WPI Smart World Building Analysis and Alternative Design

A Major Qualifying Project Proposal
submitted to the faculty of

Worcester Polytechnic Institute

in partial fulfillment of the requirements for the
Degree of Bachelor of Science in Civil Engineering

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Abstract

This project provides an analysis of the earned value and design of WPI's Smart World Building. This was done by analyzing the building through its design process, following the construction of the building, and researching alternatives to the design. By reviewing the implications of design choices and weighing potential changes to the design, this project was able to show the impact of construction project management decisions on the building. Examining this is beneficial to the industry because it provides insight on the impact of design choices and construction decisions.

Acknowledgements

We wish to show our appreciation and gratitude to the significant individuals who assisted in the completion of this Major Qualifying Project. We would like to acknowledge the support of Consigli Construction Company, Inc. for providing the WPI Smart World Building as a learning laboratory for this project. thank We are grateful for the key individuals that provided us with extensive insight throughout the construction process: John Lehane, Justin Billings, Caroline Meyer, Stephanie Jones, and Blake Hill. We would like to express our thanks to our advisor Professor Leonard D. Albano for his constant guidance and support throughout the process of this project. We would also like to acknowledge Professor Walter T. Towner for his support on the axiomatic design and time value money analysis of this project.

Authorship

All members of the team equally contributed to the creation of this report, including research, writing, and editing. The breakdown for major contributions is as follows:

Kayla Baez:

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Executive Summary

The goal of this Major Qualifying Project (MQP) was to investigate the design and construction of the WPI Smart World Building and recommend improvements for each aspect analyzed. An earned value analysis (EVA) was conducted to provide feedback on the management of the project by the Consigli Construction team. The EVA is a project management tool used to measure a project's progress in terms of its time and budget. Using work reports, daily logs, requisition summaries, and project schedules, the EVA was created to analyze the project's actual scheduling and budget to determine whether they were on schedule and within their budget.

A time value money analysis (TVM) was conducted on the WPI Smart World Building using the project's net present value (NPV). This allowed us to reflect the return on investment (ROI) that the project would incur for WPI's initial investment. In addition, a constructability analysis focused on three major issues the general contractor faced during the construction process. There were complications regarding their curtain wall system, their brick façade, and the removal of contaminated soil from the site. Suggestions were made on how to better solve their problems in each situation, including an analysis of a design alternative for their brick façade. The safety protocols enforced by Consigli Construction were also investigated. Our team analyzed the effects of these precautions on the project, the supervision of the standards, and their effectiveness at promoting health and wellbeing.

A design analysis was performed to measure the overall building performance in terms of energy usage, daylight access, and HVAC system performance. Using the results from each analysis, recommendations for improvements were made to enhance the building performance. To further analyze the construction process, a building information model was created to

visualize how the different phases would come together. With this 5D model, recommendations were made to potentially fast track the schedule and lower costs.

To eliminate wasted time on our project, an axiomatic design tool was used. Once our team determined the direction of our project based on the sponsor's needs, the axiomatic design broke down every component of the project to show us exactly what our project entailed and allowed us to divide work up accordingly.

Capstone Design Statement

This project focused on the analysis of the WPI Smart World Building throughout the design and construction process. An earned value, design, and constructability analyses were performed on this building in which we assessed the project as a whole and made necessary recommendations for improvement. This project also included the investigation of a design alternative for the brick facade along with an application of axiomatic design. As a capstone design experience, this work acknowledged the economic, environmental, sustainability, constructability, safety, and ethical/social aspects for the design alternative and for the recommendations made during the analyses.

Economic

This report examined the project's budget throughout construction and looked at how the budget progressed, which showed us the financial completion of the project. An earned value analysis was completed based on the monthly requisition summaries, which we used to create correlations to show how the overall project was progressing. A time value money analysis was conducted using the net present value; these results showed us that the initial investment would incur revenue to hit a break-even point and bring in a positive return on investment.

Environmental & Sustainability

This report analyzed the environmental challenges faced with the removal of contaminated soil during construction. Finding appropriate landfills, meeting regulations, and satisfying safety hazard standards was a major operation due to the high arsenic levels in the soil of Worcester County. This report also explored potential ways to reduce the building's energy consumption and improve performance, such as alternative window designs and the installation of roof solar panels.

Constructability

During construction, the project managers faced many setbacks due to COVID-19 such as the lack of resources and personnel available. This impacted many decisions such as the curtain wall system, brick façade, and soil removal. This MQP proposed changes and refinements to the design that would benefit the construction process and provide better access given the many setbacks. This project also incorporated a Building Information Model (BIM) in which communication between subcontractors and project managers would improve. The BIM allowed for better visualization of the construction process and assisted with any recommendations and changes.

Safety

This project reviewed Consigli's site construction safety plan and their site specific COVID-19 plan in order to analyze their effectiveness and applicability. The construction began before the onset of COVID-19, therefore they had to adapt to new regulations as they were added and updated. An evaluation of the safety requirements and reports was conducted; it was found that the safety conditions were satisfactorily met with few safety violations. The effectiveness of the safety program showed our group the importance of properly developing a safety program for a project in order to prevent injury.

Ethic/Social

This project allowed us to gain real-time experience in project and construction management. Our team was permitted to sit in on their weekly Owner-Architect-Contractor (OAC) meetings and also gained access to their construction management program, Procore. We reviewed legitimate design plans, field reports, inspection reports, and official documents for the construction of WPI Smart World Building; the building aims to create a learning environment for students and researchers. We took into account social factors and the needs of the intended users during the design analysis. This experience allowed us to become more innovative in our critical thinking and gain insight on what a career in construction management truly entails.

Professional Licensure Statement

A professional engineering (PE) license is a legal requirement for an engineer to prepare, sign and seal, and submit engineering plans and drawings to an authority having jurisdiction or client. The act of stamping a drawing means that an engineer is accepting responsibility for their work and anyone who would be affected by their work. In addition, a PE license acts as client assurance that the engineers contracted work will follow all professional and ethical standards a civil engineer is subject to under local, state, and federal law. A PE license is often required by employers in the field of civil engineering due to its importance as proof of competency. To acquire a PE license, it is necessary to obtain a bachelor's degree in civil engineering from an institution with an accredited program. After receiving a degree, the engineer will need to take the fundamentals of engineering (FE) exam. The FE exam is intended for recent graduates and draws its questions from all areas of civil engineering. Once the exam is passed, the engineer becomes what is known as an engineer in training (EIT). An EIT spends four years under a PE licensed engineer after which they are allowed to take the PE exam. In addition, a review of their work as an EIT is done as part of their application. If the EIT passes the PE exam, they will then become a Professional Engineer. Due to its importance in the field of engineering, a PE license has several implications for this project. As stated, a PE license serves as a proof of competency and that the licensed engineer is accepting full responsibility for the project.

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Abbreviation List

BIM - Building Information Modeling

CN - Customer Needs

CON - Constraints

DP - Design Parameters

EIT - Engineer in Training

EVA - Earned Value Analysis

FE - Fundamentals of Engineering

FR - Functional Requirements

MQP - Major Qualifying Project

NPV - Net Present Value

PE - Professional Engineer

PV - Process Variables

ROI - Return on investment

TVA - Time Value Money Analysis

WPI - Worcester Polytechnic Institute

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1.0 Introduction and Problem Statement

Worcester Polytechnic Institute (WPI) has been experiencing a consistent growth in student population in the past decade, which the school has promoted and encouraged. However, this exposes a problem in which more students require additional academic and residential facilities. Consequently, WPI has also been pursuing major construction projects and land acquisition. Recent buildings and projects include the 2018 Foisie Innovation Studio and Messenger Hall, the 2013 Faraday Hall dormitory, and their newest project Smart World.

The current construction of the WPI Smart World allows for a unique opportunity for our team to analyze its construction process and the relationship between design and construction decisions. Construction projects are a complex, coordinated effort with many different professional disciplines involved throughout their lifespan. The construction and design of WPI Smart World has experienced numerous changes throughout its construction lifetime. The project began construction in October 2019 and was originally slated for completion before the 2021-22 school year. The impact of the COVID-19 pandemic has heavily affected the execution of the construction operations for the building, distorting the original planned costs and timeline. Through the use of this building, the school is actively investing in the future of engineering education for their students. The scope, challenges, and importance of the WPI Smart World makes it a great research project for students.

2.0 Objectives

The scope of this project is to examine the building's design and construction progress through the lens of project management. We have conducted an earned value analysis, a design and constructability analysis, and have developed potential alternative design choices for the building. Through researching the construction of the building through financial, engineering, and management perspectives, our MQP team has been able to better understand the complexities and processes of a construction project.

2.1 Project Management

Our MQP consisted of using a variety of project management tools to evaluate the Smart World construction project. Using tools like an earned value analysis (EVA) and time value money analysis (TVA), our objective was to be able to analyze the performance of the project at any given point and time using EVA while being able to use the TVA to find out the return on investment of the project. Finally, we used an axiomatic design to plan out our MQP. The objective of the axiomatic design was to break down our MQP's main components and to fast-track our schedule as we progressed through the project.

2.2 Construction Management

Our team collaborated with Consigli Construction for first-hand experience of what career in construction management entails. Our objective was to conduct a thorough review of their construction process by examining the ways they resolved their issues and presenting our own recommendations when possible. Through analyzing the most prominent issues they faced during construction, we checked for schedule impacts, cost impacts, and the effects of COVID-

19 on their progress. Our objective for the design alternative was to create an alternate solution for the brick façade that would have potentially met their required specifications and fit their construction timeline. Our objective for their safety protocols was similar to the analyses, in which we reviewed their multiple safety plans dealing with on-site construction and COVID-19 impacts.

2.3 Building Information Modeling (BIM)

Our objective with BIM was to create 3D and 5D models, which were used to visualize and analyze the design of the building. Using tools such as an energy analysis and daylighting analysis, our team researched how certain design elements affected the overall use and purpose of the building. With the 5D model, our team reviewed how the schedule and cost changes were impacted by project collaboration. Using BIM, our team proposed a solution to minimize on-site complications and promote a more efficient way of communication.

3.0 Methods

The goal of the project was to analyze the WPI Smart World's design and construction progress. To accomplish this, our team split our focus into three main objectives: project management, construction management, and building information modeling. An earned value analysis was conducted to determine how the project was performing based on logistical factors such as scheduling and budgeting. A constructability analysis evaluated how Consigli Construction responded to issues that arose during construction, including a design alternative that was developed for the building's brick façade. The design analysis explored different aspects of the design to optimize building performance using building information modeling. The safety protocols used during construction were analyzed to determine how well the project adhered to national safety standards. To ensure that the report was developed in accordance with the goals of the MQP team an axiomatic design methodology was used.

3.1 Earned Value and Time Value Money Analyses

To calculate the EVA, our team found and documented the projects's planned value, manpower, associated cost of work performed, budgeted cost of work performed, cost of work scheduled, and time variance. The team was given access to the following documents from Consigli Construction: requisition summaries, activity flow analysis, GMP summary, design development (DD) budget, and project schedules. In addition, the team was given access to Procore, a construction project management platform used by Consigli Construction. Using information found within the documents listed above, our team used the equation feature within Excel to determine the time variance per month. Within Excel a visual was also created which compared the manpower, actual cost, and the original schedule of the project.

The requisition summaries were used to determine the cost per month, percent financial completion, and planned value. These were then placed into an Excel spreadsheet that showed these values from November 2019 to January 2021. The manpower hours were found within the Procore platform. To find the total manpower, the report conditions were modified to show the total man hours per month by selecting the date range for the start and end of each month. To find the monthly percentage of manpower, the monthly values were divided by the total amount. The budgeted cost of work scheduled was calculated and implemented into the Excel spreadsheet as a percent value. Then, the manpower percentages, percent financial completion, and budgeted cost of work scheduled were plotted on a graph that showed their progression over the project's timeline. The time variance was found by subtracting the budgeted cost of work scheduled, from the percentage manpower per month. Using these values and figures, our team analyzed the WPI Smart World timeline and financials to determine how well the project was performing in accordance to its planned budget and schedule.

To calculate the TVM of WPI Smart World, we first established the variable values of the equation. Since we do not know the exact amount of revenue the building will generate once it is completed, we defined an estimated value that we all agreed upon to reflect how much the building will generate once it is open. Given that the building will be home to a lot of labs, we believe lots of revenue will be generated to research and project funding, and think a substantial benchmark would be $8,000,000(C) per year for revenue. Even though the valuation that is specified in the FY 2020 report for sponsored awards for projects and research, states that WPI Smart Worlds initial gain is about $6,000,000(Office of Vice Provost for Research, 2020). Since the trajectories of awards and sponsorships being donated to the school is on a steep incline we believe that amount of $6,000,000 could easily reach $8,000,000 by the time WPI Smart World opens its doors. Next, we needed to decide upon an interest rate to reflect a discount rate of the revenue; we decided a rate of 8% would be suitable to reflect a substantial growth over the years. Finally, a spreadsheet was created with these values and using the excel functions for NPV we are able to calculate the progress of the investment. Using the values calculated by each year, we are able to find which year they break even on the investment to start bringing in positive income on the project.

3.2 Constructability Analysis

Our team looked into two major value engineering applications during construction: the brick façade and the curtain wall systems. We also examined the issues the general contractor faced surrounding the removal of contaminated soil. We researched the original plans for each instance using meeting notes, reports, and additional information provided to us from Consigli Construction and through their construction management software Procore. We evaluated the problems they faced, their approach to a new plan, and their final solution.

For the curtain wall, our team examined their original system, the obstacles presented in the initial plans for installation, and how Consigli Construction resolved the problem with an alternate system. We assessed the design changes made to the original curtain wall system and their installation timeline. We also explored the problems they faced after installation and options for how they can improve on their systems.

For the brick façade, our team explored how the original Endicott brick was not a viable option and the reasons behind Consigli's decision to use the Belben brick. We assessed their initial comparisons of the original Endicott brick versus the alternative options: the Belden brick, the Cloud Ceramic brick, and the Yankee Hill brick. We analyzed their specified comparisons of the Endicott brick to the Belden brick and their through-body comparisons of the Belden brick options.

For the soil removal, our team assessed the contaminated soil of Worcester county and how its high arsenic levels created a challenge in finding suitable landfills. Through Procore, we reviewed their daily reports to gain information on the volume of soil they removed with each truckload and how much time was spent on transportation. We also reviewed different landfill rules restrictions to assess the general contractor's solution to removing the soil.

3.3 Design of Alternative Brick Façade

Our team investigated various solutions to the problem presented by the brick façade during construction and chose a new design alternative. We researched the original design plan for the brick façade, referencing initial construction documents and specifications. We documented the decision-making process for the original plan, along with Consigli Construction’s final solution to the brick façade. Our team then analyzed the design alternative chosen for the brick façade and suggested a new alternative. The meeting notes, RFIs, change orders, and reports provided us with the information necessary to fully assess the requirements needed for this change.

3.4 Design Analysis

The design analysis explored how the building was designed and why those design choices were made. Our team deconstructed the building into its individual parts and created a model using Revit software. The 3D model created using building information modeling (BIM) gave an accurate representation of what is being constructed on-site. The construction drawings were used as a base for creating the model. In addition, references to any change orders and bulletins were directly applied to the model. With the 3D model completed, the building efficiency was determined using the energy analysis feature within Revit. Our team reviewed the analytical results and made necessary changes and recommendations to qualify for a net-zero status. A lighting analysis was also performed to determine the amount of natural light that enters the building throughout the day. This analysis enabled us to determine whether the current building orientation and design is optimized for natural lighting.

Once a thorough analysis was completed for the 3D model and all necessary recommendations were made, our team created a 5D model using BIM. We gathered information on the project phasing, sequencing, schedule, and costs. This information came directly from Consigli Construction. Since access to some of these documents was limited, the 5D model was an estimate and close representation of the design. With the project milestones and phasing, we divided the 3D model into its respective sections and assigned its associated timeline with each phase. With sequencing in place and organized to represent real-time construction, each phase was further broken down into the CSI divisions and matched up to the current project schedule. We exported the Revit file into Navisworks to create a visual representation of the project schedule. Adjustments to the schedule will be necessary as the project continues. Project costs were added to each of the phases to also allow for visual representation and easy tracking of how the project costs were distributed throughout the duration of the project. This 5D model gave us a complete analysis of all the elements of this building and helped to assess how to best improve and refine the design of the building.

3.5 Safety Protocols

To assess the efficiency of the construction site safety plan, our group analyzed the published safety program that Consigli Construction implemented on its site. We looked at the precautions taken in the site safety program, compared them to what the state workplace safety and health program regulations require, and assessed the level of safety and risk that the plan accounts for (Mass.gov, 2021). Critical to assessing the protocol is to view the field reports from on site inspectors. These reports gave us insight into the reality of the safety program, as we can see how it was being enforced, if the standards were being met, and aided us in determining whether there are any gaps in the plan that needed to be addressed. Additionally, due to the onset of COVID-19, a site-specific safety plan was implemented during construction. This was analyzed to see what the plan encompasses, how it compares to state requirements, and if it is effective at keeping the personnel safe from the virus (Mass.gov, 2020).

3.6 Axiomatic Design

An axiomatic design decomposition was created to eliminate wasted iterations of figuring out what our project goals were. The methods associated with the axiomatic design started by establishing what the CNs were. The way we went about this was by meeting with the team to recap what was discussed during meetings with the sponsor, and from that, the team determined what the sponsor wanted to see. It was determined that most of what the sponsor asked of us was that they wanted to see multiple types of analyses that dealt with different areas of focus within the WPI Smart World Project. Once that was determined, we then moved on to breaking down the project into the FRs and DPs where the FRs were the goals that needed to be achieved, and the DPs were the methods associated with fulfilling the FRs. The method behind how the FRs and DPs (zig-zag mapping method) interact with one another is depicted in the figure below:

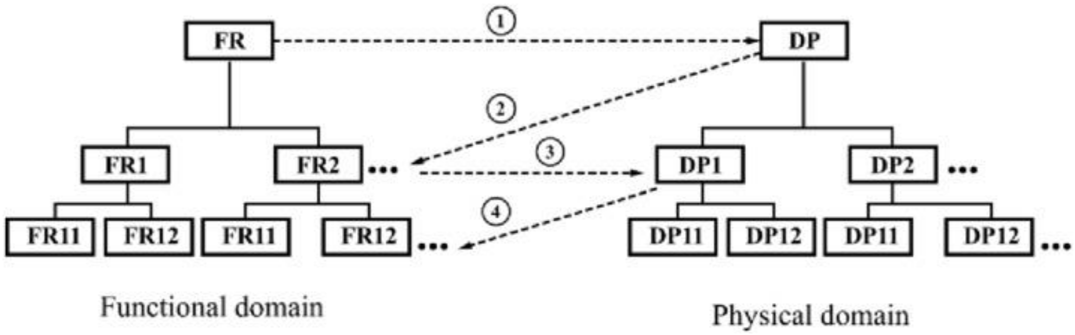


Figure 3.1: Axiomatic Design Flow of FRs and DPs

Finally, the team re-convened and discussed the matrix along with what specifically needed to be done. From here, as a team we addressed the constraints (CONs) which were to be used in order to execute the project and fulfill all requirements needed to complete it. Since the axiomatic design decomposition was not based around the design of a physical project we decided PVs were not necessary to the project.

3.7 Conclusion

The goal of this project was to provide a thorough report of the design and construction process for WPI Smart World. The earned value analysis tracked the progress of the build, and was used to point out areas that may be ahead/ behind of schedule, or over/ under budget. The constructability analysis monitored the construction process and was used to assess problems and complications within the build, to then suggest alternative solutions. The design alternative focused on one of the major project setbacks, and proposed an alternative design that would avoid any further complications. The design analysis reviewed the project as a whole and researched ways to optimize the design of the building. The safety protocols used on the construction site were also monitored and reviewed for maximum efficiency. The axiomatic design assisted with the creation of this report and assured that each goal and objective was met.

4.0 Earned Value and Time Value Money Analyses

An Earned Value Analysis is a management tool used to determine whether a project is progressing on schedule and within budget. To develop the EVA, our team analyzed data from the project's requisition summary and project scheduling documents, and determined the following elements: associated cost of work performed, budgeted cost of work performed, cost of work scheduled, and budgeted cost of work scheduled. This allowed our team to determine the performance of the project in terms of schedule and budget at any given point of time.

4.1 Background

In project management, a project's performance is based on its schedule and budget. An EVA is used to calculate whether or not a project is performing well in accordance with the pre-planned schedule and budget. There are three possible states for a project's schedule and budget; under, meeting, or exceeding the planned amount. It is ideal for a project to be under budget and ahead of schedule. This is ideal because it means that less expenses were incurred than were planned; therefore, there is extra money left over. A project that progressed faster than planned, means there is room in the schedule in the event of a delay. A project that exceeded its planned budget and schedule means that the company will need to use added time and money to see the project completed, which could lead to a loss in profit. Delayed projects can cause important deadlines to be missed with financial penalties, and reflect poorly on the company. An EVA calculates two end values to determine the associated cost variance and time variance. If a time variance is a positive number, it means that the project is ahead of schedule, a negative value means it is behind schedule, and a value of zero would signal that the project is exactly on schedule. If a cost variance has a positive value it means the project is under budget, a negative value means the project is above budget, and a value of zero means the project is on budget (Cullen, S. W 2016). An EVA is an important tool as it allows for determining whether or not a project team needs to take action to bring a project back on track and on budget.

