Final Report

The Apartment Building

East Coast, USA

B. Kerem Demirci | Construction Option | Advisor: Dr. Messner | Spring 2015

Source: JMAV

The Apartment Buidling

East Coast, USA

Rendering from NW Corner

Source: JMAV

Project Team

Owner: BMPI, LLC

GC: John Moriarty and Associates

ARCH: Rust Orling Architecture

STRUC: Structura Inc.

MECH: Mechanical Design Group LTD

ELEC: Power Design Inc.

CVL: Urban LTD

Project Overview

Size: 151,000 SF

Stories: 10 above grade + 2 below grade

Building Height: 99 ft

Delivery Method: CM at Risk

Contract Type: Negotiated GMP $29,949,641

Construction Dates: 2.11.13 - 2.19.15

Architecture

- Brick, stone, and metal panel facade
- 165 high- quality units
- 10,000 SF public pedestrian park with outdoor pool
- Amenities include lounge, business center, fitness room, club room and accessible terraces

Structural System

- Cast-in-place concrete
- Postensioning used starting on second floor
- Average slab thickness of 8in

Mechanical System

- Centrally located mechanical room
- Two Rooftop Units (5580 and 6150 CFM)
- Split system heat pumps condition inviidual units and common areas

Electrical System

- Main electrical room and transformer vault located on G2 level
- 208/120V
- Four 100A switchgears supply the 16-20 load centers located on

View from SE

Source: B. Kerem

B. Kerem Demirci | Construction Option | Messner

https://www.engr.psu.edu/ae/thesis/portfolios/2015/bkd5069/index.html

MORIARTY

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EXECUTIVE SUMMARY

The Apartment Building is a $32.7M, ten story building, totaling approximately 151,000 SF. This space provides room for 165 high quality apartment units that average 767 SF per unit. Amenities include a public pedestrian park, outdoor pool, lounge space, business center, fitness center, club room, and accessible terraces. Opportunities to improve the construction process were identified through project team interviews, site visits, and background research. The four analysis that address these opportunities are as follows:

Analysis 1: Effect of Eco Certifications on Marketability

As part of the critical industry research for this course, a literature review was completed to determine if a rent premium existed for buildings with eco-certifications, such as LEED. Rent premiums exist and range anywhere from 0.1% to 20%. It is recommended that The Apartment Building upgrades to LEED Silver by the addition of three LEED Points that are feasible to achieve at this point in construction, green power and a mechanical system flush.

Analysis 2: Exterior Enclosure Acceleration

Due to a harsh winter, the overall construction schedule was delayed 26 days. By implementing a panelized brick veneer system (PBVSS), a 44 day reduction of the onsite schedule, which is the ultimate driver of the project. This system will cost $70,132 more than the original brick veneer assembly but can be justified by the reduction in schedule as well as the increased quality and safety benefits of offsite prefabrication. In addition, the thermal and hygrothermal properties, with slight modification, of the PBVSS system can surpass the original. A structural analysis showed that the additional loads from the PBVSS system can easily be accommodated by the existing post-tensioned concrete structure.

Analysis 3: SIPS Implementation for Interior Fit-Out

Due to the stringent schedule dictated by the phased turnover of the building, high level of quality and the repetitive nature of the apartment units, short interval production scheduling (SIPS) was implemented for interior fit out of apartment units on the 2nd through 10th floor. A guide was produced that outlines the schedule development process as well as keys to proper implementation.

Analysis 4: Tools to Support SIPS Implementation

Building off Analysis 3, a combination of tools was selected to complement the SIPS process for interior fit out. Tools were selected using the House of Quality, a decision making tool that ensures the customer's requirements are met. The recommended combination of tools are: design authoring, 3D coordination, crew balance charts, flow diagram and process chars, foreman delay surveys, and video time lapse. The tools were then added to the guide that was created in Analysis 3.

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John Moriarty and Associates of Virginia

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SPECIAL THANKS TO

Mom, Dad, Deniz and Arif

PROJECT BACKGROUND

Figure 1: Sketch of The Apartment Building (Source JMAV)

The Apartment Building is a new building being built on the East Coast. It is primarily a post tensioned cast-in-place concrete structure enclosed by stone and brick veneer. The building extends ten stories above grade, reaching a height of 99 feet and totaling approximately 151,000 SF. This space provides room for 165 high quality apartment units that average 767 SF per unit. Ten of the units are designated affordable housing for 40 years which allows the maximum zoning height restriction to increase from 77 feet to 99 feet. Below grade, lie two garage levels that provide 153 parking spaces for the building tenants. A 10,000 SF public pedestrian park along with an outdoor pool is located outside the south face of the building. The ground floor houses amenities such as a lounge, business center, and fitness room. An additional club room is located on the fifth floor. Accessible terraces are located on the fifth and eighth floor and include gas grills, gas fire pits, and water/gas features. The average rental price for the apartment units is roughly $2,100 per month.

THE CLIENT

The client for The Apartment Building is BMPI. BMPI is a partnership between three main investors of which one is the owner of the general contractor of this project, John Moriarty & Associates (JMA). The other two partners are a developer out of Boston and a local developer. The goal of BMPI is to promote the growth of an up and coming metro accessible area. According to an economic impact study, conducted by Delta Associates, The Apartment Building will increase the value of nearby single family houses by 2.9% per year.

PROJECT DELIVERY METHOD

The delivery method on this project is a CM at Risk. The advantages of this delivery method is that only one party is responsible for construction and it allows the contractor to be involved early on in the design phase. Since this is a private project and one of the owners is also the owner of JMAV, the contract is a sole source negotiated contract. The contract type between the owner and the general contractor is a negotiated GMP, which includes open book accounting. This project also included two design-build subcontractors. Power Design Inc. and Mechanical Design Group, the electrical and mechanical/ plumbing respectively. The these two design build subcontractors hold contracts with the general contractor but have key communication paths with the architect, Rust Orling Architecture.

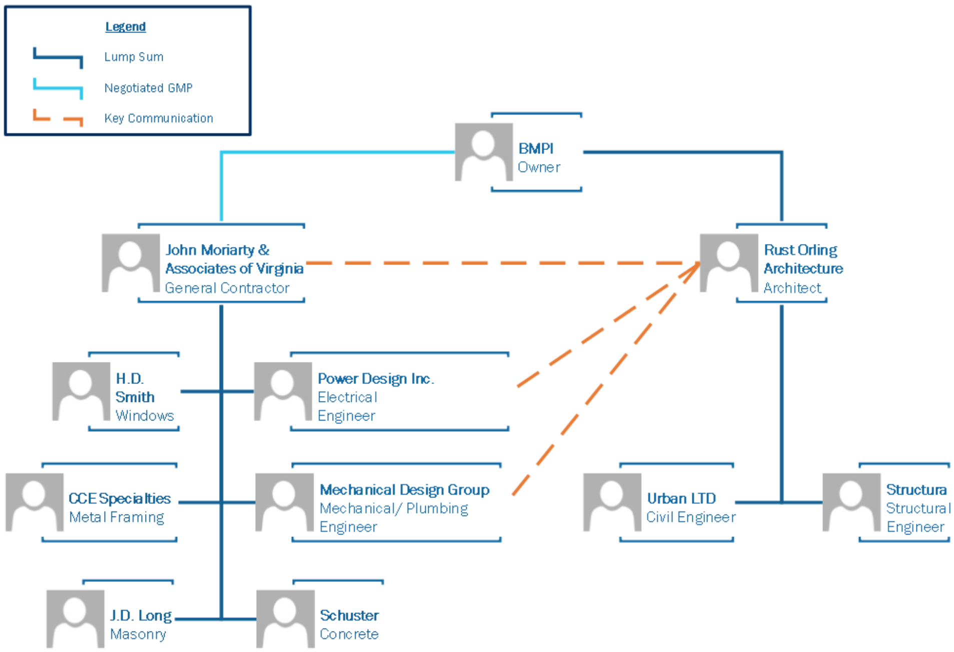


Figure 2: Project Org Chart

EXISTING CONDITIONS

This building is being built on what used to be an old middle school which closed in 1979. Since the closing of the middle school, multiple office buildings and residential buildings have been built nearby. Currently, the site is surrounded by two four story office buildings, townhomes and an eight story condominium. Above grade the existing buildings appear to be a modest distance away from The Apartment Building. However, many of the existing buildings have underground parking levels that extend further than their above grade footprints. This makes the construction site much more congested than it appears. Since there are already existing buildings nearby, utility lines are in close proximity to the new building. The majority of the utility lines run up Main Street. Some utilities, such as sanitary, storm, and water lines branch off Main Street and wrap around the west side of the construction site and down 2nd Street and tie into other existing buildings. Traffic in the area is not extremely heavy since it is primarily a residential area with office buildings. Due to request by neighboring buildings, construction parking will not be available onsite and street parking is prohibited. All construction personnel must park in a designated off-site parking lot then be bussed to the job site.

