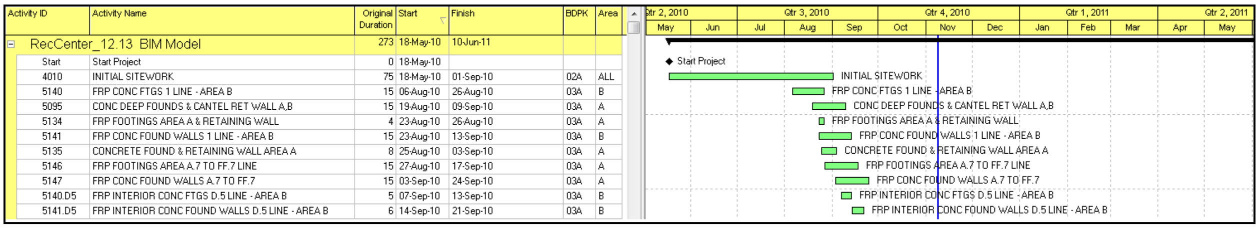


Figure 8: Activities and Gantt Chart from Primavera Software

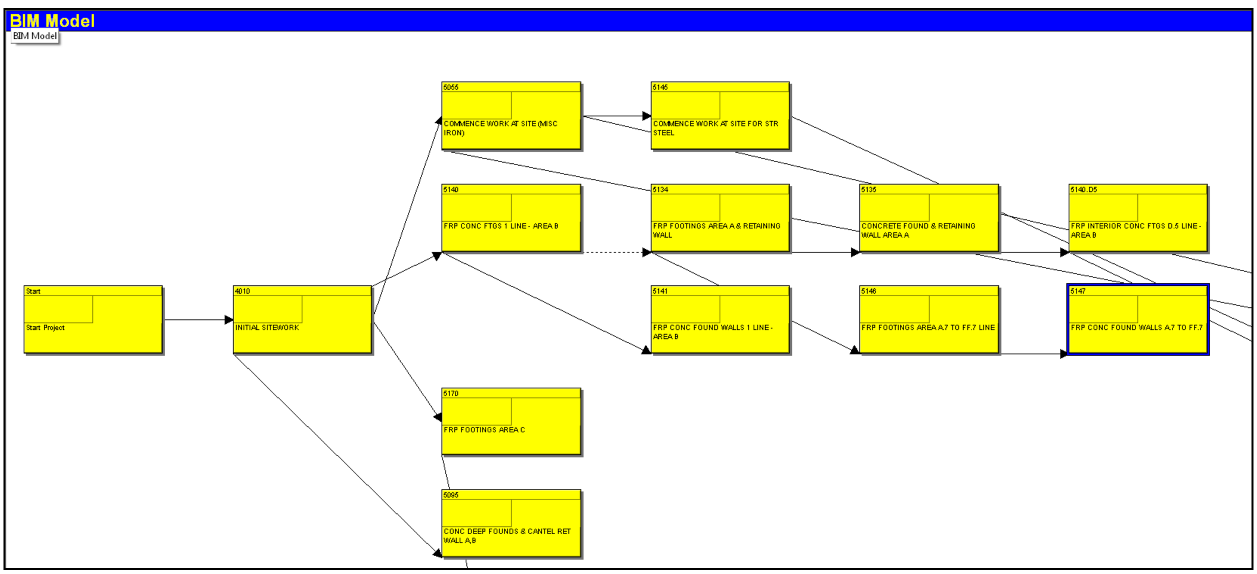


Figure 9: CPM Diagram from Primavera Software

Primavera software enables project managers to alter the schedule and generate new Gantt charts and CPM Diagrams in minutes. Additional information such as cost per activities and any other user-defined category may also be added to each activity, which can be used to generate the Earned Value Analysis and the Lazy S Curve.

2.2 Building Information Modeling

Building information modeling, or BIM, as it is commonly referred to by project managers, architects, and other professionals who use it, is a process of creating and managing building data during the construction process (Lee, 2006). BIM is a framework in which a designer combines a three-dimensional model of a construction project with other information to provide more than just the visual representation of the physical building. The designer as well as the construction manager can then add in other dimensions to create a multidimensional model that not only encompasses the physical building itself, but a variety of other important factors in the project life cycle. Examples of higher dimension models are: a four-dimensional model that incorporates time into the project, or a five-dimensional model incorporating time and economic considerations. These models can help to avoid construction issues involving scheduling, cost, or construction problems that may occur.

The common mistake people make with understanding what BIM is truly about, is that BIM is more of an idea or a theory rather than a program in itself. BIM is the combination of various programs to create one multidimensional model, rather than opening up software titled "BIM", and creating the entire model in one place. As it stands now, the three-dimensional image of the building must be constructed in one software and then combined with other dimensions and information from other sources.

2.2.1 History

According to the article "Are we forgetting design?", Professor Charles M. Eastman of Georgia Tech is credited with the term BIM; however, this is a disputed claim as Phil Bernstein was the first person to actually use the term (Laiserin, 2002). Despite this dispute, Eastman is considered to be the accepted origin because of early referencing to a building product model in the 1970s (Eastman, 1999). The first use of BIM was in the virtual building concept by Graphisoft in 1987 using a program called ArchiCAD (Laiserin, 2003) Graphisoft is not the only company that has software that can be used for BIM, as the program Revit is offered by Autodesk.

In August of 2004 the U.S. National Institute of Standards and Technology published a report called "Cost Analysis of Inadequate Interoperability in U.S. Capital Facilities Industry". This report said that over ten billion dollars a year were lost by capital facilities in the United States because of a lack of standardization (Gallaher, 2004). If there is no standard to govern the way information within the model regarding materials, design, cost, schedule, etc. is communicated to everyone who is a part of the construction process, information can be left out and decisions can be made without all the necessary background. Making decisions without all the necessary information can be a costly mistake. With this statistic being widely publicized more and with the increased efficiency afforded by BIM, more companies are moving towards incorporating a BIM model into their construction process.

2.2.2 Modeling

There are different types of BIM models that can be developed from three-dimensional to greater multidimensional models. A three-dimensional model is simply a visual representation of the building. However, this model includes an exact construction list of all the materials used. This facility provides an easy way to quantify the materials that are used to construct the building, and may also provide a detailed list of the items inside. Example queries would be cubic yards of concrete, or how many beams of a certain size are used in the building. A four-dimensional model (4-D) would be a combination of the three-dimensional model plus either time, determined by the schedule, which is the typical choice for the 4-D, or the cost . A five-dimensional model would be a combination of both the schedule and cost added to the three-dimensional model.

The four-dimensional (4-D) model with respect to time is a useful tool in project management. This allows the project manager to visually associate the 3-D digital representation of the building with its actual construction progress. This model provides a visual representation that can be used as a tool to show whether the project is on schedule, ahead of schedule, or behind schedule easily based on the progress of the construction site. This information allows the project manager to better communicate what is to be expected in order for construction to progress on time. The model allows for better management of resources because it combines them into a simpler form.

2.3 Structural Design

In addition to using 4-D modeling in tracking and updating the construction of the Recreation Center, the support system for the 4th floor gymnasium was examined to explore vibration loads and create an alternative design. The alternative design aimed to replace the pre-cast concrete arches with a system of steel trusses. The two designs were analyzed for the current frequency on the structure and also with an increase in the excitation force consistent with a sporting event to that of a dance, thus increasing the vibration load. The current design was used to first determine the appropriate steps in modeling and analyzing a support system for static and dynamic response, and then how to apply this design in creating an alternative support system.

2.3.1 Current Design

The 4th floor of the WPI Recreation Center has over 29,000 square feet of open space dedicated to four basketball courts, but this space can also be used for other functions. Events, specifically Commencement, are currently held in Harrington Auditorium during inclement weather, despite the limited capacity that Harrington possesses. The open-style gymnasium provides a better solution to Commencement relocation and would allow for other large-scale events, such as dances or fundraisers. When exploring a current design, the effects of vibration on the floor system were examined and an alternative design was proposed. The new design aimed to replace the current support system of the structure while also accounting for an increase in loads and vibration without altering the architectural design of the building.

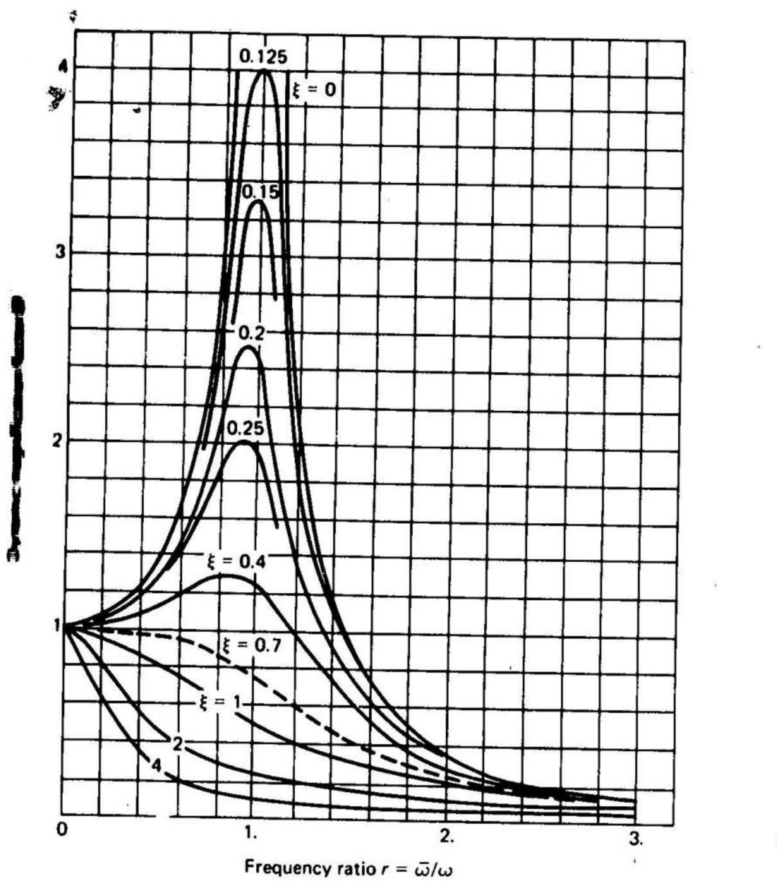
The current design of the Recreation Center accounts for a large standing capacity within the 4th floor gymnasium while using a design vibration frequency of 6 hertz, according to the structural notes given by Cannon. An increase in this vibration frequency from the 6 hertz design to 9 hertz, a value associated with rhythmic dancing, was explored for the two different support systems (Murray, Allen, & Ungar, 1997). The characteristic vibration frequency of an activity such as rhythmic dancing or aerobics is 50% larger than the frequency of walking (Murray, Allen, & Ungar, 1997). By designing for the occupancy of the building as opposed to the dynamic characteristics of the loading and the structure, the risk of inadequate resistance to resonance arises. Therefore, the dynamic characteristics of the use for the 29,000 square foot gymnasium are equally as important as the maximum allowable static capacity. When assessing the effects on the building due to higher vibrations, factors such as resonance and damping, as well as dynamic magnification factors were addressed.

2.3.2 Effects of Vibration on Buildings

The vibrations in buildings caused by the added live load and excitation of internal sources such as running or dancing, or external forces such as earthquakes or strong winds, can cause resonance with the structure (Rainer, 1984). When resonance is reached, the amplitude of motion becomes very large. Rhythmic activities are known to cause resonance and can be a serious problem on floor systems (Murray, Allen, & Ungar, 1997). Resonance in a building can affect both the strength of the structure, as well as the serviceability.

When exploring the vibration of a floor system, dynamic analysis was used to determine the dynamic magnification factor (DMF) for the response of the structure. During cyclical forces, such as walking or dancing activities, the continued excitation on the structure causes vibration. If the motion of the structure reaches a steady-state, a dynamic magnification factor may be applied to the system in order to calculate the peak response (Science Advisory Desk, 2008). DMF involves an inverse of the activity frequency ratio to the structure's natural frequency and the damping coefficient. The formula for the dynamic magnification factor is,

D $=1/\sqrt[2]{(1-r^2)^2+(2r\zeta)^2}$ where r is the ratio of the activity frequency to the structural frequency and ζ is the damping ratio. Figure 10 below shows the DMF as a function of frequency ratio and various damping ratio's (Paz, 1985). If resonance in the structure occurs, there will be a very large dynamic magnification factor because resonance is when the structural frequency equals the activity frequency, making the DMF inversely proportional to the damping ratio (Science Advisory Desk, 2008). Damping is defined as the resistance to motion caused by vibrations in a building due to the materials used in the structure (Breyer, 2007). If the stiffness of the structure cannot be altered to lessen the effects of vibration in the building, the materials used will need to be strengthened. Using thicker supports or a heavier material can help to create damping in the building (McCormac, 2008).



Dynamic magnification factor as a function of the frequency ratio for amounts of damping.

Figure 10- DMF vs. Frequency Ratio (Paz, 1985)

Damping in a structure is typically considered to be a force relative to the magnitude of velocity and opposite in direction to the motion (Paz, 1985). The damping ratio is the proportion of the damping coefficient to the critical damping (Paz, 1985). Structures can be over damped, under damped, or critically damped. A structure is considered over damped when the damping ratio zeta, ζ, is greater than one, under damped when zeta is less than one, and critically damped when zeta is equal to one (Weisstein, 2010). Damping in the structure is important in minimizing the effects of resonance and examining DMF. The damping ratio is different depending on the use of the structure. For example, offices, residences and churches use a Damping ratio of between 0.02 and 0.05 (Murray, Allen, & Ungar, 1997).

2.3.3 Alternative Design

The current design of the Recreation Center has precast concrete arches supporting the 4th floor gymnasium. These supports are used exclusively for the vertical floor loads and are not part of the lateral load resisting system. Separate structural frames are used to resist wind and earthquake loads. If redesigning the arches or removing them was necessary, the lateral resistance system would have been examined to ensure the new support did not add too much weight to the building, affecting the seismic forces on the structure.

When redesigning the supports for the fourth floor, the focus of the design was on the vibrations of the building, rather than the standing room capacity. The new design would be compared with the current design for resistance to the increased vibration frequency as well as for potential additional costs incurred by switching from precast concrete to structural steel.

3.0 Building Information Modeling and Project Management

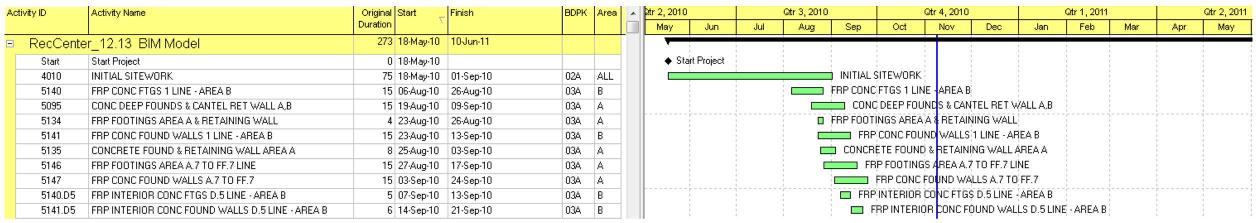
BIM is a technology-based collaborative approach to construction and project management that includes 3-D communication of information. To develop a four-dimensional (4-D) model of a construction project, the first thing that needed to be created was a working schedule of the activities. After completing the planned schedule, the Revit model of the complete construction was broken into monthly phases. Then, using Revit, the quantities of the materials used were extracted for each phase and an earned value analysis (EVA) was completed. After construction began, the actual progress was tracked with the project schedule and the process was repeated.

3.1 Project Schedule

The project schedule is used to show the sequence of activities and when each activity is expected to happen. The project schedule is essential to both the EVA and BIM models because it dictates the expectations of the project and it can be used to track the work as it is completed. By using Primavera Software (Primavera) to complete the EVA, the project manager is able to use one central file to assess the project. Additionally, Primavera can produce Lazy S curves and other graphs to track the progress of the schedule. When creating the BIM model, the Primavera file provides a complete schedule of all the activities completed along with the expected dates of completion.

Planned Schedule

The first step in tracking the project was identifying the planned schedule for each month. Using schedules from Gilbane Building Company (Gilbane), starting with the one developed in June 2010 and ending with the one developed in August 2010, a Primavera file was developed. The created schedule included only the activities within the Concrete and Steel bid packages, Divisions 3 and 5 respectively, because the bulk of those divisions were completed during the 2010-2011 school year. Figure 11 below is a sample of the information entered for each activity.



Activity ID	Activity Name	Original Duration	Start	Finish	BDPK	Area
RecCenter_12.13 BIM Model		273	18-May-10	10-Jun-11		
Start	Start Project	0	18-May-10			
4010	INITIAL SITEWORK	75	18-May-10	01-Sep-10	02A	ALL
5140	FRP CONC FTGS 1 LINE - AREA B	15	06-Aug-10	26-Aug-10	03A	B
5095	CONC DEEP FOUNDS & CANTEL RET WALL A,B	15	19-Aug-10	09-Sep-10	03A	A
5134	FRP FOOTINGS AREA A & RETAINING WALL	4	23-Aug-10	26-Aug-10	03A	A
5141	FRP CONC FOUND WALLS 1 LINE - AREA B	15	23-Aug-10	13-Sep-10	03A	B
5135	CONCRETE FOUND & RETAINING WALL AREA A	8	25-Aug-10	03-Sep-10	03A	A
5146	FRP FOOTINGS AREA A.7 TO FF.7 LINE	15	27-Aug-10	17-Sep-10	03A	A
5147	FRP CONC FOUND WALLS A.7 TO FF.7	15	03-Sep-10	24-Sep-10	03A	A
5140.D5	FRP INTERIOR CONC FTGS D.5 LINE - AREA B	5	07-Sep-10	13-Sep-10	03A	B
5141.D5	FRP INTERIOR CONC FOUND WALLS D.5 LINE - AREA B	6	14-Sep-10	21-Sep-10	03A	B

Figure 11: Screen shot from Primavera Software

As seen in the above figure, the Activity ID, Activity Name, Original Duration, Planned Start Date, Planned End Date, Bid Package (BDPK), and Area were input into the software after being extracted from the schedules provided by Gilbane. Using the End Date, the schedule was broken into eight phases that began and ended on the 15th of each month, starting on August 15, 2010 and ending on April 15, 2011. In order to make progress monitoring easier, these dates were further modified. Depending on the Planned End Date, each activity's planned end date was changed to end on the 15th of the month of the phase in which it was completed. For example, an activity that ended on March 3 was changed to end on March 15, and an event that was planned to end on March 16 was edited to end on April 15. By doing this, the schedule could be compared directly to the phases which provided consistency in the results. A spreadsheet containing the activity list from Primavera can be found in Appendix C. This spreadsheet has all the information input into the Primavera software and shows the successors to each activity.

Actual Schedule

The next step involved evaluating the progress of actual work completed. Using the photos of the site, updates from the Owner's Meetings, and personal communication s with the

Project Engineers from Gilbane, the project was monitored. After identifying which activities were completed within each phase, the Primavera file was updated to include information about Actual Start and End Date. For consistency with the defined phases, activities that ended on or before the 15^{th} of the month were assigned an Actual Start date of the 16^{th} of the previous month and an Actual End Date of the 15^{th} of that month.