4.2 Earned Value Analysis of Smart World

The EVA allowed our team to determine Consigli Construction's effectiveness in keeping the project both on budget and on schedule. With the cost and time variances available from November 2019 to January 2021, the team was able to use them to measure the progress of the project towards completion, and observe if the project was on budget and on schedule, or if steps needed to be taken to bring it back on track. As seen in Figure 4.1 the cost variance was negative at the first monthly benchmark, becoming positive at the fifth month benchmark where it stayed positive for the rest of the project's monthly benchmarks. Hence, during the beginning phases the project was over budget until July 2020 where it began to become increasingly under budget as shown by the increasing cost variance. This trend is seen in Figure 4.2 by comparing the orange line which represents the budgeted cost for work performed in the form of manpower percentage, to the blue line which represents the percent financial completion. The orange line is at first below the blue line only to rise above it as time goes on starting at the fifth month. This shows that Consigli Construction was able to effectively manage their project to bring it from being over budget to under budget.

Table 4.1: Cost and Time Variances

Month	Time Variance	Cost Variance
1	-6.48%	-1.18%
2	-7.49%	-1.15%

3	-6.96%	-0.37%
4	-6.14%	-1.25%
5	-4.79%	0.90%
6	-4.82%	1.92%
7	-3.83%	2.76%
8	-0.81%	5.42%
9	4.38%	9.76%
10	9.86%	14.79%
11	15.70%	18.48%
12	22.30%	24.73%
13	29.69%	31.77%
14	37.19%	42.71%
15	33.81%	42.78%

As for the time variance at the first month as seen in Figure 4.2 the value was negative at the first benchmark and did not become positive until the ninth month, which it stayed for the rest of the project's timeline. Hence, during the beginning phases the project development was behind schedule at November 2019 and would continue to be behind until July 2020. However from July 2020 onwards the project's time variance only grew larger meaning that it was ahead of schedule for the past several months and based on this trend will continue to be ahead of schedule for the remainder of the project.

Consigli Construction was able to effectively manage the project until it caught up to the planned timeline and eventually went ahead of schedule. This trend is seen in Figure 4.2 by comparing the orange line which represents the budgeted cost for work performed in the form of manpower percentage to the grey line which represents the budgeted cost of work schedule

(BCWS) for the original schedule. During the early phase of the project, the orange line was below the grey line however, over time the orange line rose above the grey line at the eight month mark. This shows that Consigli Construction was able to effectively manage their project to bring it from being behind schedule to ahead of schedule.

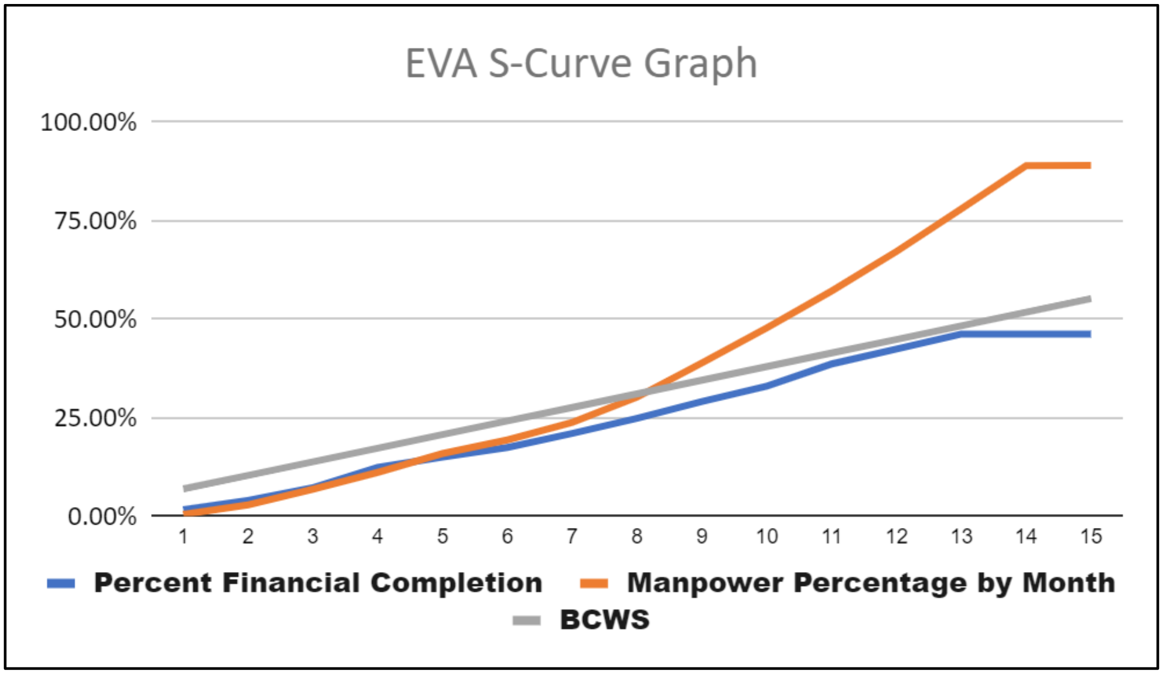


Figure 4.2: EVA S-Curve Graph

4.3 Scheduling Delay Effects

No matter how well planned a project is, a project manager must expect that there will be delays of some kind as several factors are out of their control. These delays include but are not limited to, weather delays, union strikes, and issues from subcontractors. In addition to traditional sources of delay, Consigli Construction also needed to plan around the impact of the COVID-19 pandemic which caused several delays in many different areas. A project manager when faced with serious delays must find a way to both resolve the issue, and keep the issue from slowing down the project's progress. If a serious delay is not planned for and a project manager cannot find a way to resolve it, then the project would soon go over budget from having to pay workers and other expenses more than expected, which reflects poorly on the company, and runs the risk of contract termination if the client no longer wishes to work with the company.

4.3.1 Weather Effects

The weather's impact on construction projects in New England is a well-known issue with heavy precipitation such as snow or rainfall forcing construction to stop its progress. Additional steps may also be taken to allow for site operations to continue, such as the purchase and use of additional equipment. The delay can last any length of time ranging from a day to several days depending on the severity of the weather. Similarly, the length of time required to remove snow and ice from the project grounds can add to that delay. However, Consigli Construction suffered from no serious delays from the weather. Consigli prevented delays by enclosing the building using tarps, and scheduling the project so the majority of work done during the winter months was interior work. Consigli Construction effectively avoided any serious delays in the project schedule caused by weather effects.

4.3.2 COVID-19 Effects

The COVID-19 pandemic had a significant impact on the project. In fact, even after Consigli revised their plans, the project still suffered from delays due to the pandemic. First, the project had to effectively be put on hold while it was determined how the project could be continued in a safe manner while following all COVID-19 regulations placed by Consigli Construction and state governments. The impact of COVID-19 was to the extent that the project was scheduled to be finished one month after it was first planned. At first it was planned that the end date be January 13, 2022. However, an updated schedule set the finish date as February 16,

2022. Due to COVID-19, fewer workers were on site at any given time, several rules and regulations were placed to keep COVID-19 from spreading among the workforce, and members of the workforce and project management team were required to self-quarantine. It was repeatedly noted during their weekly meetings that there was a delay on supplier's materials. Specifically, materials such as fire protection insulation mineral wool, metal boxes, PVC, steel pipe, elbows, and fittings. In addition, WPI was following quarantine protocols which meant that there were less students on the campus; this component helped Consigli Construction with logistics as there was no need to plan around students and campus operations. This enabled the construction team to proceed with certain steps that they would have otherwise not been able to.

4.4 Time Value Money Analysis

A time value money analysis determines how long it will take for the investment to break even and meet interest rate criteria. To find where the break even point is, the net present value (NPV) must be calculated, which is a tool we can use to see the initial investment grow to a point where the project will break even and begin to incur a positive return on investment (ROI). In this case, WPI made a $60,000,000 investment into the WPI Smart World Project. By calculating the projects NPV, we were able to distinguish the ROI and we can estimate how many years it will take for the initial investment to be paid off, and any more income from the building can begin to be reinvested into projects and research. The NPV can be found using the equation NPV= C / (1+i)^t - ini, where C equals the cash flow per periods/years, i is the interest rate, t is the number of periods/years, and finally the initial investment (ini).

This analysis was also put into a visual perspective and used to show the investor where their money is being dispersed and how their money will grow based on the constraints set. The visual perspective on the analysis can be seen below in Figure 4.3.

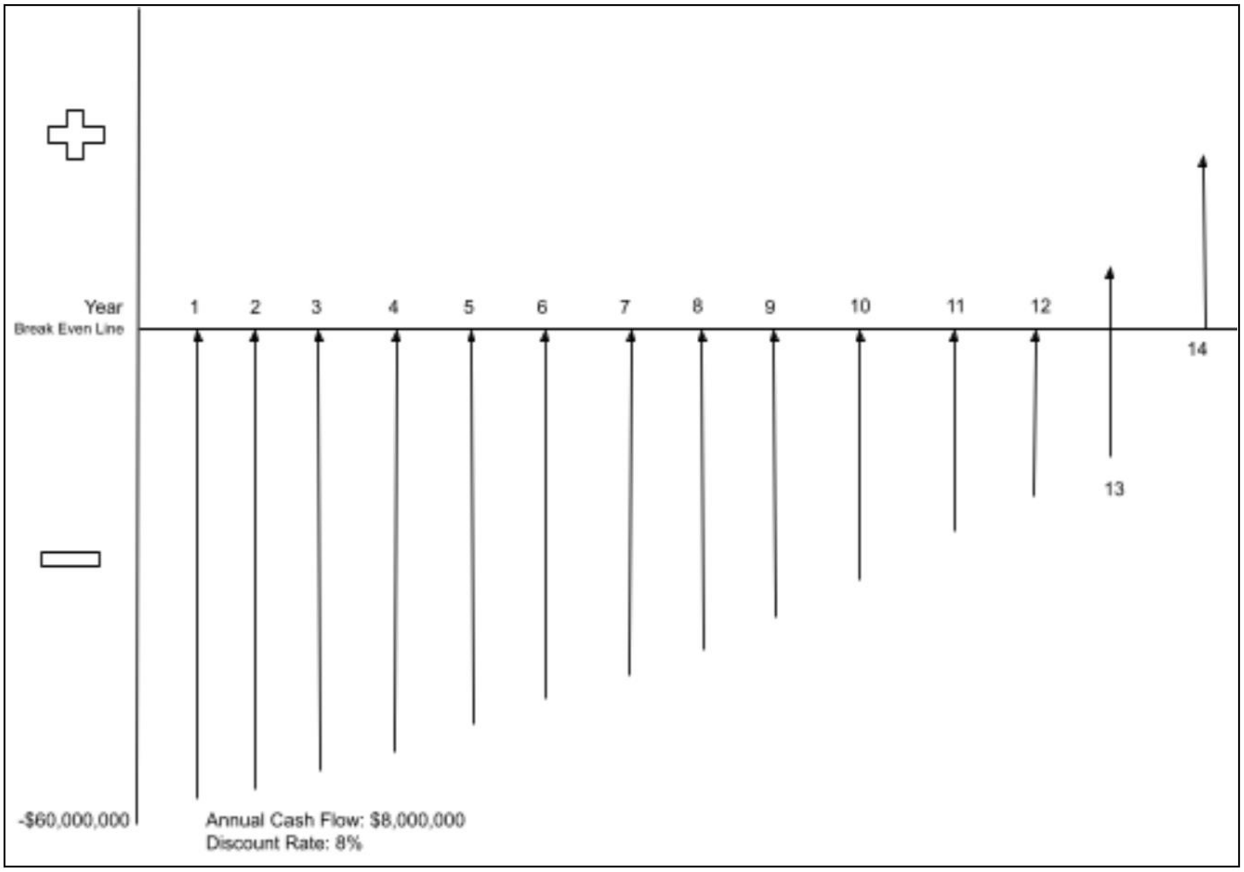


Figure 4.3: NPV Graph

After conducting the NPV analysis of the project, we discovered that by year 13 the project will break even and begin to generate positive revenue. That is only if the project sustains a consistent revenue of $8,000,000 per year at a discount rate of 8% per year. We believe that the estimate we went with was a conservative one because we believe the building could easily pull anywhere from 5-10 million from research, projects, and funds from student tuitions, so 8 million per year was a suitable median to use.

The initial investment of $60,000,000(ini) is depicted on the left side of the figure, and the subsequent cash flows of $8 million per year can be seen after the initial investment. The bars indicate the shrinking value of the negative value and growing to hit the break even point of 0. After it reaches the breakeven line any revenue after that is a positive ROI. We can see during year 13, the investment hits its break even mark to begin incurring positive revenue for the investor.

5.0 Constructability Analysis

Our team analyzed the major challenges that the general contractor faced during the construction process of WPI Smart World. We focused on two principal value engineering challenges, the brick façade and the curtain wall systems, and our team also examined the removal process for contaminated soil. Through collaboration with Consigli Construction, our team researched the original plans using the meeting notes, field reports, and relevant documents found in their construction management software, Procore. Also, we often received additional information that the contractor felt would be pertinent to our analysis. After gathering all the data, our team investigated the methods and rationale behind each construction change while also exploring viable alternative options.

5.1 Value Engineering

Our team explored the general contractor's application of value engineering during the construction process. Value engineering in construction management is defined as an organized effort towards analyzing the building systems, features, equipment, and material selections for the purpose of reaching essential functions at the lowest life-cycle cost (U.S. General Services Administration, 2017). The construction contractor usually proposes a value engineering change to construction requirements, materials, or methods because of unanticipated conflicts with schedule, costs, or design. The change aims to not increase the cost of construction or the life-cycle cost of the building while maintaining building performance, design quality, safety, and appearance (U.S. General Services Administration, 2017). The COVID-19 pandemic had a significant effect on the availability of materials and the workers' construction timeline due to the state of emergency and quarantine. As a result, there were significant design changes that were necessary to ensure the productivity of the construction effort and to stay on schedule.

5.1.1 Curtain Wall Systems

Consigli Construction ultimately used two different types of curtain wall systems in their construction of Smart World: “Clearwall” and “unitized” systems. The clearwall system was installed in the smaller sections of the curtain wall. It is called clearwall because it clears multiple floors of the building, and there is one slab that essentially supports all the dead load. The clearwall system was installed in the first floor curtain wall and the North/South rectangular curtain wall; the dead loads for these sections are supported on the third floor and tied back to the structure on the other floors for the wind load.

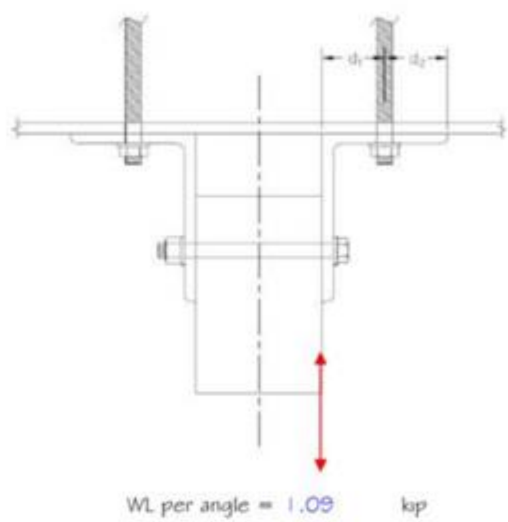


Figure 5.1: Top-view of the embed system used in “Clearwall”

As shown in Figure 5.1 above, the embed system required dowels that were cast-in-place within the concrete slab to attach the clearwall sections. The clearwall system was the general contractor's original plan for all the curtain walls, but they realized it was not a viable option for every area. In some places, they determined that one slab could not withstand the dead load, and they decided to install a different system.

The other system they chose was called the unitized system; it was used in the south face of the fifth floor, in the bridge, and in the southeast cantilever section of the building. Unlike the clearwall system, the unitized system evenly distributes the load on each slab through an alternate embed connection.

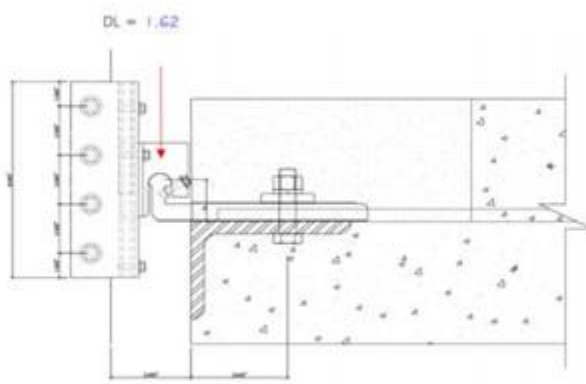


Figure 5.2: Side-view of the embed system used in "Unitized"

Instead of using dowels like in the clearwall system, this alternate system used embedment plates that were cast into the concrete slab. The plates were flat with an L-type fitting at the exterior; it also required a "female" type piece on these embedments that would be used for attachment. Figure 5.2 above shows how installation looks different in the unitized system with flat plates and the female-type piece, compared to the embed system with dowels in Figure 5.1 for the clearwall system.

The installation of the curtain wall systems required multiple pre-installation steps in the critical path. Consigli Construction's critical path to enclose the building started with exterior framing, to exterior sheathing, to waterproofing, then finally window and curtain wall installation. They had to coordinate the locations of the couplers with the locations of embeds so there would not be conflicts when being installed in-field later. Since their timeline for 2020 had them completing steel in July and placing slabs in August, they had to make sure embeds were approved in spring, and it was finalized in May. They had to make sure all elements were submitted and approved, the openings waterproofed, and embeds installed before they were ready to start placing slabs because both curtain wall systems had parts that were cast into the concrete deck. Once the frames for the curtainwall were installed, the subcontractors then had to install some additional flashing/waterproofing to make the systems weathertight. The exterior framing and sheathing were done by their contracted drywaller, H. Carr & Sons, while the waterproofing was done by Heritage Restoration.

One major problem the Consigli team faced after installation was visible condensation in all of the shadowboxes of the curtain walls. They first noted the condensation on December 16, 2020 during an inspection for deficiencies, and it was only visible in the clearwall curtain wall on the North elevation, as shown in Figure 5.3 below. When they went back to observe if there were any developments on January 2, 2021, they noted that there were visible water streaks in the shadowboxes for the unitized curtain wall on the West elevation as well, shown in Figure 5.4.

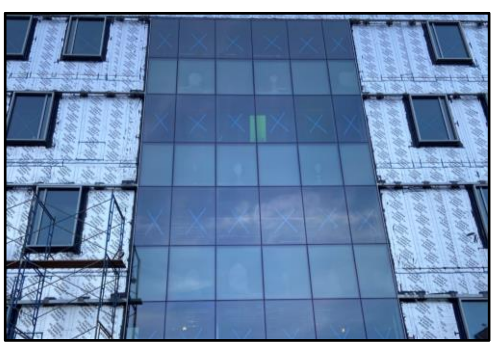


Figure 5.3: 12/16/20 Visible condensation in the shadow boxes (North elevation)

Figure 5.4: 01/07/21 Visible condensation in the shadowboxes (West elevation)

From their inspection report, the Consigli team presumed the condensation was due to moisture that got into the assembly during construction of the curtain wall which started to condense on the cold glass. Using their past experiences with shadowbox construction, they noted that the condensation should eventually clear up once the building is climate controlled. They were advised to dry out the internal moisture if the problem still persisted afterwards.

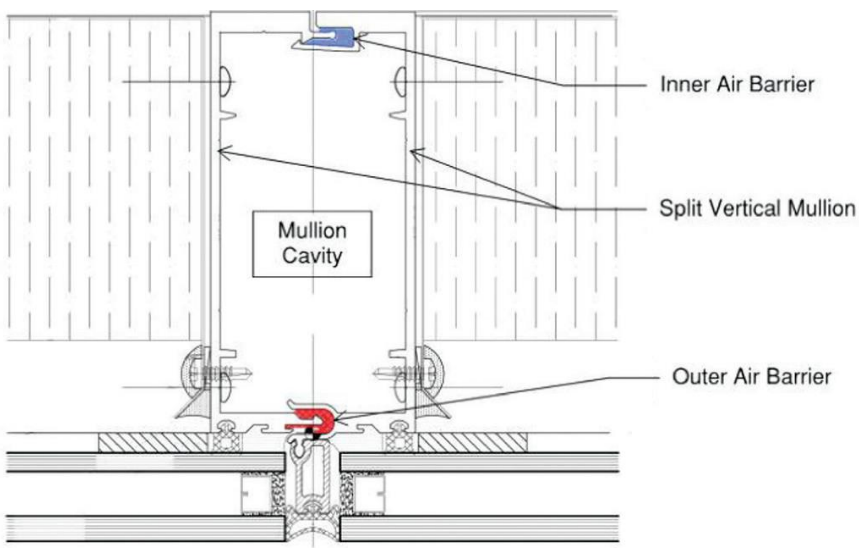


Figure 5.5: “Unitized curtain wall split mullion showing the air barriers required for ventilation to the mullion cavity” (Walsh, 2019)

To get rid of the moisture and condensation in the shadow boxes, we recommended a plan to push ventilation indirectly to the exterior by creating mullion cavities in the curtain wall system (Walsh, 2019). A potential design of the shadow box ventilation, shown in Figure 5.5 above, demonstrates the use of a mullion cavity in a unitized curtain wall system and how the air barriers are used to prevent direct contact with the exterior. These mullion cavities would be used as a “weeping” system to drain out water and facilitate airflow to the exterior; the indirect ventilation would also relieve pressure and prevent debris from entering the shadow boxes (Walsh, 2019).