PROJECT COST

The total contract value of the negotiated GMP contract is $32,752,717, or $216.75 per SF. The major budget items can be found in Table 1.

Table 1: Major Budget Items

	Cost	Cost per SF
Total Construction Costs	**$32,752,717**	**$217.75**
General Conditions	$2,009,211	$13.30
Earthwork	$1,132,175	$7.49
Concrete	$6,221,434	$41.17
Masonry	$1,946,150	$12.88
Glazing	$1,414,737	$9.36
Gypsum Board Assemblies	$2,115,050	$14.00
Plumbing/ HVAC	$3,169,500	$20.06
Electrical	$3,169,500	$20.98

PROJECT SCHEDULE

The Apartment Building receive the notice to proceed on February 11th, 2013 and will reach substantial completion on February 13, 2015, resulting in a duration of roughly 24 months. The post-tensioned concrete structure was completed in June, 2014, roughly 16 months after notice to proceed. Turnover of this building will be done in phases, allowing early revenue for the owner. The first phase of turnover is planned for December 10th, 2014 and includes the garage through the 2nd floor. From this point on the schedule dictates a turnover rate of a floor per week. A summary schedule of construction is shown below in Figure 3.

ID	Task Name	Duration	Start
0	**Summary Schedule**	**1058 days**	**Tue 2/1/11**
1	Conceptual Design and Estimate	370 days	Tue 2/1/11
2	Design Development Design and Estimate	162 days	Sun 7/1/12
3	NTP	0 days	Mon 2/11/13
4	Site Prep	123 days	Mon 2/11/13
10	Install Permanent Power	348 days	Wed 3/27/13
8	Install Temp Power	26 days	Mon 4/29/13
9	Temp Power On	0 days	Mon 6/3/13
11	Permanent Power On	0 days	Thu 7/25/13
5	Excavation	107 days	Thu 8/1/13
12	Insall Footing and Tower Crane	1 day	Wed 10/30/13
13	Place Mat Slab	26 days	Tue 11/26/13
14	Foundation Walls, Pits etc	22 days	Tue 12/17/13
15	Form Supported Slabs Through Ground Floor	57 days	Tue 12/24/13
16	Reinforce Supported Slabs Through Ground Floor	54 days	Fri 12/27/13
17	Place Supported Slabs Through Ground Floor	54 days	Tue 12/31/13
18	Form Supported Slabs Above Ground Floor	59 days	Tue 3/18/14
19	Reinforce Supported Slabs Above Ground Floor	60 days	Thu 3/20/14
20	Place Supported Slabs Above Ground Floor	59 days	Mon 3/24/14
23	Install Brick	95 days	Thu 3/27/14
25	Rough-In Mech/Elec/ TD	127 days	Thu 4/3/14
22	Frame/ Sheath/ Tyvek	77 days	Tue 4/22/14
26	Finishes	156 days	Fri 5/30/14
24	Install Windows	65 days	Wed 6/4/14
21	Structure Top out	0 days	Thu 6/12/14
7	Courtyard Improvements	64 days	Mon 7/28/14
28	Final Inspections	144 days	Mon 8/4/14
6	Site Improvements	61 days	Thu 8/7/14
27	Punchlist/ Owner Walks	92 days	Fri 9/12/14
29	Turnover Garage - Second Floor	0 days	Wed 12/10/14
30	Turnover 3rd Floor	0 days	Wed 12/17/14
31	Turnover 4th Floor	0 days	Wed 12/24/14
32	Turnover 5th Floor	0 days	Wed 12/31/14
33	Turnover 6th Floor	0 days	Wed 1/7/15
34	Turnover 7th Floor	0 days	Wed 1/14/15
35	Turnover 8th Floor	0 days	Wed 1/21/15
36	Turnover 9th Floor	0 days	Wed 1/28/15
37	Turnover 10th Floor	0 days	Wed 2/4/15

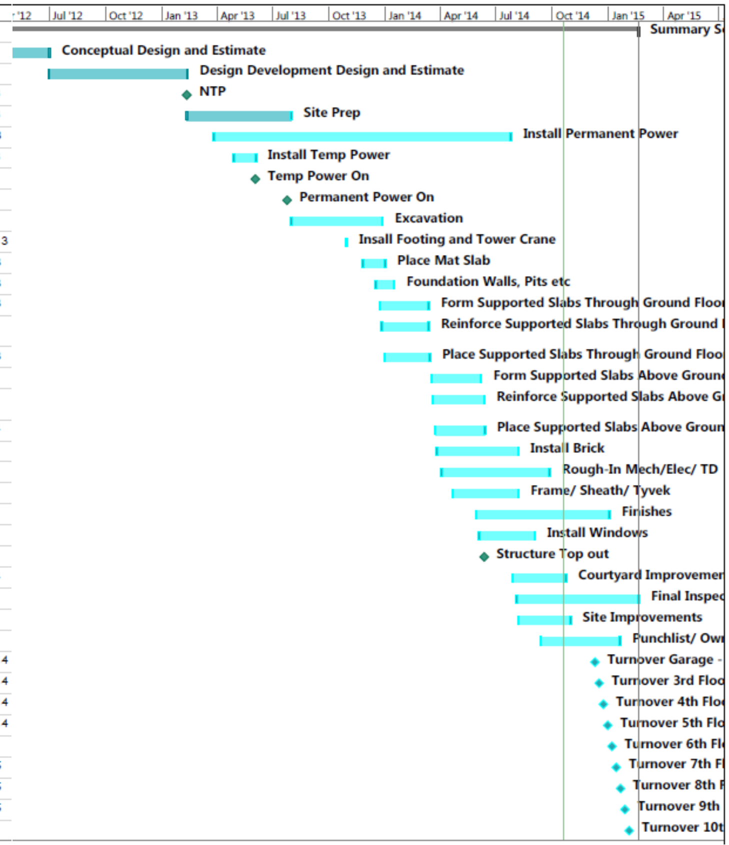


Figure 3: Summary Schedule

BUILDING SYSTEMS SUMMARY

STRUCTURAL SYSTEM

The structural system is primarily cast-in-place concrete. The foundation is comprised of series of mat slabs and spread footings. Beginning on the second floor and up through the roof, post-tensioning is used in the slabs which allow for a thinner slab thickness, eight inches on average. The post-tension tendons are low-relaxation strands that are comprised of seven wires and have a minimum ultimate strength of 270 KSI.

BUILDING ENCLOSURE

The Apartment Building uses a multitude of different materials for the façade. The primary materials are brick, architectural concrete masonry units (ACMU), and metal cladding. Each elevation of the building utilizes these three primary façade materials. Although the materials are the same for each elevation, various colors, patterns, and mortar types create different visual appearances throughout the façade of the building.