3.2 4-D Models

A four-dimensional (4-D) model of a construction project, where the fourth dimension is time, is based on the phases of construction. The first 4-D model of the project was created based on the planned schedule of activities defined in Primavera. The flow chart below, Figure 12, outlines the process of constructing a phase in Revit and adding an element to it, and there are more detailed instructions in Appendix G.

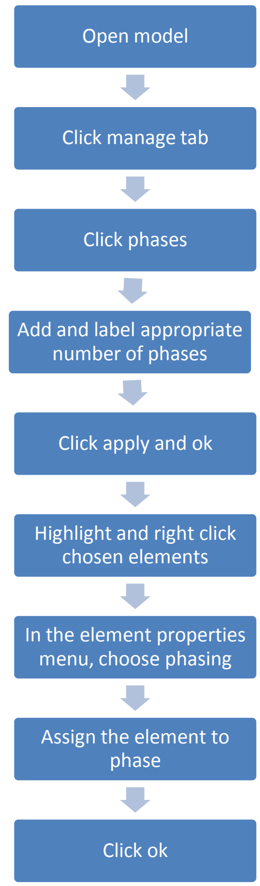


Figure 12: Revit Software Phasing Flow Chart

First, the entire Revit model was opened and then the phases were set up through the management function. With the phase menu opened, eight additional phases before the phase called "New Construction", which is the complete project, were created. After each phase was added to the Revit file, the next step was including the individual elements into said phases. This was completed by opening the plans of each of the floors. Then, by clicking on each of the elements a menu opened and the element properties menu on the left hand side of the Revit screen appeared. At the bottom of this menu there was a drop down box that allowed for the placement of the element into any one of the phases that had been created. This properties box can be seen in Figure 13 below.

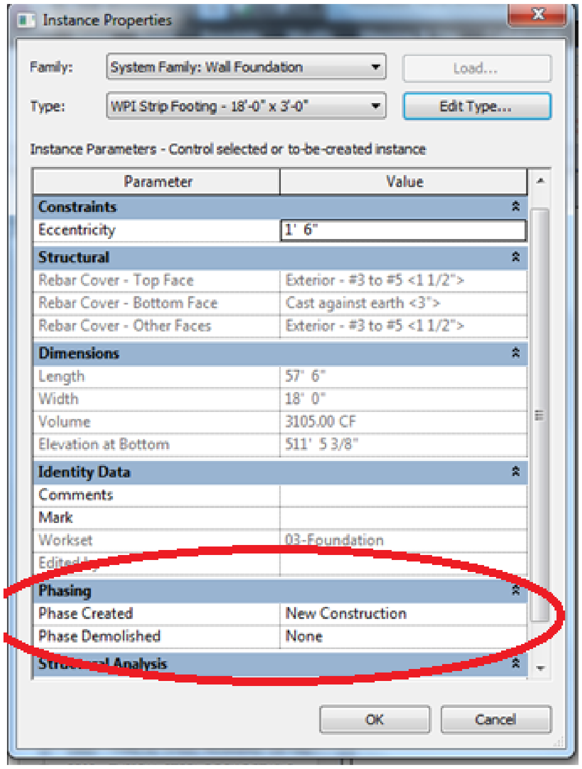


Figure 13: Instance Properties

The next step of creating the 4-D models was to export images of the phases. This was done first by clicking the view tab and clicking 3-D view. A new 3-D view was created and then, only after renaming it, could another 3-D view be made. The properties needed to be changed by right clicking the view and changing them in the drop down menu. The 3-D images were extracted from Revit by pressing the print screen button, pasting the image into Microsoft Paint, and cropping the image to encompass only the phase. The image was then saved as a jpeg, which can easily be input into PowerPoint to provide a visual comparison of the phases.

3.3 Earned Value Analysis

Earned value analyses (EVA) are used to track the progress of work on a project (Oberlender, 2000). Earned-value systems use ratios to predict cost overruns and schedule delays, thus enabling the project managers to adjust their budgets and work productivity accordingly. This is done by completing EVAs on a monthly basis. These EVAs involved three aspects of the project: the project schedule, the work completed, and the cost of the concrete and steel packages for the project. The aspect that makes this EVA different than any other is its integration with BIM technology. By using Primavera software in conjunction with Microsoft Excel (Excel), each task is assigned a quantity and cost. The model created in Revit was used to derive the quantities of the project, which saved additional calculation time.

3.4 Quantities

Using the Revit file of the project obtained from Cannon Design, the quantities of concrete and steel were extracted. This was done by creating "schedule" takeoffs of the different components of construction per each phase. The process to create a schedule takeoff is listed in Figure 14 below and Appendix G has a more detailed walkthrough.

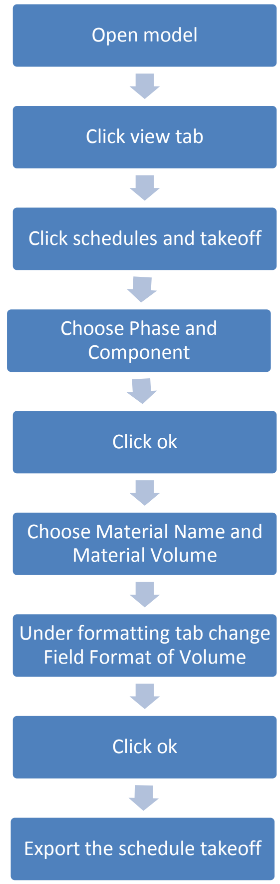


Figure 14: Revit Quantity Take Off Procedure

The exported components were: Floor, Structural Framing, Structural Foundations, Walls, and Structural Columns. The Floors included the concrete on deck as well as the concrete mats. The Structural Framing included steel and concrete, specifically girders and lateral bracing for steel and the precast concrete structures. The Structural Foundations included all the structural foundations for the work completed the corresponding phase. Walls included foundation walls and any other walls containing concrete. The Structural Columns were composed of all steel columns and any concrete columns that were also in the phases. The information extracted from each phase was not a tabulation of how much of each component was included in each phase; it was the accumulated result of all of the concrete or steel in phases up to the current phase. The information was then copied and pasted intoExcel and the totals for each phase as well as the total for the entire construction project were calculated.

After quantities were extracted from the Revit file, the next step was to equate them with monetary values. This was done by determining the average cost per cubic yard of five different categories of concrete work and the average cost per ton of steel for a typical three to six-story office building. These unit costs were derived from RSMeans 2007, so additional inflation was also included. Full Excel calculations can be found in Appendix E. Tables 1 and 2 below show which numbers were used to calculate the cost of each of the different types of concrete work and the steel in the project.

Table 1: Unit Cost Concrete

Concrete Work	Material Cost	Total Cost
Structural Columns	Concrete, 6,000 psi, $147.17 Columns, 24", $33.57	$201.62 $ 45.99
Structural Foundations	Concrete, 6,000 psi, $147.17 Footings, 5CY, $20.66 Walls, 12", $16.90	$ 201.62 $ 28.30 $ 23.15
Walls	Concrete, 6,000 psi, $147.17 Walls, 15", $25.81	$ 201.62 $ 35.36
Structural Framing	Concrete, 6,000 psi, $147.17 Columns, 24", $33.57 Elevated beams, small, $51.51	$ 201.62 $ 45.99 $ 70.57
Floor	Concrete, 6,000 psi, $147.17 Elevated Slabs, 6" - 10", $19.36	$ 201.62 $ 26.52
Total	$ 937.23	$ 1,284.01

Table 2: Unit Cost Steel

Steel (per ton)	Material	Labor	Equipment	Total
Offices, 3-6 stories	$ 2,877.00	$ 500.05	$172.62	$ 3,549.67

Using the total quantities for the project obtained from Revit, the total cost of concrete was determined to be roughly $1.5 million for materials. Typical industry standards called for percent increases of 7% for equipment, 15% for labor costs, 10% for waste, and 5% for construction contingencies, all factors that would have been included in the contractor's bid, the total comes to approximately $2.1 million. The concrete package was bid at $4.2 million, which is double the calculated value. This difference was in part due to the fact that slabs were not selected in the model. The steel total was estimated to be $3.5 million. This is slightly higher than the $3.2 million bid and can be attributed to the inflation rate and assumed material, labor, and equipment costs. Using the method of equal distribution among each activity in the phase, the costs were entered into the Primavera file. Appendix C contains the Primavera files in Excel form and shows the breakdown of the cost that was assigned to each activity.

Using the unit costs of concrete and steel the EVA was completed. Since the budgeted cost of work scheduled (BCWS), or projected costs, and the budgeted cost of work performed (BCWP), or actual costs, were calculated for the schedule variance (SV) and schedule performance index (SPI). This was completed for both the concrete and the steel and Tables 3 and 4 below show these values.

Table 3: Concrete Earned Value Analysis: Scheduled Variance and Schedule Performance Index

Concrete	SV		SPI
	CY	$	CY
Phase 1	-708.64	$ 44,704	0.68
Phase 2	752.91	$ 353,058	1.83
Phase 3	-310.38	$ (15,905)	0.76
Phase 4	-40.98	$ (15,705)	0.95
Phase 5	-509.07	$ (3,865)	0.30
Phase 6	-696.55	$ (109,412)	0.38
Total Thus Far	-1512.71	$ 252,874	0.79

Table 4: Steel Earned Value Analysis: Scheduled Variance and Schedule Performance Index

Steel	Scheduled Variance		SPI
	Ton	$	Ton
Phase 1	0.00	$ -	0
Phase 2	0.00	$ -	0
Phase 3	8.76	$ 31,095	1.11
Phase 4	-13.20	$ (46,856)	0.00
Phase 5	-14.62	$ (51,896)	0.80
Phase 6	-350.16	$ 1,242,935)	0.00
Total Thus Far	-369.22	$ 1,310,591)	0.28

These tables detail the cubic yards, tons, and/or dollars that the project is ahead of or behind schedule. For SV, a negative number means the bid package was behind schedule for that phase. For SPI, a number greater than one means the project was ahead of schedule and a number less than one represents that the project was behind schedule. As you can see in Phase 4 of the steel package, Table 4, the SPI is zero because there was no work completed.

3.5 Monitoring Project Performance

Through creating the PowerPoint presentation with the corresponding phases from the two different 4-D models side by side, the viewer can easily see distinguish the differences. This was due to the fact that the bulk of the construction that was completed within the phase durations was highly visible and on a large scale. This was a simple and effective way to communicate the progress and performance; however, there are discrepancies. When there are construction complications that slow a certain component of construction, other activities may have increased production to cover the differences and keep the overall project on schedule for its completion date. This was completed by taking the total amount of the materials in the phase, and dividing it by the total amount of material for the construction project to establish a percentage complete.

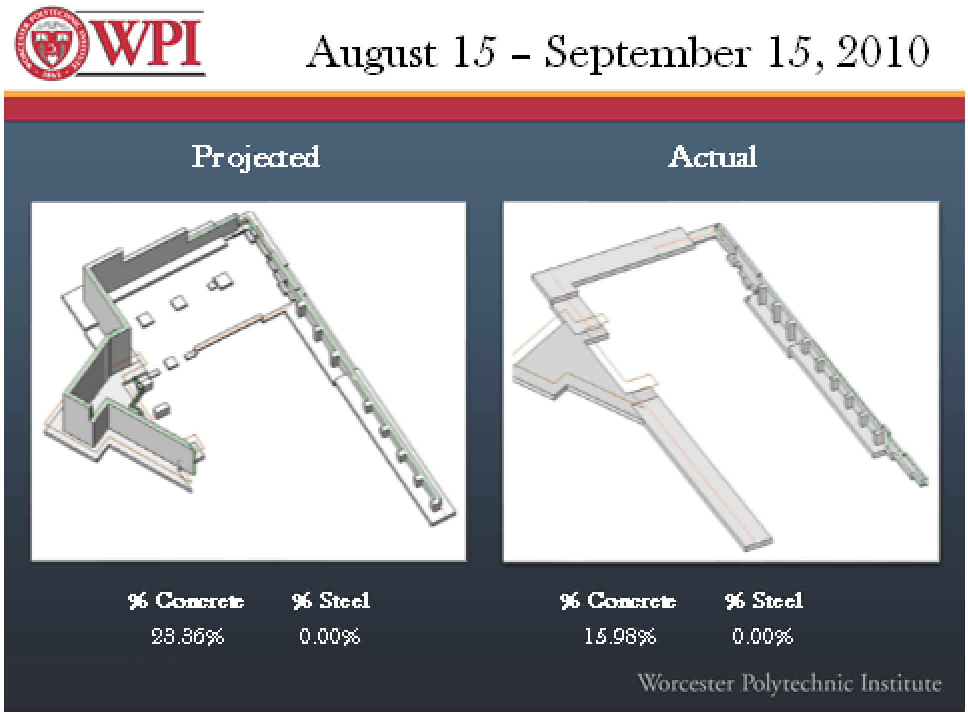


Figure 15: Phase 1 Comparison

The first set of phases ranged from August 15, 2010 until September 15, 2010 and can be seen in Figure 15 above. The footings are completed in area A and part of area B for both the projected and the actual, but the actual is far behind in completion of the foundation walls on top of those footings. The planned schedule is visually much farther along than the actual phases. Notable differences are the completed foundation walls in area A, along with the footings. The percentages show about an eight percent difference between the amount of concrete completed for each phase. This difference is potentially due to the change of concrete vendors in the early stages of construction.

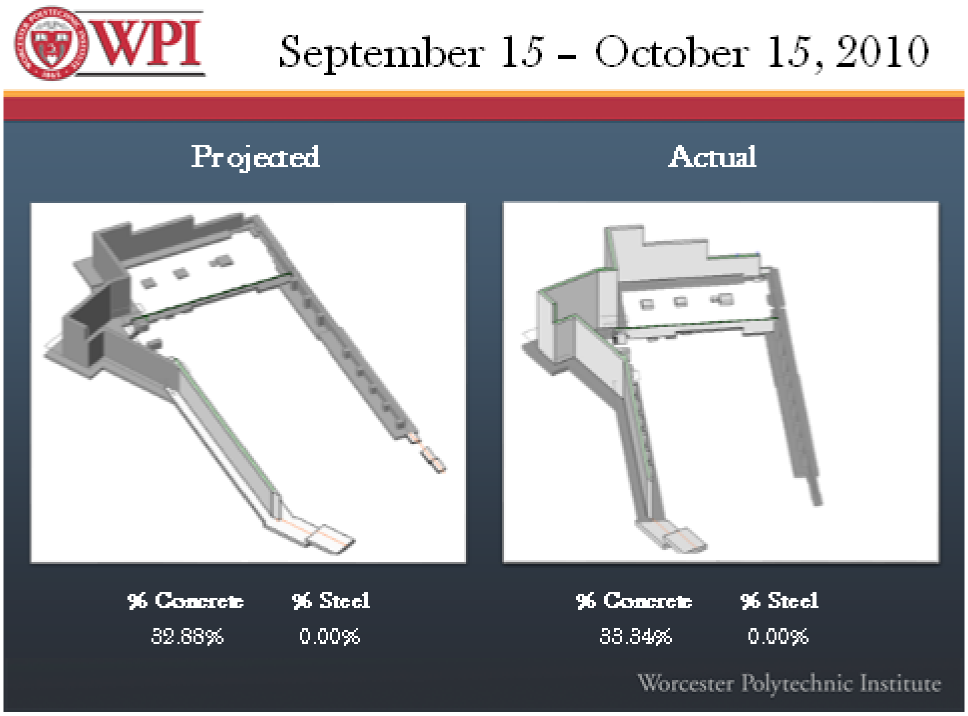


Figure 16: Phase 2 Comparison

The second set of phases ranged from September 15, 2010 until October 15, 2010 and can be seen in Figure 16 above. The footings and foundation walls are caught up with one another in the actual compared to the projected, along with the interior footings of area A for the steel to begin in area A. Also all of the footings for the precast arches have been completed so that assembly of those can begin. The percentages are within one percent of one another which means the project completed more work than was scheduled for this phase.

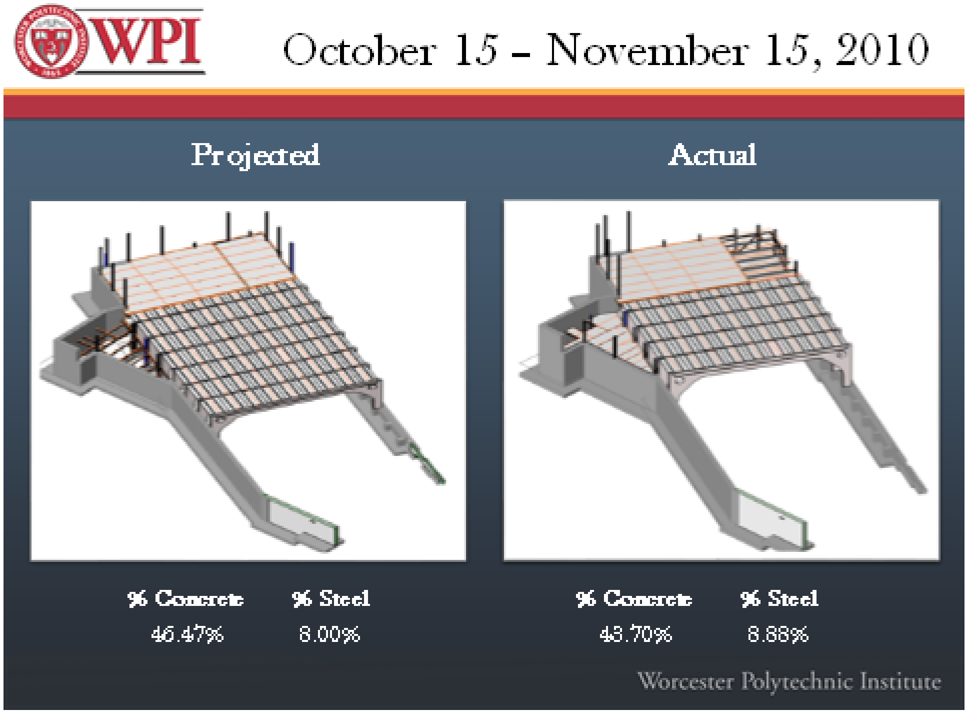


Figure 17: Phase 3 Comparison

The third set of phases ranged from October 15, 2010 until November 15, 2010 and can be seen in Figure 17 above. The most obvious completions were the construction of part of the precast arch support system. On the model there is a direct visual difference, but in reality the projected had to be estimated because the duration spanned more than one phase, so one can assume that the phases are similar to one another in completion for precast. The steel has obviously been constructed in area A, along with the decking for the floor slabs. The steel is slightly behind in the actual, and this is due to issues with the company that was contracted out for the steel. The percentages show that the concrete is about three percent off, and this is because of the further planned progress of precast arches assembly, and the steel is within one percent.