5.1.2 Brick Façade

To help determine which brick would best match the coloring and design of the original façade, Consigli Construction had to examine the brick samples in multiple outside-light settings throughout most of the day. The design choices as to the color, texture, and shape of the bricks were left to the building architect. It was the job of the general contractor to ensure that the brick material was brought onto the site on time and to maintain the construction schedule.

Due to the COVID-19 pandemic and the school-wide transformation to online learning, Consigli Construction wanted to capitalize on the empty campus to continue construction. Unfortunately, COVID-19 also caused many problems in material production, availability, and transportation. The original brick chosen, the dark ironspot velour modular from Endicott Products, was unable to be used for the brick façade because of late timing. As a result, the general contractor had to use value engineering to find an alternative solution for the brick façade. They reached out to their masonry subcontractor for new brick samples that would fit the price range for the client. They compared the original design to the samples based on specifications like color, texture, and size; pricing was also a leading aspect when considering alternative bricks. After careful review from the general contractor, the alternative options were presented for the design team to choose.

Figure 5.6: Current brick façade with two masonry velours

The original design of the brick façade used a face brick method with a corbel brick pattern. Because the masonry velours didn’t affect the brick installation method, the use of two different brick colors was acceptable. The installation of the two bricks did require more attention since the wrong order of colors was very obvious with the face and corbel brick pattern as shown in Figure 5.6 above. As a result, the masonry needed more time than originally planned even though the installation method is the same for both bricks.

Figure 5.7: South facing view of original brick sample and alternate brick samples
(left to right: Endicott, Belden, Cloud, Yankee Hill)

The initial brick alternative samples given to the design team were from three brick manufacturers: Yankee Hill Brick & Tile, Cloud Ceramics, and Belden Brick Company. As pictured in Figure 5.7 above, the façade design needed a brick in the gray family with a slightly noticeable level of surface texture. The brick also needed to have a nominal 12-inch width, which is called a Norman shaped brick. The design team was aiming towards a more contemporary aesthetic, but it also brought limitations. The specified width was commonly in smaller, limited supply compared to a typical 8-inch width brick.

Figure 5.8: Final Belden brick velours chosen for brick façade

The Belden brick was ultimately chosen because its light color variation was more desirable to the design team. When choosing a velour, they needed a product with "through-body" coloring to stay consistent with the pattern in the brick façade. As a result, Consigli Construction chose the Ashberry and Sienna Blend velours for the Belden brick, pictured in Figure 5.8 above. But even after replacing the original brick with the Belden brick, they continued to face issues with their subcontractor. Around the start of our research in September 2020, they reportedly were looking for another brick alternative after the supply of the Belden brick fell through. The Consigli team had to quickly search for a new brick again that would not change the whole look of the brick façade or cause any delays in the original timeline. This inconsistency led our team to explore other brick alternatives and create a potential design in our report, which is further explained in Chapter 6.0.

5.2 Soil Removal

Because the building is located on the side of the campus hill, significant grading and site work needed to be completed. The building site is located on the eastern side of WPI's campus, next to the Gordon library. Before ground breaking, the site had a significant slope with grades ranging from (elevation) El. 515 to El. 560 (NAVD 88). Features surrounding the area included concrete stairs, walkways, and stone retaining walls which were adjacent to the library on the hillside. A parking lot is located below the site on the street level, and underground utilities previously existed beneath the site. The multi-level design of the building resulted in a lack of balance between cut and fill for the site work, with an excess of cut soil from the site. Therefore, much of the soil on the hill had to be removed and shipped away before construction even began.

The existing soil needed to be characterized for contaminants and suitability of construction. Unsuitable soils included fill, topsoil, loam, subsoil, excessively wet, saturated, or loose soils, soils disturbed during construction, and contaminated soils. These were removed from the site after grading. Amongst the excavated soils, a soil testing team performed an analysis of contaminants. While many pollutants were found in the samples taken, they were found to be consistent with other natural soil levels within Worcester County, and could be excavated and removed as normal. An example of this was that the measured levels of arsenic were above the state’s level that required reporting (20 mg/kg), but because of the prevalence of arsenic in Worcester’s soil, this data is exempt from being necessary to report as a result of provisions in the Massachusetts Contingency Plan (Mass.gov, 2014). Other contaminants found during the soil analysis are shown in the Table 5.9 below. Eleven samples of the soil were bored 9.5 ft below the surface, which was used to characterize the soil for its contaminants and reuse characteristics.

Table 5.9: Soil Sample Results

Metal	Maximum in Soil Proposed for Reuse (mg/kg)	MassDEP Natural Background (mg/kg)
Antimony	ND(4.53)	1
Barium	87.4	50
Beryllium	0.508	0.4
Nickel	26.8	20
Selenium	ND(2.44)	0.5
Silver	ND(0.488)	0.6
Thallium	ND(2.44)	0.6
Vanadium	31.6	30
Zinc	51.4	100
Arsenic	36.8	20
VOCs Ex: Acetone	Very few detected 3.4 (Below Reportable)	N/A
Herbicides & Pesticides	ND	N/A

* Note: ND indicates not detected; value in parentheses in the maximum reporting limit.

The amount of soil removed totaled 17,500 cubic yards, equating to 29,800 tons. This soil was delivered to a landfill in Clinton MA for reuse and according to the soil testing contractor, Haley & Aldrich INC., the soils are acceptable for reuse at the site. The sloped site resulted in the inability to balance cut and fill during grading, which impacted the cost of the project more than a similar project on a more neutral site would have. Soil transportation costs are generally a significant expense that construction companies aim to avoid through site work and grading, however in the case of this project, the removal of soil was unavoidable, and thus the cost was accounted for in the construction budget from the beginning.

6.0 Brick Façade Alternative

For the building's brick façade, our team investigated the benefits and drawbacks of Consigli Construction's alternative design while also generating a design alternative of our own. We considered multiple factors such as color, texture, size, shape, type, grade, and availability when analyzing the current brick façade and while exploring alternatives. Based on those characteristics, we narrowed down our options to an innovative lightweight brick called NewBrick.

6.1 Background

The greatest drawback of choosing the Belden Brick was how its availability did not fully correlate with the construction schedule. After deciding on the Belden Brick, Consigli Construction still faced many problems involved with getting the materials on time for the assembly of the brick façade. As a result, the subcontractor was unable to stay fully consistent in colors during installation, and they used three velours in total for the brick façade. For this MQP, our team explored design alternatives that met the WPI Smart World design requirements and required a shorter transportation time based on manufacturer location.

6.2 NewBrick

A potential improvement to the building's design would have been to alter the choice of materials for the brick façade and use an improved material, NewBrick. NewBrick is a product that has several benefits over traditional brick veneers which could improve many aspects of the building from construction to performance (Newbrick, 2021). NewBrick is much lighter and thinner than traditional brick. It has a weight of 2.45 lbs/sf and is only about 2 inches thick, while a brick of the same thickness is around 20 lbs/sf. This would allow for the façade to place a much smaller load on the structure, simplifying the design. The reduction in weight means it has a minimized drop risk, increasing safety in multi-story construction, and productivity is increased from a reduced load on the worker.

NewBrick has thermal insulation engineered into the design of the brick as seen in Figure 6.1. When combined with a NewBrick continuous insulation system, it can contribute to LEED credits and help to make the building more energy efficient. The product is fire resistant as well, meeting NFPA285 requirements. NewBrick can include air and water resistive barriers, drainage systems, continuous insulation, and a simple cladding system. The composition of the brick is not only insulating, but it is also more fracture resistant, durable, and flexible than traditional brick. This means it isn't susceptible to cracking or being easily damaged, but even if they become damaged, they are easily replaceable.

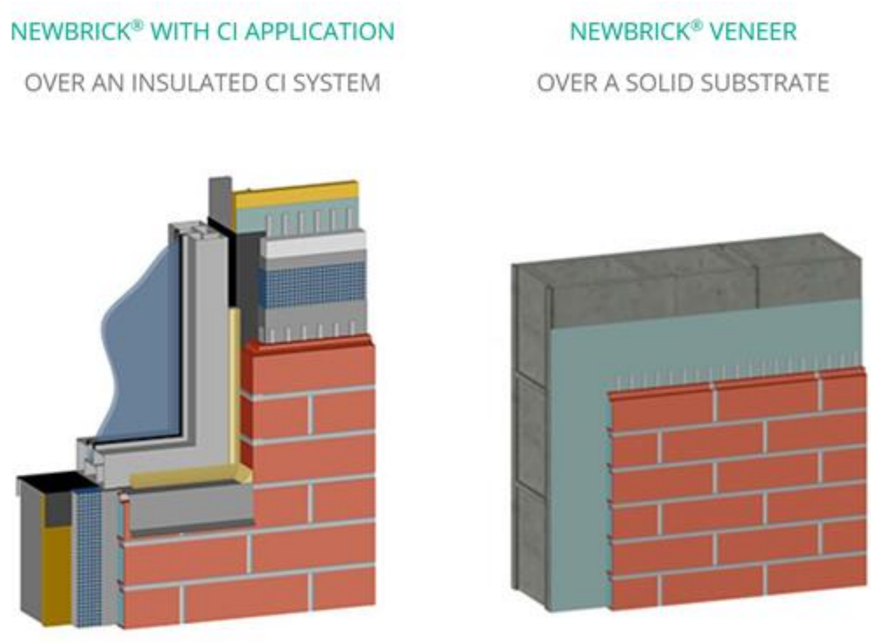


Figure 6.1: NewBrick Façade Layers

(Taken from newbrick.com)

NewBrick is much easier to install than traditional brick façades. Brick ties, anchors, bearing shelf angles and mortar nets are not needed when installing NewBrick. This saves on materials cost and reduces the amount of time and number of trades needed to install the façade. NewBrick also claims that workers are able to install about 35.25 sf of NewBrick per man day which is about 50% better than the productivity rate of 23.67 sf per man day for traditional brick. As a result of the productivity gains, a single contractor is able to conduct the framing, sheathing, resistive barrier and façade installation, improving scheduling and trade coordination.

While there are many benefits to using NewBrick, it comes with drawbacks. The main issue is cost, as it is much more expensive than traditional masonry. This is offset however by the many benefits of the product. Costs from transportation, construction, labor are reduced with NewBrick, and time is also saved due to the improved scheduling and streamlined trade coordination. Because of these benefits, we recommend NewBrick as a superior alternative to the current brick façade.

7.0 Design Analysis

Our team conducted a design analysis by looking into different aspects of the design such as energy usage, orientation, and daylighting levels. To properly represent the building, we constructed a 3D model in Revit using the construction drawings provided by Consigli. The completed model was then used for energy and daylighting analyses. With these results, we further examined the pros and cons for each analysis and made appropriate recommendations for improvement. Using the 3D model, we were then able to create a 5D model to allow for better visualization of the project phases, procurement, scheduling, and cost. With the expected schedule integrated into the 5D model, our team recommended ways to expedite the current schedule.

7.1 Building Information Modeling

Building Information Modeling (BIM) is an incredibly powerful visualization and documentation tool within the construction industry. BIM is a 3D model that encompasses construction planning, designing, building, and operating, to allow for easier collaboration among architecture, engineering, construction, and facilities management professionals. Within this project, Autodesk's Revit software was used to coordinate the BIM process. With BIM integration, a wide array of simulation tools can be utilized, such as energy, solar, and daylighting analysis. Building Information Modeling is the ideal process to optimize project visualization, promote team coordination, and support collaborative decision making.

Every project requires the cooperation of different specialities. To avoid each team referencing their own 3D model, BIM incorporates the plans of each speciality and combines those plans into one main 3D model. Within this model, changes may be made, parts can be updated, and users can visualize how different components interact. With this, all MEP components can be accounted for and placed strategically within the building using the "Clash Detective" tool within Navisworks. This process creates a more productive construction environment that fosters better communication between project managers.

7.1.1 Schedule Integration - 4D Model

Once the 3D model has been created, the 4D model comes together by integrating the schedule into the original model. With this 4D model, users can visualize the project phase by phase, this allows for better planning and preparation for the construction. In order to integrate the time component into the model, the use of Autodesk's Navisworks software is needed.

Within Navisworks, the user first uploads the project's Revit file directly into Navisworks, from there the schedule can be linked to each phase that was created in Revit. By adding tasks within each phase, along with start to finish dates, the complete detailed schedule can be added to the 3D model, creating the 4D model. The 4D model is significant for helping project managers plan and coordinate the site logistics. Using features such as geolocation, neighboring traffic, and site-access, the 4D model helps to see how the project impacts each of those items, thereby allowing for a smoother flow during construction.

7.1.2 Cost Integration - 5D Model

With the 4D model created, the 5D model comes together by integrating the project cost. By using the schedules created in Revit, the user can gather information on material quantity for each trade then attach the associated cost per unit in Navisworks. With these quantities, the percent complete can be determined for each trade during each phase or even each week. By adding the cost element to the model, the 5D model can help project managers visualize and compare the percent complete by the cost spent. This allows for better budgeting and planning throughout the project.

7.2 BIM with Smart World

Using the given construction, schedule, and financial documents from Consigli Construction, the team created a BIM 5D model. With the detailed construction documents, a Revit model was first created that closely portrayed the WPI Smart World Building, views of the model are shown in Figures 7.1 - 7.3 with additional views located in the Appendix.

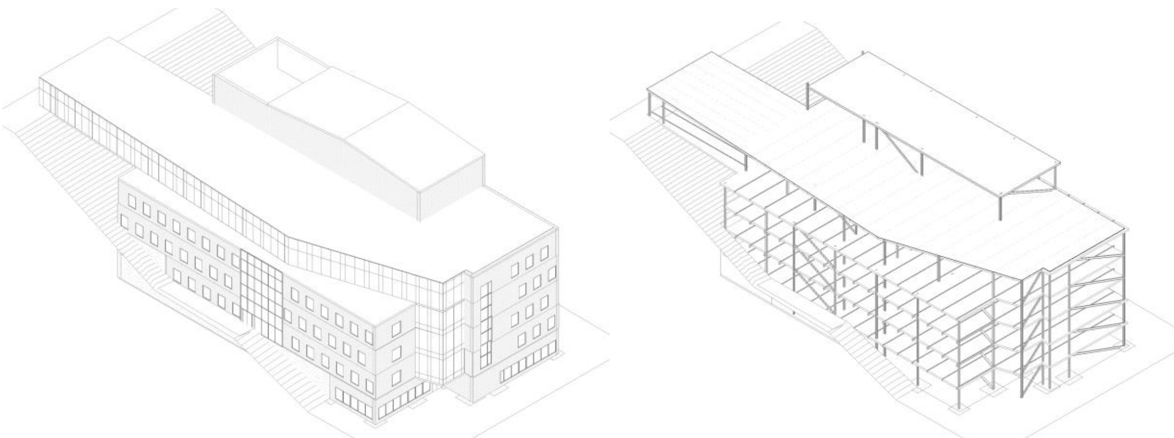


Figure 7.1: 3D Model Isometric and Structural Views

Figure 7.2: Final Building Section 1

Figure 7.3: Final Building Section 2

Using the 3D model, we ran various analyses on the overall design and function of the building. With the project schedule and gantt chart, we integrated the time component of the project into the 3D model, thus creating the 4D model in Navisworks. With the itemized financial documents, we integrated the cost component into the 4D model, thus creating the 5D model in Navisworks. Using the BIM process, scope, time, and cost of the project was visually represented in the final 5D model. This allowed for greater analysis of the project where further improvements and recommendations were made.

7.2.1 Energy Analysis

The energy analysis feature in Revit measures the energy consumption from the building based on location, materials, and HVAC systems. Insights on building performance allows for architects and engineers to optimize energy efficiency within their designs. This feature creates an energy analytical model within revit as seen in Figure 7.4.

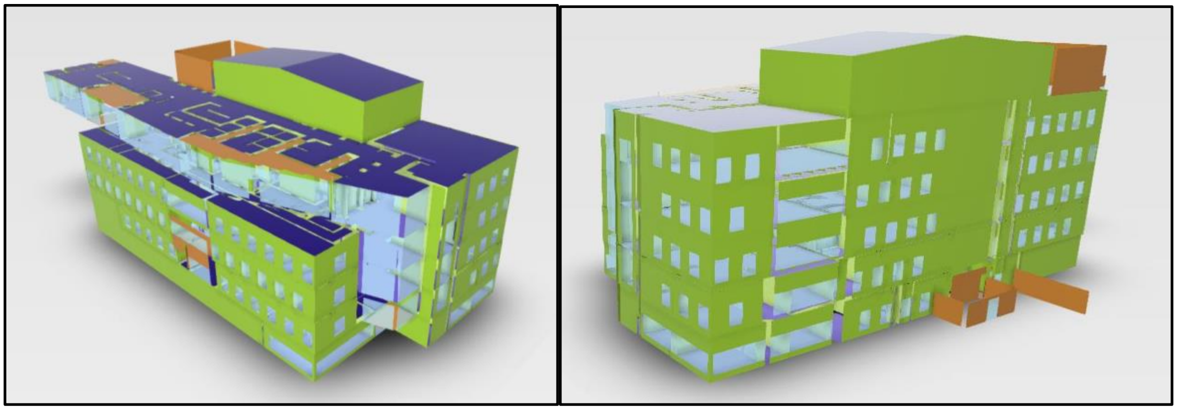


Figure 7.4: Energy Analytical Model

With this model, users can visualize key design changes and how each change impacts the overall building performance. Optimal building energy consumption would be net-zero, where the building generates as much energy as it uses. Ways to generate additional energy would be through renewable energy sources such as solar panels. The WPI Smart World building optimizes the efficiency of building systems to minimize energy usage. Referencing Figure 7.5 below, the ideal HVAC system for this building is a high efficiency package terminal AC unit, with this system the energy consumption cost would drop below net-zero, thereby making money from additional energy generated.

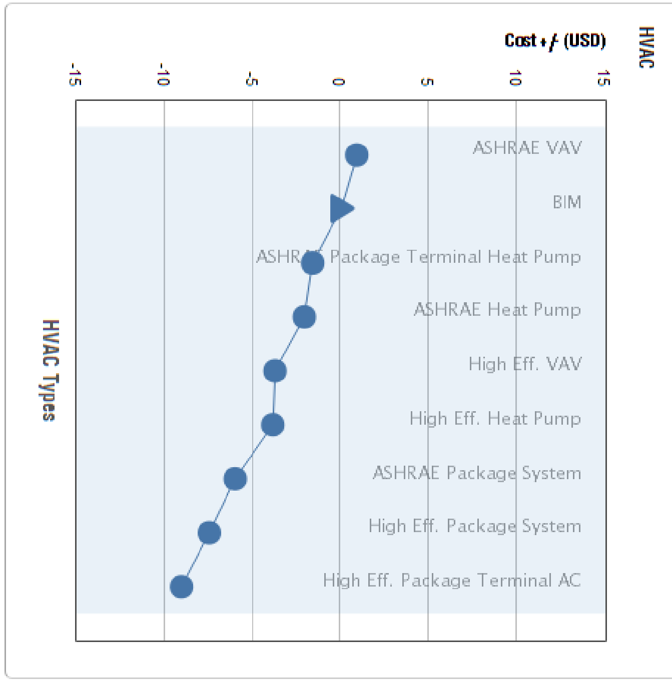


Figure 7.5: HVAC Performance Range

The energy analytical model is also used for performance indicators such as building orientation, wall and window construction, and even shade variations to be used on the windows. Key performance indicator visuals are shown in Figures 7.6 to 7.8, with a triangle representing the design used to create the models. The triangle marker is not an accurate representation of the specific HVAC system used for the building.

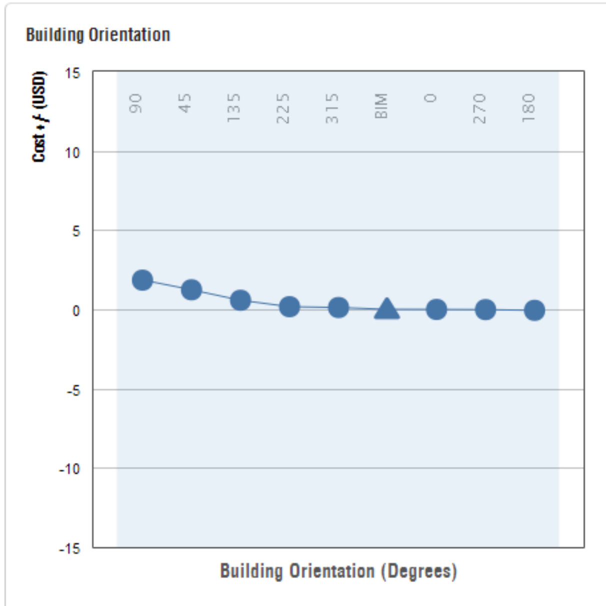


Figure 7.6: Building Orientation Performance Range

In regards to the surrounding buildings and area, the current building orientation is ideal for a net-zero energy consumption as shown in Figure 7.6.