From the ground level to the third floor, the façade is primarily comprised of Type 1 ACMU and Type 2 brick. Type 1 brick is used from the third floor through eighth floor. From the eighth floor up a combination of metal cladding, Type 2 brick, and Type 1 brick are used. In addition to the three main façade materials, cast stone is used in horizontal bands that encompass the building as well as window sills. Additional features of the building enclosure include aluminum windows, metal railings, prefinished aluminum trellis and projected metal sunscreens (5^{th}, 8^{th} and 10^{th} floor). The majority of the façade is supported by anchoring to 3-5/8" metal studs that are supported by the post-tensioned concrete structure. A typical exterior wall assembly, from outside to inside, is made up of the façade material, air space, rigid insulation, air barrier, gypsum sheathing, metal studs with batt insulation, then interior gypsum board. The thicknesses of each component vary based on the façade material being supported and the intended fire rating. Punch windows are used throughout the exterior of the building. In addition, four story curved segmented aluminum window assemblies are located at each of the main entrances. Both glazing systems are prefinished aluminum.

MECHANICAL SYSTEM

The primary mechanical room is located in a central location on the ground floor. Two primary types of mechanical systems are used to service the various spaces within the building. Two roof top units, 5580 and 6150 CFM, serve the main corridors of the building. The individual apartment units, and common areas are conditioned by split system heat pumps. The sizes of these split system heat pumps range from 300 CFM to 3000 CFM. In addition electric unit heaters are used in stair cases, the trash room, pump room and storage rooms.

ELECTRICAL SYSTEM

The electrical connection point is located in the northeast corner of the building. The main transformer vault and electrical room are located at the G2 level. The Apartment Building runs on 208/120V which is typical for residential buildings. Four 1000A switchgears supply the 16 to 20 load centers located on each floor.

ANALYSIS 1: EFFECT OF ECO CERTIFICATIONS ON MARKETABILITY

RESEARCH PROBLEM

A successful apartment building is ultimately measured by marketability and demand. The marketability of an apartment building is dictated by many variable such as location, amenities, and rental price. As consumer preferences shift, it is necessary for developers to identify the shift and preferences and translate it in order to maximize marketability. Shifting consumer preferences may even have a positive effect on the building. For example as consumers shift towards more sustainable goods, apartments may shift to become more sustainable which would help reduce the carbon footprint of the built environment.

PROBLEM STATEMENT

The Apartment Building is a high-end residential building located in an up and coming metropolitan area. BMPI LLC is the main investor on the project. Since The Apartment Building is an investment for BMPI LLC, one of their main goals is to maximize the marketability of the building which will in turn increase revenue and ultimately defines the success of the project. BMPI LLC is comprised of three main investors. One is the owner of John Moriarty and Associates, the general contractor on The Apartment Building. This dynamic ensures that construction decisions commonly align with the goals and perspectives of the owner.

Based on previous value engineering decisions, it is clear that maximizing marketability and higher rental rates are primary goals of the investors. On The Apartment Building, value engineering decisions were made based on the effect on rental rates that could be achieved. By implementing alternative materials or systems, cost reduction can be achieved and the saved money can be used for additional amenities that increase the tenant's perceived value and ultimately raise the rental rate of the units. Aside from value engineering, are there other ways to increase the perceived value of the building, which can increase rental rates? Following is a potential alternative.

Green building has gained much popularity and interest in the last decade and has become a relevant topic in all sectors of the real estate and construction industry. However, this raises some concerns for the developers. Will tenants be willing to pay more for a green building? Research on the effect of green building on marketability is relatively new, due to the growth of eco certified green buildings, such as LEED, data is now starting to become available to further study the economic impacts of these certifications. Therefore, as part of the critical industry research for this thesis, a literature review of material related to the effects of green building on marketability of buildings. This analysis will culminate with a recommendation for the current LEED plan for The Apartment Building.

INTRODUCTION TO GREEN BUILDING

WHAT IS GREEN BUILDING?

The term "green" has gained much popularity over the last decade and has developed into a common buzzword in the real estate and construction industry. Green building is also known as sustainable or high performance building. According to the U.S Environmental Protection Agency (EPA), green building is the practice of increasing the efficiency with which building and their sites use and harvest energy, water, and materials; and simultaneously protecting and restoring human health and the environment, through the building life-cycle("Frequent Questions" n.d.). The green movement has grown rapidly due to the recognition of the detrimental effects of global warming and urban sprawl which has caused consumer preferences to change (Das et al. 2011), especially when it comes to buildings. The demand for green buildings correlates with the increase in energy prices since 1998 (Pivo and Fisher 2010). On a global scale, approximately 30% of the CO_2 emissions and 40% of the energy consumption are from the built environment (Unep 2010) In the United States, buildings account for 38% of CO_2 emissions, 39% of the energy consumption, 68% of total electricity consumption and 12% of the total water consumption ("Why Build Green?" 2003) .

It is evident that green building has a plethora of environmental benefits as it can enhance and produce the bio diversity and ecosystem, improve air and water quality, reduce waste streams as well as conserve and restore natural resources. In addition, green building has economic and social benefits. Some economic benefits include reduced operating costs, improved occupant productivity, and improved economic performance over the life-cycle. Green building also has social benefits such as enhanced occupant comfort and health, higher aesthetic qualities, minimal strain on local infrastructure, and on overall improved quality of life ("Why Build Green?" 2003). All these benefits can directly affect developers and investors of an apartment building project. In particular, green buildings are likely to have longer economic lives that will maximize the cash flow of the investment. In terms of risk, green buildings have a lower marketability risk and are also at lower risk of being affected by technical and regulatory obsolescence (Eichholtz et al. 2010). Energy efficiency is a key component of green building and this can help mitigate the effect of increasing energy prices and associated government regulation (Reichardt et al. 2012).

ECO CERTIFICATIONS AND RATING SYSTEMS

As the trend for green building emerged, various eco-certifications have been developed to provide information regarding a building's environmental effect. These eco-certifications have many benefits. They serve as a tool that customers can use for comparison between products on a consistent scale. Eco-certifications also encourage the green movement towards a more environmentally responsible consumption which in turn encourages suppliers to develop better products and technologies. Eco-certifications are part of the continual improvement cycle for green building.

Eco-certifications and rating systems are prevalent on an international scale. The first green rating system was developed in the 1990 in the United Kingdom. The Building Research Establishment (BRE) developed the Building Research Establishment Environmental Assessment Methodology (BREEAM). BREAM is the longest running green rating system and has been used in over 50 countries in the world. Table 2 summarizes international eco-certification and rating systems.

Table 2: International rating systems

Rating System	Country	Managing Organization
Beam	Hong Kong	Business Environmental Council
BREEAM	UK	Building Research Establishment
CASBEE	Japan	Japan Sustainable Building Consortium
Green Mark Scheme	Singapore	Building Construction Authority
Green Star	South Africa	Green Building Council of South America
Pearl Rating System for Estidama	United Arab Emirates	Abu Dhabi Urban Planning Council
LEED	United States	United States Green Building Council
Energy Star	United States	Environmental Protection Agency
Green Globes	United States	Green Building Initiative

In the United States, four primary eco-certification and rating systems exist: Energy Star, LEED, Green Globes, and The Living Building Challenge (Table 2). Energy Star and LEED are currently the most developed rating systems, while Green Globes and The Living Building Challenge have gained traction recently and are gaining popularity.

Energy Star, the first rating system in the United States, developed by the EPA and the U.S. Department of Energy in 1992 focuses on energy performance of buildings based on the EPA's National Energy Performance Rating System. A score of 1-100 is given to a building based on a benchmark system that compares the building's energy consumption to similar buildings. In order to become Energy Star rated, the building must receive a score of 75 or above. The Energy Star rating system is also included in LEED.

The most popular eco-certification and rating system in the United State is LEED, developed by the United States Green Building Council (USGBC) and first implemented in 1998 with LEED1.0. The system has been modified multiple times and the latest version, LEED v4, has recently been released. Unlike Energy Star, which focuses strictly on energy performance, LEED takes a holistic approach to sustainability and includes nine main categories of which energy is one. The nine categories are as follows: Integrative Process, Location & Transportation, Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, Indoor Environmental Quality, Innovation and Regional Priority. Depending on how many of the 110 total points are achieved, a LEED rating is awarded. Figure 4 shows the necessary points needed to achieve each level of LEED certification.