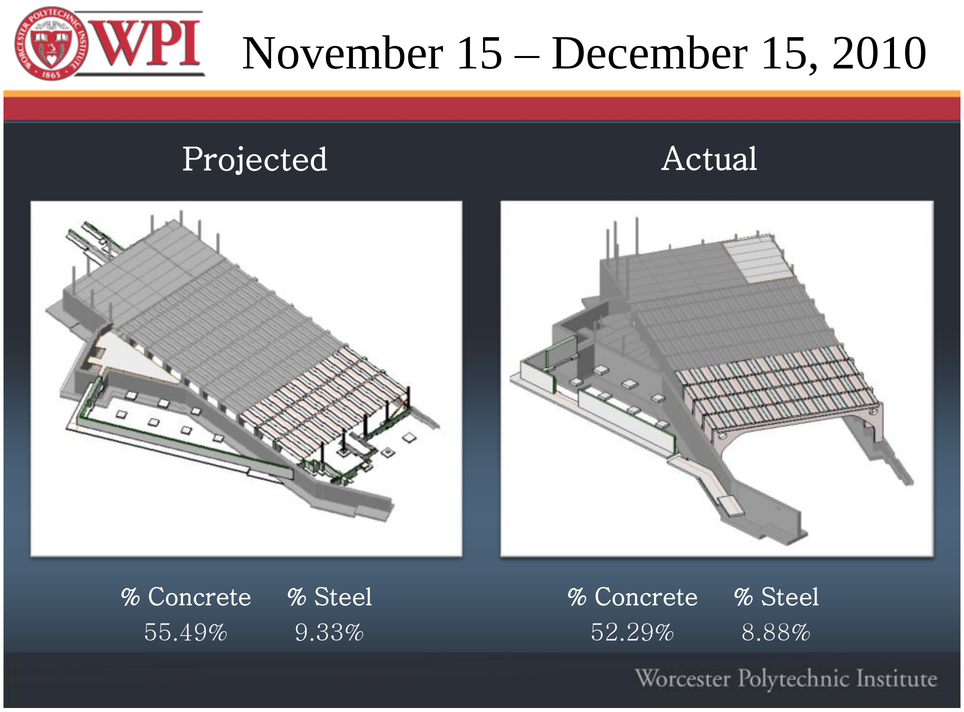


Figure 18: Phase 4 Comparison

The fourth set of phases ranged from November 15, 2010 until December 15, 2010 and can be seen in Figure 18 above. This phase has minor differences also. The precast is completed, along with the structural-T supports between the arches. However, the projected has the footings and steel system to support the connecting structural-T's between area B and D. Section C has been started, the interior footings have been placed, and the strip footings on the outer wall for the foundation walls have been started. The biggest difference is that in the actual phase there was a wall section left out so that workers could get inside and do work on the internal section of C. Also the walls aren't as far as the projected suggests on the C footings, but the C footings progressed further than was expected. The percentage of concrete is about three percent off, which was the same as the previous phase, so construction is flowing consistently. Also, the steel is within half a percent, and this is only due to the columns and footings in areaD that are supporting the structural-T's .

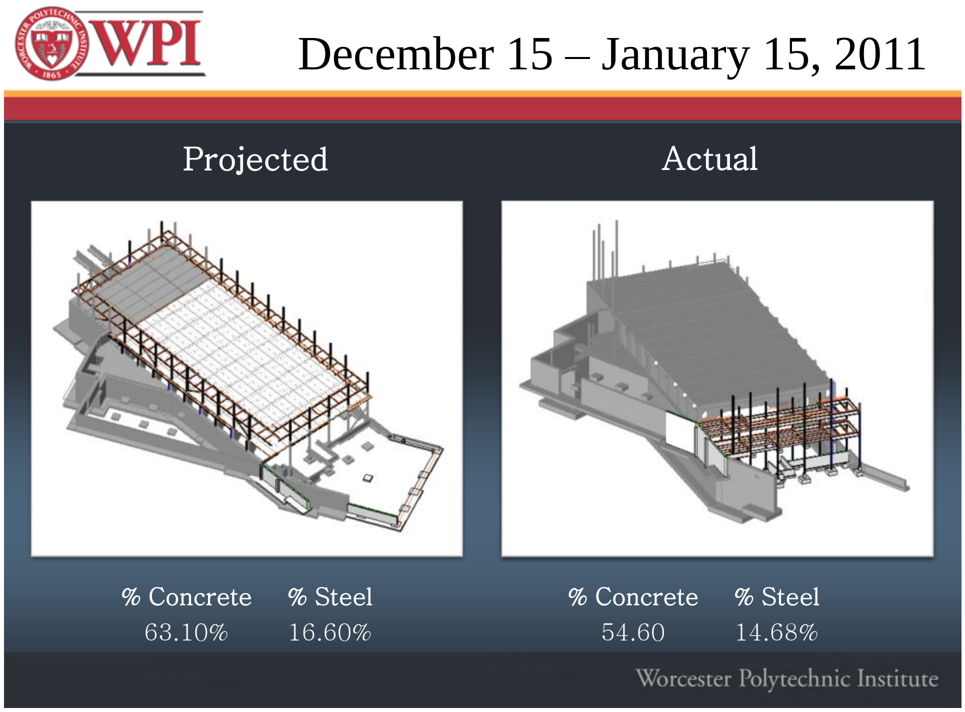


Figure 19: Phase 5 Comparison

The fifth phase's duration ran from December 15, 2010 until January 15, 2011and can be seen in Figure 19 above. Due to inclement weather the concrete decking on top of area B was unable to be placed, which in turn made it impossible to have the steel erected upon area A and area B. However, the actual construction compensated by erecting some of the Area D steel and footings which helped offset some of the difference in the schedule. The percentage of concrete is almost a ten percent difference, but this is because the footings at the end of D have been completed and the concrete decking has been placed. The steel percentage is relatively the same, only a difference of two percent.

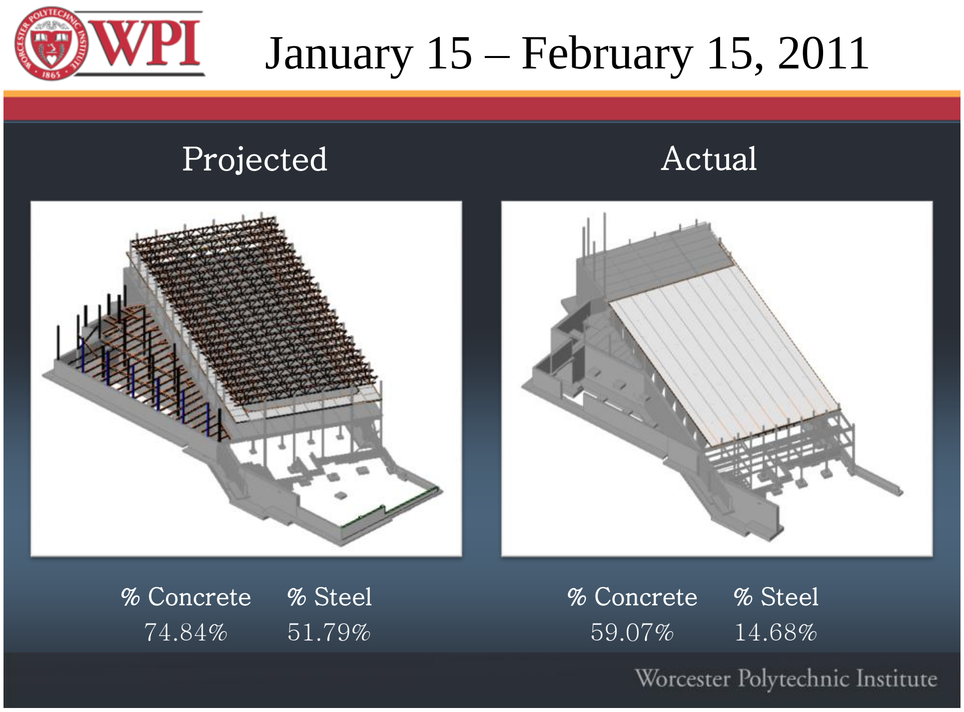


Figure 20: Phase 6 Comparison

The sixth phase began on January 15, 2011 and completed on February 15, 2011 and can be seen in Figure 20 above. Unfortunately for the progress of the project, there was a large amount of inclement weather in this time frame. This caused the concrete decking to not be able to be placed until the very end of the phase. Obviously, there is a noticeable difference in the amount of steel that was completed in the projected phase, which has made the percentage different. The concrete however seems to be catching up as the percentages are within six percent of one another, compared to the ten percent difference in the previous phase.

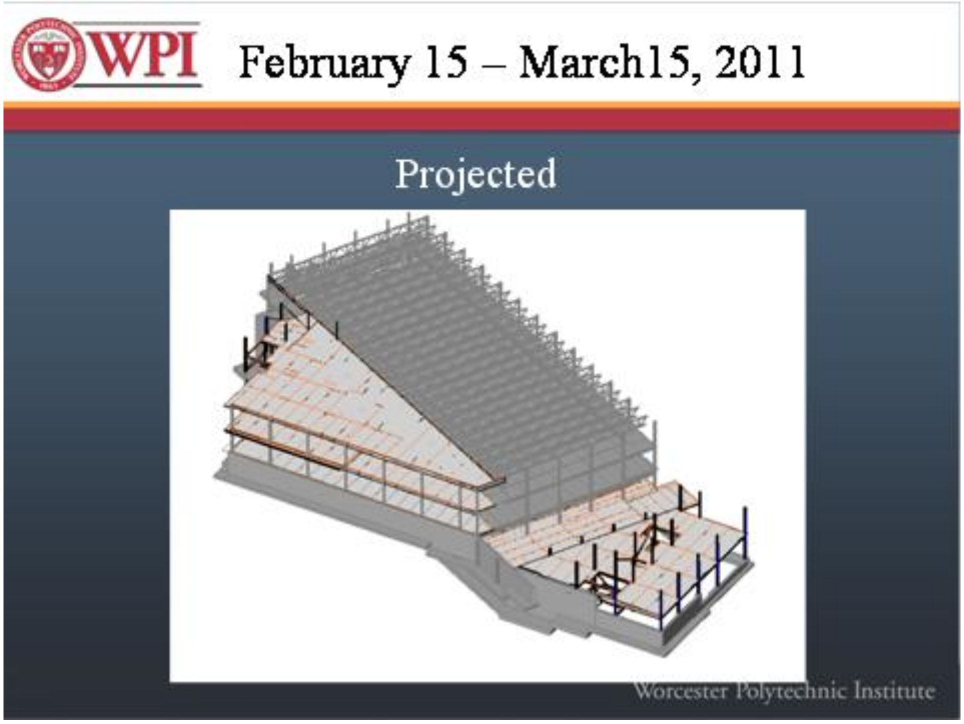


Figure 21: Projected Phase 7

The seventh phase of construction started on February 15, 2011 and ended on March 15, 2011 and can be seen in Figure 21 above. The projected phase is shown without the actual phase because the actual construction won't be completed until after this report has been submitted. In this phase the second floor steel was competed for Area D, and the steel and decking up to the roof is completed in Area C.

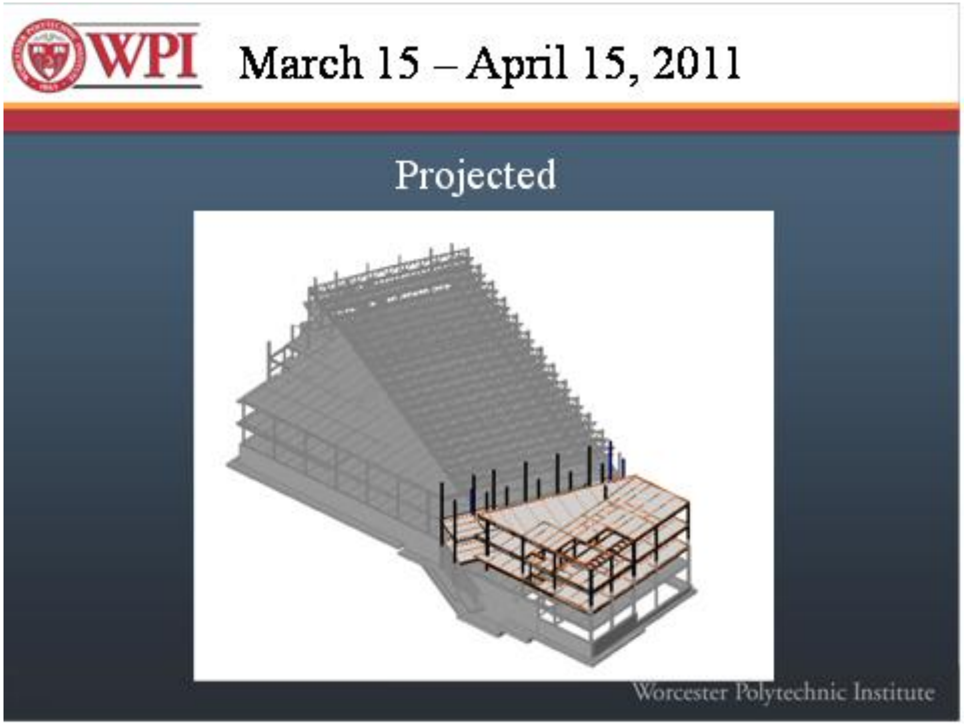


Figure 22: Projected Phase 8

The eighth phase was from March 15, 2011 until April 15, 2011 and can be seen in Figure 22 above. As with the previous phase, the figure above only shows the projected progress of the construction. In this phase the steel in Area D has been competed up to the roof, including the concrete decking on each floor.

Table 5 below shows whether the project was ahead of schedule, on schedule, or behind schedule for each bid package in each phase.

Table 5: Progress Assessment by Phase and Bid Package

Phase #	Concrete	Steel
Phase 1	Behind	No Progress
Phase 2	Ahead	No Progress
Phase 3	Behind	Ahead
Phase 4	Behind	Behind
Phase 5	Behind	Behind
Phase 6	Behind	Behind

The various tools utilized, including BIM technology and EVA, enabled this graph to be created. This simplified table shows that the project was behind schedule more than it was ahead of schedule. However, further investigation into the EVA shows that this project is only a small percentage behind in each phase. Additionally, the analysis of the model shows how Gilbane, as the CM, reworked the schedule to ensure that weather delays did not affect the schedule excessively. It is through the use of each of these tools that the project is more effectively monitored. By considering each component, the project manager is able to monitor how their efforts affect the project phase by phase. In order to find actual applicability of this technology, a presentation to the parties involved in the owner's meetings was scheduled.

4.0 Structural Design and Dynamic Performance

An alternative design of the support system for the 4th floor gymnasium was explored to gain understanding of design for dynamic conditions and to explore the differences that accompany a change in the vibration frequency (forcing frequency) of the floor loads. The current design addressed a 6 hertz forcing frequency, which is often associated with excitation due to walking, or other low impact activities (Murray, Allen, & Ungar, 1997). The alternative design implemented a forcing frequency of 9 hertz which is the accepted value for activities such as rhythmic dancing or aerobics (Murray, Allen, & Ungar, 1997). The structural response of the current design was first examined for the 6 hertz forcing frequency, and then the forcing frequency was increased to 9 hertz to establish a comparison point with the alternative design. By increasing the vibration frequency, a change to the structural supports was addressed in the alternative design to ensure the design retains its resistance to the gravity loading. Also, though the area of study is not part of the lateral load resisting system, the alternative needed to be designed with consideration of the effect of any added weight on the seismic forces.

4.1 Examining the Current Design

The current design used nine precast concrete arches starting on the first floor natatorium and extending to the bottom of the 4th floor gymnasium. The natural frequency of the precast arches was examined to create a baseline for the alternative design. Determining the natural frequency of a typical arch in the current design and its response to the 6 hertz forcing frequency was the first step. In order to do this, the design criteria in Table 6 below were used in conjunction with the modeling program RISA-2D. Included in the design criteria was a distributed dead load calculated from the gymnasium floor that sits atop the arches, which was designed to be 100 psf, combined with the self weight of the precast arch.

Table 6: Design Criterion for Current Design

Design Criterion	Current Design
ϒ, Unit weigh of Concrete (pcf)	145
f'c, compressive strength (psi)	6,000
Design Load, (psf)	100
Modulus of Elasticity	4,463 ksi
Weight of Arch (kips/foot)	3.13
Dead Load of Floor and Arch(kips/foot)	5.059
Point Load of Floor and Arch (kips)	67.7

A model of the arch was designed in RISA-2D, seen below in Figure 23, to establish an estimate for the actual natural frequency. A modal analysis was performed using the RISA software to determine the natural frequency, and a static analysis was performed to find the member deflection. These two values were necessary to calculate the dynamic magnification factor and the associated dynamic response of the structure.

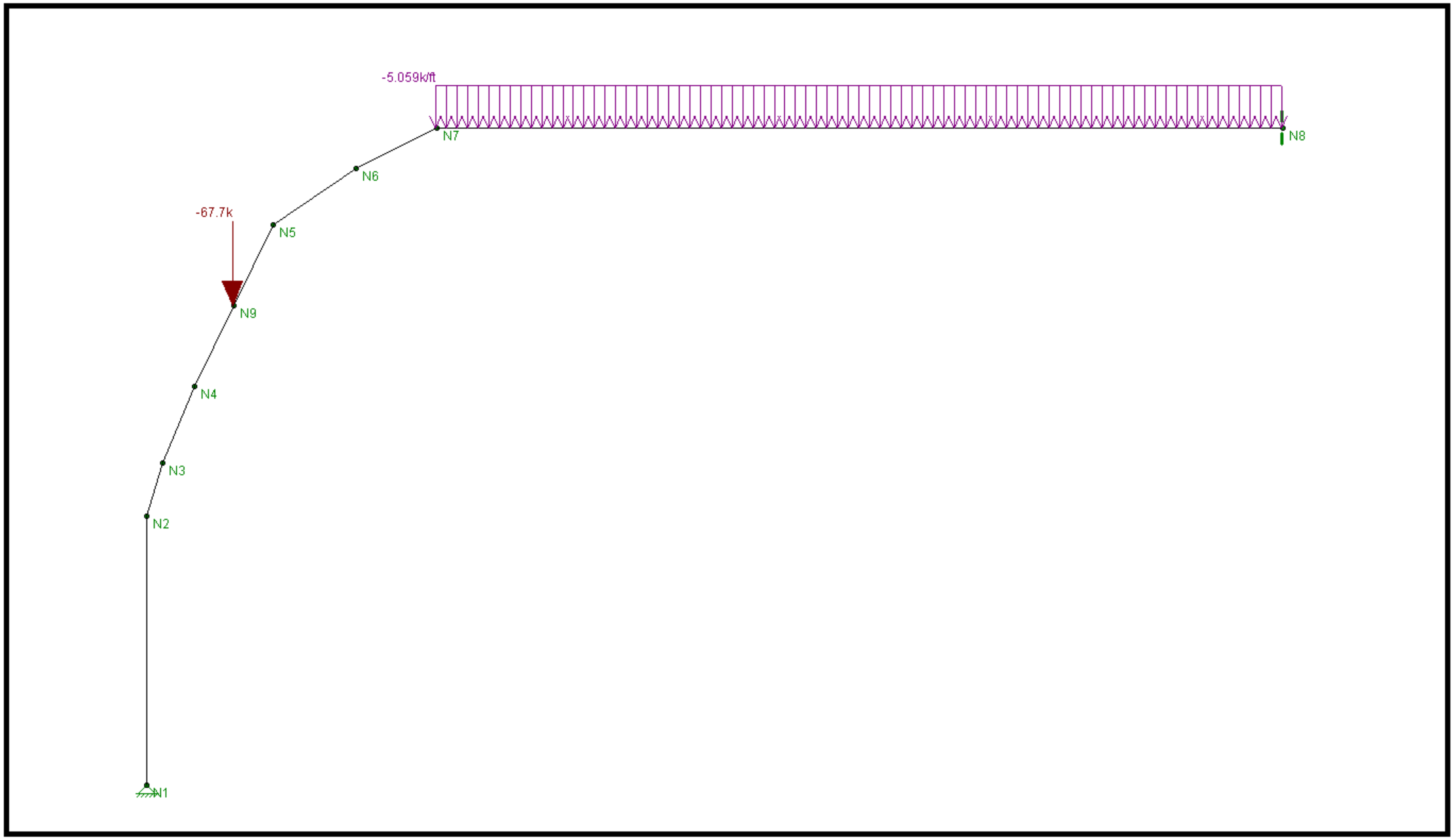


Figure 23: Risa-2D Precast Arch Model

When creating the RISA model, the centerline of the arch was used to define the longitudinal axis of a single-layered member, allowing for a distributed load to be applied. The combined weight of the floor and arch created the distributed load. The weight of the floor, 100 psf, was multiplied by the width of the floor area tributary to each arch, which was 19'4''. Also, the weight of the arch was found using the cubic yardage of concrete and multiplying it by the unit weight of the concrete. The symmetrical shape of the arch allowed for the model to be split half way with a fixed boundary added at the center to account for the symmetry plane. To ensure that the arched part of the model accounted for the weight of the gymnasium floor along its entire span, a point load was applied to the center of the haunch. The point load was calculated by taking the distributed load and multiplying it by the tributary area of the haunch, which was the distance between node 1 and node 7, as seen in Figure 23. Also, the material properties needed to be accounted for when designing the model. Using Equation 2 in Appendix H, the modulus of elasticity for the precast concrete was found to be 4,463 ksi, and was applied to all the members. Running the modal analysis provided a natural frequency in the structure of 5.2 Hz. The static analysis produced a deflection of 1.22", used for both the 6 and 9 hertz forcing frequencies. These values would be necessary when examining the effects of DMF on the structure.