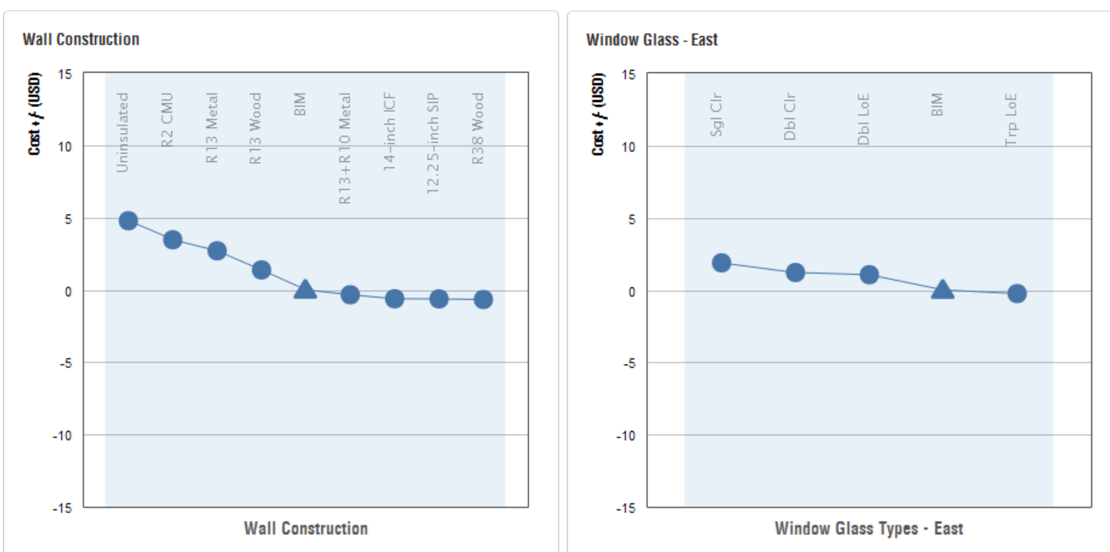


Figure 7.7: Wall and Window Construction Performance Range

The current exterior wall construction is ideal for a net-zero design as shown in Figure 7.7, although for a higher efficiency wall type, it is recommended to use a R38 Wood wall construction. While a wood construction may improve the overall building energy usage, other factors have to be considered such as material access, ease of installation, and structural integrity. With these factors in mind, an R13+R10 Metal wall construction is recommended, which would improve energy performance without drastically altering the design.

The current window type used on each side is also ideal for a net-zero design as shown in Figure 7.7, although for a slightly higher efficiency, it is recommended that a triple glaze, low E window type be used instead.

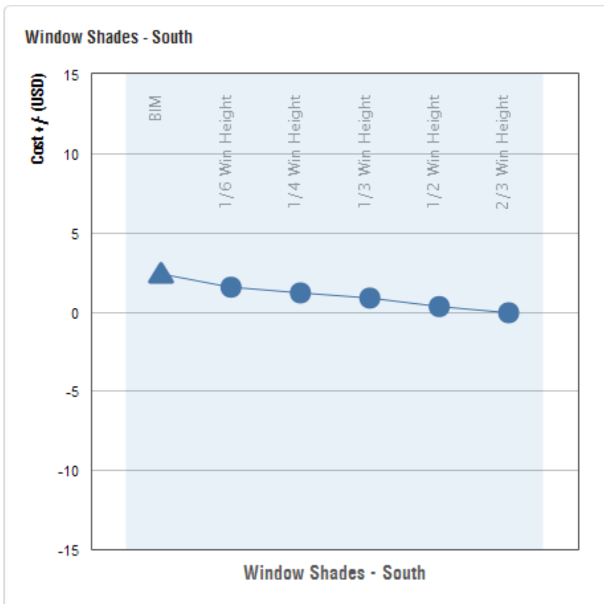


Figure 7.8: Window Shade Performance Range

Window shades were not incorporated into the 3D model design; Figure 7.8 shows the default setting for window shades. Reducing energy consumption is dependent on climate control within the building. The glass exposure on this building creates additional thermal gains and losses, in which the HVAC system then needs to use more energy to correct these gains/losses. The south side of the building features the large curtain facade and would benefit most from the use of shades to reduce energy consumption. The ideal shade would be lowered ⅔ down the window height, which would create a net-zero design.

One of the most efficient ways to generate energy for a building is through solar panels. Given the design of the building and orientation, Figure 7.9 shows the ideal layout for solar panels on the roof of the building and Figure 7.10 shows the levels of energy generated for different surface coverage percentages.

Figure 7.9: Solar Panel Roof Layout with Key

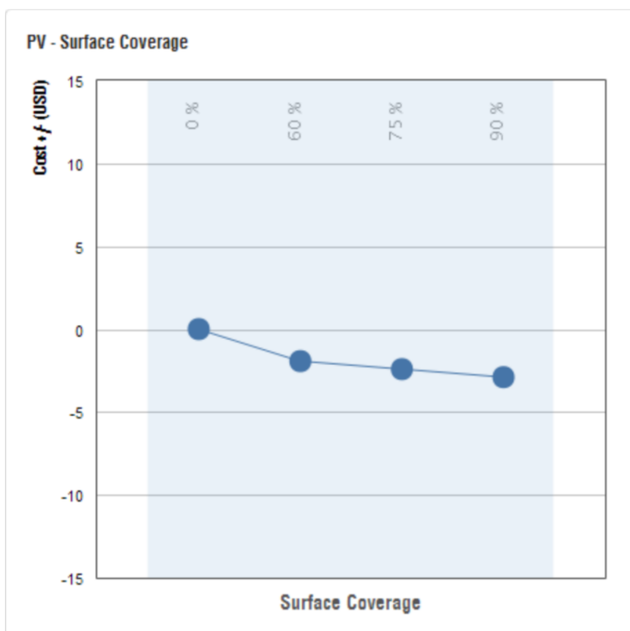


Figure 7.10: Solar Panel Surface Coverage Performance Range

The areas covered in bright yellow would be the ideal locations to place solar panels along the roof. While a 90% roof coverage would maximize the efficiency, even a 60% solar panel roof coverage would obtain a net-zero building.

7.2.2 Daylight Analysis

The daylight analysis feature in Revit measures the lux in each room of the building based on the project location and building orientation. With this feature, architects can incorporate daylight strategy into the building design and optimize the amount of daylight that travels through the building. This feature also benefits electrical designers; by understanding how much lux is already generated from the sun in each room, the designers can then adjust the amount and type of artificial lighting accordingly.

For the daylight analysis performed on the WPI Smart World 3D model, all results were generated at the time 9AM. The main curtain wall feature of this building lies on the south wall, and by generating a daylight analysis at 9 AM, we can see how this feature not only adds to the design of the building but also the functionality. Referencing Figures 7.11 to 7.15, the dark red areas have minimal to no daylight illumination, the blue and green areas have suitable amounts of daylight illumination, while the yellow areas have direct daylight illumination.

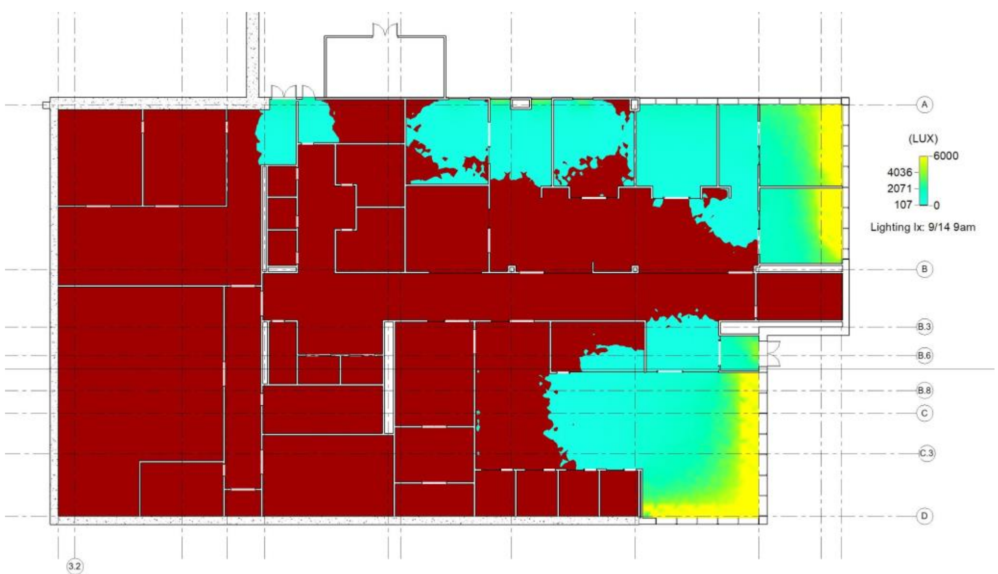


Figure 7.11: Daylight Analysis Results Floor 1

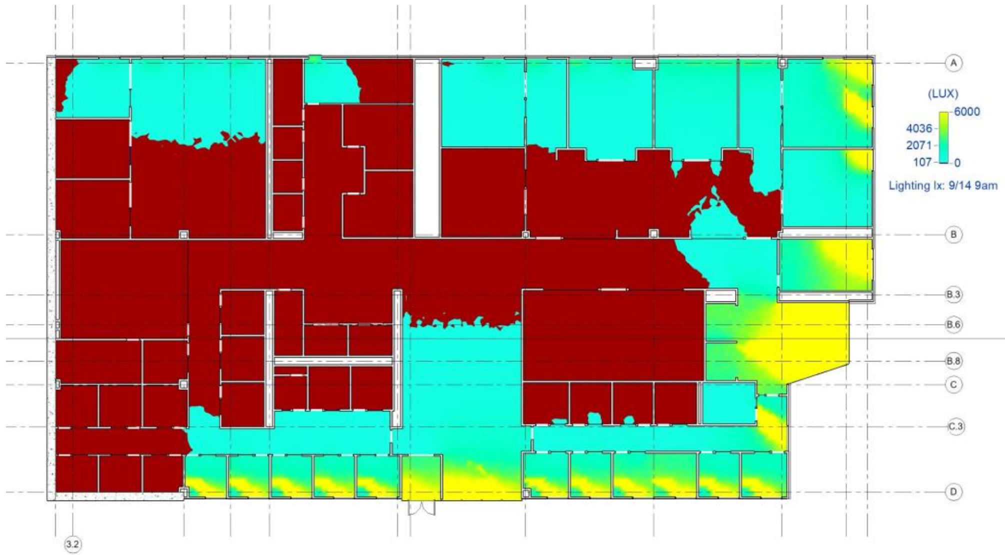


Figure 7.12: Daylight Analysis Results Floor 2

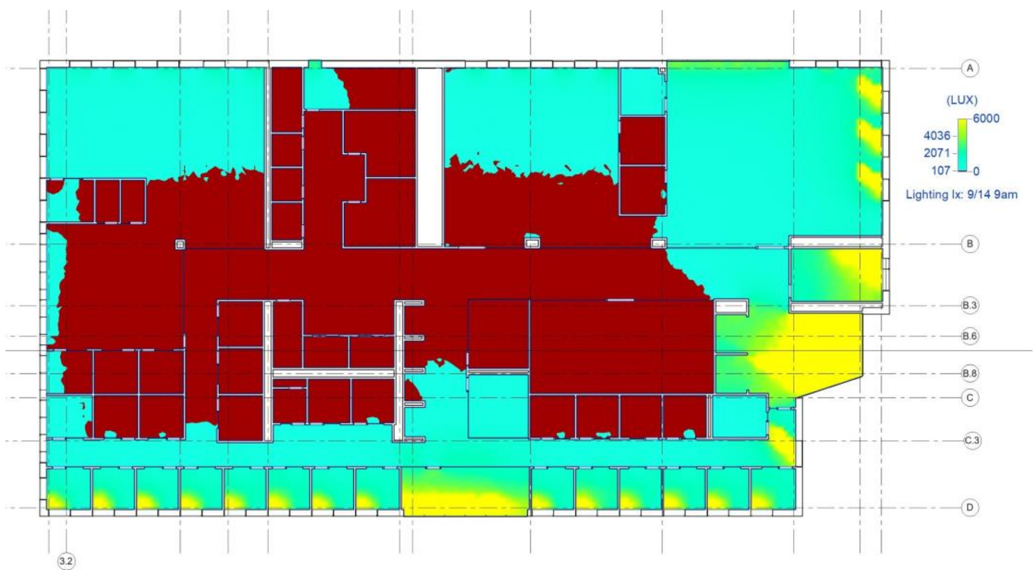


Figure 7.13: Daylight Analysis Results Floor 3

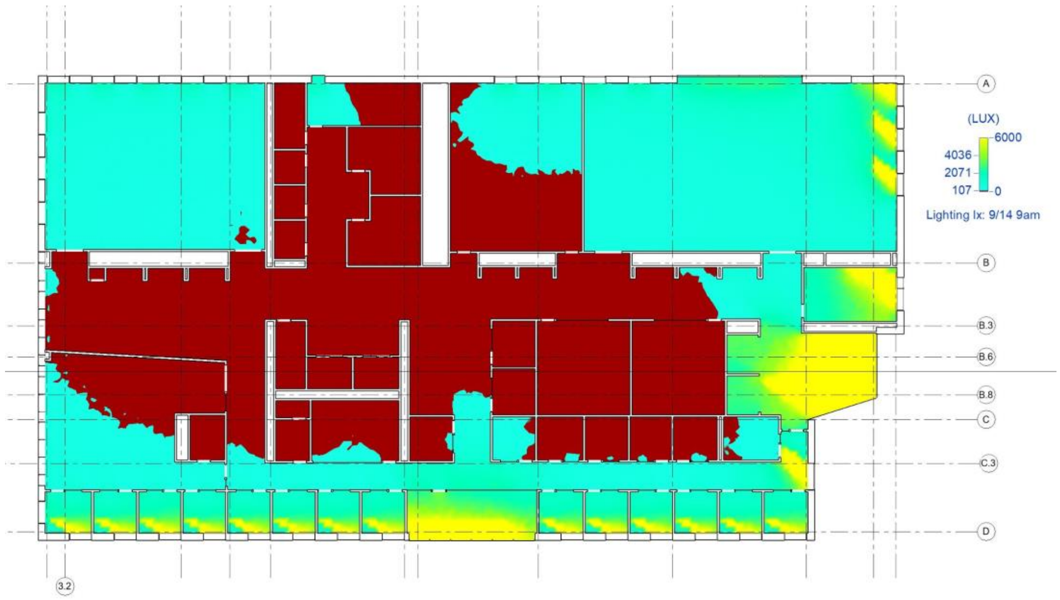


Figure 7.14: Daylight Analysis Results Floor 4

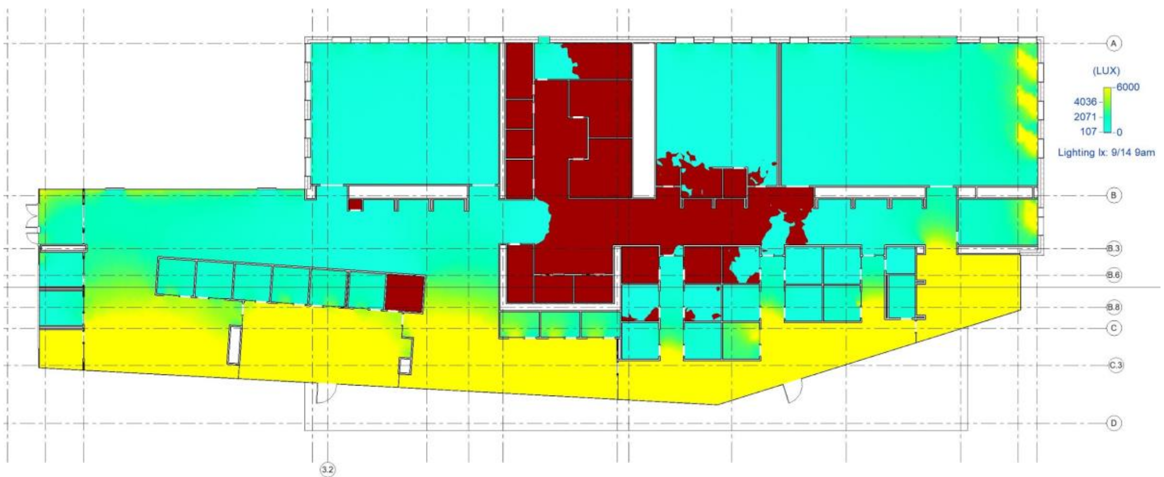


Figure 7.15: Daylight Analysis Results Floor 5

The Smart World building is built into a hill, leaving some parts of the first 3 levels lacking daylight completely. Given the large size of the building, it is also common for the central parts to have a shortage of daylight access. As seen in the figures above and with these considerations in mind, the main areas with minimal daylight are the corridors, restrooms, and service areas.

Potential improvements to minimize the amount of dark red areas within the analysis would be to create an open area inside the building where curtain walls are used. Currently, levels 2 through 4 have interior walls enclosing the curtain wall areas, thereby restricting the daylight flow to only one or two rooms. With the current layout of the floors, the rooms with the most natural lighting are mainly offices. A possible improvement would be to reconfigure this layout so that the common areas receive the most natural daylight, which would create a more calm and focused ambiance throughout the whole building.

7.2.3 Creating the 5D Model

The 5D model was created in Navisworks using the current 3D model, the project schedule, and the financial overview documents. In order to maintain the most up to date visualizations, the 5D model is constantly changing with each revision and change order. For this analysis, the model was kept up to date until January 2021; from this point on, any further revisions are not visible in the analysis. A clip of the model can be seen below and a link for the full video can be found here.

Figure 7.16: 5D Model Visualization

As shown in Figure 7.16 above, the model in the center is progressively built in phases similar to how it was actually built on site. The timestamp for each of the phases can be seen in white text on the top left side of the clip. The cost associated with each phase can also be found on the top left side in green text. Given the environmental circumstances, the progression of construction remained steady throughout the entire project. Potential improvements to further maintain a steady progression would be to stay on top of procurement and have backup plans available in the event of backorders or cancellations.

8.0 Safety Protocols

Worksite safety is critical for a construction project in order to eliminate the possibility of injuries and bodily harm. Consigli Construction implements an overall corporate safety program aimed at establishing high safety standards for their worksites. They have also tailored a site-specific safety and health program for the academic building's construction. In addition to these, further safety measures have been put into place because of the COVID-19 Pandemic. We analyzed the effects of these safety precautions on the project, the supervision of the standards, and their effectiveness at promoting health and wellbeing.

8.1 Background

Safety is essential in the construction industry in order to protect workers from harm. Maintaining a stringent safety regimen is important for ethical and moral reasons, as well as financial and legal ones. Safety programs impact a company's ability to keep on track with construction timelines, maintain profit margins, and avoid lawsuits and loss of reputation. Construction companies have a vested interest in keeping high safety standards because of these reasons, and our society and government have also agreed that it is important to place safety as the first priority in construction. Several regulations and organizations govern worksite safety in Massachusetts, including the U.S. Department of Labor on the federal level as well as state and city regulators. These organizations place requirements on construction sites that improve the safety and survivability of workers on construction sites, such as requiring first aid stations and evacuation plans, fire safety regulations, equipment operator licenses or qualifications, and many other safety contingencies. In addition to these standard procedures, this project had an additional safety hurdle: COVID-19. This caused rather significant overhauls to the site safety plan, and regulators put out additional guidelines in order to address the pandemic. The amount of regulations in place to maintain the safety of workers shows how much importance our industry and society place on our workers in construction.

8.2 Construction Worksite Safety

The site-specific safety plan included all contents listed in the overall Consigli Construction safety program, with added sections that apply solely to the WPI Smart World project. These additions included a call hierarchy, local emergency services, along with directions to the closest hospital. In the event of an emergency, safety data sheets were readily available, and a building/site evacuation plan was thoroughly laid out. The Consigli Construction safety culture is based on the philosophy that with leadership and training, all accidents are preventable. Each site specific safety plan acknowledges the type of equipment and tools that will be used during the project and specifically addresses safety plans for each item.

Maintaining these protocols proves very vital to the Consigli and overall construction team. Roughly every month, an inspector from Simpson Gumpertz & Heger (SGH) would perform a site visit and issue a report on the general observations, outstanding work items, and new work items to be corrected. Some months, a site visit would take place a few times a month depending the severity of the work item to be corrected. These field reports would then be discussed in weekly OAC meetings, where project managers would track the completion of these work items. This process is highly efficient in minimizing risk, and has helped Consigli Construction maintain a very low number of work related incidents.

8.3 COVID-19 Specific Safety

With the onset of COVID-19, additional safety standards had to be implemented on the site. Consigli Construction proactively established a response team that was responsible for monitoring state regulations and guidelines and was also in charge of implementing COVID-19 safety protocols on site. Main efforts of this team were to prevent the spread of the virus on site, stop potential COVID-19 patients from entering the site, and to keep safety protocols as effective as possible as the pandemic progressed.

The enacted safety plan included social-distancing changes and physical preventative measures which helped to prevent the spread of the virus, but also preserved the working effectiveness of the construction crew. Every morning, all workers on site participated in “Toolbox Talks" that discussed COVID-19 safety policies for the worksite. These were conducted at the first-floor space in areas with open airflow and in groups of 10 workers or smaller. In addition, these talks were conducted while practicing social distancing, with each person standing at least six feet apart from one another. This spacing would be observed at all times on site. Before entering the site, all workers went through a screening process which involved having their temperature measured, certifying they had no symptoms of COVID-19, had not been in contact with a person diagnosed with COVID-19, and had not traveled out of the northeast US. Workers who didn’t pass the screening process were directed to leave the site and seek medical attention, and if this occurred, workers would have to provide a negative COVID-19 test or meet Consigli Construction’s human resources standards for clearance to return to the site.