Figure 4: LEED Rating System (www.usgbc.org)

Green globes is an emerging eco-certification and rating system in the United States. It was developed in Canada and was based on BREEAM in the United Kingdom. The Green Building Initiative (GBI) is the managing organization that brought Green Globes to the United States and the first green building organization that is accredited by The American National Standards Institute (ANSI). Green Globes is a holistic rating system, similar to LEED. The rating system is based on 1000 possible points broken up into seven main categories: i) Project Management, ii) Site, iii) Energy, iv) Water, v) Materials & Resources, vi) Emissions, and vii) Indoor Environment. Depending on the percentage of these total points that are earned, one to four Green Globes are awarded to the building. A major difference of Green Globes, as compared to LEED, is that there is a project management category and life-cycle assessments. Green Globes is designed to be more flexible, interactive and economical than LEED.

PREMIUM FOR GREEN PRODUCTS?

Green products are not new to the consumer industry. According to a 2007 survey by Accenture, two thirds of people are willing to pay a premium for green products. Out of 7,500 consumers in 17 countries surveyed, 64% would be willing to pay a premium of 11% for products that reduced greenhouse gas emissions. Buildings are considered products, so will people be willing to pay for green buildings? The way green buildings are priced and the associated rent premium have not been heavily studied. However, in recent years research is beginning to emerge due to the quickly increasing number of green buildings. It is clear that the price difference between green buildings and non-green buildings is determined by the demand. If it is proven that green buildings are associated with a significant price or rent premium, there is a monetary incentive for developers (Yoshida and Sugiura 2014). In addition, green building can help build a company's corporate and social responsibility (CSR). CSR is a management philosophy that integrates social and environmental concerns into business operations. There is a strong positive relationship between CSR and financial performance because by appealing to key stakeholders, companies may be able to bring in more investors and consumers (Orlitzky et al. 2003).

REVIEW OF EXISTING LITERATURE

Previous studies have been conducted to quantify the economic value of green building and eco-certifications in terms of rent, sales, and occupancy premiums compared to non-green buildings. This field of study is relatively new and emerged because of the growing number of green buildings in the United States and the increased customer awareness of the environment. The first study was conducted in 2008 by Miller et al which set the framework and methodology for future studies. The typical method of analysis is empirical and utilizes a hedonic regression model. Rosen (1974) generalized Hedonic modeling as a method of estimating demand or value of a product by separating the product into a variety of characteristics that are used as the independent variables (Fuerst and McAllister 2009) such as site area, stories, building size, building age, year of sale, amenities, and public transportation. In real estate research, hedonic models have become the standard method of analyzing price differences.

Most studies conducted in the U.S. focus on LEED and Energy Star ratings as they are currently the two most promienent green rating systems in the U.S.. Eco-certified buildings are then matched with similar non-certified buildings in the same submarket. CoStar, a real estate database service, is the most common data source for these studies. Up to this point, the majority of the studies focus on green office buildings due to the higher number of green office buildings in the database. However, In recent years a few studies focussing on the residential sector have emerged as green building in the residential sector has become more popular. Studies on this topic are not unique to the U.S., multiple studies have been conducted in Europe as well.

Figure 5 shows the existing studies on the topic of eco-certification and its effect on marketability.

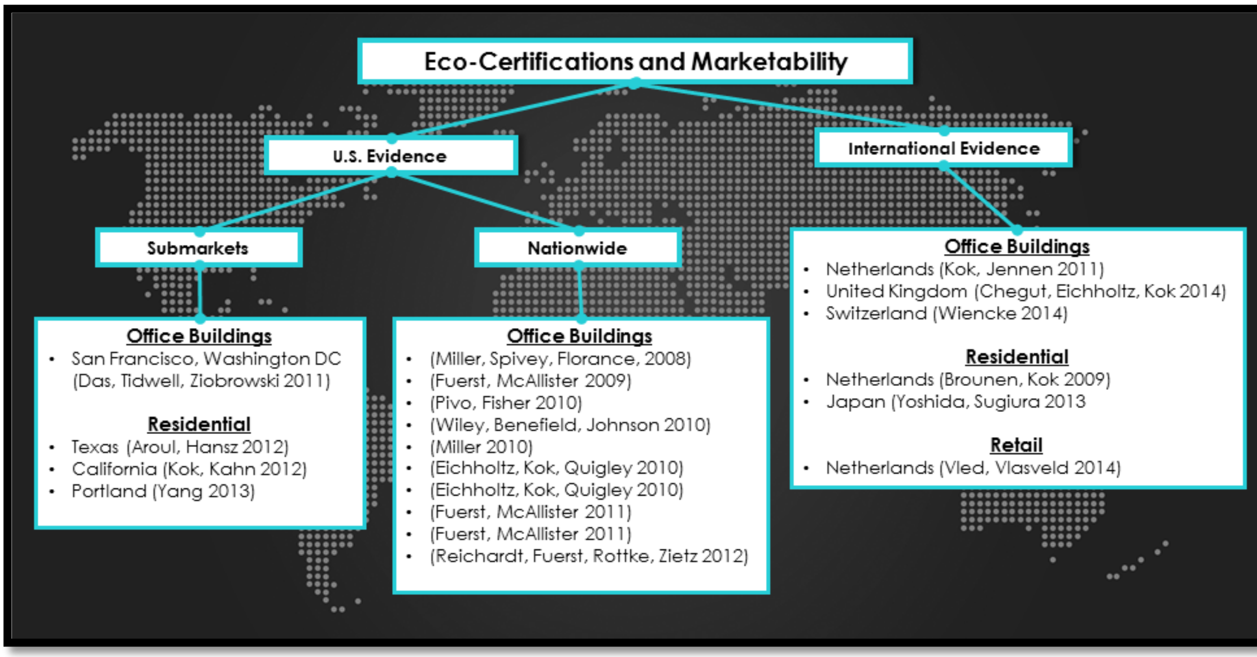


Figure 5: Literature Map

OFFICE BUILDINGS

As mentioned earlier, the first study on the topic of eco-certifications and its effect on marketability was conducted by Miller et al. (2008). Prior to this study, only a handful of case studies existed on the benefits of green investments. This study by Miller et al (2008) was the first to empirically analyze eco-certifications and the pay offs. Their study focused on Energy Star and LEED office buildings in the U.S. utilizing the CoStar database from 2005 through 2008. Through a hedonic analysis with age, location and time of sale controlled it was found that there was a 10% sales premium for LEED buildings and 6% sales premium for Energy Star rated buildings. This price premium may have been due to the shortage of green buildings and their high demand (Miller et al. 2008). Miller (2010) conducted a follow up study and found that a rent premium still exists for LEED building. However, more interestingly, LEED buildings had a higher average vacancy rate. Miller believed the vacancy rate will decrease as green buildings become more popular and as tenant expectations change. (Miller 2010)

One of the first studies to follow up on Miller et al. (2008) call for further research was conducted by Fuerst and McAllister (2009). Similar to the initial study, the CoStar database was used to find office buildings in the U.S. with LEED and Energy Star certifications. The sample consisted of 626 LEED buildings and 1,282 Energy Star rated buildings. Through a hedonic analysis, complemented by logistic regression framework, they determined a 6% and 5% rent premium for LEED and Energy Star buildings and 35% and 31% sales premium for LEED and Energy Star buildings, respectively (Fuerst and McAllister 2009). However, the sample size for LEED buildings was too small to be valid. A limitation to this study is that it is a cross sectional and only provides a snapshot in time, which does not reflect the dynamic nature of the real estate market.