The formula for calculating DMF, D $=1/\sqrt{(1-r^2)^2+(2r\zeta)^2}$ involved the variables r, the ratio of forcing frequency to natural frequency found in the modal analysis, as well as a damping ratio, ζ, of 0.02. The damping ratio 0.02 was chosen from Table 4.1 in *Floor Vibrations Due to Human Activity* by Allen, Murray, and Ungar. This value is often associated with shopping malls and offices (Murray, Allen, & Ungar, 1997). The reason for choosing that damping ratio was the similarity in walking excitation between a gym and the open floor space of a shopping mall. The DMF was then applied to the deflection calculated from a static analysis to determine the peak dynamic response of the system, which was then compared with the allowable deflection of L /360. The values for the dynamic response are found in Table 7 below. The peak response of the system is less than the allowable deflection, ensuring that the precast concrete arch can withstand the dynamic properties of the applied forcing frequencies.

Table 7: Dynamic Response for Current Design for 6 Hz and 9 Hz Forcing Frequencies

	Current Design 6 Hertz	**Current Design 9 Hertz**
Deflection	1.22 inches	1.22 inches
L /360	3.67 inches	3.67 inches
Natural Frequency	5.2 Hertz	5.2 Hertz
Frequency Ratio	1.16	1.73
DMF	3.51	0.501
Peak Response	3.51 inches	1.44 inches

4.2 Alternative Design

The alternative design explored the effects of an increased vibration frequency on the structural supports for the 4th floor gymnasium, and proposed changes to those supports to accompany this increase. Replacing the precast concrete arches with a steel truss that will span across the width of the gymnasium floor is the proposed option.

The steel truss needed to meet certain structural requirements, seen in Table 8 below, to ensure that the stability of the building remained intact. First, the weight of the truss was examined to determine if the change in seismic weight would affect the lateral force resisting system. If the change in weight was too great and the set of steel frames already in place could not accommodate the increase, the current lateral force resisting system would need to be changed. Also, the dynamic magnification factor was used to calculate the response of the system due to the dynamic interaction between its natural frequency of vibration and the activity frequency. Once the proposed design was complete and met the structural requirements, a cost analysis was performed.

Table 8: Design Criterion for Alternative Design

Design Criterion	
Design Load, (psf)	100
Modulus of Elasticity	29,000 ksi
Weight of Truss (kips/foot)	0.13
Dead Load of Floor and Truss (kip/foot)	2.06

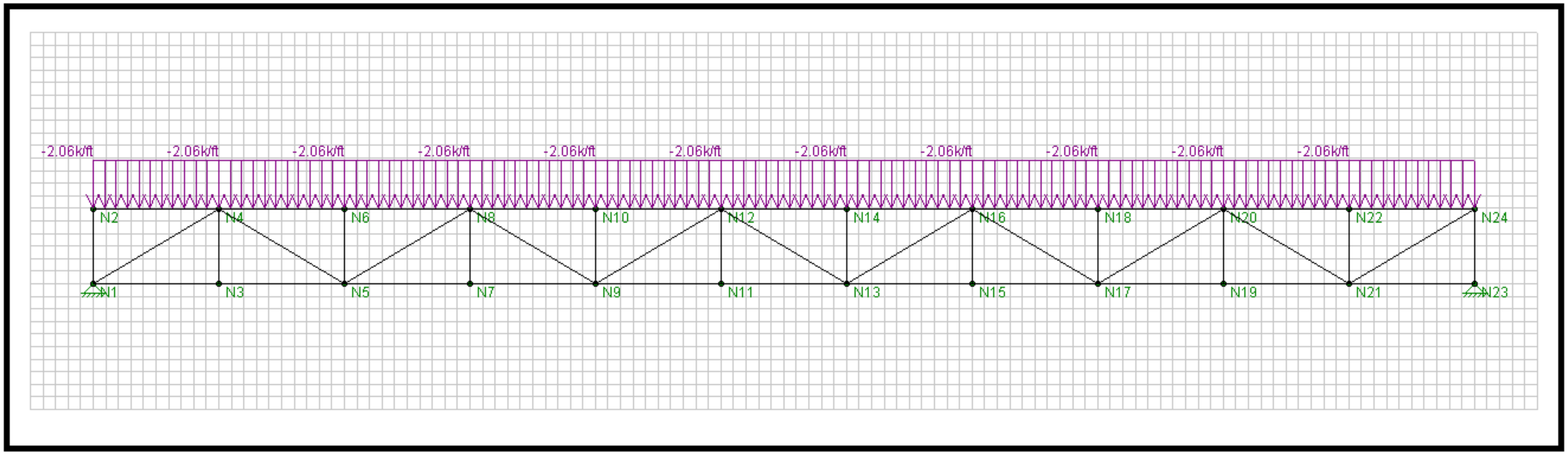


Figure 24: Risa-2D Truss Model

Analysis of the steel truss was performed using RISA-2D software and can be seen in Figure 24 above. RISA was necessary because trial and error was required when making the model. The truss consisted of 45 beams of lengths varying between 6 feet and 11.66 feet in length. The beam sections were broken down into W18x35's across the top and bottom spans as well as the vertical sections, and W10x12 sections used for the diagonals. The distributed load on the truss was calculated similar to that for the precast concrete arch, with a different self-weight found. A static analysis was performed to determine the deflection in the truss, and a modal analysis defined the natural frequency. These values would then be compared with the 9 Hz forcing frequency to predict the truss' dynamic response and to compare its performance with the precast concrete arch. Static analysis produced a deflection of 6.54 inches, greater than the allowable deflection of 3.67 inches. The modal analysis yielded a natural frequency of 3.74 Hz. The dynamic magnification factor was then addressed to determine if the structure could withstand the forcing frequency exerted on the system. These values are used for both the 6 and 9 Hertz forcing frequencies and are summarized in Table 9 below. A complete comparison of the current and alternative designs dynamic response is summarized in Table 10. Examining these tables, the peak response for the 6 Hertz frequency is no greater than the allowable deflection. However, because the static deflection in the truss initially exceeded the L/360 limit, the truss would need to be cambered a few inches to compensate for this deflection. This would allow the peak response in the truss to adequately resist the forcing frequencies on the system.

Table 9: Dynamic Response for Alternative Design

	Alternative Design 6 Hertz	**Alternative Design 9 Hz**
Deflection	6.54 inches	6.54 inches
L /360	3.67 inches	3.67 inches
Natural Frequency	3.74 Hertz	3.74 Hertz
Frequency Ratio	1.60	2.41
DMF	0.64	0.21
Peak Response	4.19 inches	1.37 inches

Table 10: Dynamic Response Results

	Current Design 6 Hertz	Current Design 9 Hertz	Alternative Design 6 Hertz	Alternative Design 9 Hz
Deflection	1.22 inches	1.22 inches	6.54 inches	6.54 inches
L /360	3.67 inches	3.67 inches	3.67 inches	3.67 inches
Natural Frequency	5.2 Hertz	5.2 Hertz	3.74 Hertz	3.74 Hertz
Frequency Ratio	1.16	1.73	1.60	2.41
DMF	2.88	0.501	0.64	0.21
Peak Response	3.51 inches	1.44 inches	4.19 inches	1.37 inches

4.3 Cost Comparison

Using the properties of the concrete arches, such as the weight and total area, as well as the material properties of A992 steel, a cost analysis was determined for the two designs. The fabrication times as well as the erection time for placement of the trusses were necessary to compare scheduling differences with the current design.

A comparison between the precast concrete arches and the steel truss was performed to determine the value of each method. Table 11 below displays the properties used for each design in determining the cost per member, as well as calculations for individual costs and cost of the entire support system. The steel truss system was approximately 2.42% less expensive than the concrete arch system.

Table 11: Material Cost Comparison

	Precast Concrete Arch	Steel Truss
Material Cost	215.08 dollars per cubic yard	2877.00 dollars per ton
Labor Cost and Equipment	47.32 dollars per cubic yard	672.67 dollars per ton
Total Cost	262.40 dollars per cubic yard	3549.67 dollars per ton
Amount of Member	87.83 cubic yards	6.5 tons
Cost Per Member	87.83*262.40= $23,046.59	6.5 * 3459.67 = $22,487.86
Cost of System	23,046.59* 9 = $207,419.31	22,487.86* 9 = $202,390.74

5.0 Conclusions

This report examined some aspects of the construction process in regards to the Recreation Center being constructed on the WPI campus. The application of Building Information Modeling was studied to determine possible uses of 4-D modeling and its applicability and usability in Project Management. The findings were compiled into a PowerPoint presentation and presented at one of the owner's meetings held at WPI, and feedback was recorded and incorporated into determining the conclusions about BIM. Also, the supports to the fourth floor gymnasium were analyzed and an alternative design was created to compare the dynamic response of the two systems as well as the cost. The results were used to determine if an alternative design was feasible.

5.1 Building Information Modeling and Project Management

Creating 3-D models with other dimensions connected to them creates a versatile platform that can be used by a project manager. It creates a visualization that can be used as a tool to not only track performance, but to also update the parties involved in the construction project that may not be able to see the project in person. Previously, the only way for someone to find out the progress of construction was with a chart or a graph showing the different values illustrating the progress. While this way has been useful in the past, it can become very complex and difficult to understand. BIM allows for the compilation of these charts and graphs with a visual representation of the project that can be easily understood

This combination of separate technologies is a supplement to one another. When something happens that prohibits the project from moving forward in bid packages that are highly visible, for example the steel construction in a certain area of a building, it may seem that the building is very far behind schedule. In the new Recreation Center for WPI, there was a case where this happened, however, with the information extracted from the BIM model, it was easy to show that because one area may be behind, other areas were increasing production and the percentage of steel completed was relatively the same. Another use for BIM is to track changes. If the same situation with the steel arises, one can easily change the phase that it is in and establish quantity differences.

There are limitations however, that were specifically pointed out at the presentation by the parties involved. First, Revit can be difficult software to use to create these models. If the person who is using the software does not have a substantial background and knowledge of the capabilities of the system, it will be difficult and frustrating. The interface of Revit lacks a way to un-click or an “undo” button, so if a person is highlighting multiple elements to be put into a phase and clicks on the wrong thing, example of such being a hatch mark, all the elements cannot be input into a phase and have to be re-highlighted. Also, with the factor of ease being based on experience and knowledge, the amount of time to create a model varies from person to person. The need for the model must be compared to the amount of dedication required to create the model and whether spending this time is worth it or not. When Revit updates their software with BIM in mind, or when another software is developed that is more user-friendly and simpler, this will become the industry standard. As was stated at the presentation by Brent Arthaud, “This is the future of our industry”.

5.2 Earned Value Analysis

Earned Value Analyses (EVA) are not a new concept to project management, but incorporating BIM technology into the EVA brings a difference aspect into the analysis. The ability to extract quantities from Revit enables project managers to complete a detailed analysis and compare the progress based on any phasing deemed useful. Feedback from the group’s presentation at the Owner's Meeting of the project provided insight into the applicability of incorporating BIM technology into meetings. One topic that the attendees found intriguing was the ability to track the percent complete based on phasing. Additionally, from the project manager's point of view, tracking the full EVA would also include the actual cost of work performed (ACWP) and would enable evaluating of the cost variance (CV) and cost performance index (CPI). If all of this information were entered into the BIM model, using other software available such as NAVISWORKS, the project manager would have one central location to access progress monitoring information. These capabilities not only reemphasize the importance of completing an EVA, but also validate the idea of linking the EVA to the BIM model.

5.3 Structural Analysis

The alternative design was performed to not only determine if a steel truss could effectively replace the concrete arches for supporting the 4th floor gymnasium at current and increased vibration frequencies, but to also see if the alternative would be time and cost effective. For construction purposes, a system of steel trusses can be fabricated off site and erected on site quickly. This can be seen from the current truss system supporting the roof at the new Recreation Center project site.

The modal and static analyses for the alternative design showed that the proposed truss could effectively withstand the 6 Hz forcing frequency used for the current design, as well as the increased vibration frequency of 9 Hz. Though the deflection in the steel truss was greater than the deflection in the concrete arch, the dynamic response of the system was still less than the allowable deflection over the given span, if the truss was cambered. Before the truss could be substituted for the concrete arches, a cost analysis was performed to determine the practicality of such a transition.

The cost analysis to compare the two designs took into account material costs, we well as labor and equipment costs and yielded nearly a 3% decrease in cost for the steel truss over the concrete arch. Based on the reasons above, the system of trusses was determined to perform as well as the precast concrete arches and is another option for supporting the 4th floor gymnasium.

5.4 Owner's Meetings

Attendance at the Owner's Meetings provided valuable insight into the role of the project manager and the general operation of a project. Because every construction project has aspect unique to that specific project, the role of the project manager often varies. WPI's relationship with Cardinal Construction, the Owner's Representative, was different than their relationship with Gilbane Building Co. (Gilbane), the CM @ Risk, and from their relationship with Cannon Design, the designer. Using contractual agreements provided a collaborative, efficient team that addressed important project issues and identified potential conflicts. The meetings used a number of engineering software, including Primavera and Prolog, and the parties involved also used Revit to create structural drawings and produce a number of drawings and rendered images of the site. The capabilities of BIM technology can further enhance these meetings by providing a 3-D, or 4-D, visual for the less technical members of the audience, facilitating the communication of design alternatives, and potentially enhancing the construction updates given by Neil Benner, senior project manager.

One potential issue identified in the presentation at the Owner's Meeting was that there may not always be the need for the model, but in discussions where visualization is essential, these models could be prepared by an experienced modeler and not only have a positive impact on the discussion but could also reduce the time of the discussion by providing more views of potential changes and special orientation within the facility. The benefits of BIM technology could provide a graphic compliment to many topics discussed, especially as research into this technology grows. There is value added by using 3-D modeling for the clients, as well as the contractors, because it provides a simpler way to view construction. However, there is a need to pre-plan the model prior to the owner's meetings so that it is catered to the needs of the specific meeting, and also because navigating the Revit model can be difficult. This problem is disappearing with model segmentation, smaller but better coordinated models, allowing for easier manipulation of the structure as a whole. With the progress in technology, one shouldn't be surprised if they come across this in the near future.

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Appendix A: Proposal

GFS-1101
LDA - 1102

WPI Recreation Center:
Construction Management and Alternative Design Analysis

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

Submitted By:

Kristopher Fournier
Stephanie Munion
Joel Stella

Sponsoring Agency:
Gilbane Building Company

Submitted To:
Project Advisors: Guillermo Salazar
Leonard Albano

Date: December 16, 2010

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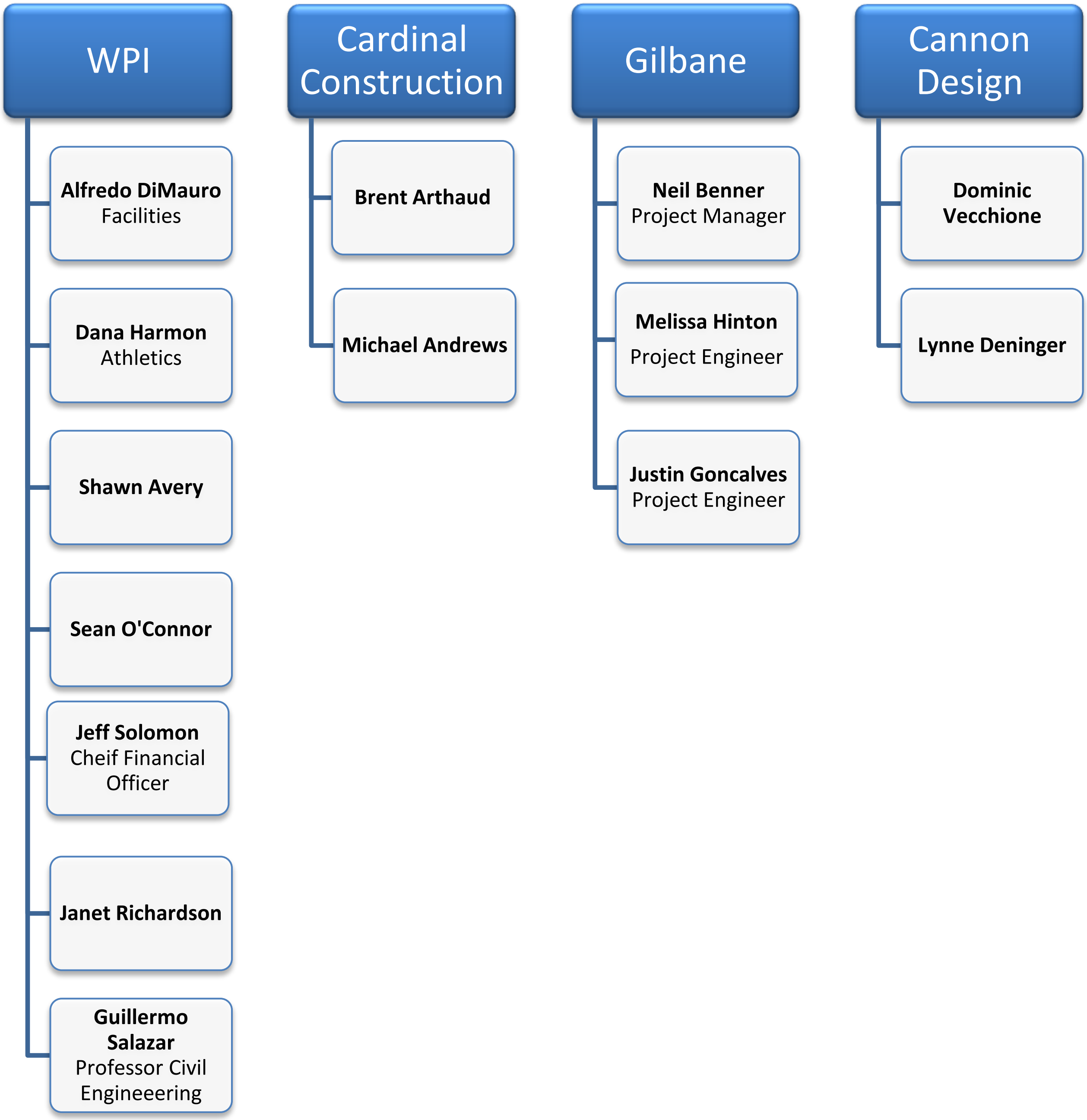
Appendix B – Attendance at WPI Recreation Center Owner's Meetings