After workers passed the screening process, additional COVID-19 safety considerations were still implemented on site. Cleaning plans were established for the site, and these included frequent cleaning and disinfecting of all common or office areas, all bathroom facilities, all shared equipment, and any weathertight area. COVID-19 safety signage was also posted around the site which included procedures for decontamination and cleaning. Workers also had to wear personal protective equipment (PPE) at all times. This included face masks supplied by Consigli Construction, cut resistant gloves, and face shields if masks could not be worn for medical reasons. The site had hand wash stations which workers were encouraged to use along with practicing good personal hygiene such as minimizing the spread of coughs/sneezes, not sharing food or equipment, and not touching the eyes or face.

Workers were required to self-report if they met certain criteria, which included if they contacted anyone with a positive laboratory test, if they traveled out of the country or approved states, or if they developed symptoms. These personnel were tracked by safety professionals who checked in with the individuals, confirmed their self quarantine, and cleared workers to return to the site. If workers themselves tested positive for COVID-19, they needed to report the case to Consigli Construction as soon as possible and provide information as to their close contacts, visited areas, and follow the state’s self reporting guidelines. In order to enforce and supervise the regulations, professionals were responsible for monitoring compliance with the safety protocols. These individuals conducted site inspections, screenings, and helped proactively prevent potential issues regarding COVID-19.

9.0 Axiomatic Design

Axiomatic design is a project management tool that clearly expresses the goals and the objectives that need to be made in order to achieve those goals. Using the coupling matrix, we were able to understand the six upper level FRs or goals for this MQP and the six DPs to accompany the FRs which depict specific deliverables needed to achieve these goals. The axiomatic design decomposition was used to keep the MQP team on track by clearly communicating what needed to be accomplished in order to fulfill all requirements of the project.

9.1 Background

In 1990, Professor Nam Suh published a book named *The Principles of Design* that discussed his own theory, which he named the axiomatic design process, and described how the process can be used to analyze different designs by establishing a set of parameters that the design is supposed to meet (Mistree, 1992). This method can be used to objectively compare different designs by evaluating them under specific parameters. The method breaks down the hierarchical design into a coupling matrix that relates different domains, such as customer needs (CNs), functional requirements (FRs), design parameters (DPs) and process variables(PVs); while all being bound by constraints (CONs)(Suh, 1990). CNs are requirements that are normally set by the client because they are the things that the client's wishes to get out of the design, for example, a client would normally set some sort of functional restraint needed that they would like to get out of the design because they wish for it to look a certain way. FRs are the functional aspects of the design in which it is supposed to perform in a certain way. DPs are the methods of fulfilling the FRs. PVs are the details associated with completing a task within the design. Finally, CONs are boundaries that are established on the design.

Suh states, “After systems are designed, they are sometimes modeled and simulated. In many cases, they have to be constructed and tested. All these very expensive and unpredictable processes are done to debug and improve the design after heuristic design solutions are implemented in hardware and software”(Suh, 1998). With this being said he created and promoted the use of Axiomatic Design to ultimately eliminate all the wasted time and money that goes into the design and development process. He believes if the design is broken down and mapped out before any work is done, then it will save a lot of lost time and money that gets invested into the failed iterations that come in between the first and final iteration of a design. And this same theory can be applied to a multitude of disciplines.

9.2 Axiomatic Matrix

The axiomatic design created a bridge for our team to reduce wasted time in the early stages of our MQP because it communicated what exactly was needed of the team and navigated us around any wasted iterations that may have been associated with finalizing the direction of our project. The project consisted of multiple major tasks for which we divided ourselves into three sub-teams to work in the different areas to ensure completion of the task list in a timely manner. The axiomatic design decomposition gave us a perspective to understand how the DPs would fulfill our FRs .

To begin the application of axiomatic design, a design matrix was created to break down our project into the different sections. FRs are the functional aspects of the design in which it is supposed to perform in a certain way. DPs are going to be the deliverables that follow the FRs to fulfill the need they require. To establish these FRs and DPs we had to start with the CNs this way we can easily list out the goals needed to fulfill those CNs. Once the CNs, FRs, and DPs were finalized we needed to understand what CONs limited our activities and decisions. The CNs and the constraints (CONs) even though not depicted in the matrix are as follows:

CNs	- Multiple Project Analyses of:
	    - Financials
	    - Design
	    - Construction & Safety
	    - COVID-19 affects

CONs	- Abide by Gantt Chart Schedule - Finish Project by end of C-term - Get Advisor to Accept the Project

Using the FRs and DPs to create a matrix it showed our group a clear cut breakdown of the project and all the deliverables associated with each goal we agreed upon. Our axiomatic design matrix for the project can be seen in Figure 9.1 and Figure 9.2.

	[FR] Functional Requirements	[DP] Design Parameters	FR Measurement
0	Analyze the Project Management processes for the WP	Documentation of the Project Management Processes for the WPI	
1	Perform Earned Value Analysis (against budgets and	Quantative Analysis	
1.1	Analyze Project Budget	Project Budget Evaluation	
1.1.1	Determine Estimated Budget	Analyze Estimated Budget	
1.1.2	Calculate Current Costs	Current Costs vs Estimated	
1.1.3	Caluclate Extra Costs Due to COVID-19	Include extras cost due to COVID-19	
1.2	Calculate Work performed	Work Performed Calculations	
1.2.1	Analyze Construction Schedules	Breakdown Construction Schedules	
1.2.2	Determine COVID-19 setbacks	Include COVID-19 Setbacks	
1.3	Time Value Money Analysis	Analysis of project value	
1.3.1	Net Present Value(NPV) Calculation	NPV Graph	
2	Perform a Constructabililty Analysis	Time Phased budget and Schedule	
2.1	Analyze Curtain Wall/Design Chnage	Review Design Change	
2.2	Analyze Current Brick Facade	Determine Reasons for Changing Design	
2.2.1	Analyze Choice of Material	Evaluation of Material Choice	
3	Develop CAD Models (for energy, design and	CAD Models	
3.1	Create 3D Model	3D CAD Model	
3.1.1	Conduct Energy Analysis	Energy Analysis Report	
3.1.2	Conduct Lighting Analysis	Lighting Analysis Report	
3.2	Create 5D Model	5D CAD Model	
3.2.1	Include Construction Phases/Schedule	5D Simulation	
3.2.2	Add Costs of Each Phase	5D Simulation with Phase Costs	
4	Analyze Safety Protocols	Safety Protocol Evaluation	
4.1	Analyze COVID-19 Protocols	COVID-19 Protocol Evaluation	
5	Analyze Contaminated Soil Removing process	Report regarding process effectiveness/provide reccomendations	
5.1	Search for Landfills that will take contaiminated soil	Landfill Location	
6	Design a Alternative for Brick Facade	Brick Facade design including 3D CAD Design	
6.1	Research Brick material alternatives	Pick Brick Material	
6.2	Analyze types of brick orientations	Pick Brick orientation	

Figure 9.1: Axiomatic Design FRs and DPs List

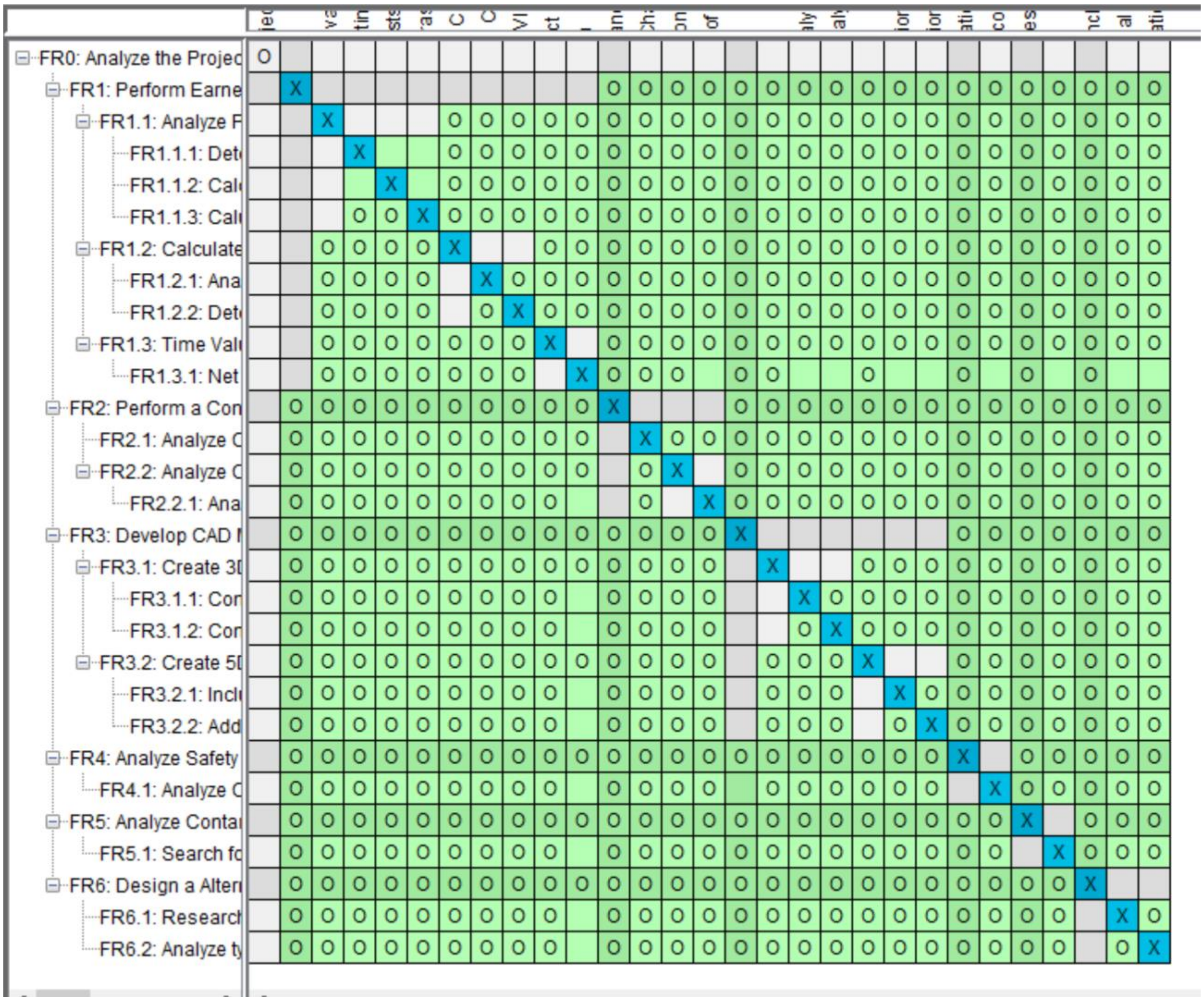


Figure 9.2: Fully Expanded Axiomatic Design Matrix

In figure 9.2, it can be seen the matrix created is an uncoupled matrix meaning each FR has its own distinct DP and known have any crossover where the same task is needed for any other FR. This shows that the process of the project has multiple parts that are all independent of each other but still all work together to achieve the same overall goal of the project, which is distinguished as FR0.

10.0 Conclusions

10.1 Earned Value and Time Value Money Analysis

Creating an earned value analysis allowed for the MQP team to gain a valuable understanding of how proper construction management determines the project's health. To develop the EVA the team learned how to read several types of construction management documents such as GIMP summaries, DD estimates, requisition summaries, daily logs related to weather impacts, and workforces hours logs. Our team also attended the Consigli Construction owner-architect-contractor (OAC) meetings and analyzed both the official minutes and our own notes on each meeting's activities.

By looking through these official documents the team learned all the different factors that influence a project's health from the various types of delays to how they can be dealt with. Our team was able to observe how a construction manager responds to unforeseen developments such as COVID-19, which had a significant impact on the project's operations. With the help of Consigli Construction who offered explanations for reading the documents needed for an EVA, the team was able to observe the project's budget and scheduling trends and observe when they were either below or above the planned mark. With this it became apparent why an EVA is an important tool for project management. The team learned how to create an EVA to determine if a project's schedule and budget is within specifications, and if they are part of a trend or a lone outlier in the monthly benchmarks. Therefore the team gained further understanding on how projects can be managed effectively in spite of delays regardless of their scale such as the COVID-19 pandmeic.

After completing NPV analysis of the project, we learned at which point the investment made on the project will turn positive based on the constraints we decided upon. These constraints included the estimated value of grants and donations the building will receive for its project and research efforts that will be conducted once it opens its doors. After reading through the, “Sponsored Research Activities Report” we determined on average the building may receive $6-8 million in research grants and donations, but we decided to use $8 million as our benchmark. Finally, the last constraint was the discount rate in which the ROI will be created and we chose 8% as our benchmark. We found that after 13 years the project will begin to gain a positive ROI, meaning WPI has the ability to use those returns for other projects and research for the students and faculty of WPI. Using this method to figure out this time period is a great tool to communicate to a client or an investor to show them exactly where their money is going and how long it will take for them to turn a positive ROI. Which is the main goal of any investment being made. The investor wants to see their money grow to the point where they can see a ROI. Also, creating a graph showing how the investment grows over the year easily depicts the path in which the investment takes. By using this visual tool, it allows WPI to see after construction if the building receives $8 million in grants and donations yearly and including a discount rate of 8%, then shows by year 13 the ROI will surpass the break-even mark. This allows WPI to gauge year by year how much aid may be received to fund other projects on campus to give back to the students and faculty. WPI will orient their strategies to make sure those marks are being hit and having a model to build those goals off of is a great tool to utilize for any investor. Especially, when it is being used on a civil engineering project. Where the client must understand how they need to operate their finished building in order to make their way to a positive ROI, where the building will begin making money for them.

In WPI’s eyes, knowing this can prove very useful for the future because they can figure out how they need to operate to ensure that the investment they made is being utilized to the fullest extent. Also, having the NPV model allows them to show how the building will gain more awards, sponsorships and donations to keep innovating and creating great things on WPI's campus. Then even look into the future of expanding the building itself or invest into a whole new building using the profits incurred from the original investment.

10.2 Constructability Analysis

The constructability analysis helped our team to gain real-time experience in construction management; we built skills in identifying, analyzing, and solving an array of construction issues while also interacting with the general contractor, Consigli Construction, in a professional manner. We were permitted to sit in on their weekly Owner-Architect-Contractor (OAC) meetings and also gained access to their construction management program, Procore. We reviewed actual design plans, field reports, inspection reports, and official documents for the construction of Smart World. This experience exposed us to the daily responsibilities of a typical general contractor and the realistic variety of problems they could face during the construction process.

With Consigli Construction's guidance, we were able to analyze the real-time problems they faced with the curtain wall systems, the brick façade, and the contaminated soil removal. By examining their particular solutions, we were able to formulate our own suggestions and recommendations that could have improved their construction plans and schedule. This experience allowed us to become more innovative in our critical thinking and gain insight on what a career in construction management truly entails.

10.3 Brick Façade Alternative

Analyzing an alternative for the brick façade helped our team explore issues that arise during a construction project. We were able to view the impacts of logistics and their effects on design. From this, we were able to explore how these issues could have been prevented or bypassed. The construction suffered from setbacks due to the choice of brick selected for the façade. Materials procurement was a large logistical issue for the façade which impacted the schedule and appearance of the project. This struggle resulted in changes to the original color of the brick, so the façade had a visual change on top of the issues with the timeline. Because of these reasons, our team recommends an alternative brick for the façade: NewBrick. This brick selection was recommended because of its potential to reduce the time and money spent on the façade, as NewBrick is easier to install and is less expensive when accounting for insulation, installation, and maintenance. The product is also available from a single source located within the New England area, so the acquisition process would potentially be simplified with selecting this product. Overall, our team concluded that the existing façade's problems could have been eliminated by selecting NewBrick as an alternative.

10.4 Design Analysis

The design analysis allowed our group to explore the design and construction process through the use of Building Information Modeling (BIM). Energy and daylighting analyses were run on the 3D model. The energy analysis showed the current building performance and gave insight into potential ways to optimize the building performance, such as changing the HVAC system, using alternative exterior wall types, or adding solar panels. The daylighting analysis gave insight into how the current building location and orientation affect the amounts of natural lighting the building receives. With this analysis, recommendations were given for ways to increase natural lighting throughout main areas within the building.

Visualization of how the scope, time, and cost interact with one another was made easily accessible through use of the 5D model. With this model, only minimal recommendations were made to potentially fast-track the current schedule and improve the percent usage of cost. The use of BIM within this project assisted in the tracking of the construction process and the overall analyzation of the project's efficiency and productivity.

10.5 Safety Protocols

The analysis of the safety regimen allowed for our group to see the planning process, implementation, and effectiveness of a construction site safety plan in real time. Viewing the approved safety plan for the site and comparing it to safety reports increased the level of understanding that our group had for construction site safety protocols. Our group referenced both the site specific safety plan and COVID-19 safety plan and compared them to the regulatory guidelines to see if they properly met or exceeded the state and federal recommendations. This analysis of the safety plans helped to highlight the importance of construction site safety for our group, as university education generally focuses on design, ethics, or project management rather than practical construction site safety.

10.6 Axiomatic Design

The use of the axiomatic design process allowed our group to complete our project in a timely manner and limit wasted or unproductive time because it allowed us to identify and focus on the goal of our project very early on in the process. It also clearly depicted all the working components of our project and how everything should fit together in order to create our end product. We discovered how useful this tool was because it communicated all the tasks and deliverables in such a way that there was no need to spend time working though different scenarios in order to reach a shared vision of the completed MQP and its elements. Having this clearly broken down matrix allowed each member of the team to pick which section of the project they wanted to focus on and to work with a partner to complete the tasks for the project. From this matrix we were able to monitor progress and create a “remaining tasks" progress sheet to track all the progress of any outstanding tasks.

Also, we were able to establish our constraints (CONs) for the project, which are the aspects that would help us finish our project and keep us bound and on track to the finish line. These CONs were used to keep us on track and moving in the correct direction throughout the length of the project. One of our main CONs was adhering to the Gannt chart we created to schedule out approximately how long each task should take and where we should schedule our milestones to reconvene to discuss how the project is progressing and whether or not each task is on track. To continue, another constraint was finishing the project by the end of C-term because ideally all MQP’s are given to the end of C-Term to be completed, but there are some occasions where they do spill into D-term. With the careful planning and the use of the axiomatic design approach and its design matrix, our group was able to move swiftly and complete our project on time. Finally, our last CONs was to have our project accepted by our advisor, which meant we had to ensure as we progressed through the project we checked in with him regularly to make sure we were meeting all of the requirements and adhering to his standards of how he wanted everything organized.

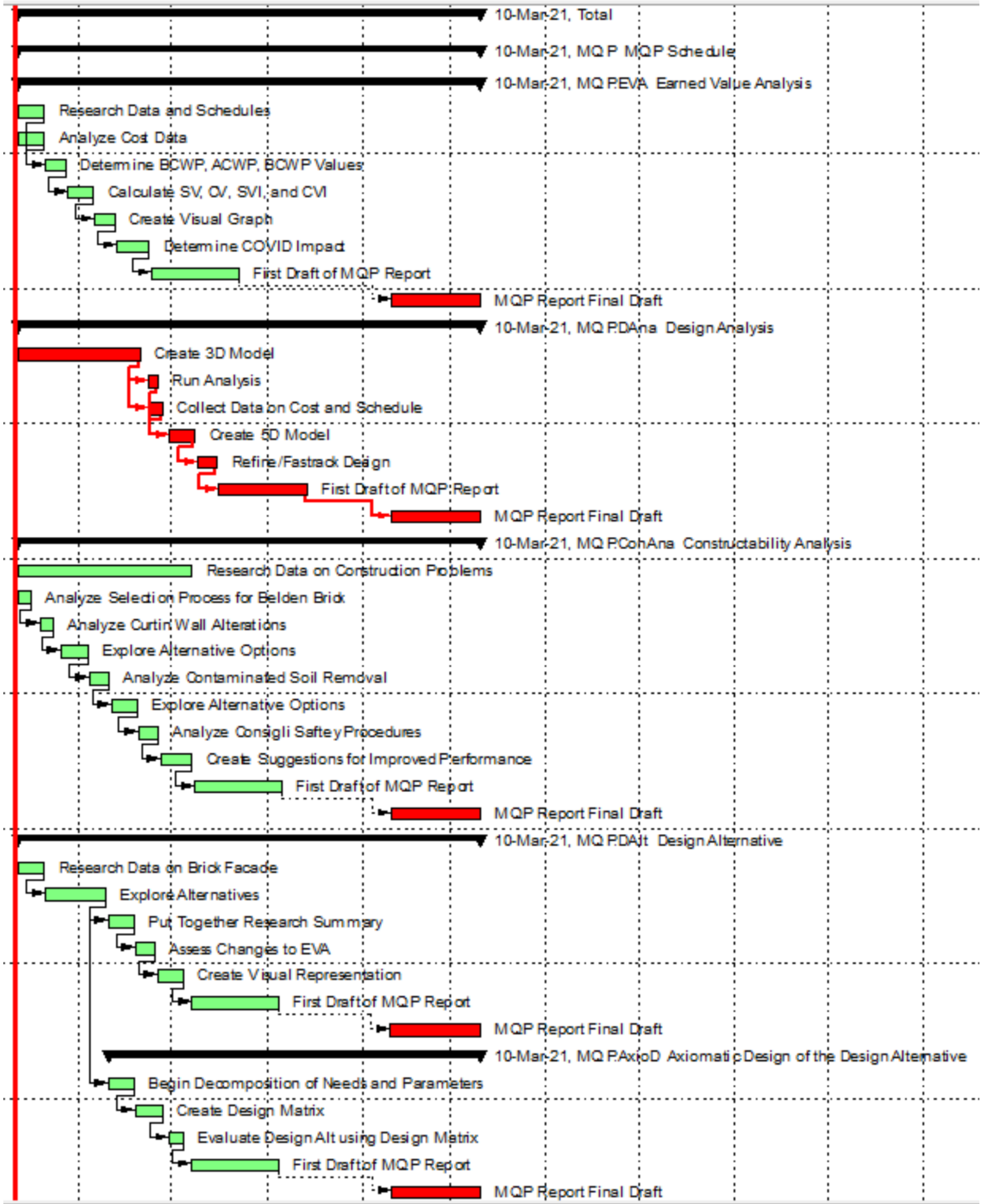
10.7 Conclusions and Future Potential Projects

The focus of WPI Smart World is to foster a more connected campus by creating a hub filled with research collaborations, active learning, student success, and campus accessibility. This project analyzed the decisions made during the design phase and tracked parts of the construction phase. With this project being on a time restriction, the analyses and construction tracking were bounded up to February 2021, any events or changes made after this date were not accounted for in this report. With the conclusions and recommendations listed in sections above, this project would be best used for any remodeling or future construction work on this building.