Pivo and Fisher (2010) added eco-certifications under the umbrella of Responsible Property Investing (RPI). The goal of RPI is to address social and environmental issues without hindering financial returns for a project by comparing the financial performance of RPI properties and non-RPI properties the relationship between RPI, market value and investment returns. Unlike previous studies, Pivo and Fisher (2010) used an international survey instead of a hedonic analysis. Five RPI property types were analyzed: Energy Star labeled properties, suburban regeneration, CBD regeneration, suburban transit, and CBD transit. It was found that in each of these cases, RPIs did not cause a decrease in income or value and every property type, other than suburban regeneration, was associated with higher incomes and values. Energy Star in particular contributed to a 3% premium (Pivo and Fisher 2010).

Wiley et al. (2010) conducted a hedonic analysis similar to previous studies except brought occupancy into the equation. So now rent premiums, sales premiums, and occupancy became key metrics. The study used 7,308 properties for 46 different office building markets from the CoStar database. The study found a rent premium for LEED and Energy Star labels between 16-17%, and 7-9% respectively. In addition, occupancies improved from 10 to18% (Wiley et al. 2010)

In the study of Eichholtz et al. (2010), 1360 green office buildings from the CoStar database were used to determine the economic outcomes of sustainable buildings. Similar to previous studies a premium for eco-certification exists. There was a rent premium of 5% for LEED and 3% of Energy Star buildings as well as a 16% sales premium for green buildings. Another important finding was that eco-certifications tend to add more value in smaller markets on the outskirts of a large metropolitan area (Eichholtz et al. 2010).

Later on, Fuerst and McAllister (2011) utilized the CoStar database in conjunction with a hedonic analysis to test the presence of a premium for eco-certifications. They found that a rent premium of 4 and 5% existed for Energy Star and LEED building, respectively, while a sales premium of 18% existed for Energy Star and 25% for LEED. Occupancy rates were also analyzed in this study and found an occupancy premium for Energy Star buildings but a negative occupancy rate for buildings with a LEED rating. This could have been due to downturn of the housing market between 2007 and 2009.

Fuerst and McAllister (2009) also pointed out an important limitation to the hedonic analysis method of determining the price premium for eco-certifications. Hedonic analysis is a cross sectional method and only provides insight into a moment in time. Real estate pricing is dynamic in nature and must be studied overtime. The data used for most hedonic analysis of eco-certifications and its economic effect have been spread across the nation. Das, Tidwell, and Ziobrowski (2011) focused on two specific submarkets, Washington DC and San Francisco, the two submarkets with the largest number of green buildings in the CoStar database. The study used panel data, empirical analysis and a random effects model to examine the rental rate dynamics of these green office buildings. Consistent with previous studies, green office buildings experience rental premiums that are dynamic. It was found that green office buildings had more stable rental rates over time which in turn would offset the negative effects of a down market. The rental premium was found to be significantly positive in down markets (+2.4%) but reduced in up markets (+0.1%).

Reichardt et al. (2012) addressed the limitation of the cross sectional approach. This study used the CoStar database to determine 7,140 buildings across 10 metropolitan markets in the U.S. In order to measure the dynamic market, a difference-in-difference (DID) estimator was used. This method compares eco-certified buildings to non-certified building in the same submarket over time. Energy Star data ranged from 2004 to 2008 and LEED data ranged from 2008 to 2009. For Energy Star labeled buildings, the average rent premium was 2.5% over the duration of the time frame but the premium increased over time. For LEED buildings, the average rent premium was 2.9%. Unlike Energy Star, the premium for LEED buildings was highest at the beginning and decreased over time which may be explained by the downturn in the real estate market. This study exposed the dynamic nature of the premium associated with eco-certifications. (Reichardt et al. 2012)

Internationally, some evidence exists for a price premium for office buildings with eco-certifications. Kok and Jennen (2011) looked at green buildings in the Netherlands and found that a building with an energy label achieved a 6.5% rent premium compared to a building without an energy label. The oldest green rating system, BREEAM, has been used since 1999 in the United Kingdom. Chegut et al. (2014) conducted a study in the United Kingdom between 1999 and 2009 and determined a rent premium of 19.7% and a sales premium of 14.7%. Evidence exists in Switzerland that supports a premium for eco-certified buildings. Results from a corporate real estate and sustainability survey given by the Center of Corporate Responsibility and Sustainability at the University of Zurich show that a willingness to pay a premium existed and was about 1.3%. This type of research depicts stated preference which uses a hypothetical situations. In contrast, previous hedonic analysis are a form of revealed preference that refer to real transactions(Wiencke 2013).

RETAIL

One of the most recent studies did not find a rent premium for green retail properties in the Netherlands (Op't Veld and Vlasveld 2013). More than 100 retail properties that varied widely in age, the oldest was built in 1820, were used from the CBRE Global Investor Database. The study checked for statistical difference between properties that had energy performance certificates and those without. This study did not find evidence supporting a premium for green building. Properties without an energy performance certificate had significantly higher rents and values. The difference may not have been caused by the energy performance certificates but other factors that influence the performance of the retail property such as age, location, etc.

RESIDENTIAL

As mentioned earlier, due to the available data, the majority of the studies on the economic impact of eco-certifications have been on green office buildings. In recent years a few studies on residential sector have been done, both in the U.S. and internationally. These studies tend to focus on specific submarkets as opposed to an entire nation.

The first mandatory residential green building program was implemented in Frisco, Texas. A 2012 study used the standard hedonic analysis procedure on residential properties in Frisco and compared to properties in McKinney, an adjacent city with similar demographics but no residential green building program. The study found that a sales premium of 2%-4% existed for properties with eco-certifications (Aroul and Hansz 2012).

Kok and Kahn (2012) studied the value of eco-certification in the California housing market. The hedonic model was used to analyze 1.6 million production homes sold in California between 2007 and 2012. The primary types of eco-certifications were Energy Star, LEED and GreenPoint. Properties with eco-certifications were found to have a sales premium of 9%. This is a significant premium considering the average traditional home is $400,000, which means the 9% premium amounts to $34,800.(Kok and Kahn 2012).

Another hedonic analysis focusing on condominiums in Portland, Oregon was completed in 2013. Data from Portland Metro's Regional Land Information System between 2009 and 2012 were used to avoid the housing downturn (Yang 2013). This study focuses specifically on the economic impacts of LEED certifications and was the first study to look at the impact of different levels of LEED certifications as well as two different versions of LEED, LEED for New Construction (NC) and LEED for Neighborhood Development (ND). Overall, there was an average sales premium of 5.8%. However, it was found that the price premium may not go up as the level of LEED certification increases.

Brounen and Kok (2010) analyzed the effects of Energy Labels on the housing market. This was the first evidence on the effects of Energy Labels, implemented by the European Union. The average sales premium for a residential property was 3.7%. Although there is a premium, the number of properties that are achieving Energy Labels have been declining. This is because of the negative image of the Energy Labels in the public media because of the lack of systematic certification and transparency in the process. The main take away from this study is an example of problems than can be encountered when implementing a new eco-certification system

Evidence showed that there is no initial premium for buildings with eco-certifications in Japan. Yoshida and Sugiura (2014) performed a hedonic analysis on properties in Tokyo and discovered that overall the transaction price of a new green condo is in fact lower than a non-green condo. However, after two years the condos are traded at a premium because they depreciate at a slower rate. Instead of looking strictly at a specific eco-certification, this study broke green building into a set of green factors: energy efficiency, resource efficiency, long life span, and planting. They found that long life designs warrant a premium price in the occupant's eyes but renewable energy and recycled materials are associated with price discounts. This study is important in that it begins to look at certain aspects of a sustainable building and include the tenant's perception, which is ultimately what defines value and warrants a premium (Yoshida and Sugiura 2014)

DISCUSSION

Through a review of existing studies on the economic impact of eco-certifications, there is a consistent trend that rent, sales and occupancy premium do exist. Table 3 summarizes all existing literature and the resulting price premium. The rent premium ranges from 0.1% up to 25% and sales premium range from 0.6% to 26%. Although the majority of the studies focused on green office buildings in the U.S. there is still evidence for a premium in other countries and for other property types.