Owner's Meeting Agenda

Meeting Minutes

Detailed, Grouped by Topic for each Meeting and by 'Old Business' and 'New Business'

WPI New Recreation Center | Project # 114775000 | Gilbane Building Company
Tel: Fax:

Owner, Architect, Contractor Meeting 31

Date	Start	End	Next Meeting	Next Time	Prepared By	Company
2/24/2011			2/10/2011		Hinton, Melissa	Gilbane Building Company

Purpose	Location	Next Location	General Notes

Attended By	Non-Attendees
Cannon Design - Vecchione, Dominic	Worcester Polytechnic Institute - O'Connor, Sean
Gilbane Building Company - Benner, Neil	Cannon Design - Deninger, Lynne
Gilbane Building Company - Hinton, Melissa	Worcester Polytechnic Institute - Salazar, Guillermo
Gilbane Building Company - Kearney Jr., William	Cardinal - Andrews, Michael
Worcester Polytechnic Institute - Harmon, Dana	Worcester Polytechnic Institute - McMenamy, Kelsey
Worcester Polytechnic Institute - McAvery, Shawn	Worcester Polytechnic Institute - Bertin, Trevor
Worcester Polytechnic Institute - Richardson, Janet	Worcester Polytechnic Institute - Schembri, Peter
Cardinal - Arthaud, Brent	Worcester Polytechnic Institute - Alvokz, Sergio
Worcester Polytechnic Institute - DiMauro, Alfredo	
Worcester Polytechnic Institute - Solomon, Jeffrey	
Worcester Polytechnic Institute - McCarron, Ann	
Worcester Polytechnic Institute - Munion, Stephaine	
Worcester Polytechnic Institute - Moynihan, Patrick	

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
001 Construction						
Old Business						
Construction Update						
001-016	2/24/11: -Capco is erecting columns in Area A and welding trusses. The trusses come in two pieces to the job site. -Capco should complete the trusses by 3/11, Area C by 4/14, and Area D around 5/14. -Capco intends to complete track framing at the same time as the trusses. -Stair #3 will be erected within the next two weeks. -Pool work is on going. -The pool slab will be placed on 3/8 and 3/9; pool walls will be placed on 3/14. -Spray fireproofing will start on 2/28. -Curtainwall materials will be arriving on site at the end of March. -GBCo is planning on installing curtainwall before masonry throughout the building. -GBCo will have a few sections of the curtainwall left out to provide means of access into the building for materials.	-Weather is still key 2.5 days lost because of wind			No	

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
	-The 4th level slab was placed on 2/14; Area A 1st floor and 3rd floor were placed on 2/11 and 2/16. -WPI will tour construction progress on 2/18. -Capco's crane is coming on 2/22. Steel should start to go up that afternoon or early the next day. -The pool slab on grade will be placed on 2/25. -Spray Fireproofing will start on 2/28 in Area A					
Steam Line (Summer 2011)						
005-001	2/24/11: -GBCo will coordinate activities with Cardigan and WPI in January. -GBCo expects the work to take 6 weeks starting after graduation this year. -WPI would like to see a plan of the construction boundaries of the steam line work for planning purposes.					No
Exterior Test Panel						
008-001	2/24/11: -GBCo will be ready for the test the week of 3/7. -The panel will be removed prior to commencement.					No
Construction Operations & Campus Issues						
019-001	2/24/11: Commencement: -Commencement will be on the quad this spring. -GBCo and WPI will work together on moving the fence back for more quad space. Backstop: -Marois has completed some work to fix the back stop but GBCo doesn't believe work is sufficient enough. GBCo will follow up with Marois to get the backstop improved. Morgan Walkway: -GBCo would like to wait till after steel erection to create the walkway near Morgan. -WPI would like the walkway to remain open once it is created. WPI does not want to repeatedly open and close the walkway. -WPI is okay with opening the walkway in March of 2011. WPI would like to review the grading outside of Morgan's dinning room with Cannon. -GBCo will try to get an opening date after the schedule update on 2/23 for WPI.					No
Steel Topping Off Ceremony						
022-001	2/24/11: -WPI and GBCo have selected a piece of steel that will be visible from the field side of the building. -It looks like the steel topping off ceremony will be in mid to late April. -WPI would like to have the steel safely available on the quad for the community to sign the beam.					No

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
040 Issue/Concerns						

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
Old Business						
Lens and Lights Equipment						
001-015	2/24/11: -WPI and Cannon have met to review Cannon's proposal prior to meeting with Lens and Lights. -WPI would like to talk in depth about the following items: -Amperage of the system -Location of the CAM outlets -Routing of Power to Quad. Would it be possible to route the power in the same trench as the steam line? -WPI would like an idea of how much adding conduit to the open steam trench would be prior to meeting with WPI students.					No

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
Design						
Old Business						
Cornerstone						
016-002	2/24/11: -Fred is finalizing his decision regarding the cornerstone and will present to Cannon and Dr. Berkey. -Currently the stone will be near PP and 15 along the north elevation. -The cornerstone should be ready for installation in September or October 2011.					No
Lobby Ceiling						
020-002	2/24/11: -WPI is interested in three tvs in the fourth floor feature wall and one by the reception desk. Brent is working on getting cuts of the support brackets for the tvs. The size of the support bracket will be incorporated into the revised elevations of the feature wall. -Cannon marked up the comments on the millwork shop drawings. -Cannon is finalizing the electrical sketches.					No
Monitors for Water Flow						
025-003	2/24/11: -Fred is interested in monitoring the amount of water that goes to three areas of the building: pool, domestic, and AHUs. -Ideally he would like the monitors to bring the information to a central location for monitoring. -Cannon is researching potential monitors. -Prof. Mathisen has reached out to Janet Richardson regarding the monitors. Cannon encourages Prof. Mathisen to come to a meeting to review the professor's ideas on the water monitoring. -Once Cannon has the chance to speak to Prof. Mathisen regarding his ideas for monitoring water; they will issue something for pricing. -GBCo will get an order of magnitude for WPI to review and determine if they want to pursue this work.					No

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
Keying						
026-002	2/24/11: -GBCo will check on the lead time for the hardware to determine the timing of the keying meeting.					No

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
Financial						
Old Business						
Procurement						
003-002	2/24/11: GBCo will review the area with WPI's crew coaches next Friday (2/25) at 11am.					No
National Grid						
025-001	2/24/11: -GBCo is expecting the bollards to be installed tomorrow (2/18).					No
Change Authorizations						
026-003	2/24/11: -No new changes were discussed.					No

finish on canopy steel
$65,000

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
General						
Old Business						
BIM Modeling						
001-017	2/24/11: -The MQP students will present their findings after the 3/3 team meeting. The team will meet in Gilbane trailer that week.					No
East Hall						
006-001	2/24/11: -Blakeslee has reviewed the fallen patches in the garage and will repair them once the weather improves. -Fred has reconciled the bills from Southern Air from the cooling situation on Labor Day weekend. GBCo has made a second request to Smardt of these bills and is awaiting their response.					No
Donor Wall						
024-001	2/24/11: WPI is reviewing internally the donor wall.					No

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
General Business						
Old Business						
Social Event						

Item	Meeting Item Description	Resp	Status	Due Date	Compl'd	Cls'd
028-001	2/24/11: -GBCo has suggested the idea of snow tubbing at Nashoba Valley after work one night. -GBCo will send out an email to everyone, date to be in early March. 3/24					No
AHU Units Visibility						
029-001	2/24/11: Cannon showed the team what the sight lines are for the AHU from the second floor of the Bartlett Center. It looks like the top 2' of the units will be visible. Cannon is recommending painting the units in lieu of cladding. The team reviewed Cannon's elevations regarding the items at the roof. WPI is concerned about the building inspector changing the location of the stacks at the roof level. Cannon and GBCo to follow up with the building inspector.					No
Plasma Lights						
030-001	2/24/11: -Cannon issued their response to the plasma lights to WPI last week.					No
New Business						
Gym Floor						
031-001	2/24/11: -GBCo had wood athletic flooring samples for WPI's review. Samples include: Gym Flooring, Specified Multipurpose Room Flooring, Alternate Multipurpose Room Flooring. -Cannon is recommending that the alternate Multipurpose Flooring be selected. The Connor Neo-shok is a floating floor.					No
Harrington Roof						
031-002	2/24/11: -WPI is concerned about the edge of the roof and controlling the snow coming off the roof. -Cannon suggested a snow fence at Harrington's roof.					No

Cc:	Company Name	Contact Name	Copies	Notes

Appendix C – Primavera File

Activity ID	Activity Name	BDPK	Area	(*)Planned Start	Actual Start	(*)Planned Finish	Actual Finish	(*)Budgeted Total Cost($)
5147	FRP CONC FOUND WALLS A.7 TO FF.7	03A	A	9/3/2010 8:00:00 AM	9/16/2010	10/15/2010 5:00:00 PM	10/15/2010	$ 62,556.00
5195	CONCRETE DECK @ AREA A	03A	A	11/19/2010 8:00:00 AM	10/16/2010	12/15/2010 5:00:00 PM	12/15/2010	$ 45,693.00
5131	FRP FTGS/FOUND WALLS LOAD DOCK	03A	A	1/17/2011 8:00:00 AM		2/15/2011 5:00:00 PM		$ -
5155	ERECT AREA A STEEL UP TO 4TH FLR	05A	A	10/28/2010 8:00:00 AM	10/16/2010	11/15/2010 5:00:00 PM	11/15/2010	$ 544,307.00
5159	COMPLETE STEEL @ TOP AREA A	05A	A	1/17/2011 8:00:00 AM		2/15/2011 5:00:00 PM		$ -
4042	ERECT PRECAST STRUCTURE AND TS	03B	B	11/8/2010 8:00:00 AM	10/16/2010	12/15/2010 5:00:00 PM	12/15/2010	$ 45,693.00
4044	COMPLETE ERECT PRECAST STRUCTURE AND TS	03B	B	12/1/2010 8:00:00 AM	11/16/2010	12/15/2010 5:00:00 PM	2/15/2011	$ 150,778.00
5220	CONCRETE DIAPHRAM SLAB ANTIC 50% AREA B	03A	B	12/1/2010 8:00:00 AM	1/16/2011	12/15/2010 5:00:00 PM	2/15/2011	$ 150,778.00
5240	CONCRETE DIAPHRAM SLAB REMAINING 50% AREA B	03A	B	12/15/2010 8:00:00 AM	1/16/2011	1/14/2011 5:00:00 PM	2/15/2011	$ 150,778.00
5255	ERECT AREA B STEEL AND DECK	05A	B	1/17/2011 8:00:00 AM		2/15/2011 5:00:00 PM		$ -
5162	FRP FOOTING AREA P LINE TO MM	03A	C	9/20/2010 8:00:00 AM	9/16/2010	11/15/2010 5:00:00 PM	10/15/2010	$ 62,556.00
5152	FRP CONC FOUND WALLS FF.7 TO P LINE	03A	C	10/8/2010 8:00:00 AM	9/16/2010	11/15/2010 5:00:00 PM	10/15/2010	$ 62,556.00
5163	FRP CONC FOUND WALLS P LINE TO MM	03A	C	10/21/2010 8:00:00 AM	9/16/2010	11/15/2010 5:00:00 PM	10/15/2010	$ 62,556.00
5170	FRP FOOTINGS AREA C	03A	C	11/23/2010 8:00:00 AM	11/16/2010	12/15/2010 5:00:00 PM	12/15/2010	$ 45,693.00
5171	FRP CONC FOUND WALLS AREA C	03A	C	12/1/2010 8:00:00 AM	11/16/2010	12/15/2010 5:00:00 PM	1/15/2011	$ 159,660.00
5273	ERECT P LINE STEEL - AREA D FOR PRECAST	05A	D	11/19/2010 8:00:00 AM	12/16/2010	12/15/2010 5:00:00 PM	2/15/2011	$ 150,778.00
5245	CONC FTGS SECT D (COLD WEATHER PLACEMENT)	03A	D	12/16/2010 8:00:00 AM	12/16/2010	1/14/2011 5:00:00 PM	1/15/2011	$ 159,660.00
5246	CONC FOUND WALL SECT D (COLD WEATHER PLACEMENT)	03A	D	1/19/2011 8:00:00 AM		2/15/2011 5:00:00 PM		$ -
Start	Start Project			5/18/2010 8:00:00 AM	8/15/2010			$ -
5134	FRP FOOTINGS AREA A & RETAINING WALL	03A	A	8/23/2010 8:00:00 AM	8/16/2010	9/15/2010 5:00:00 PM	9/15/2010	$ 57,126.00
5135	CONCRETE FOUND & RETAINING WALL AREA A	03A	A	8/25/2010 8:00:00 AM	8/16/2010	9/15/2010 5:00:00 PM	10/15/2010	$ 62,556.00
5095	CONC DEEP FOUNDS & CANTEL RET WALL A,B	03A	A	8/19/2010 8:00:00 AM	8/16/2010	9/15/2010 5:00:00 PM	9/15/2010	$ 57,126.00
5225	CONCRETE FOUND WALL P LINE - R LINE	03A	S	10/20/2010 8:00:00 AM	8/16/2010	11/15/2010 5:00:00 PM	9/15/2010	$ 57,126.00
5146	FRP FOOTINGS AREA A.7 TO FF.7 LINE	03A	A	8/27/2010 8:00:00 AM	8/16/2010	10/15/2010 5:00:00 PM	9/15/2010	$ 57,126.00
5141	FRP CONC FOUND WALLS 1 LINE - AREA B	03A	B	8/23/2010 8:00:00 AM	8/16/2010	9/15/2010 5:00:00 PM	9/15/2010	$ 57,126.00
5140	FRP CONC FTGS 1 LINE - AREA B	03A	B	8/6/2010 8:00:00 AM	8/16/2010	9/15/2010 5:00:00 PM	9/15/2010	$ 57,126.00
5151	FRP FTG AREA FF.7 TO MM LINE	03A	C	9/20/2010 8:00:00 AM	8/16/2010	10/15/2010 5:00:00 PM	10/15/2010	$ 62,556.00
5140.D5	FRP INTERIOR CONC FTGS D.5 LINE - AREA B	03A	B	9/7/2010 8:00:00 AM	9/16/2010	9/15/2010 5:00:00 PM	10/15/2010	$ 62,556.00
5141.D5	FRP INTERIOR CONC FOUND WALLS D.5 LINE - AREA B	03A	B	9/14/2010 8:00:00 AM	9/16/2010	10/15/2010 5:00:00 PM	10/15/2010	$ 62,556.00
5223	CONC FTG P-Q LINE - ENDS	03A	S	10/18/2010 8:00:00 AM	8/16/2010	11/15/2010 5:00:00 PM	9/15/2010	$ 57,126.00

Appendix D – EVA: Cost

Projected – BCWS

Concrete

Concrete - Phase 1			Concrete - Phase 2		
Structural Columns	47.33	$ 7,741.59	Structural Columns	89.82	$ 14,691.51
Structural Foundations	668.61	$ 112,033.89	Structural Foundations	1083.68	$ 181,584.02
Walls	1179.84	$ 183,832.54	Walls	1634.8	$ 254,720.50
Structural Framing	0	$ -	Structural Framing	0	$ -
Floor	345.3	$ 51,573.51	Floor	345.3	$ 51,573.51
Total (cy)	2241.08	$ 355,181.53	Total	3153.6	$ 502,569.54
Total for Project (cy)	9592.62		Total for Project	9592.62	
Percent Complete	23.36%		Percent Complete	32.88%	

Concrete - Phase 3			Concrete - Phase 4		
Structural Columns	89.84	$ 14,694.78	Structural Columns	111.87	$ 18,298.15
Structural Foundations	1088.37	$ 182,369.89	Structural Foundations	1320.24	$ 221,222.58
Walls	1806.99	$ 281,549.66	Walls	2124.68	$ 331,049.39
Structural Framing	770.54	$ 165,724.49	Structural Framing	1029.8	$ 221,485.03
Floor	702.34	$ 104,900.49	Floor	736.27	$ 109,968.23
Total	4458.08	$ 749,239.31	Total	5322.86	$ 902,023.38
Total for Project	9592.62		Total for Project	9592.62	
Percent Complete	46.47%		Percent Complete	55.49%	

Concrete - Phase 5			Concrete - Phase 6		
Structural Columns	116.87	$ 19,115.98	Structural Columns	120.2367	$ 19,666.65
Structural Foundations	1474.97	$ 247,149.51	Structural Foundations	1474.97	$ 247,149.51
Walls	2213.11	$ 344,827.80	Walls	2213.11	$ 344,827.80
Structural Framing	1118.32	$ 240,523.54	Structural Framing	1118.32	$ 240,523.54
Floor	1130	$ 168,775.17	Floor	2252.59	$ 336,443.60
Total	6053.27	$ 1,020,392.00	Total	7179.2267	$ 1,188,611.10
Total for Project	9592.62		Total for Project	9592.62	
Percent Complete	63.10%		Percent Complete	74.84%	

Concrete - Total		
Structural Columns	141.83	$ 23,198.59
Structural Foundations	2150.51	$ 360,344.61
Walls	2532.96	$ 394,664.08
Structural Framing	1154.38	$ 248,279.17
Floor	3612.94	$ 539,623.51
Total	9592.62	$ 1,566,109.96
Total for Project	9592.62	
Percent Complete	100.00%	

Steel

Steel - Phase 1			
Structural Columns	0	$	-
Framing	0	$	-
Trusses	0	$	-
Total	0	$	-
Total for Project	994.8	Ton	
Percent Complete	0.00%		

Steel - Phase 2			
Structural Columns	0	$	-
Framing	0	$	-
Trusses	0	$	-
Total	0	$	-
Total for Project	994.8	Ton	
Percent Complete	0.00%		

Steel - Phase 3			
Structural Columns	31.61	$	112,205.07
Framing	47.96	$	170,242.17
Trusses	0	$	-
Total	79.57	$	282,447.24
Total for Project	994.8	Ton	
Percent Complete	8.00%		

Steel - Phase 4			
Structural Columns	43.23	$	153,452.23
Framing	49.54	$	175,850.65
Trusses	0	$	-
Total	92.77	$	329,302.89
Total for Project	994.8	Ton	
Percent Complete	9.33%		