Future potential projects would include an analysis and survey conducted when the building is open and running. The analysis would track the progression of the building in terms of earned value, efficiency, and usage. Conducting a survey would provide insight into how previous construction management decisions have impacted the flow and usage of the building, as well as provide insight into how the final design successfully met the goals and purpose of the building. This project may also serve as a guide for any future analyses or construction work performed on the WPI Smart World Building.

MQP Schedule

Activity ID	Activity Name	Original Duration	Start	Finish	Total Float
MQP MQP Schedule		108	12-Oct-20	10-Mar-21	-21
MQP.EVA Earned Value Analysis		108	12-Oct-20	10-Mar-21	-21
EVA1	Research Data and Schedules	7	12-Oct-20	20-Oct-20	14
EVA2	Analyze Cost Data	7	12-Oct-20	20-Oct-20	14
EVA3	Determine BCWP, ACWP, BCWP Va	5	21-Oct-20	27-Oct-20	14
EVA4	Calculate SV, CV, SVI, and CVI	7	28-Oct-20	05-Nov-20	14
EVA5	Create Visual Graph	5	06-Nov-20	12-Nov-20	14
EVA6	Determine COVID Impact	7	13-Nov-20	23-Nov-20	14
EVA7	First Draft of MQP Report	21	24-Nov-20	22-Dec-20	14
EVA8	MQP Report Final Draft	21	10-Feb-21	10-Mar-21*	-21
MQP.DAna Design Analysis		108	12-Oct-20	10-Mar-21	-21
DAna1	Create 3D Model	30	12-Oct-20	20-Nov-20	-2
DAna2	Run Analysis	4	23-Nov-20	26-Nov-20	-1
DAna3	Collect Data on Cost and Schedule	5	23-Nov-20	27-Nov-20	-2
DAna4	Create 5D Model	7	30-Nov-20	08-Dec-20	-2
DAna5	Refine/Fastrack Design	5	09-Dec-20	15-Dec-20	-2
DAna6	First Draft of MQP Report	21	16-Dec-20	13-Jan-21	-2
DAna7	MQP Report Final Draft	21	10-Feb-21	10-Mar-21*	-21
MQP.ConAna Constructability Analysis		108	12-Oct-20	10-Mar-21	-21
ConAna1	Research Data on Construction Prob	41	12-Oct-20	07-Dec-20	46
ConAna2	Analyze Selection Process for Belde	5	12-Oct-20	16-Oct-20	4
ConAna3	Analyze Curtin Wall Alterations	5	19-Oct-20	23-Oct-20	4
ConAna4	Explore Alternative Options	7	26-Oct-20	03-Nov-20	4
ConAna5	Analyze Contaminated Soil Remov	5	04-Nov-20	10-Nov-20	4
ConAna6	Explore Alternative Options	7	11-Nov-20	19-Nov-20	4
ConAna7	Analyze Consigli Saftey Procedures	5	20-Nov-20	26-Nov-20	4
ConAna8	Create Suggestions for Improved Pe	7	27-Nov-20	07-Dec-20	4
ConAna9	First Draft of MQP Report	21	08-Dec-20	05-Jan-21	4
ConAna91	MQP Report Final Draft	21	10-Feb-21	10-Mar-21*	-21
MQP.DAlt Design Alternative		108	12-Oct-20	10-Mar-21	-21
DAlt1	Research Data on Brick Facade	7	12-Oct-20	20-Oct-20	5
DAlt2	Explore Alternatives	14	21-Oct-20	09-Nov-20	5
DAlt3	Put Together Research Summary	7	10-Nov-20	18-Nov-20	5
DAlt4	Asses Changes to EVA	5	19-Nov-20	25-Nov-20	5
DAlt5	Create Visual Representation	7	26-Nov-20	04-Dec-20	5
DAlt6	First Draft of MQP Report	21	07-Dec-20	04-Jan-21	5
DAlt7	MQP Report Final Draft	21	09-Feb-21	10-Mar-21*	-21
MQP.AxioD Axiomatic Design of the Design		87	10-Nov-20	10-Mar-21	-21
AxioD1	Begin Decomposition of Needs and	7	10-Nov-20	18-Nov-20	5
AxioD2	Create Design Matrix	7	19-Nov-20	27-Nov-20	5
AxioD3	Evaluate Design Alt using Design M	5	30-Nov-20	04-Dec-20	5
AxioD4	First Draft of MQP Report	21	07-Dec-20	04-Jan-21	5
AxioD5	MQP Report Final Draft	21	10-Feb-21	10-Mar-21*	-21


10-Mar-21, Total
10-Mar-21, MQP MQP Schedule
10-Mar-21, MQP EVA Earned Value Analysis
Research Data and Schedules
Analyze Cost Data
Determine BCWP, ACWP, BCWP Values
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MQP Report Final Draft
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Research Data on Construction Problems
Analyze Selection Process for Belden Brick
Analyze Curtin Wall Alterations
Explore Alternative Options
Analyze Contaminated Soil Removal
Explore Alternative Options
Analyze Consigli Saftey Procedures
Create Suggestions for Improved Performance
First Draft of MQP Report
MQP Report Final Draft
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Research Data on Brick Facade
Explore Alternatives
Put Together Research Summary
Assess Changes to EVA
Create Visual Representation
First Draft of MQP Report
MQP Report Final Draft
10-Mar-21, MQP AxioD Axiomatic Design of the Design Alternative
Begin Decomposition of Needs and Parameters
Create Design Matrix
Evaluate Design Alt using Design Matrix
First Draft of MQP Report
MQP Report Final Draft

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Appendix

Initial Project Proposal

Table of Contents

Abstract

This project provides an analysis of the earned value and design of WPI's Smart World Building. This was done by analyzing the building through its design process and following the construction of the building. By viewing the implications of design choices and weighing potential changes to the design, this project is able to show the impact of construction project management decisions on the building. Examining this is beneficial to the industry in exploring the impact of design choices and construction decisions on a construction project.

Introduction and Problem Statement

The construction and design of Worcester Polytechnic Institute's newest academic building, Smart World, has experienced drastic changes throughout its construction. The project began construction in October 2019 and was originally slated for completion before the 2021-22 school year. The impact of the COVID-19 pandemic has heavily impacted the construction process for the building, distorting the original planned costs and timeline. The building itself also attracts attention, as it is designed in order to provide a flexible floor plan design that integrates advanced engineering technology. WPI originally budgeted 80 million dollars for the building, a heavy investment taken so that the school is further prepared for the future of engineering education.

The scope of this project is to examine the building's design and construction progress through the lens of project management. We will be conducting an earned value analysis, design & constructability analysis, and will develop potential design alternatives for the building.

Background

Design and Constructability Analysis

Building Information Modeling (BIM) is used to allow for easier collaboration within the design and construction of buildings. This process uses software called Revit to create a visual representation of what is typically seen only on construction drawings, or blueprints. There are multiple layers to BIM to allow for ease of use for every profession within the design and construction team. It combines all of the blueprints and drawings into one local place for multiple groups to view, edit, or add onto. The created 3D model contains all the information needed for the planning, design, construction, and maintenance of a building. Not only does BIM bring 2D drawings to a 3D model but it can even be used to create a 4D, 5D, and 6D model. Each level portrays a different amount of information for each step during construction.

Within the scope of this project, we will create a 5D model. With the given schedule information from Consigli Construction, we will create the 4D model which takes the 3D model and adds a layer of scheduling and phases to show a representation of how the 3D model is going to be built. With the given cost information, we will then create the 5D model which takes the 4D model and adds a layer of the cost associated with each phase of construction.

Our team will explore the contractor's value engineering moments during the construction process. Value engineering in construction management is defined as an organized effort towards analyzing the building systems, features, equipment, and material selections for the purpose of reaching essential functions at the lowest life-cycle cost (U.S. General Services Administration, 2017). The construction contractor usually proposes a value engineering change to construction requirements, materials, or methods because of unsuspected conflicts with schedule, costs, or design. The change aims to not increase the cost of construction or the life cycle cost of the building while maintaining building performance, design quality, safety, and appearance (U.S. General Services Administration, 2017).

This project will consider multiple factors such as color, texture, size, shape, type, grade, and availability when analyzing the building's brick facade. We will investigate the benefits and/or drawbacks of Consigli Construction's brick alternative. We will look at their initial bricks options from four major brick manufacturers and distributors; the Endicott Clay Products Company, the Belden Brick Company, the Yankee Hill Brick, and the Cloud Ceramics.

Axiomatic Design

Axiomatic Design was created by Professor Nam Suh to analyze different designs by establishing a set of parameters that the design is supposed to meet. With this method, we can use it to systematically analyze different designs by setting them under specific parameters. The method will break down the design into a matrix that consists of different categories such as, Customer Needs (CNs), Functional Requirements (FRs), Design Parameters (DPs), and Process Variables (PVs); while all being bound by Constraints (CONs). CNs are requirements that are normally set by the client because they are the things that the client's wishes to get out of the design, for example, a client would normally set some sort of aesthetic need that they would like to get out of the design because they wish for it to look a certain way. FRs are the functional aspects of the design in which it is supposed to perform in a certain way. DPs are the parameters that set constraints on the design itself, meaning that the design we are evaluating stays within the constraints set on it. PVs are the variables that break down the process in which this design will be constructed and instances that need to be taken into account when beginning construction of the design. Finally, CONs are boundaries that are established on the design which need to be kept within these boundaries in order for the design to be feasible with what we are trying to accomplish, examples of these CONs can be budget and availability of materials.

Earned Value Analysis

An Earned Value Analysis refers to a method by which a project manager can measure the project's work by the progress achieved, and allows for them to estimate total cost and date of completion for the project. An EVA allows the manager to determine whether or not the project is on schedule or on budget, and serves to avoid project creep. The project's budget and schedule information will be analyzed to find individual planned and actual costs for each of the activities and planned actual times the project's milestones were completed.

The team will use a program called Primavera to conduct the EVA. Primavera is software designed to support project planning, reporting, and progress tracking. The primavera software allows for issue tracking, break activities into sub-activities, allows for the creation of a Work Breakdown Structure, and among other things creates a Gantt Chart and CPM diagram when the data is added and allows for them to be updated allowing it to reflect the project on real-time.

For this project, the team will use Primavera to measure the project's progress and schedule and create an Earned Value Analysis for the originally planned schedule pre-COVID-19 and the actual project schedule and timeline. With the scheduling data given by Consigli to the team showing their planned timeline for the project and the actual timeline, and associated the budgetary data a Gantt chart that shows what each project milestone cost. This will be done for each scenario, the information will be then used to calculate construction progress and costs.

The project will take into account the project's delays namely the cost of those delays, and the reading why such as the delays that occurred due to COVID-19, in addition to the cost of smaller expenses such as training, and travel costs. The team will analyze the efficiency of the Consigli team in regards to budgeting, and scheduling, and how they reacted to the unforeseen developments.

Scope of work and Methodology

Earned Value Analysis

An Earned Value Analysis is a method that is used to compare the planned value of the project and the actual planned value of the work performed. The data necessary to conduct this report will be supplied by the Consigli Smart World Team. This data will be used to create the analysis by finding the project's Budgeted Cost of Work Scheduled (BCWS), Actual Cost of Work Performed (ACWP), and Budgeted Cost of Work Performed (BCWP). The Budgeted Cost of Work Scheduled also known as the Planned Value (PV) and will be calculated by multiplying the planned percentage of the completed work and the project's Budget at Completion (BAC). Actual Cost of Work Performed or Actual Cost (AC) for short and will be found by looking at the total cost of the project when it is completed. The Budgeted Cost of Work Performed also known as Earned Value (EV) and will be found by multiplying the completed work percent and the BAC. Using these values the project's Schedule Variance (SV) and Cost Variance (CV) can be calculated. The SV will be found by subtracting Planned Value from the Earned Value, which will determine if the project is ahead, behind, or one schedule depending on the result. The CV will be found by subtracting the Actual Cost from the Earned Value and will determine if the budget is over, behind, or on budget. These in turn can be used to Schedule Performance Index (SPI) and Cost Performance Index (CPI). The SPI is a comparison to the project's planned schedule and is found by dividing the project's Earned Value by it's Planned Value, and will determine if the project is ahead, behind, or one schedule if it is more than, less than, or equal to one. The CPI is a measure of the project's cost efficiency, which is determined by dividing the EV by the AC, and if the CPI is greater than, lesser than, or equal to one which means the project is over, under, or on budget respectively. Once these calculations are complete the results will be shown in a visual format using graphs.

EVA	What	How
Projected	The projected EVA of Consigli's original plan before COVID impacts Before (3/19/20) actual up to 3/19/20	Using the original projected timeline, the value of work done before the COVID break and impact
Actual	The actual EVA of Consigli's plan	Go though schedules updated (every two weeks) the actual value of work done since 3/19/20 vs projected value of work after

Design Analysis

The design analysis will explore how the building was designed and why those design choices were made. Our team will break down the build into individual parts and model the building using Revit software. The 3D model created using building information modeling (BIM) will be an accurate representation of what is being constructed on-site. In order to fully break down the project, we will use the provided construction drawings as a base for creating the model. We will reference any change orders and bulletins and apply these directly to the model. Our team will also use Consigli Construction as a resource and request access to any 3D modeling they have available as well. With the 3D model completed, the building efficiency will be determined using the analysis feature within Revit. An energy analysis will be run to see if the building can be classified as a net-zero build. If it is not net-zero, our team will review the analysis and make necessary changes and recommendations to quality for a net-zero status. A lighting analysis will be run to determine the amount of natural light that enters the building through all parts of the day. This analysis will allow us to determine if the current building orientation is optimized for natural lighting. Structural analysis will be run to determine the effects of the structural loads and to see if these loads are code compliant. Through this analysis, our team will recommend any necessary adjustments to further improve the design of the building.

Once a thorough analysis is completed for the 3D model and all necessary recommendations have been made, our team will create a 5D model using building information modeling (BIM). We will gather information on the project phasing, sequencing, schedule, and costs. This information will come directly from Consigli, access to some of these documents may be limited, therefore the 5D model will be an estimate and close representation of the design. With the project milestones and phasing, we will divide the 3D model into its respective sections and assign its associated timeline with each phase. With sequencing in place and organized to represent real-time construction, our team will further break down each phase into CSI divisions and match up the schedule to the current project schedule. We will export the Revit file into Navisworks to create a visual representation of the project schedule. Adjustments to the schedule will be necessary as the project continues, and any methods to fast track the schedule will be reviewed. Our team will then add the project costs to each of the phases to also allow for visual representation and easy tracking of how the project costs are distributed throughout the whole project. With this 5D model, our team will have a complete analysis of all the elements of this building and be able to fully assess how to best improve and refine the design of the building.

Design Analysis	What?	How?
3D Model	Energy Analysis Lighting Analysis	Utilize Revit to build a 3D model of the building
5D Model	Adding Schedule and Cost to 3D model	Assess ways to possibly fast track the schedule and lower costs with Navisworks

Constructability Analysis

Our team will look into three major value engineering moments during construction: the brick façade, the curtain wall system, and the contaminated soil removal. We will research the original plans for each instance with meeting notes, reports, and any additional information provided by Consigli Construction and through their construction management software Procore. We will look at the problems they had, their approach to a new plan, and their final solution.

For the brick facade, our team will explore how the original Endicott brick was not a viable option, and the reasons behind Consigli's decision to use the Belben brick. We will assess their initial comparisons of the Endicott brick versus the alternative options: the Belden brick, the Cloud Ceramic brick, and the Yankee Hill brick. We will then analyze their specified comparisons of the Endicott brick to the Belden brick and their through-body comparisons of the Belden brick options. Our team will examine the obstacles presented in the initial plans to attach the curtain wall and how Consigli resolved the problem. We will look at any design changes made to the curtain wall system and its effects on cost, time, and ease of installation. We will also explore alternative options to see how the system could be further improved. Our team will look into the contaminated soil of Worcester county and how its high arsenic levels created a challenge in finding suitable landfills. Through Procore, we will review their daily reports to see how much soil they removed each truck and how much time they spent on transportation. We will review different landfill rules restrictions to assess Consigli's solution and our team will create an upgraded plan for soil removal.

Our team will gather information about the Consigli's current safety standards and procedures for construction and we will assess how these standards have changed as a result of COVID-19. Through Procore, our team will review documents like their Site-Specific COVID-19 Safety Plan and safety reports. We will create suggestions for how to improve on their safety performance and to maintain safety levels. Our team will also explore the changes in scheduling, phasing, and sequencing due to COVID-19 and its impacts on the construction process.

Constructability Analysis	What?	How?
Brick	WPI's original brick vs the alternative they chose	Analyze the reasons behind choosing the Belden brick
Curtain Wall System	Had to change the way the curtain wall was attached to the slab edge	See how this changed the design and ease of installation, what ways can the idea improve
Contaminated Soil Removal	Finding suitable landfills for soil with high arsenic levels	Evaluate options that could improve the solution used
COVID	Changes in scheduling, phasing, and sequencing due to COVID	Assess changes to critical path and timelines, see how much it impacted the project in regards to schedule, cost, time
Safety	Review safety standards and protocols	Suggest ways to refine standards and improve safety

Design Alternative

The design alternative will investigate various solutions to the problem presented by the brick façade during construction. We will research the original design plan for the brick façade, referencing original construction documents and specifications. We will document the decision-making process for the voiding of the original plan, along with noting the multitude of ways the problem could have been presented. Our team will then analyze the design alternative chosen for the brick façade and suggest a new alternative. The meeting notes, RFIs, change orders, and reports will provide us with the information necessary to fully assess the requirements needed for this change. Once our team has fully established a design alternative that will fit all the requirements and desires of the owner and construction team, we will then format this design change into a visual representation. Using the existing 3D model of the building, we will apply the design change to the model. The new design will be correlated with the existing design using energy and lighting analysis within Revit. We will also assess the cost and schedule implications affiliated with the new design alternative and directly compare those with the design used in the current construction. We will compare the two by observing the impact of any alternate design changes on our earned value analysis. We will calculate the new cost and schedule variances,along with adding a new adjusted Gantt chart using Primavera P6. With this thorough comparison, we are able to determine if the design decisions that Consigli proceeded with was the optimal design alternative.

Throughout the term, our team will keep a close eye on the progress of the construction team, therefore additional design changes are a possibility. We will be investigating any problems that may arise and offer additional solutions where possible. We will also be looking into possible missed opportunities, seeing where additional features could have been implemented or quality could have been improved.

Axiomatic Design

The scope of which our Axiomatic Design will be is that we will use this design to evaluate the decision that Consigli made to change the type of brick they are using for the exterior of the building and evaluate our version of the design. The axiomatic design will give us the scope needed to understand how these designs may have affected the project as a whole and if they are good designs based on the parameters we set for the design.

To begin the axiomatic design of this design alternative decision to change the brick we must establish multiple sets of parameters that meet the requirements in which the design is supposed to meet. These sets of parameters include: Customer Needs(CNs), Functional Requirements(FRs), Design Parameters(DPs), Process Variables(PVs), and Constraints(CONs). CNs are requirements that are normally set by the client because they are the things that the client's wishes to get out of the design, for example, a client would normally set some sort of aesthetic need that they would like to get out of the design because they wish for it to look a certain way. FRs are the functional aspects of the design in which it is supposed to perform in a certain way. DPs are the parameters that set constraints on the design itself, meaning that the design we are evaluating stays within the constraints set on it. PVs are the variables that break down the process in which this design will be constructed and instances that need to be taken into account when beginning construction of the design. Finally, CONs are boundaries that are established on the design as a whole and the final design needs to be kept within these boundaries in order for the design to be feasible with what we are trying to accomplish.