Table 3: Summary of Existing Literature

Existing Literature Results								
	Publication Year	Author(s)	Location	Data Period	Data Source	Sample	Rent Premium	Sales Premium
Office Buildings	2014	Wiencke	Switzerland	-	University of Zurich	Survey	3%	4.75%
	2014	Chegut, Eichholtz, Kok	UK	2000-2009	CoStar Database	BREEAM	20%	15%
	2012	Reichardt, Fuerst, Rottke,	US	2004-2008	CoStar Database	Energy Star	2.50%	-
				2008-2009		LEED	2.90%	-
	2011	Das, Tidwell, Ziobrowski	San Francisco and DC, US	2007-2010	CoStar Database	LEED/Energy Star	0.1% - 2.4%	-
	2011	Fuerst, McAllister	US	-	CoStar Database	Energy Star	4%	26%
						LEED	5%	25%
	2011	Fuerst, McAllister	US	-	CoStar Database	Energy Star	3-4%	18%
						LEED	4-5%	25%
	2011	Kok, Jennen	Netherlands	-	-	Energy Labels	7%	-
	2010	Eichholtz, Kok, Quigley	US	?	CoStar Database	Energy Star	2%	13%
						LEED	6%	11%
	2010	Eichholtz, Kok, Quigley	US	2007	CoStar Database	Energy Star	3%	16%
						LEED	5%	16%
	2010	Miller	US	2008-2010	CoStar Database	LEED	12%	15%
	2010	Wiley, Benefield, and Johnson	US	2008	CoStar Database	Energy Star	7%-9%	-
						LEED	16%-17%	-
	2010	Pivo, Fisher	US	-	CoStar Database	Energy Star	3%	3%
	2009	Fuerst, McAllister	US	2009	CoStar Database	Energy Star	5%	31%
						LEED	6%	35%
	2008	Miller, Spivey, Florance	US	2003-2007	CoStar Database	Energy Star	8%	6%
						LEED	8%	10%
Retail	2014	Veld, Vlasveld	Netherlands	1820 - 2007	CBRE Global Investors	Energy Performance Certificate	-0.52%	-0.60%
Residential	2013	Yoshida, Sugiura	Tokyo, Japan	2002-2009	TPIS	14	-	-
	2013	Yang	Portland, US	2009-2012	-	LEED NC Certified	-	5.80%
						LEED ND Certified	-	3%
	2012	Kok, Kahn	California, US	2007-2012	DataQuick	Energy Star/ LEED/ GreanPoint	-	9%
	2012	Aroul, Hansz	Texas, US	2002-2009	NTREIS	Green Buildings	-	2%-4%
	2011	Brounen, Kok	Netherlands	2009	Agentschap NL	Energy Labels	-	4%

BMPI is aiming for a LEED Certified status for The Apartment Building under LEED 2009 for New Construction. From the LEED scorecard, provided by JMAV, the project is pursuing a total of 47 points, out of the possible 110, which puts the project in the LEED Certified category. Figure 6 shows a breakdown of LEED points that are currently being pursued on the project. Points from the Sustainable Sites category account for the majority of the points with the least amount of emphasis on Regional Priority. A complete detailed breakdown of currently pursued LEED points can be found in the LEED scorecard in Appendix A.

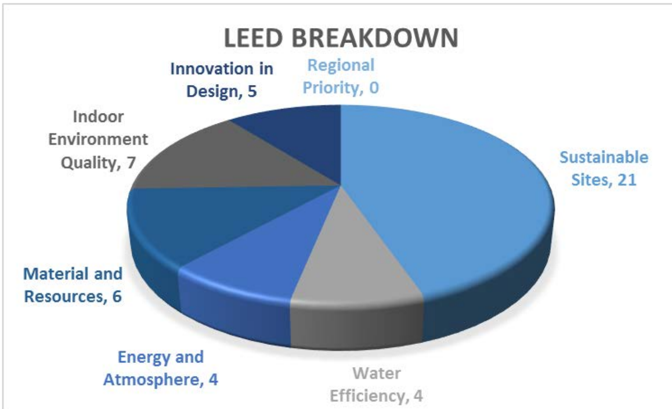


Figure 6: Current LEED Breakdown for The Apartment Building

According to the LEED breakdown, The Apartment Building is currently pursuing 47 LEED points, placing the project at the upper limits of LEED Certified. The project can easily be upgraded to a LEED Silver by pursuing three additional points.

Since this project is currently only LEED Certified, this leaves many opportunities to achieve these three additional points. However, these additional points must take into consideration that design is complete and the building is currently in the latter phase of construction. These additional points should not cause any design changes because the building is far along in construction and any changes would be costly. A possible option is to pursue Green Power (2 points) and Construction IAQ Management before occupancy (1 point). The addition of these points would bring the point total to 50, improving the buildings rating to LEED Silver.

Green Power is credit 6 of the Energy and Atmosphere category and is worth two points. According to LEED 2009 for New Construction, the intent of Green Power is to, “encourage the development and use of grid-source, renewable energy technologies on a net zero pollution basis”. These points can be earned by simply purchasing a two-year contract for green power for at least 35% of the building’s electricity needs. Green Power includes solar, wind, geothermal, biomass or low-impact hydro sources. This can be purchased directly from the local electricity provider who buys certified renewable energy from local facilities. Although this option is more expensive than traditional electricity, it is an easy solution that has no impact on the design and construction of the building. Green power is typically priced at an additional $0.15 per kWH. According to the Energy Star's benchmark, multifamily housing uses 78.8 kBtu/ft^2-year ("Technical Reference U . S . Energy Use Intensity by Property Type" 2014)and if 35% of this energy is to be green power for two years, it will cost The Apartment Building a total of $363,730 (see Appendix B for calculations). Typically the energy usage of a building is comprised of owner usage and tenant usage. Assuming energy usage is by the owner and tenant is equal, the cost to the owner to implement green power is $181,865 over a two year period (Table 4).

Credit 3.2 of Indoor Environmental Quality is implementing a construction IAQ management plan before occupancy. This credit can be achieved by flushing the building with 14,000 cu.ft/SF of outdoor air upon substantial completion. This precautionary activity can help mitigate sick building syndrome and building caused illnesses from air contaminants from paint, materials, finishes and furnishings. Since this can be done right before occupancy, this credit will have no impact on design and construction. The cost of perform a mechanical system flush is comprised of supervision and electricity, which according to Paladino, the green building and sustainability consulting firm for The Apartment Building, would cost around $30,000.

Table 4: Possible Credits to Achieve LEED Silver

Credit	Points	Cost
Green Power	2	$181,865
Mechanical System Flush	1	$30,000
Total (over two years)	**3**	**$211,865**

These three additional credits can improve The Apartment Building's rating from Certified to Silver. There are many other possible combinations of points that could be pursued, however, the ones suggested can be implemented at the current stage in the construction process and will required a minimal amount of additional work and will not interfere with work that has already been put in place. Can the rent premium from having an eco-certification justify the additional cost of upgrading to LEED Silver?

RECOMMENDATION

Past studies have shown that there is a rent premium for buildings with eco-certifications. Although only a handful of studies have been done residential properties, the results are consistent with previous studies on office building in the U.S. and abroad. The only residential study that did not find a premium for eco-certifications the study of Yoshida (2014) in Tokyo. He did find that after two years, green building developed a premium because they depreciated in value slower than their non-green counterparts. BMPI has made the right choice to implement LEED certification on The Apartment Building.

The question now is whether or not The Apartment Building should pursue a higher LEED certification. The different levels of LEED certification was addressed only in one study, which reported the price premium may not go up as the level of LEED certification increases. The study found that LEED NC gold buildings actually had a price discount of 11.5% and LEED ND gold building had a price discount of 21.4%(Yang 2013). He also justified that this price discount was due to a small sample size and not enough variety in the sample. Therefore, this study is not significant enough to support or refute the effect of higher levels of eco-certification call for an increased price-premium.