Steel - Phase 5			
Structural Columns	76.78	$	272,543.66
Framing	88.31	$	313,471.36
Trusses	0	$	-
Total	165.09	$	586,015.02
Total for Project	994.8	Ton	
Percent Complete	16.60%		

Steel - Phase 6			
Structural Columns	100.771	$	357,703.80
Framing	264.305	$	938,195.53
Trusses	150.169	$	533,050.39
Total	515.245	$	1,828,949.72
Total for Project	994.8	Ton	
Percent Complete	51.79%		

Steel - Total			
Structural Columns	200.41	$	711,389.36
Framing	644.22	$	2,286,768.41
Trusses	150.17	$	533,050.39
Total	994.80	$	3,531,208.17
Total for Project	994.80	Ton	
Percent Complete	100.00%		

Actual – BCWP

Concrete

Concrete - Phase 1		
Structural Columns	36.15	$ 157,744.16
Structural Foundations	955.68	$ 160,136.03
Walls	195.31	$ 30,431.53
Structural Framing	0	$ -
Floor	345.3	$ 51,573.51
Total	1532.44	$ 399,885.23
Total for Project	9592.62	
Percent Complete	15.98%	

Concrete - Phase 2		
Structural Columns	93	$ 405,814.84
Structural Foundations	1103.76	$ 184,948.67
Walls	1655.81	$ 257,994.10
Structural Framing	0	$ -
Floor	345.3	$ 51,573.51
Total	3197.87	$ 900,331.12
Total for Project	9592.62	
Percent Complete	33.34%	

Concrete - Phase 3		
Structural Columns	93.02	$ 405,902.12
Structural Foundations	1107.33	$ 185,546.87
Walls	1806.3	$ 281,442.15
Structural Framing	566.14	$ 165,724.49
Floor	619.18	$ 92,479.83
Total	4191.97	$ 1,131,095.46
Total for Project	9592.62	
Percent Complete	43.70%	

Concrete - Phase 4		
Structural Columns	97.94	$ 427,371.03
Structural Foundations	1289.15	$ 216,013.07
Walls	1954.95	$ 304,603.52
Structural Framing	1012.89	$ 221,485.03
Floor	660.84	$ 98,702.11
Total	5015.77	$ 1,268,174.76
Total for Project	9592.62	
Percent Complete	52.29%	

Concrete - Phase 5		
Structural Columns	112.23	$ 489,726.88
Structural Foundations	1361.35	$ 228,111.07
Walls	2089.8	$ 325,614.69
Structural Framing	1012.89	$ 240,523.54
Floor	660.84	$ 98,702.11
Total	5237.11	$ 1,382,678.29
Total for Project	9592.62	
Percent Complete	54.60%	

Concrete - Phase 6		
Structural Columns	112.23	$ 489,726.88
Structural Foundations	1361.35	$ 228,111.07
Walls	2089.8	$ 325,614.69
Structural Framing	1048.57	$ 240,523.54
Floor	1054.57	$ 157,509.06
Total	5666.52	$ 1,441,485.24
Total for Project	9592.62	
Percent Complete	59.07%	

Steel

Steel - Phase 1			
Structural Columns	0	$	-
Framing	0	$	-
Trusses	0	$	-
Total	0	$	-
Total for Project	994.8	Ton	
Percent Complete	0.00%		

Steel - Phase 2			
Structural Columns	0	$	-
Framing	0	$	-
Trusses	0	$	-
Total	0	$	-
Total for Project	994.8	Ton	
Percent Complete	0.00%		

Steel - Phase 3			
Structural Columns	31.7	$	112,524.54
Framing	56.63	$	201,017.81
Trusses	0	$	-
Total	88.33	$	313,542.35
Total for Project	994.8	Ton	
Percent Complete	8.88%		

Steel - Phase 4			
Structural Columns	31.7	$	112,524.54
Framing	56.63	$	201,017.81
Trusses	0	$	-
Total	88.33	$	313,542.35
Total for Project	994.8	Ton	
Percent Complete	8.88%		

Steel - Phase 5			
Structural Columns	54.09	$	192,001.65
Framing	91.94	$	326,356.66
Trusses	0	$	-
Total	146.03	$	518,358.31
Total for Project	994.8	Ton	
Percent Complete	14.68%		

Steel - Phase 6			
Structural Columns	54.09	$	192,001.65
Framing	91.94	$	326,356.66
Trusses	0	$	-
Total	146.03	$	518,358.31
Total for Project	994.8	Ton	
Percent Complete	14.68%		

Appendix E – EVA: Schedule Variance & Schedule Performance Index

Concrete	BCWS			BCWP			SV		SPI
	%	CY	$	%	CY	$	CY	$	CY
Phase 1	23.36%	2241.08	$ 355,182	15.98%	1532.44	$ 399,885	-708.64	$ 44,704	0.68
Phase 2	9.51%	912.52	$ 147,388	17.36%	1665.43	$ 500,446	752.91	$ 353,058	1.83
Phase 3	13.60%	1304.48	$ 246,670	10.36%	994.1	$ 230,764	-310.38	$ (15,905)	0.76
Phase 4	9.02%	864.78	$ 152,784	8.59%	823.80	$ 137,079	-40.98	$ (15,705)	0.95
Phase 5	7.61%	730.41	$ 118,369	2.31%	221.34	$ 114,504	-509.07	$ (3,865)	0.30
Phase 6	11.74%	1125.9567	$ 168,219	4.48%	429.41	$ 58,807	-696.55	$ (109,412)	0.38
Total Thus Far	**74.84%**	**7179.23**	**$ 1,188,611**	**59.07%**	**5666.52**	**$ 1,441,485**	**- 1512.71**	**$ 252,874**	**0.79**

Steel	BCWS			BCWP			SV		SPI
	%	Ton	$	%	Ton	$	Ton	$	Ton
Phase 1	0.00%	0	$ -	0.00%	0	$ -	0.00	$ -	0
Phase 2	0.00%	0	$ -	0.00%	0	$ -	0.00	$ -	0
Phase 3	8.00%	79.57	$ 282,447	8.88%	88.33	$ 313,542	8.76	$ 31,095	1.11
Phase 4	1.33%	13.2	$ 46,856	0.00%	0.00	$ -	-13.20	$ (46,856)	0.00
Phase 5	7.27%	72.32	$ 256,712	5.80%	57.7	$ 204,816	-14.62	$ (51,896)	0.80
Phase 6	35.20%	350.155	$ 1,242,935	0.00%	0	$ -	- 350.16	$ (1,242,935)	0.00
Total Thus Far	**51.79%**	**515.25**	**$ 1,828,950**	**14.68%**	**146.03**	**$ 518,358**	**- 369.22**	**$ (1,310,591)**	**0.28**

Appendix F- Design Calculations

Current Design for 6 Hertz and 9 Hertz Frequency

Design Criterion Chart:

Design Criterion	6 Hertz	9 Hertz
ϒ, Unit weigh of Concrete (pcf)	145	145
f'c, compressive strength (psi)	6,000	6,000
Design Load, (psf)	100	100
K, (design constant)	1.7 (lively concert or sports event)	2.0 (aerobics or rhythmic dancing)
F, forcing frequency (Hertz)	5	8.25
w_p, effective weight per unit area of participants (psf)	31	4.2
w_t, effective total weight per unit area (psf)	131	104.2
a_o/g, ratio of peak acceleration to acceleration due to gravity	0.05	0.06
α_i, dynamic coefficient	0.05	0.1

Equation 1 (Required Natural Frequency of structure):

$$(f_n)\text{req'd} = f * \sqrt[2]{1 + \frac{k}{a_o/g} * \frac{\alpha_i * w_p}{w_t}}$$

For 6 Hertz Frequency:

$$(f_n)\text{req'd} = 5 * \sqrt[2]{1 + \frac{1.7}{.05} * \frac{.05*31}{131}} = 5.92 \text{ Hertz}$$

For 9 Hertz Frequency:

$$(f_n)\text{req'd} = 8.25 * \sqrt[2]{1 + \frac{2.0}{.06} * \frac{0.1*4.2}{104.2}} = 8.8 \text{ Hertz}$$

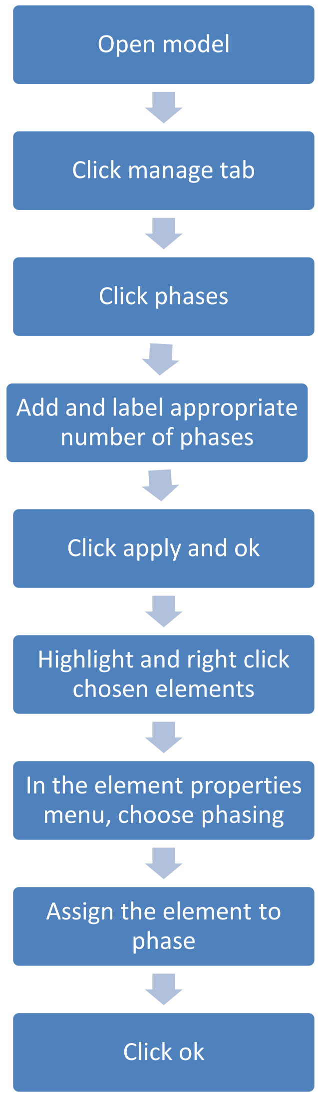
Equation 2 (Modulus of Elasticity for Concrete):

$$E_c = 33 * w_C{}^{1.5} * \sqrt{f'c}$$

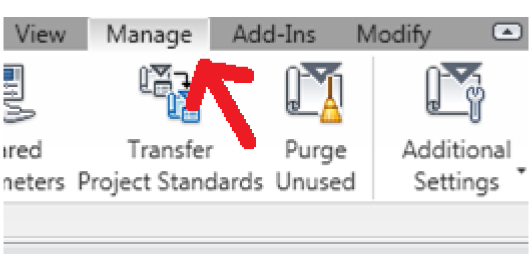
$$E_c = 33 * 145(pcf)^{1.5} * \sqrt{6{,}000\ (psi)} = 4{,}463{,}151 \text{ psi} = 4{,}463 \text{ ksi}$$