To decide what our parameters will be, we must think about many aspects of the design and understand multiple components of how the design will work with the whole building system. The way in which we will be able to accomplish this task will be to ask ourselves multiple questions on what this design is trying to accomplish. For reference to some questions we may ask, refer to the table below:

Axiomatic Design Parameters	Questions To Ask
CNs	What does the client want out of the design? - Aesthetics?
FRs	How does this design function? - Protection from the elements? - Insulate Interior? - Shed water? - Prevent air infiltration?
DPs	Is it structurally sound? Does it meet the specified code requirements?
PVs	What is the process to construct it? - Pre-Fabricated? - The machinery needed to apply to the building?
CONs	What are the variables it needs to be bounded by? - Cost/Budget - Schedule/ length of the build - Supply chain

Once we establish our parameters in which the design will reside, we can begin evaluating it based on all of these parameters and since we will create our own design we can use this same matrix to evaluate our design as well. The way in which we plan to conduct this evaluation is to create a matrix that includes all of the parameters we have set for the designs and start cross-checking whether or not the design is meeting these requirements. After we have gone through all of the matrices we will be able to see how many parameters were met and from that, we will be able to decide how effective the designs will be. Then, from this we can see if our design meets the feasibility of the design that Consigli created.

Capstone Design Statement

This Major Qualifying Project has the following goals regarding the WPI Smart World Building being constructed by Consigli: creation of an Earned Value Analysis, a Design and Constructability Analysis, an Alternative Design, and a section Axiomatic Design. The capstone design for this project will analyze the effectiveness of the Smart World building in terms of its budget, schedule, design and structural analysis, construction, and safety.

Economic

This report will examine budgets of the Smart World project and how they may have changed due to the COVID-19 pandemic. It will also include an analysis of the costs associated with our design alternative of the brick facade. An Axiomatic Design will be created for the design alternative and cost constraints will be made for the design to ensure that alternative complies with the budgets that are set for the project. An Earned Value Analysis will be done to analyze how the project's budget changed over time, and what impact COVID-19 had.

Environmental

This report will explore the environmental challenges faced when removing soil during construction. Due to the fact the soil in Worcester County is highly contaminated with arsenic, finding appropriate landfills and meeting regulations proved to be a major obstacle for Consigli Construction. This project will search for alternative options to satisfy safety hazard standards and to protect the environment.

Constructability

The Design Analysis will entail using Revit to model the building and determine its overall efficiency. As a result we will make recommendations to Consigli by analyzing its energy, light, and structural properties to see if the building has an optimized design in regards to the lighting, code requirements, and net-zero energy usage.

This report will analyze multiple constructability issues faced by the construction contractor of Smart World. The analysis will investigate Consigli Construction’s brick alternative for the building’s brick façade. It will compare bricks from multiple brick manufacturers based on characteristics such as texture, size, shape, color, cost, and availability. There will also be an assessment of the design changes made to the curtain wall system. It evaluates the installation problem faced during construction and explores any alternative options for improvements in the system design, cost, and schedule.

Safety

This report will investigate the Consigli Project Team’s decisions in regards to safety. To be specific the responses, and measures taken to hazards that occurred during the project such as common construction hazards, and preventing the spread of COVID-19 among everyone involved with the project. The effectiveness of measures they have taken due to COVID-19 will be examined through their Site-Specific COVID-19 Safety Plan, which describes all the measures Consigli and its workers are to take. For example, having the project team conduct virtual meetings, worker self vertifiction, site access, and guidelines on what is expected in the event of a confirmed case in addition to the safety measures that are standard on construction sites.

Ethic/Social

Each week the Consigli Project team met among themselves to discuss the project and inform each other of any updates that have occurred in the interim since they last met. During each of the meetings, the team planned on at least one of their members being present at these meetings to observe. In addition to observing the project's progress, the MQP team member present took note of how the Consigli team conducted the meetings, and interacted with one another. It will examine how the ethics Consigli team influenced the meeting. The ethics observed will be how they present themselves when contributing to discussion, how they behaved during disagreements, and followed their contracted responsibilities.

Deliverables

Earned Value Analysis

One of the analyses that our team will conduct for Consigli's Smart World building project will include an Earned Value Analysis (EVA), which will allow us to calculate the Schedule Variance (SV) and the Cost Variance (CV). Deliverables that can be expected from this portion of the project will include a breakdown of the EVA calculations and one graph showing the correlations. The one graph will include the projection of the Earned Value of the project pre-COVID-19 and the present EVA that includes the challenges COVID-19 brought to the project. These will be presented over the period of time in which the project is being completed (% of completion). From this, we may be able to analyze the effectiveness of the plan Consigli made to combat the COVID-19 pandemic and how they were able to rearrange the project schedule to get the project back on track while keeping everyone's health and safety in mind. Furthermore, this analysis will provide us the scope of how the budget and schedule may have changed since they had to make some drastic changes in order to resume construction.

Design Analysis

The design analysis will consist of the creation of a 5D model using Building Information Modeling (BIM). With the created model we will run multiple analysis on the building to evaluate the energy usage, lighting efficiency, and performance of the building. We will create the 5D model by gathering information regarding the projected schedule and costs, and linking these to the 3D model with the project phases and sequences. Throughout the project our team will update the model to best represent the as-built drawings.

With the data collected from the analysis, our team will brainstorm ideas to fast track the schedule by overlapping item start dates, minimizing durations, and accelerating fabrication/ delivery timelines. As for a deliverable, we will present Consigli Construction with a report of building efficiency along with various changes and methods to increase the overall efficiency and design of the building.

Constructability Analysis

The constructability analysis will present an in-depth study of three value engineering events during construction and any alternative ideas from our team. The analysis report will be on the brick facade, the curtain wall system, and the contaminated soil removal issue. We will also present Consigli Construction with a report of their current safety regulations and procedures with suggestions on how to improve their standards.

Design Alternative

While analyzing the construction process, our team will put together a mockup for a design alternative. Depending on how the construction proceeds we may offer multiple design alternatives. The alternative designs will feature a side by side comparison with the design used in construction and the proposed design. We will analyze the cost, schedule, and quality impacts associated with the alternative. Alongside these direct impacts, there will be analysis to see how the alternative design will impact the existing earned value analysis.

One design alternative will review Consigli's decision to change the brick subcontractor and the method of applying the brick. We will evaluate the reasons behind this decision, and the selection process for the new subcontractor and bricklaying method. Once adequate data is obtained we will then explore other options, separate from the design alternative chosen during construction. The selection for alternative brick subcontractors will be based on the quality of work, the cost of labor, and availability. As for a deliverable, we will fully implement our design change into a 5D model of the building and present this change to Consigli, listing out the various impacts and improvements of the design alternative.

Axiomatic Design of The Design Alternative

As our team begins evaluating the decision to change the brick subcontractor and the method of applying the brick, an axiomatic design will be conducted alongside it, to evaluate its cost-effectiveness, functionality, and aesthetic. The axiomatic design will allow our team to revolve the design around *Customer Needs* (CNs), *Functional Requirements* (FRs), *Design Parameters* (DPs), *Process Variables* (PVs), and *Constraints* (CONs). By determining these variables we can create a design that meets all the needs the first time while making sure the design is the most efficient in the sense of cost, constructability, and functionality while being the most appealing option as well.

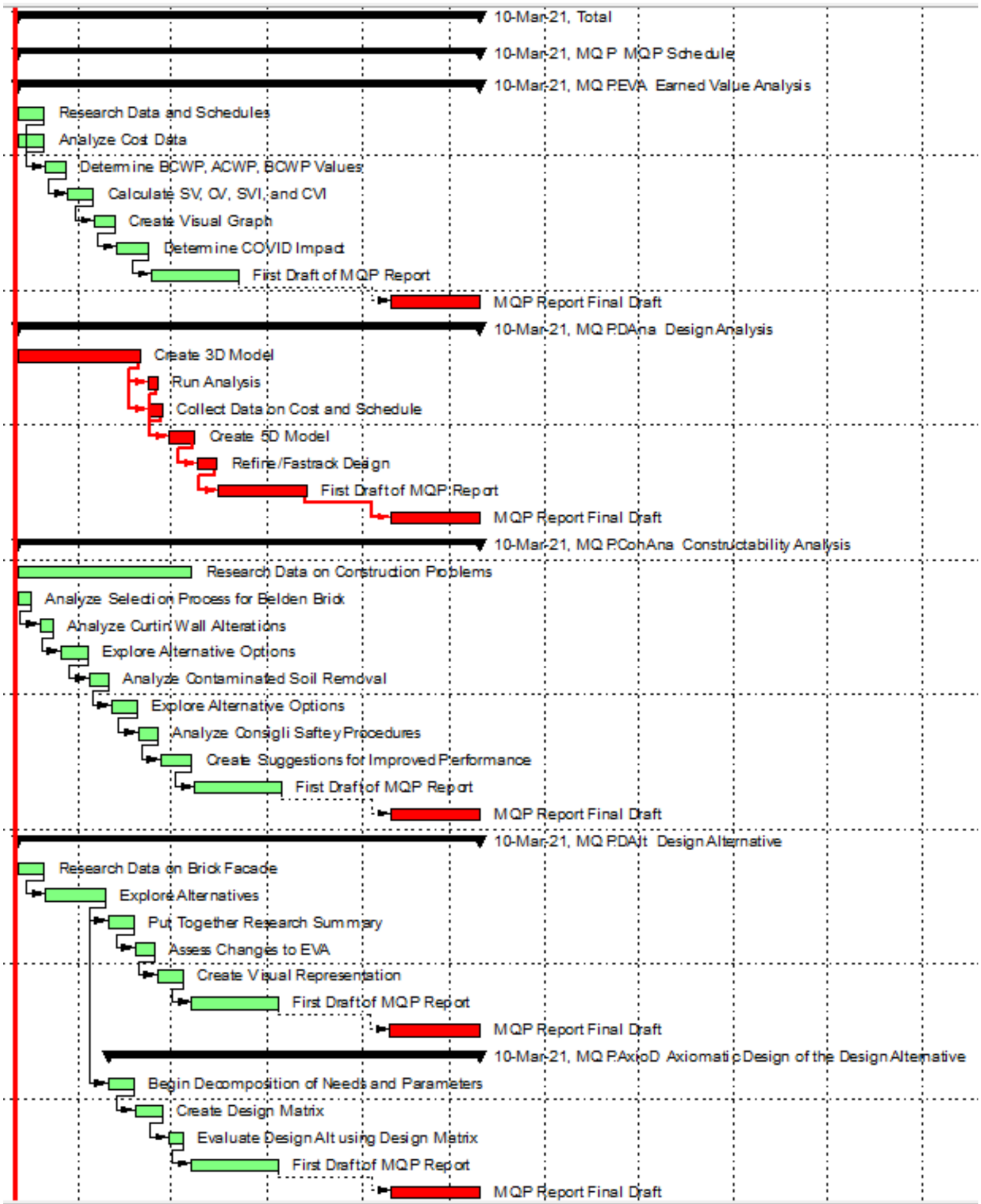
As for a deliverable, we will create a design matrix that can evaluate the design we have created and also evaluate the design Consigli has created as well. This matrix will include multiple variables that will be able to cover all parameters that the design may be bound by.

Conclusions

Once we complete our project, we expect to gain information about the Smart World project through our analyses of it. The information we hope to gain from this project will allow us to create an Earned Value Analysis(EVA), which helps us understand how the projected budget did versus the real time cost of the project through the time of construction and the percent of completion. As we conduct this analysis, we hope to implement the events of COVID and how these events may have hindered the project in any way. With this information, we can analyze the overall efficiency of the project even with the COVID restrictions in place. Following this, we will perform a constructability analysis of three value engineering events during construction to see the feasibility of constructing them and provide any alternative design ideas from our team. Furthermore, as our team analyzes the construction process of the Smart World Building we will create a mock up design alternative for some aspect of the project. With this, we can create a side by side comparison of the actual design versus our alternative design. As we go through the design process, a member of the team will be creating an axiomatic design matrix for our design alternative. Using this as we navigate our way through the process, it will help us understand what is the most optimal design for this alternative. Therefore, when we present our alternative design option, we will know it was the leading option based on the parameters and constraints set and keeping the design within those boundaries.

Schedule

Activity ID	Activity Name	Original Duration	Start	Finish	Total Float
MQP MQP Schedule		108	12-Oct-20	10-Mar-21	-21
MQP.EVA Earned Value Analysis		108	12-Oct-20	10-Mar-21	-21
EVA1	Research Data and Schedules	7	12-Oct-20	20-Oct-20	14
EVA2	Analyze Cost Data	7	12-Oct-20	20-Oct-20	14
EVA3	Determine BCWP, ACWP, BCWP Va	5	21-Oct-20	27-Oct-20	14
EVA4	Calculate SV, CV, SVI, and CVI	7	28-Oct-20	05-Nov-20	14
EVA5	Create Visual Graph	5	06-Nov-20	12-Nov-20	14
EVA6	Determine COVID Impact	7	13-Nov-20	23-Nov-20	14
EVA7	First Draft of MQP Report	21	24-Nov-20	22-Dec-20	14
EVA8	MQP Report Final Draft	21	10-Feb-21	10-Mar-21*	-21
MQP.DAna Design Analysis		108	12-Oct-20	10-Mar-21	-21
DAna1	Create 3D Model	30	12-Oct-20	20-Nov-20	-2
DAna2	Run Analysis	4	23-Nov-20	26-Nov-20	-1
DAna3	Collect Data on Cost and Schedule	5	23-Nov-20	27-Nov-20	-2
DAna4	Create 5D Model	7	30-Nov-20	08-Dec-20	-2
DAna5	Refine/Fastrack Design	5	09-Dec-20	15-Dec-20	-2
DAna6	First Draft of MQP Report	21	16-Dec-20	13-Jan-21	-2
DAna7	MQP Report Final Draft	21	10-Feb-21	10-Mar-21*	-21
MQP.ConAna Constructability Analysis		108	12-Oct-20	10-Mar-21	-21
ConAna1	Research Data on Construction Prob	41	12-Oct-20	07-Dec-20	46
ConAna2	Analyze Selection Process for Belde	5	12-Oct-20	16-Oct-20	4
ConAna3	Analyze Curtin Wall Alterations	5	19-Oct-20	23-Oct-20	4
ConAna4	Explore Alternative Options	7	26-Oct-20	03-Nov-20	4
ConAna5	Analyze Contaminated Soil Remov	5	04-Nov-20	10-Nov-20	4
ConAna6	Explore Alternative Options	7	11-Nov-20	19-Nov-20	4
ConAna7	Analyze Consigli Saftey Procedures	5	20-Nov-20	26-Nov-20	4
ConAna8	Create Suggestions for Improved Pe	7	27-Nov-20	07-Dec-20	4
ConAna9	First Draft of MQP Report	21	08-Dec-20	05-Jan-21	4
ConAna91	MQP Report Final Draft	21	10-Feb-21	10-Mar-21*	-21
MQP.DAlt Design Alternative		108	12-Oct-20	10-Mar-21	-21
DAlt1	Research Data on Brick Facade	7	12-Oct-20	20-Oct-20	5
DAlt2	Explore Alternatives	14	21-Oct-20	09-Nov-20	5
DAlt3	Put Together Research Summary	7	10-Nov-20	18-Nov-20	5
DAlt4	Asses Changes to EVA	5	19-Nov-20	25-Nov-20	5
DAlt5	Create Visual Representation	7	26-Nov-20	04-Dec-20	5
DAlt6	First Draft of MQP Report	21	07-Dec-20	04-Jan-21	5
DAlt7	MQP Report Final Draft	21	09-Feb-21	10-Mar-21*	-21
MQP.AxioD Axiomatic Design of the Desigr		87	10-Nov-20	10-Mar-21	-21
AxioD1	Begin Decomposition of Needs and	7	10-Nov-20	18-Nov-20	5
AxioD2	Create Design Matrix	7	19-Nov-20	27-Nov-20	5
AxioD3	Evaluate Design Alt using Design M	5	30-Nov-20	04-Dec-20	5
AxioD4	First Draft of MQP Report	21	07-Dec-20	04-Jan-21	5
AxioD5	MQP Report Final Draft	21	10-Feb-21	10-Mar-21*	-21


10-Mar-21, Total
10-Mar-21, MQP MQP Schedule
10-Mar-21, MQPEVA Earned Value Analysis
Research Data and Schedules
Analyze Cost Data
Determine BCWP, ACWP, BCWP Values
Calculate SV, CV, SVI, and CVI
Create Visual Graph
Determine COVID Impact
First Draft of MQP Report
MQP Report Final Draft
10-Mar-21, MQPDAna Design Analysis
Create 3D Model
Run Analysis
Collect Data on Cost and Schedule
Create 5D Model
Refine/Fastrack Design
First Draft of MQP Report
MQP Report Final Draft
10-Mar-21, MQPCohAna Constructability Analysis
Research Data on Construction Problems
Analyze Selection Process for Belden Brick
Analyze Curtin Wall Alterations
Explore Alternative Options
Analyze Contaminated Soil Removal
Explore Alternative Options
Analyze Consigli Saftey Procedures
Create Suggestions for Improved Performance
First Draft of MQP Report
MQP Report Final Draft
10-Mar-21, MQPDAlt Design Alternative
Research Data on Brick Facade
Explore Alternatives
Put Together Research Summary
Assess Changes to EVA
Create Visual Representation
First Draft of MQP Report
MQP Report Final Draft
10-Mar-21, MQPAxioD Axiomatic Design of the Design Alternative
Begin Decomposition of Needs and Parameters
Create Design Matrix
Evaluate Design Alt using Design Matrix
First Draft of MQP Report
MQP Report Final Draft

Earned Value Analysis

Over the course of B term team members, Javier and Michael will begin working on creating an Earned Value Analysis for the Consigli Smart World Project. To do this once B term begins, they will go through the data and schedules that they have already been given access to by Consigli. The data concerning the project's budget may take some time to be sent to the team. Analyzing the cost data should only take a week. Then they would determine the BCWS, ACWP, and BCWP of the project, which will then be used to find the cost and schedule variances.

This process should only take a week or two to complete. Once these values are determined the analysis of their significance can be completed. Then using the comparison of data from the actual project timeline and original pre-COVID timeline to determine the impact of the COVID pandemic. Then the effectiveness of Consgili's team in regards to the project will be determined.

Design Analysis

At the start of B term, our team member Kayla will begin to design the 3D model using the provided construction documents in ProCore. This should take 3-4 weeks to complete. Upon finishing the 3D model we should have access to the updated construction schedule, and possible access to rough cost estimates for the different phases of construction. We will then implement the schedule and cost data into the 3D model to create a 5D model. This should take 1 week to complete. During the last week of B term, our team will thoroughly review the models to refine, improve, and fastrack as much as possible.

Constructability Analysis

At the beginning of B-term, our team member Jessica will begin deeper research on all the information and any related documents Consigli Construction will provide us with. First, we will start on assessing Consigli's process of solving the brick façade. Next, we will move onto analyzing the curtain wall system. Then, we will begin research for the contaminated soil removal. We will take around two weeks per value engineering event to analyze the issue, investigate alternative solutions, and come up with suggestions on how to improve further. After analysis of the value engineering is done, our team will then start evaluating Consigli's safety standards and protocol. It will take around two weeks to finish our analysis and come up with suggestions for improved performance.

Design Alternative

During the first 2 weeks of B-Term, our team member Evan will comb through the data provided regarding the brick facade. We will put together a research summary and overview of the problem, solution options, and the option Consigli proceeded with. The next 2 weeks, we will begin researching alternative solutions to the problem. After a valid, superior approach is determined, we will thoroughly research the pros and cons of this idea, and also assess how it will impact the current earned value analysis. We will put together a report with detailed sketches and comparisons. During the 5th week, once the 3D model is completed, we will reflect the design alternative onto the model for a better visual representation of the change recommended. The last two weeks of B term will consist of researching other design alternatives that can be put into place. We will brainstorm, research, and meet with Consigli to decide upon another design alternative to add to this project. Once we have decided upon another design change, we will spend the beginning weeks of C term following through with the same process as the brick design alternative. 2 weeks into C term our team should have both design alternatives in a formal report and added into the 3D model. The remainder of the term will consist of refinements, and documentation.

Axiomatic Design of Design Alternative

Once B-term begins, our team member Michael will begin his axiomatic decomposition of the FNs and DPs to create his subcategories to help us create the best design solution. This will take 1-2 weeks. Then, CONs should be established after to keep the FRs and DPs bound within these CONs. This will take another week or so. Once all of these parameters are established, then the design alternative can be analyzed and see if it meets the optimal parameters that were set. From this we can tweak the design, so it meets all the parameters and still stays within the CONs set on the design.

References

Mistree, Farrokh. (1992). Review of 'The Principles of Design' by Nam P. Suh, Oxford University Press, 1990. Research in Engineering Design. 3. 243-246.

Suh, N. P. (1998). Axiomatic design theory for systems. *Research in Engineering Design, 10*(4), 189-209. doi:10.1007/s001639870001

Suh, N. P (1990). *The principles of design*. New York: Oxford University Press.