Since The Apartment Building can be upgraded to a LEED Silver rating by the addition of three points, it would be a safe investment move. The cost of obtaining the necessary points can be justified by the inherent rental premium for having an eco-certified building. Based the literature review, the rental premium would be likely fall between 3-4%. Using rental rates of a similar apartment building in the same market, the breakeven point of upgrading to LEED Silver can be calculated. The Apartment Building can be estimated to bring in a monthly revenue of $326,530 (Table 5). The monthly rent premium can then calculated from the estimated revenue. If the actual rent premium is 4%, then the investment becomes profitable at roughly 6.5 months, Figure 7. At the end of the two year contract of green power, the overall profit for the investment will be $101,604. If the actual rent premium is 3.5%, then the investment becomes profitable at roughly 8.8 months, Figure 8. At the end of the two year contract of green power, the overall profit for the investment will be $62,420. If the actual rent premium is 3%, then the investment becomes profitable at roughly 14.52 months Figure 9. At the end of the two year contract of green power, the overall profit for the investment will be $23,236.

Table 5: Approximate Rental Income

Unit type	SF	Quantity	Average Rent
Studio	523	26	$1,600
Jr. One Bedroom	669	40	$1,700
One Bedroom	738	37	$1,780
One Bedroom + Den	811	38	$2,290
Two Bedroom	956	15	$2,545
Two Bedroom +Den	1054	9	$2,875
Total monthly revenue			$326,530