Appendix G – Phasing

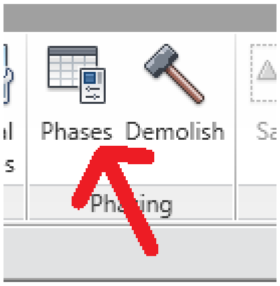
Developing a Phase



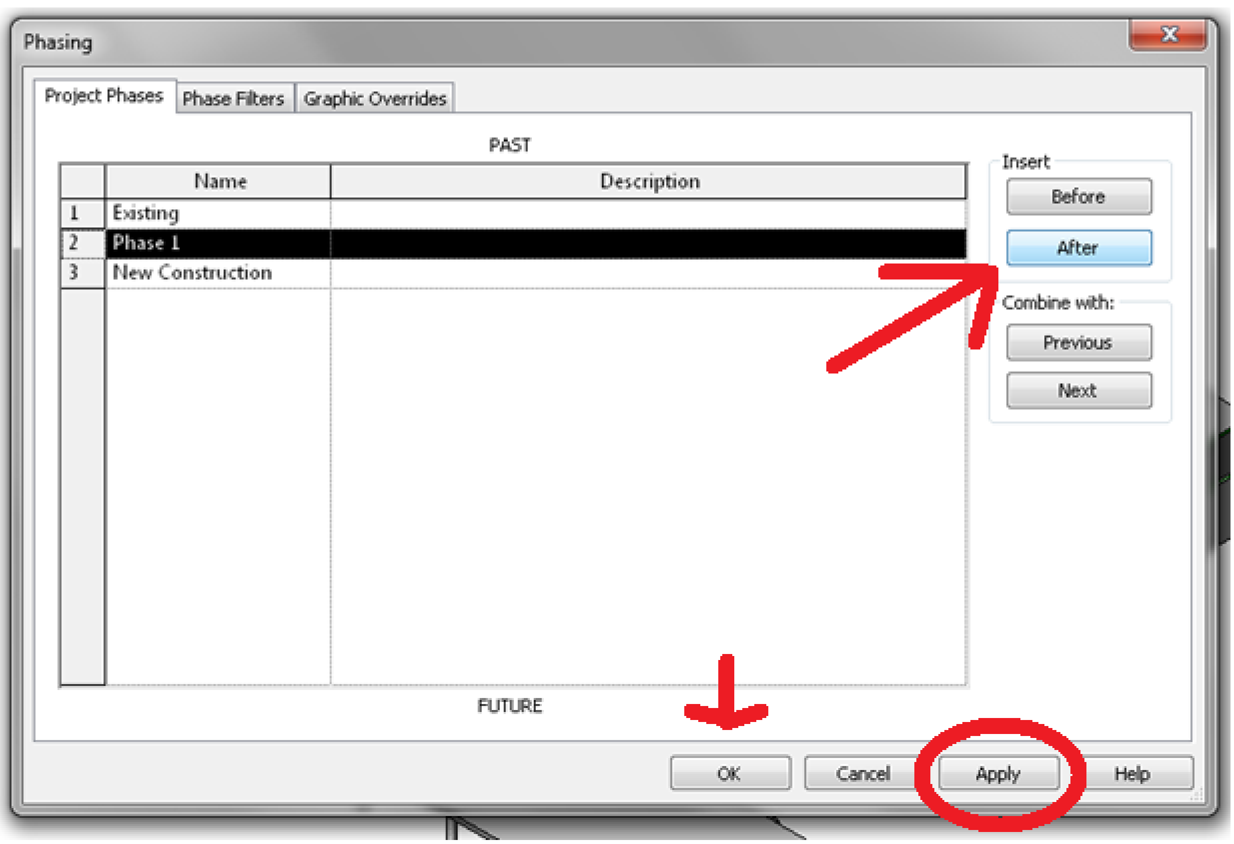
Click Manage Tab



Click Phases

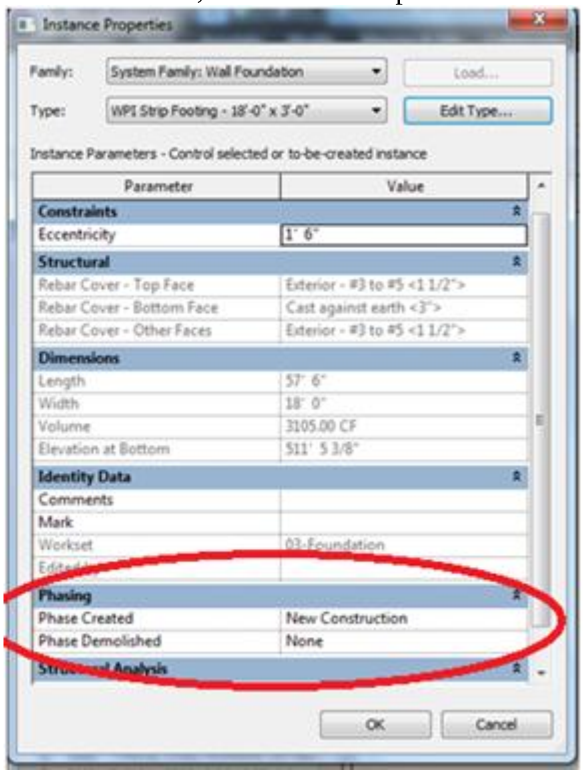


Add Phases, Apply, Click OK

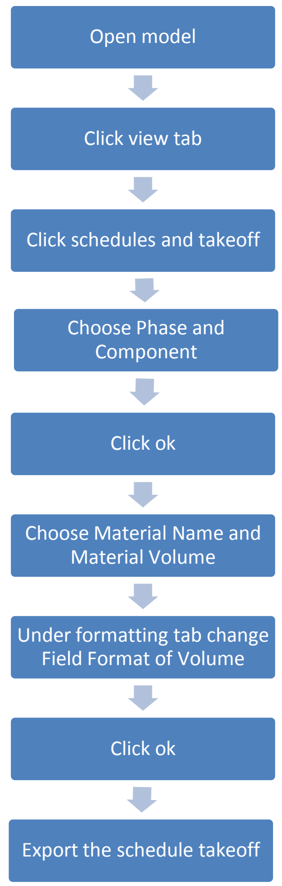


Adding Element to a Phase

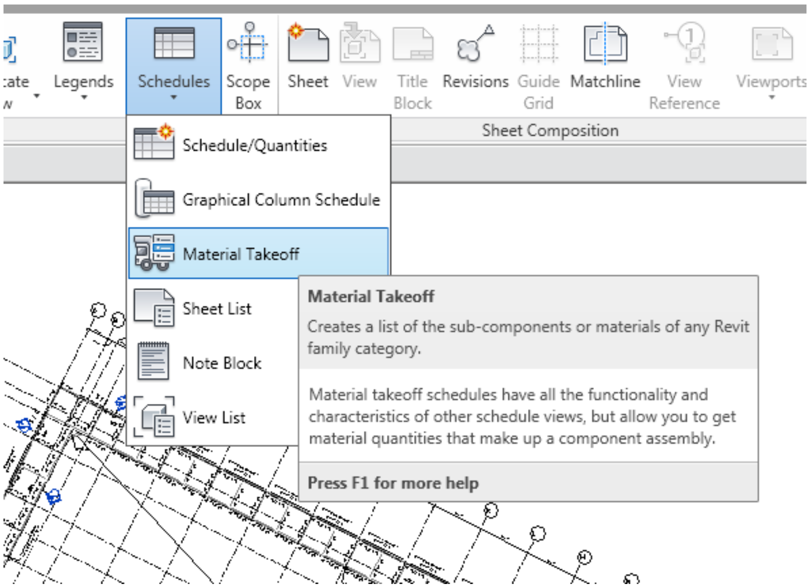
Choose Element, Alter Phase Properties



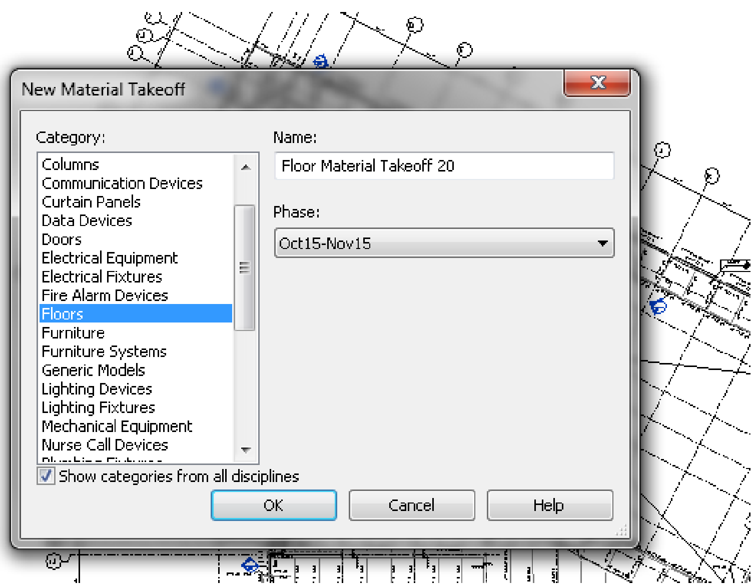
Quantity Takeoffs



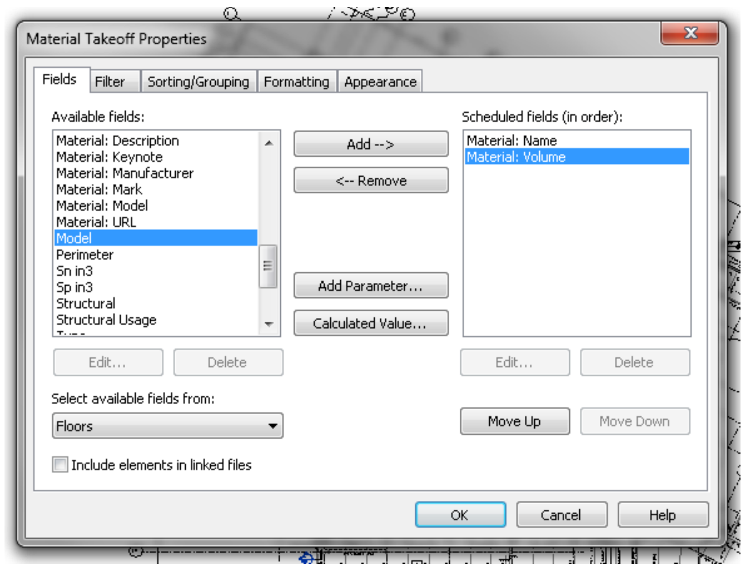
Click Schedules and Material Takeoff



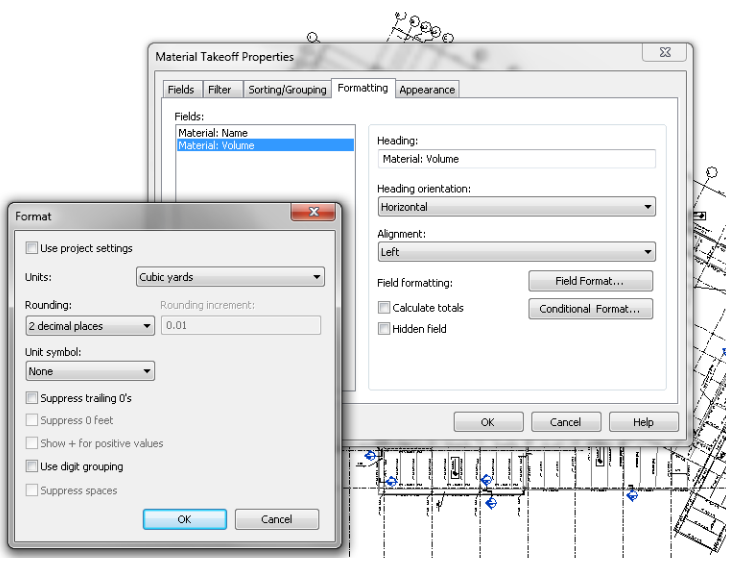
Choose Phase and Category



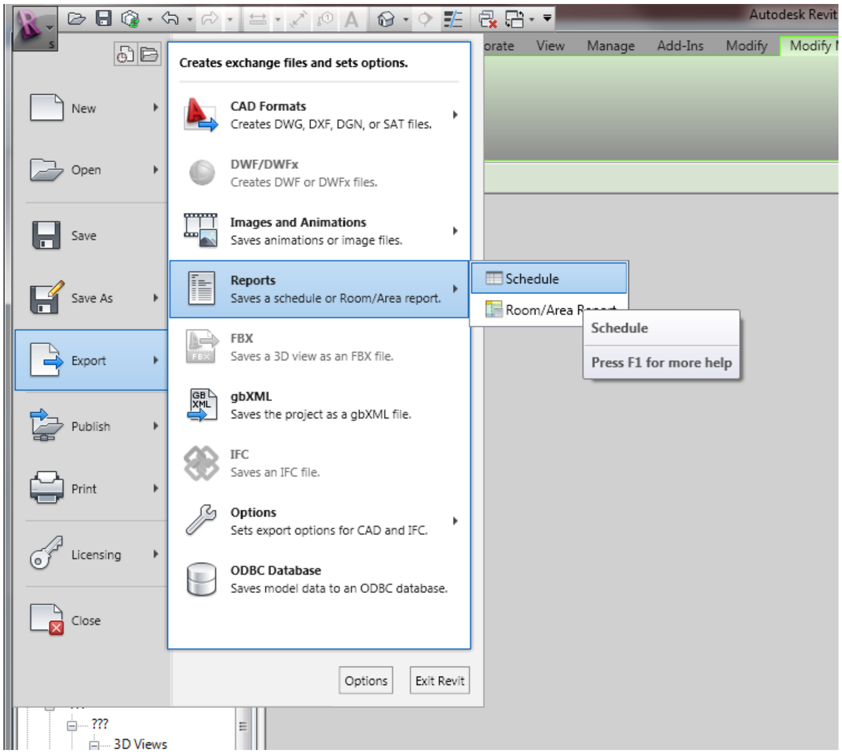
Add Material: Name and Material: Volume



Change the Units

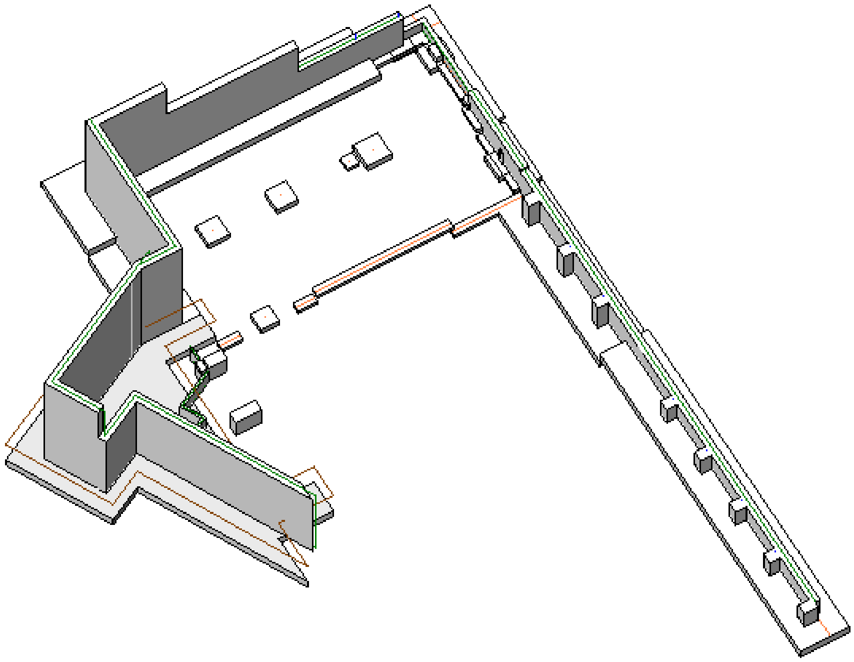


Export the Schedule Takeoff

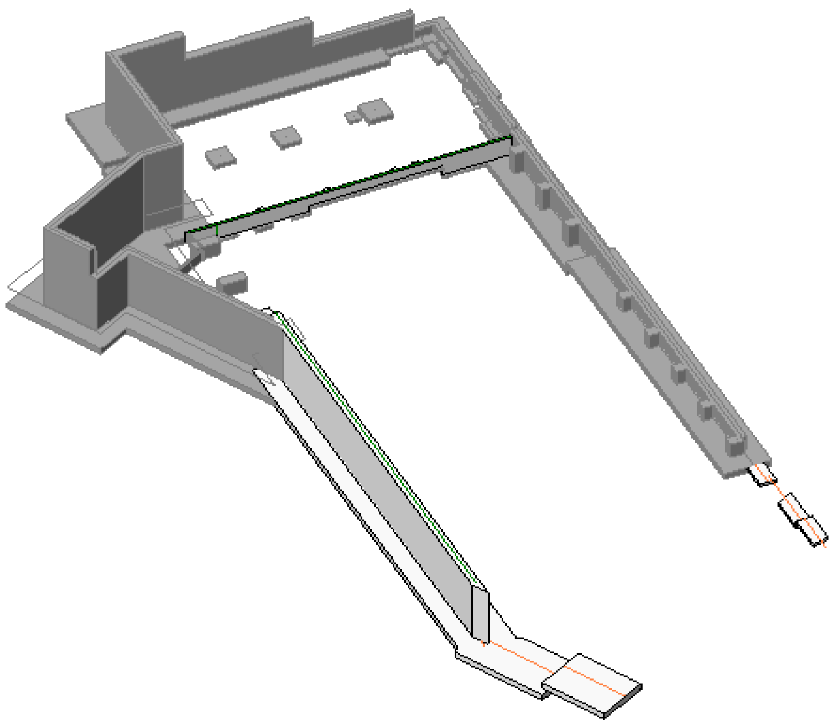


Proposed Phases

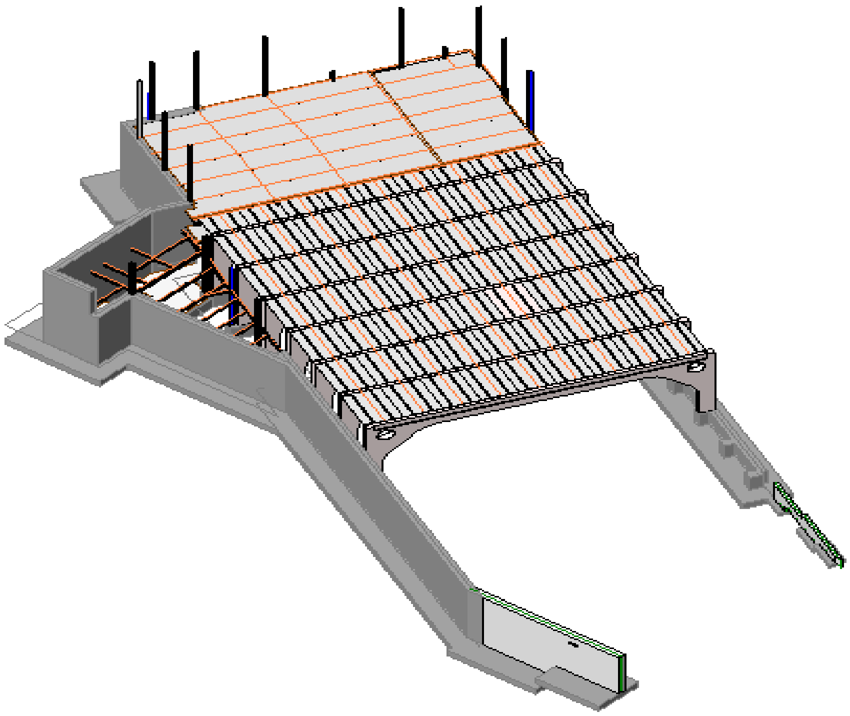
Phase 1: August 15, 2010 to September 15, 2010



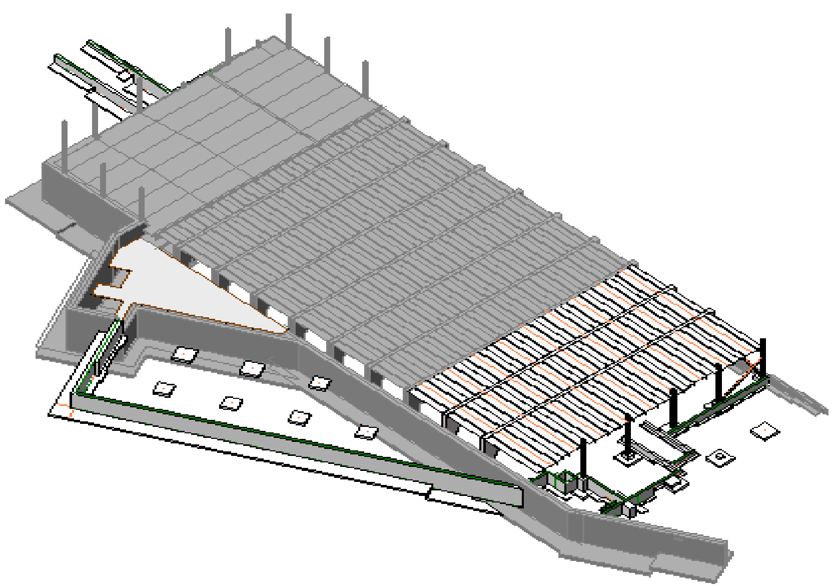
Phase 2: September 15, 2010 to October 15, 2010



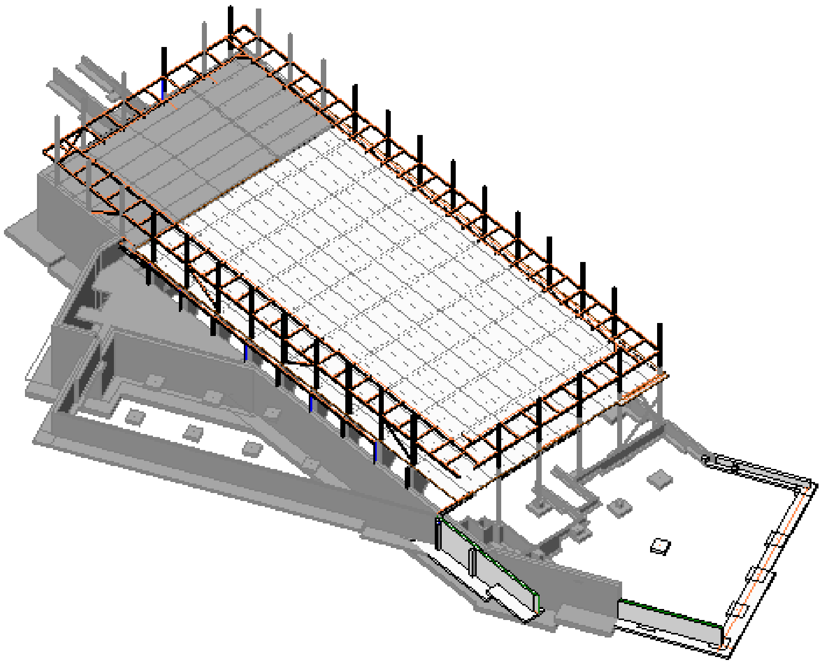
Phase 3: October 15, 2010 to November 15, 2010



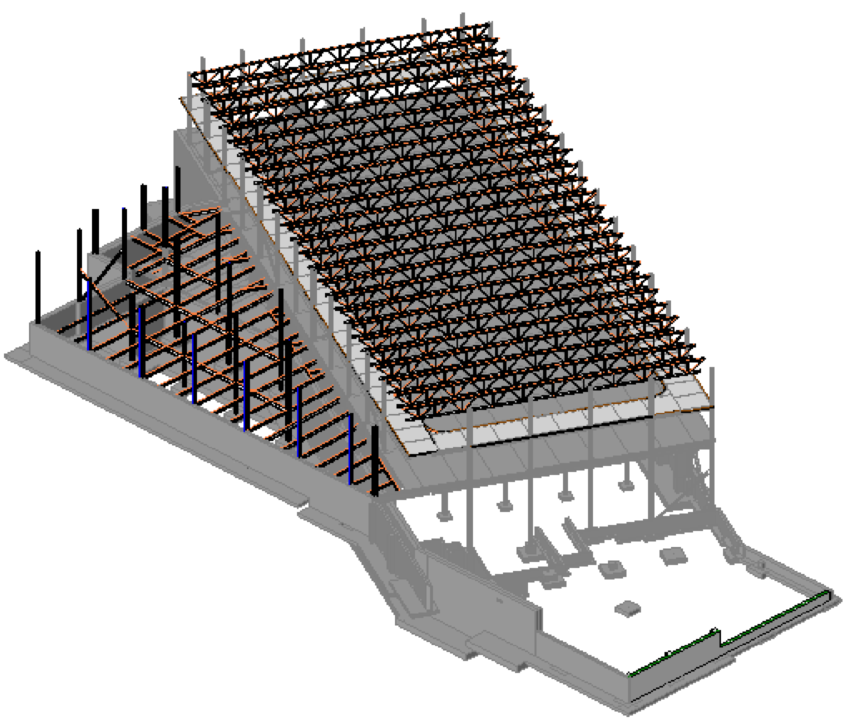
Phase 4: November 15, 2010 to December 15, 2010



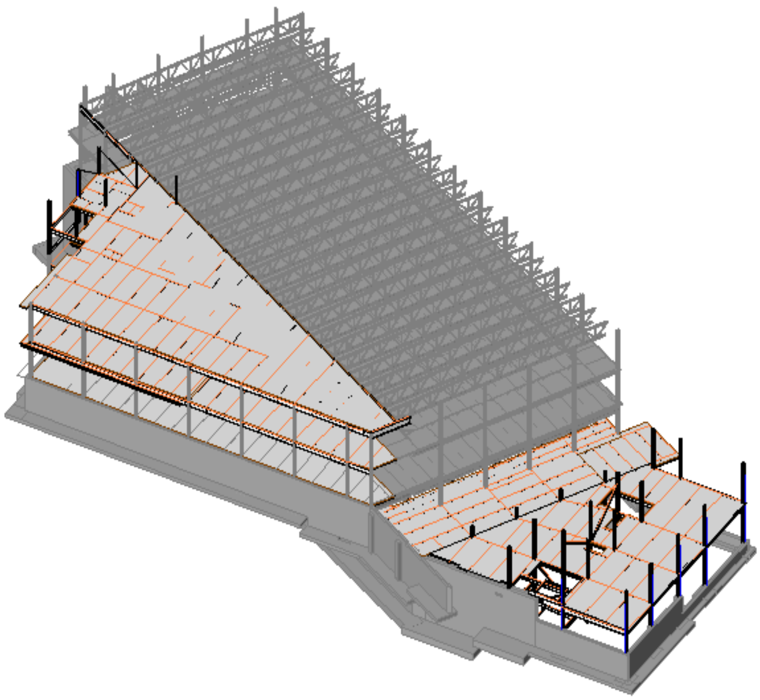
Phase 5: December 15, 2010 to January 15, 2011



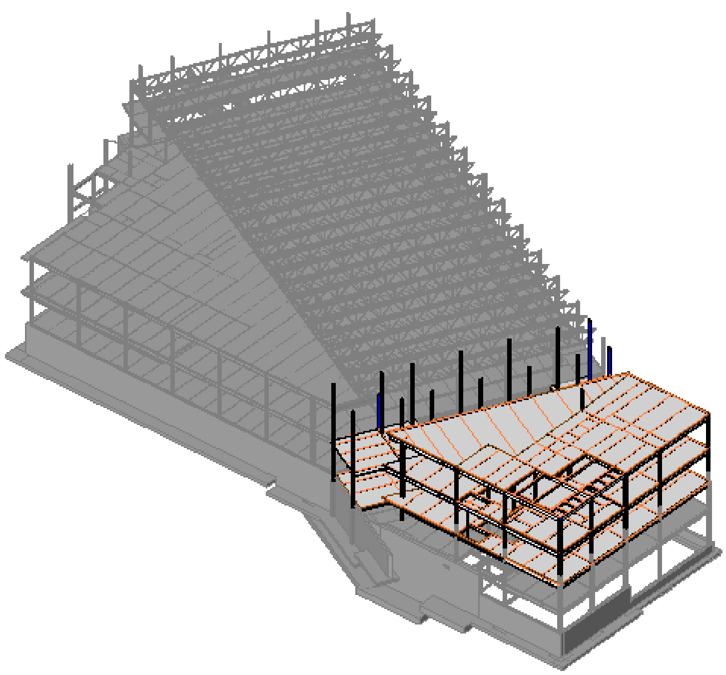
Phase 6: January 15, 2011-February 15, 2011