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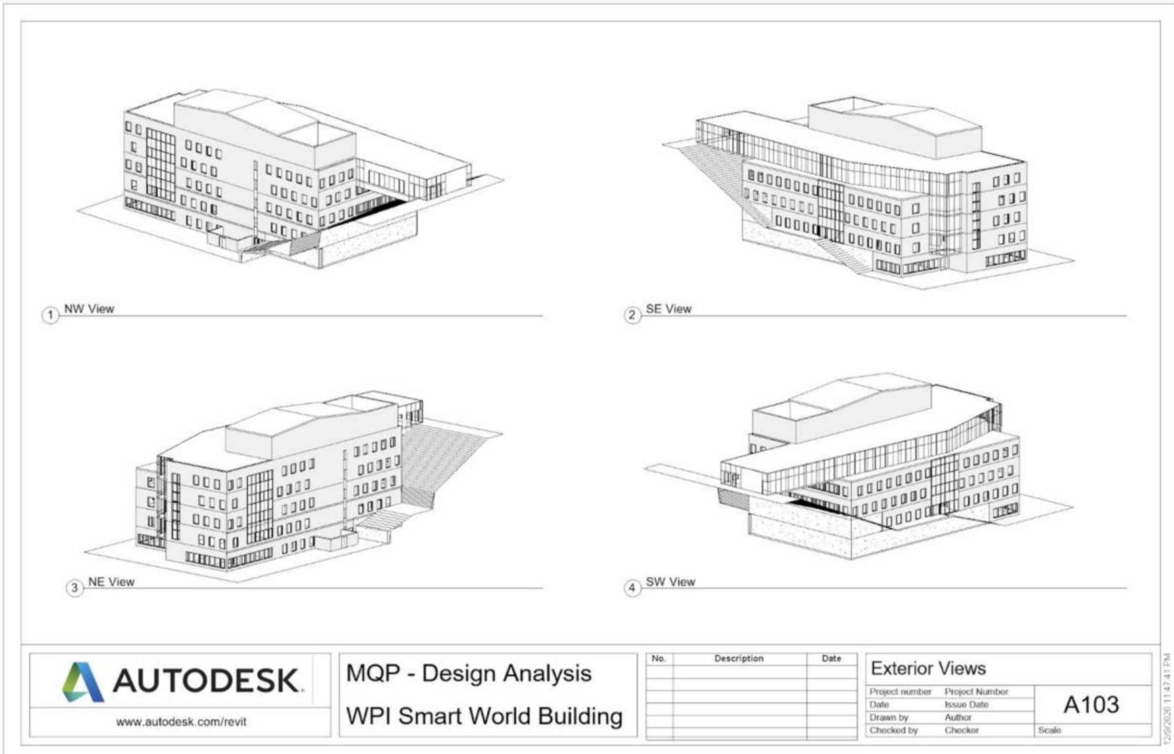
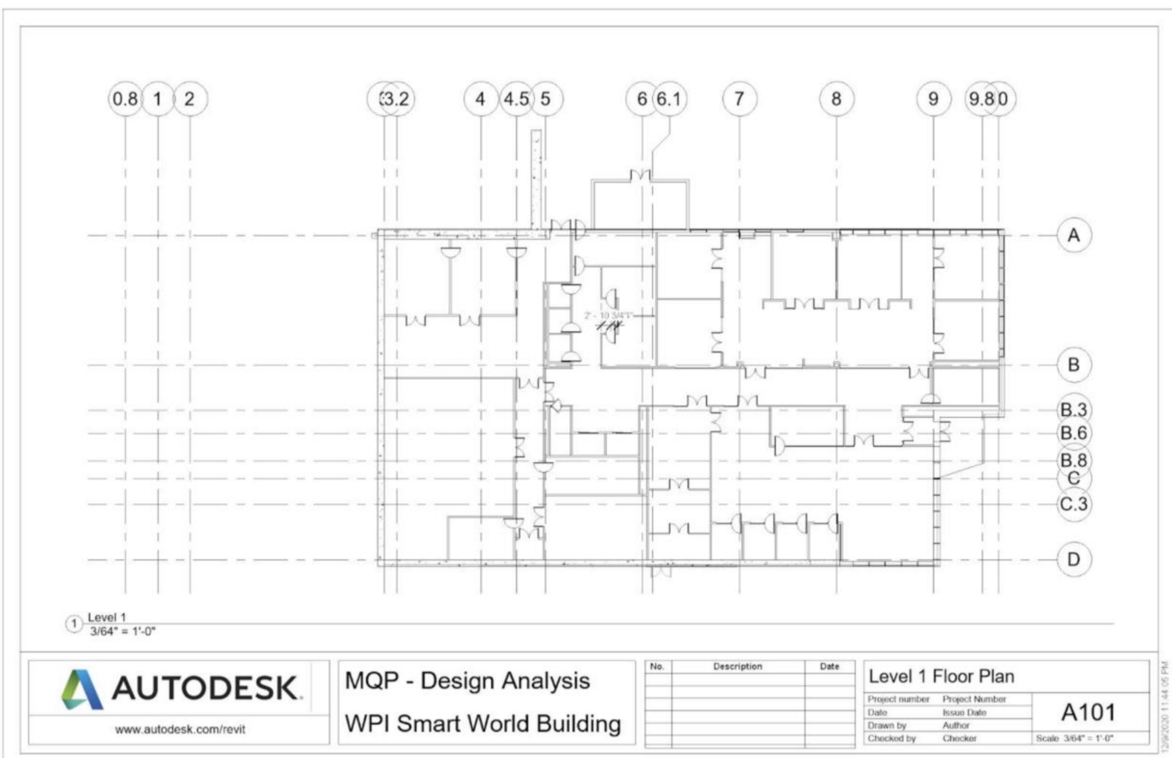
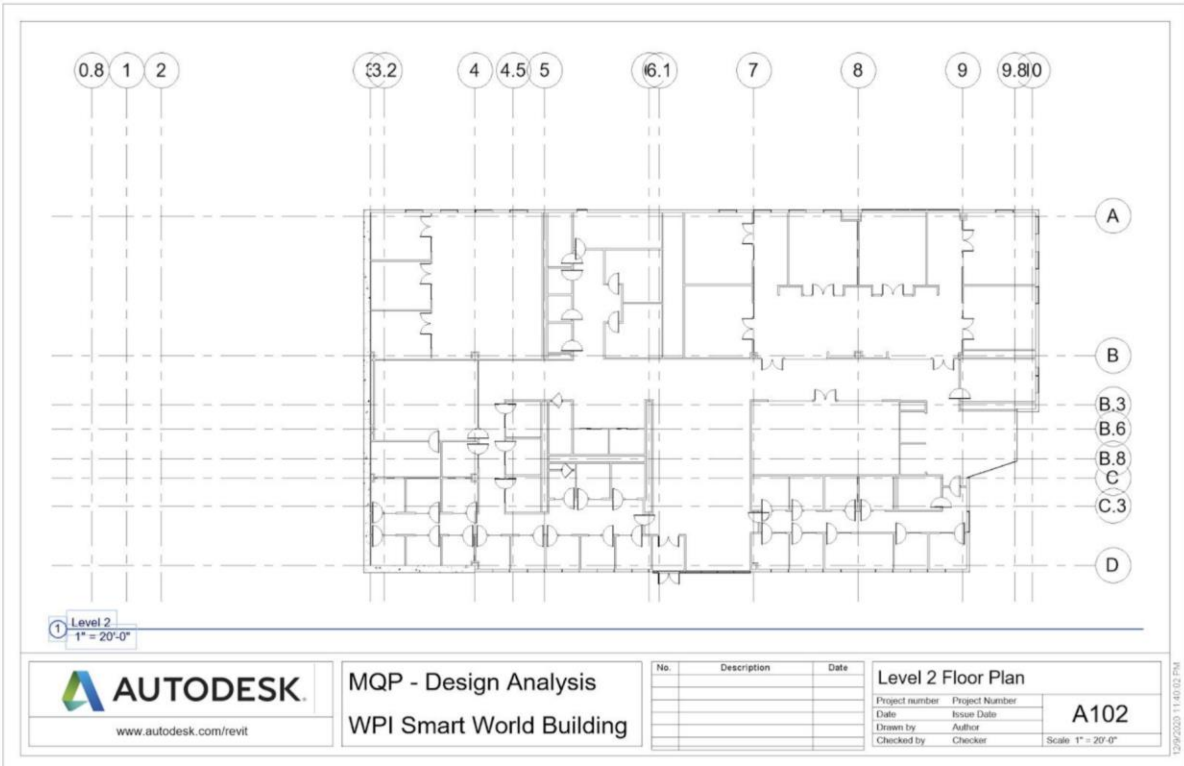
Goo, B., Lee, J., Seo, S., Chang, D., & Chung, H. (2019). Design of reliability critical system using Axiomatic design WITH FMECA. *International Journal of Naval Architecture and Ocean Engineering, 11*(1), 11-21. doi:10.1016/j.ijnaoe.2017.11.004

3D Model Sheet Views



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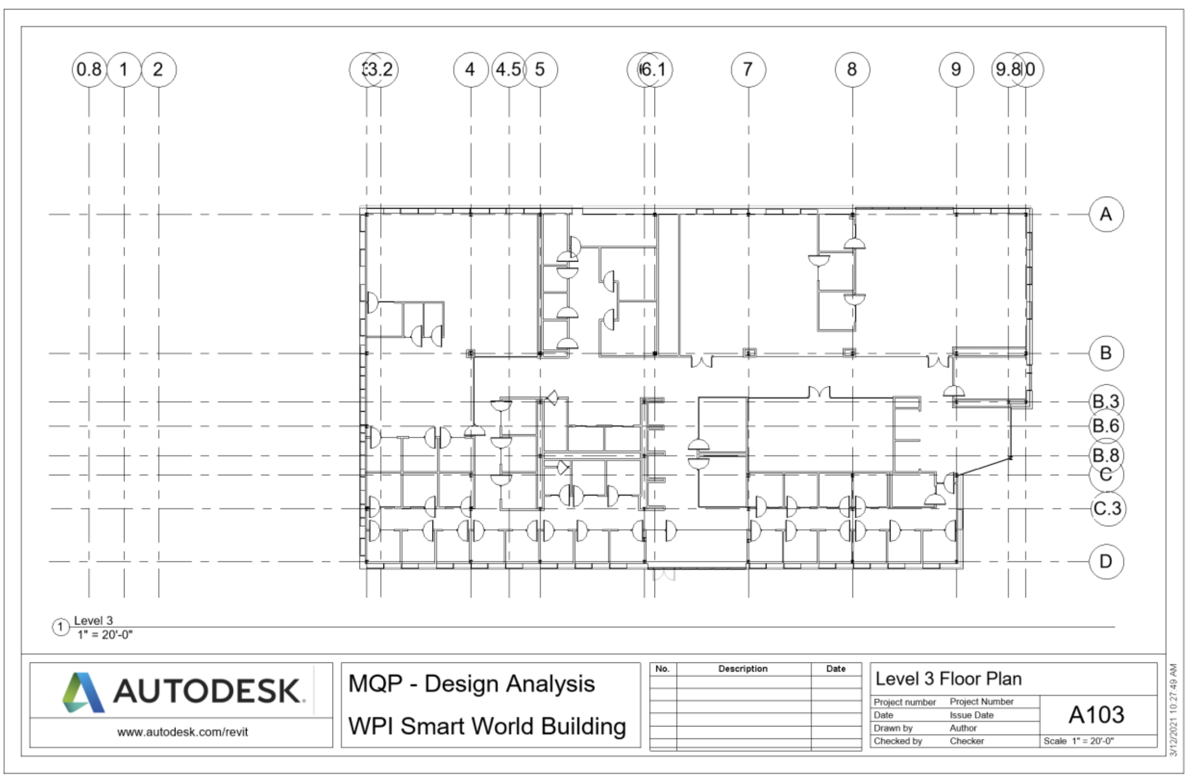
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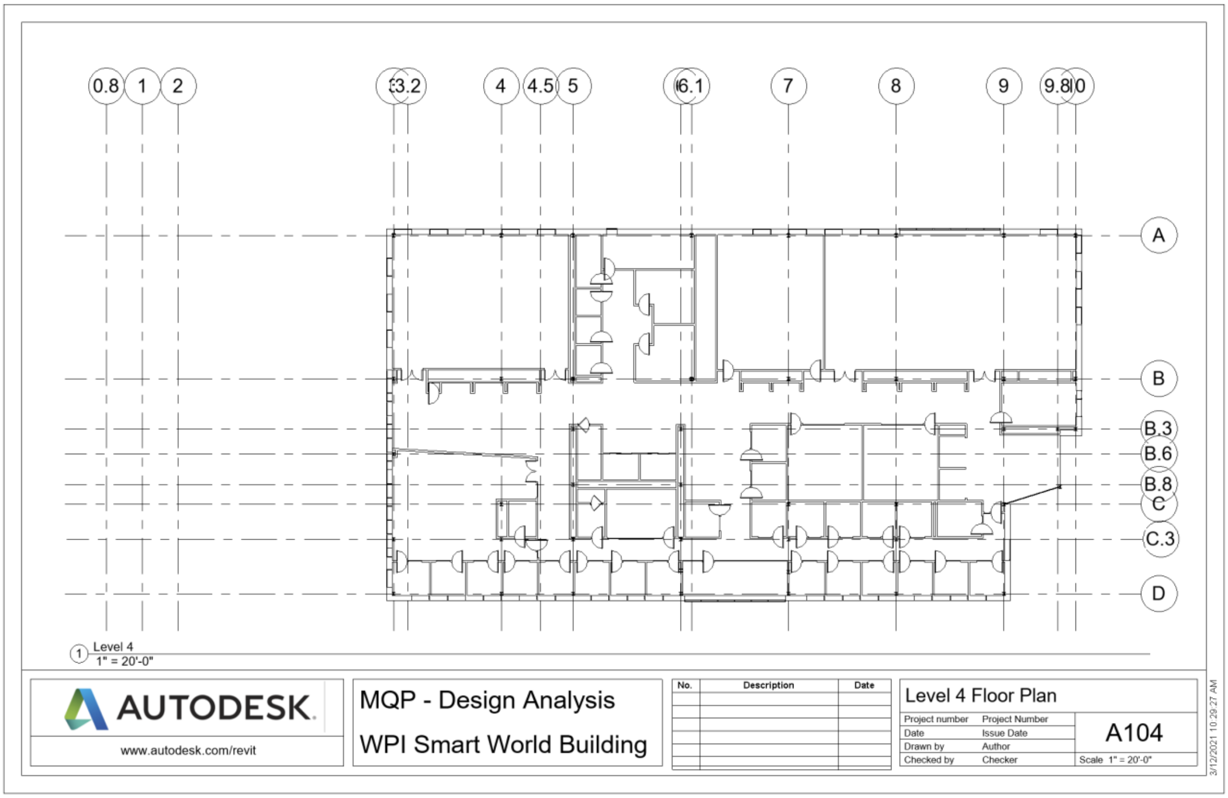

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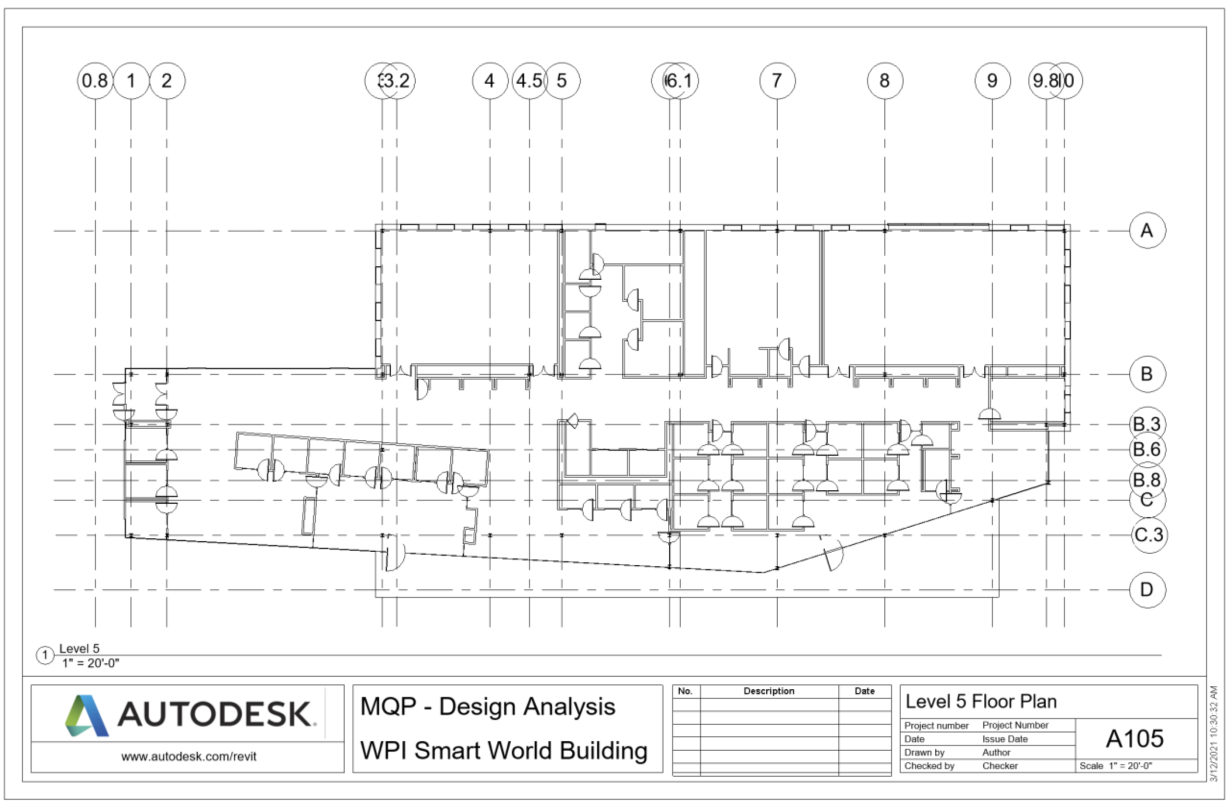

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Group Dynamics

Overall our group dynamic worked very well because of the group structure that we had established early on. We first came together in A-term to begin our proposal process and set time aside to figure out what everyone's goals were and worked out the main interests of everyone on the team. Once we gathered our options of what our project could be about, we came together to set up sub-teams because our project grew into something with a lot of branches we needed to touch on. The teams ended up being Evan and Jessica as Team 1, Javier and Mike as Team 2, and finally Kayla worked on her own, to create a 3D model of the Smart World Building. Evan and Jessica were the team who took a look into the soil analysis, design alternative, and safety protocols. Javier mainly worked on the EVA with assistance from Mike, while Kayla was the lead person on the 3D and 5D models of our project. As the Management Engineer, Mike would bounce around facilitating direction of the project and working on the Axiomatic Design decomposition and other tools to help manage the project and ensure it was on the right track. Using the structure we created, we were able to adopt a divide-and-conquer strategy to fulfill all the tasks for the project. We had weekly meetings to reconvene and check in on progress, and go through our task tracking sheet that we created to ensure all tasks would get completed in the right order and on time. With our teams within a team structure we were able to plug and play as the project would progress because if others needed help in another area and if another team had less work or was ahead they could easily transfer to the other team and aid in whatever was needed.

In conclusion, our team worked very well together and stayed on top of each other's responsibilities. The way we established our group structure early on really helped us in the long run because we knew how everything was going to work together as a system to complete our project. Being able to have a clear cut plan helped the team excel because it gave us the ability to dive in working at max efficiency. It took our team longer to pick a project because there was a lot of options to go on with but we ended up deciding to do a little bit of everything, so we were a little behind early on in the project but since we set up a good team structure we hopped right into the project like a well we got right back on track.

Applying Management Engineering

Using management engineering in our group allowed us to work at a higher efficiency since it helped us create tools that allowed us to fully understand what was needed from our group. These tools clearly communicated to us what our project looked like on paper and all the necessary components required to fulfill our project. Not only did it give us a better understanding of what direction our project should go in, but it showed us the worth of the project. Which reflected how useful understanding the financial end can be because it allows us to look at a civil engineering project and communicate to the client whether or not this investment is worth it. Having the ability to show a client how long it will take for them to break even on their investment and start generating a positive growth gives a client the satisfaction of making their investment.

The skills we learned were how to use an axiomatic design process to eliminate any time that we would have wasted, initially trying to figure out how we should go about our project. Using this great tool we were able to list out our sponsors needs and from that we were able to create our goals (FRs) for the project and follow those with the ways we were going to achieve those goals (DPs). Having this mapped out it clearly communicated to us what needed to be done. From there, we were able to create constraints (CONs) that bound all the FRs and DPs to keep us aligned with what was required and not move off into a different direction. In the long run, this whole process allowed us to finish our project by the end of C-term even with the late start we got early on in the project, this gave us a clear-cut direction to move in.

Finally, a TVM analysis was conducted to show the NPV of the project. Which shows the initial investment and how the money grows over time until it hits the break even point. This reflects the amount of time it takes until that investment gains value to break even and start generating positive revenue. Understanding the financial end of any project can prove useful in any discipline because it gives you the ability to communicate to the client whether or not this investment will be worth it to them and help guide them to something that will be more worth it to them.

Overall, management engineering is very important in any field of engineering because it provides guidance to all the engineers that are working on a project. It allows the engineers to work with direction and understand what they can and cannot do by setting guidelines for what needs to get done while eliminating wasted time from trial and error that may occur when engineers create multiple prototypes and iterations of something. Management engineering gives the best of both by understanding how an engineer operates, their thought processes, and the principles they use to create the things they do. While understanding these factors it allows guidance to be provided in such a way to maximize efficiency, eliminate wasted time and money, and provide an end product that is acceptable.