Phase 7: February 15, 2011 to March 15, 2011



Phase 8: March 15, 2011 to April 15, 2011

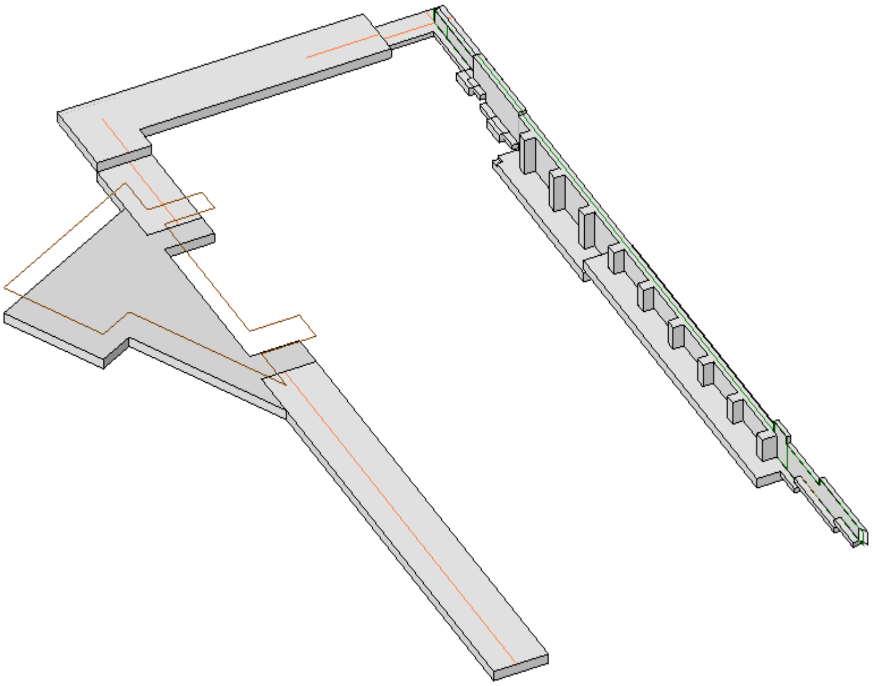


Phase Activity Breakdown

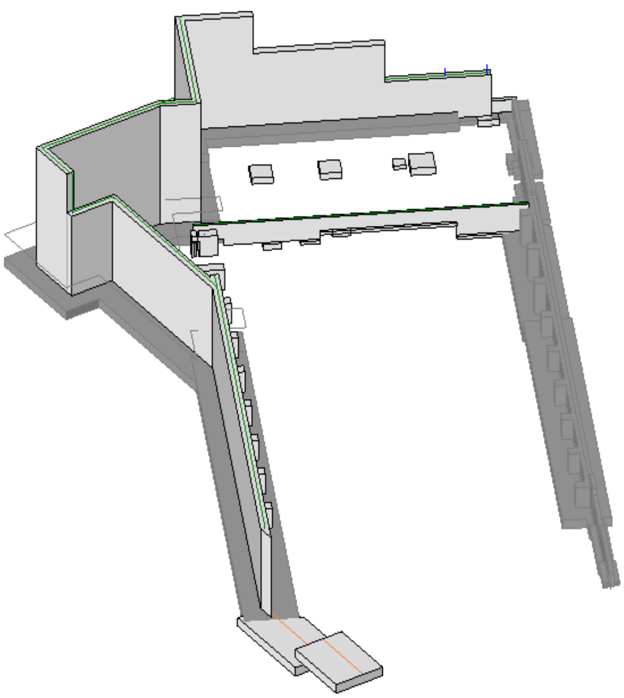
Phase 1	**Phase 5**
FOOTINGS AND RETAINING WALL AREA A	STAIR 3 AREA A
DEEP FOUNDATIONS AND CANTILEVER WALL A,B	COMPLETE DIAPHRAM SLAB AREA B
CONCRETE FOUNDATION AND RETAINING WALL A	COMPLETE STEEL ON TOP AREA A
CONCRETE FOOTING LINE 1 AREA B	FOOTING AND WALLS P-Q LINE
FOOTINGS D.5 LINE AREA B	FOOTING SECTION D
CONCRETE FOUNDATION WALLS LINE 1 AREA B	WALLS SECTION D
FOUNDATION WALLS A7-FF7	ERECT AREA B STEEL AND DECKING
PHASE 2	**PHASE 6**
COMPLETE FOUNDATION WALLS A7-FF7	COMPLETE WALLS SECTION D
COMMENCE MISC IRON WORK	SLAB ON GRADE 1ST FLOOR AREA A
FOUNDATION WALLS D5 LINE AREA B	COMPLETE STAIR 3 AREA A
FOOTINGS FF7-MM LINE	ERECT STEEL DECK FOR TRACK
FOUNDATION WALLS FF7-P LINE	STRUCTURAL STEEL AREA C
FOUNDATION WALL P-R	TEMPERARY ROOF AREA A
FOOTING P-Q	ROOF TRUSSES/DECK AREA A/B
FOOTING P-MN	
PHASE 3	**PHASE 7**
FOUNDATION WALL P-R	COMPLETE STRUCTURAL STEEL AREA C
START STRUCTURAL STEEL	ERECT AREA D STEEL AND DECKING
AREA A STEEL UP TO 4TH FLOOR	CONCRETE ON DECK AREA B
AREA A STEEL DECK 4TH FLOOR	CONCRETE ON DECK AREA B - TRACK
FOUNDATION WALLS P-MN	ERECT STAIR 4 FIRST FLOOR AREA A
ERECT PRECAST STRUCTURE AND T'S	CONCRETE ON DECK AREA C
ERECT STAIR 4 A.1	
PHASE 4	**PHASE 8**
COMPLETE PRECAST STRUCTURE AND T'S	COMPLETE ERECTION AREA D STEEL AND DECKING
FOUNDATION WALLS ON LOADING DOCK	ERECT STAIR 2 D-1
WALLS AND FOOTINGS AREA C	CONCRETE ON DECK AREA D
CONCRETE DECK AREA A	FRP AHU CONCRETE PAD 3RD FLOOR AREA D
STAIR 3 AREA A	SLAB ON GRADE 1ST FLOOR AREA D
CONCRETE DIAPHRAM SLAB AREA B	CONC ON DECK 4TH FLOOR, D-4
ERECT P LINE STEEL - AREA D FOR PRECAST	COMPLETE ERECT CANOPY STEEEL AND DECK
	CONC ON DECK @CANOPY STEEL

Actual Phases

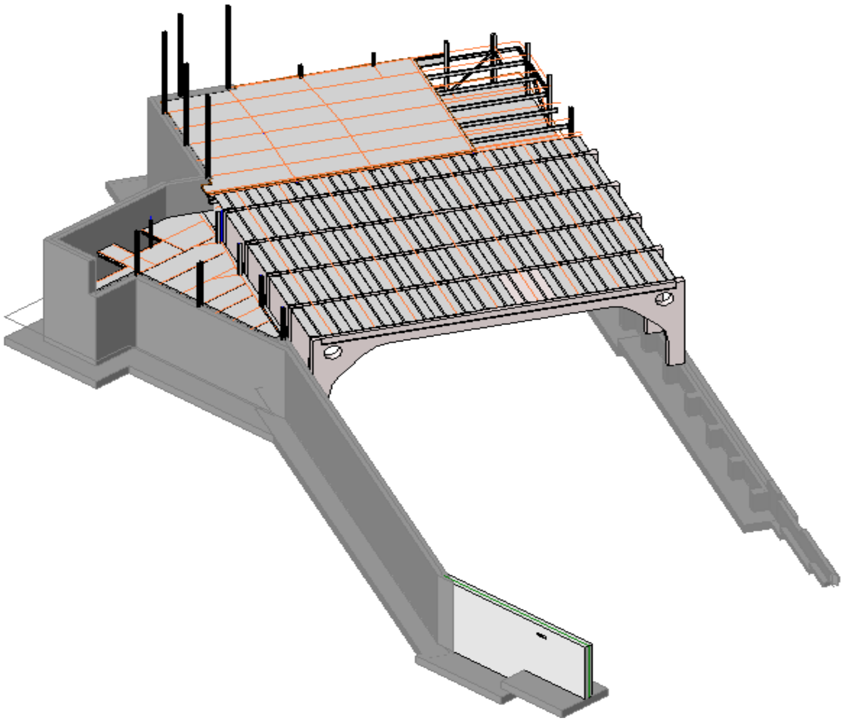
Phase 1: August 15, 2010 to September 15, 2010



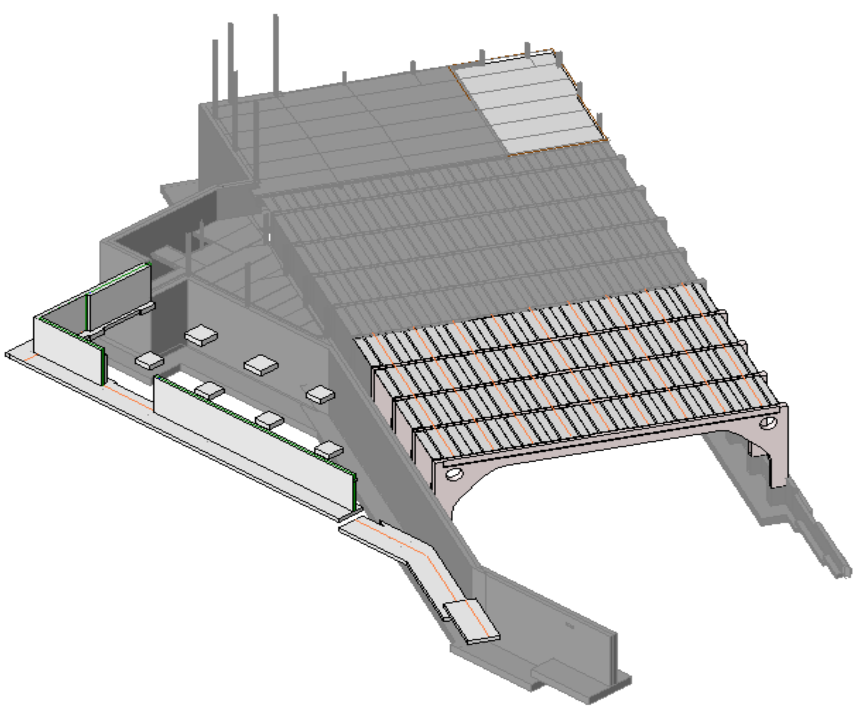
Phase 2: September 15, 2010 to October 15, 2010



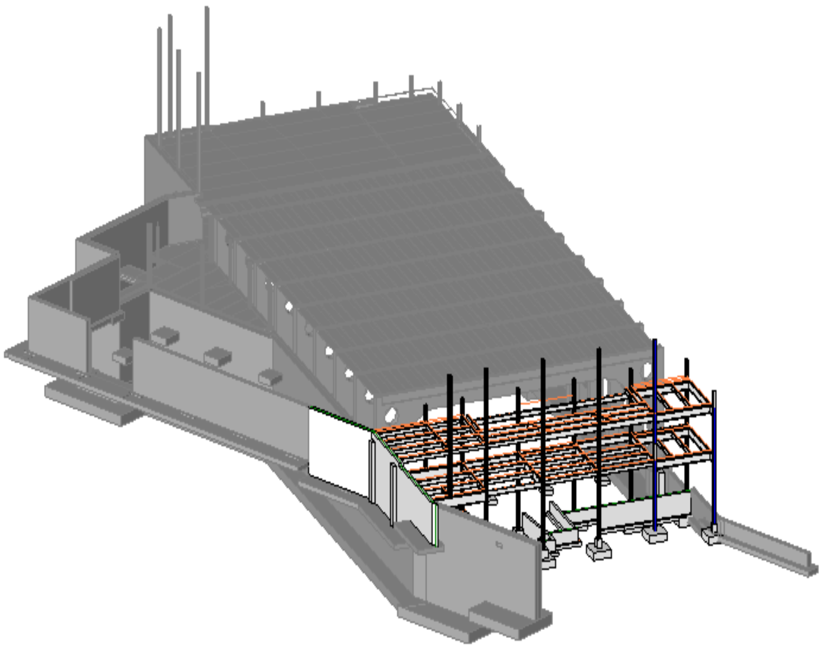
Phase 3: October 15, 2010 to November 15, 2010



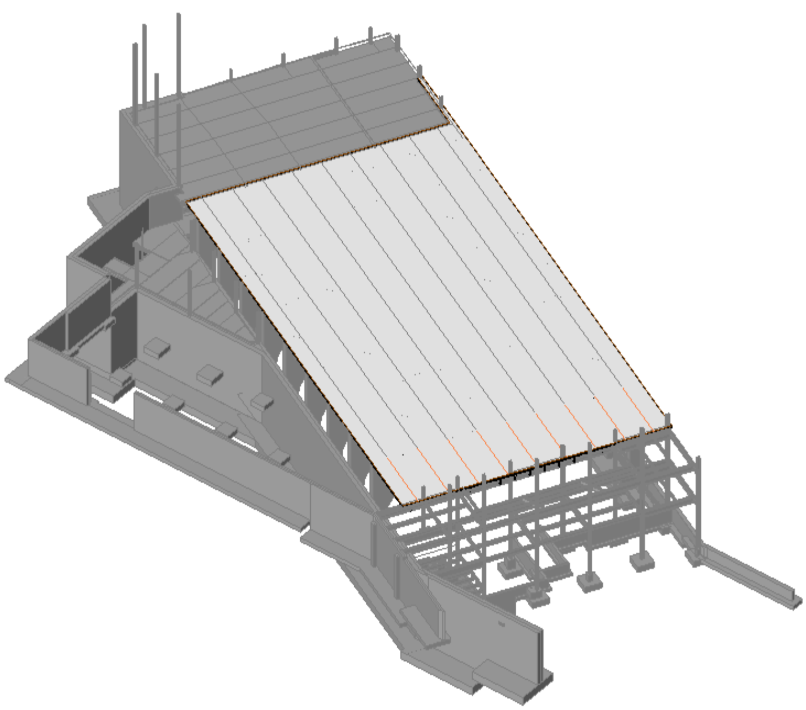
Phase 4: November 15, 2010 to December 15, 2010



Phase 5: December 15, 2010 to January 15, 2011



Phase 6: January 15, 2011-February 15, 2011



Appendix H: Design Constants and Calculations

Current Design for Current and Alternative Designs

Design Criterion Chart:

Design Criterion	Current Design
ϒ, Unit weigh of Concrete (pcf)	145
f'c, compressive strength (psi)	6,000
Design Load, (psf)	100
Modulus of Elasticity	4,463 ksi
Weight of Arch (kips/foot)	3.13
Dead Load (kip/foot)	7.09
Point Load (kip)	94.8

Design Criterion	Alternative Design
Design Load, (psf)	100
Modulus of Elasticity	29,000 ksi
Weight of Truss (kips/foot)	0.18
Dead Load (kip/foot)	2.95

Dynamic Response Comparison:

	Current Design 6 Hertz	**Current Design 9 Hertz**	**Alternative Design 6 Hertz**	**Alternative Design 9 Hz**
Deflection	0.697inches	0.697 inches	3.88 inches	3.88 inches
L /360	3.67 inches	3.67 inches	3.67 inches	3.67 inches
Natural Frequency	5.291 Hertz	5.291 Hertz	4.13 Hertz	4.13 Hertz
Frequency Ratio	1.13	1.70	1.45	2.18
DMF	3.56	0.529	0.90	0.27
Peak Response	2.48 inches	0.369 inches	3.49 inches	1.05 inches

Design Calculations:

Current Design

γ_w = 145 pcf
f'c = 6,000 psi
DL = 100 psf
Tw = 19'4"

87.83 yd³ of concrete per arch

$\Delta_{all} = \frac{L}{360} = \frac{110' \times 12''}{360} = 3.67''$

$E_c = 33 \cdot W_c^{1.5} \sqrt{f'c}$

$E_c = 33 \times 145^{1.5} \sqrt{6000\ psi}$

$E_c = 4{,}463{,}151\ psi = 4{,}463\ ksi$

$w = \left((100\ psf \times 19.3\bar{3}) + \left(\frac{87.83 \cdot 3^3 \times 145}{110'} \right) \right) = 5{,}059\ plf$

$w = 5.059\ klf$

$PL = 5.059\ klf \times (15.8761' - 2.5') = 67.7\ K$

From Risa-2D

Δ = 1.22"
fn = 5.2 Hz

$$DMF = \frac{1}{\sqrt{(1-r^2)^2 + (2r\xi)^2}}$$

$\xi = 0.02$

For 6 Hz

$r = \frac{6\ Hz}{5.2\ Hz} = 1.16$

For 9 Hz

$r = \frac{9\ Hz}{5.2\ Hz} = 1.73$

For 6 Hz

$$DMF = \frac{1}{\sqrt{(1-1.16^2)^2 + (2\times1.16\times0.02)^2}}$$

DMF = 2.88

Peak Response = 1.22" × 2.88 = 3.51" < 3.67"

For 9 Hz

$$DMF = \frac{1}{\sqrt{(1-1.73^2)^2 + (2\times1.73\times0.02)^2}}$$

DMF = 0.501

Peak Response = 2.88" × 0.501 = 1.44" < 3.67"

Alternative Design - Nodes every 10' and 6' high

DL = 100 psf
E = 29,000 ksi

W18 x 35 and W16x12 sections

22 x 35 lb/ft x 10' = 7700 lbs
12 x 35 lb/ft x 6' = 2520 lbs
11 x 22 lb/ft x 11.66' = 2822 lbs
13,042 lbs = $\frac{13.042 \text{ K}}{110'}$ = 0.13 klf

$\omega = \left(\frac{100 \text{ psf} \times 19'4"}{1000} + 0.13\right) = 2.06$ klf

From RISA-2D

$\Delta = 6.54"$
$f_n = 3.74$ Hz

For 6 Hz

$r = 6/3.74 = 1.60$

$$DMF = \frac{1}{\sqrt{(1-1.60^2)^2+(2\times0.02\times1.60)^2}} = 0.64$$

Peak Response: 6.54" × 0.64 = 4.19" > 3.67" (camber)

For 9 Hz

$r = 9/3.74 = 2.41$

$$DMF = \frac{1}{\sqrt{(1-2.41^2)^2+(2\times0.02\times2.41)^2}} = 0.21$$

Peak Response = 6.54" × 0.21 = 1.37" < 3.67"

Cost Comparison:

	Precast Concrete Arch	Steel Truss
Material Cost	215.08 dollars per cubic yard	2877.00 dollars per ton
Labor Cost and Equipment	47.32 dollars per cubic yard	672.67 dollars per ton
Total Cost	262.40 dollars per cubic yard	3549.67 dollars per ton
Amount of Member	87.83 cubic yards	10.1 tons
Cost Per Member	87.83*262.40= $23,046.59	10.1 * 3459.67 = $35,851.67
Cost of System	23,046.59* 9 = $207,419.31	35,851.67* 9 = $322,665.03