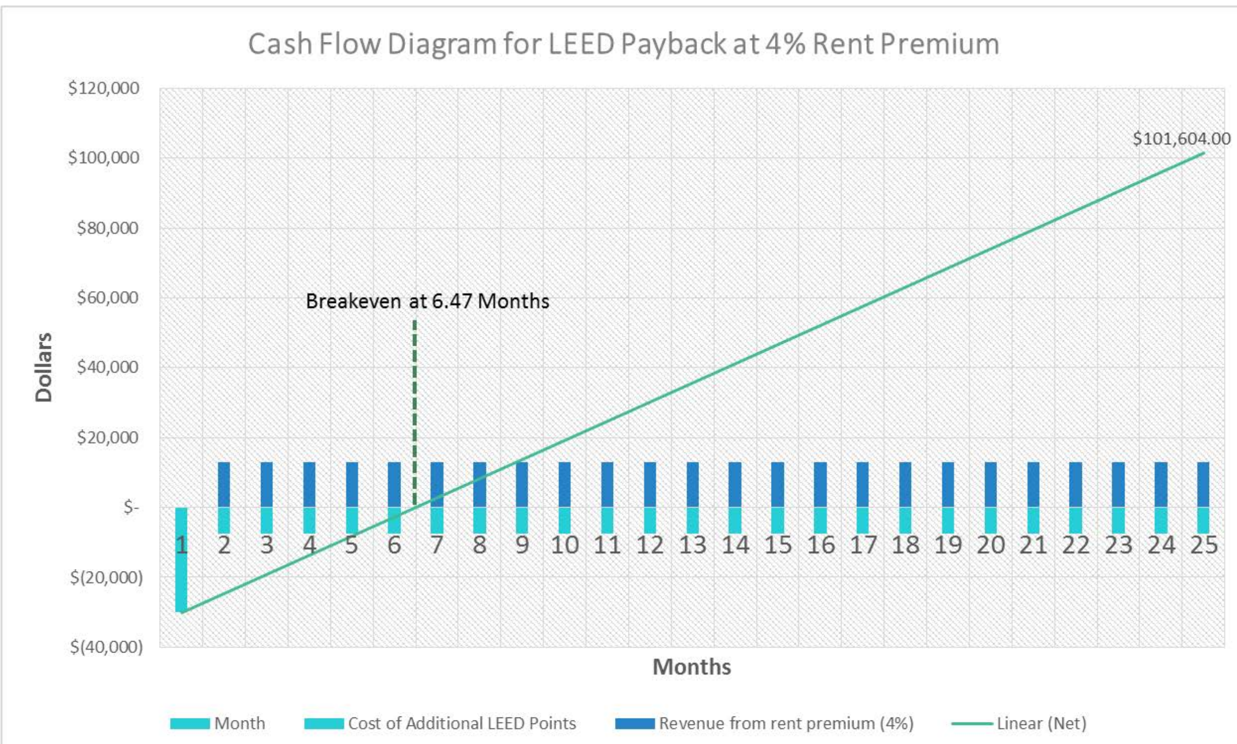


Figure 7: Cash Flow Diagram for LEED Payback at 4% Rent Premium

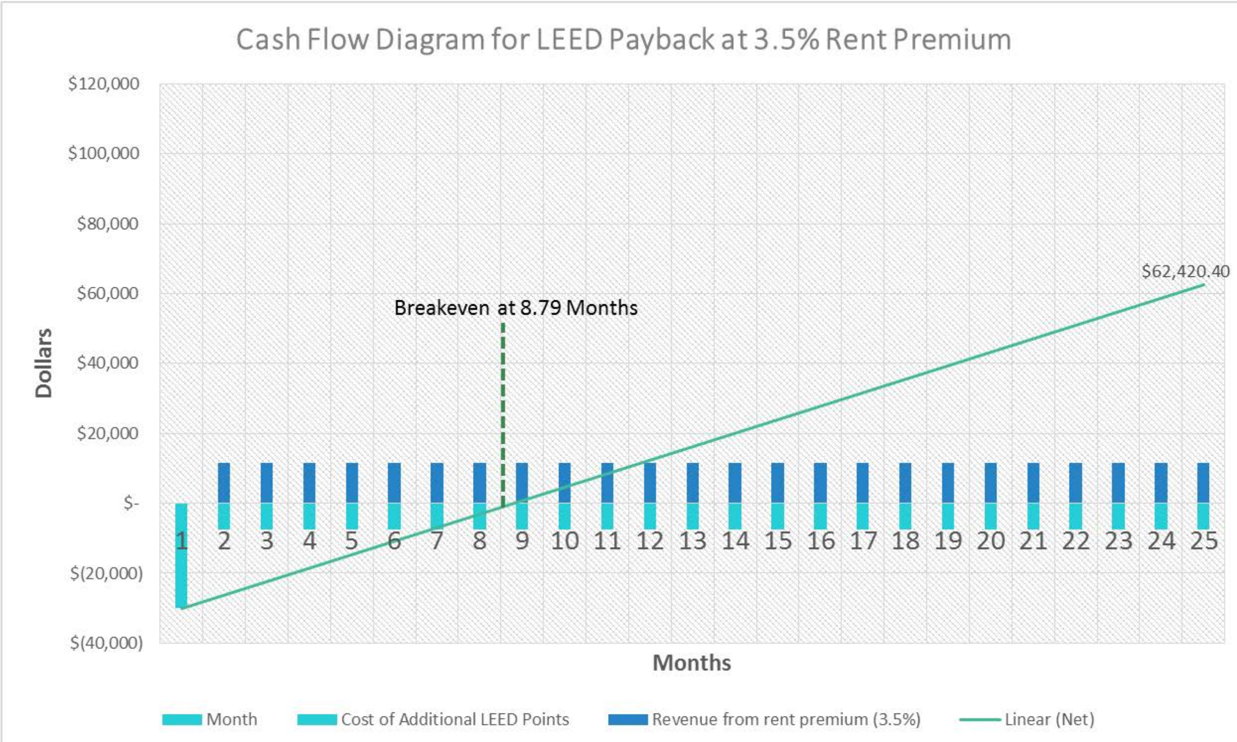


Figure 8: Cash Flow Diagram for LEED Payback at 3.5% Rent Premium

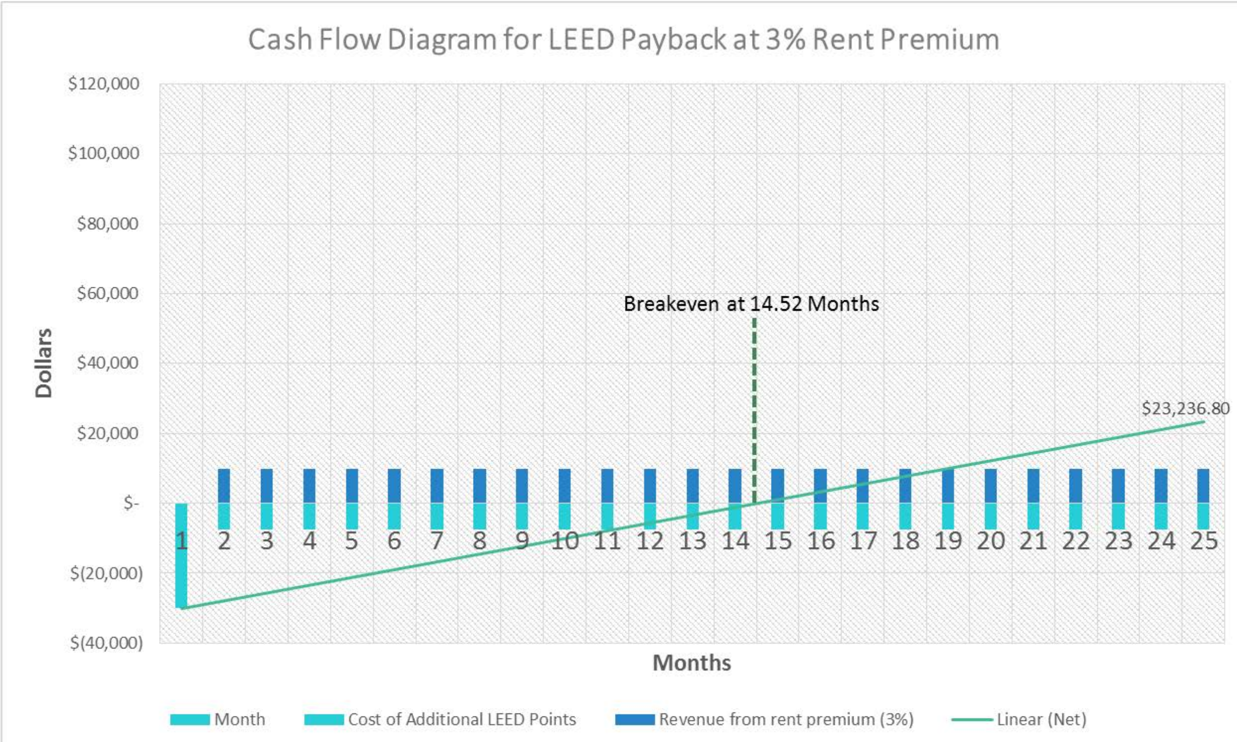


Figure 9: Cash Flow Diagram for LEED Payback at 3% Rent Premium

The actual rent premium may not fall within the range of 3-4%, but this is a reasonable expectation based on the literature review. In the three rent premium cases that were analyzed, the investment to upgrade to LEED Silver would be break even in a short amount of time and become profitable by the end of the two year green power contract.

There are many other possible combinations of points that could be pursued to obtain a LEED Silver rating. The ones suggested can be added at this point in construction with a minimal amount of additional work and no redesign of work that has already been put in place.

AREAS FOR FURTHER RESEARCH

The effect of eco-certification on office buildings on a national scale have been well studied. Slowly, research has begun to focus down the scope of data to smaller submarkets and metropolitan areas. As more green building are being built, data is becoming more and more available every day to conduct these types of analysis. It would be a useful real estate tool for consultants and owners to conduct more hedonic analysis of specific submarkets for their individual use.

Hedonic analysis show revealed preference since actual transaction data is used. More stated preference research, like surveys of Wiencke (2013) conducted in Switzerland, can help further understand user perception of green building. Additionally, understanding which specific green factors that contribute to a premium should be studied. Similarly, Yoshida (2014) reported that long life designs warrant a premium price in the occupant's eyes but renewable energy and recycled materials are associated with price discounts.

Lastly, most studies don't look at the various levels of certification within each green rating system. Yang's (2013)study was the only one to break up each eco-certifications into its different levels. Nowadays, achieving LEED certified is not as challenging as it used to be, and LEED Platinum is becoming more and more popular. As green building continues to improve, it would be interesting to look at the premiums associated with each level of certification.

ANALYSIS 2: EXTERIOR ENCLOSURE ACCELERATION

RESEARCH PROBLEM

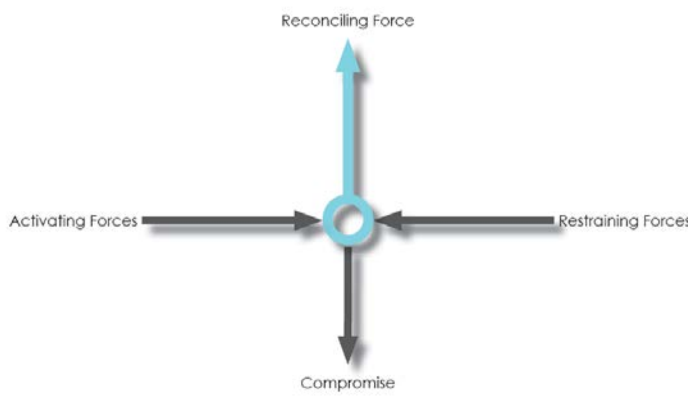


Figure 10: Law of Three Framework

The law of three framework can be applied to any construction project (Figure 10). The activating forces that drive the project include the owner's goals and ambition while the restraining forces include schedule, cost, and quality. It is a common belief in the industry that a compromise must be made between the activating forces and restraining forces. However, there may be instances where a reconciling force exists that allows all forces to be maximized and create a win-win situation. By doing so, project can be completed faster, cheaper, safer, and at a higher level of quality.

PROBLEM STATEMENT

According to the baseline schedule, exterior masonry work on The Apartment Building was scheduled to begin during the winter. Due to a harsh winter, the overall construction schedule was delayed 26 days. Excessive rain and snow delayed the concrete structure and consequently the building enclosure. The building enclosure is a vital component of any building and is the critical path. The enclosure for The Apartment Building is complex and uses a multitude of façade materials: four types of brick, six types of architectural masonry units, metal cladding and three types of cast stone. In a previous interview with the project manager, it was mentioned that it was difficult to streamline the exterior enclosure process due to the many types of materials. This lack of flow is not ideal especially after the delay of schedule due to weather.

The current enclosure design consist of a hand laid brick veneer supported by metal studs. Laying brick on site is a tedious labor intensive process that is at risk for delays from weather. Implementing a prefabricated panelized system may be a method of improving the schedule. Therefore, the objective of this analysis will involve implementing a panelized brick veneer system and comparing it to the existing enclosure system. Cost and schedule will dictate if the proposed system is an appropriate alternative.

INTRODUCTION TO PREFABRICATION

WHAT IS PREFABRICATION?

At its core, prefabrication is the offsite manufacturing of components of an assembly. Prefabrication is a broad term that refer to components that vary drastically in size and complexity. There are four main categories of prefabrication: modular structures, panelized structures, prefabrication components, and processed materials (Schoenborn 2012). Figure 11 provides examples of the various levels of prefabrication. The larger the amount of prefabrication, the less onsite labor is required. The need for prefabrication stems from many different factors such as a need for a competitive edge, lower prices, lack of skilled construction labor, increasing use of BIM, and a need for increased productivity (Cowles and Warner 2013)

Modular Structures	Panelized Structures	Prefabricated Components	Processed Materials
apartment unit modules	Wall panels	plumbing racks	glulam beams
http://www.themodulesattempletown.com	http://media.point2.com	http://www.gjhopkins.com	http://www.rosboro.com

Figure 11: Levels of prefabrication

BENEFITS OF PREFABRICATION

If implemented properly, prefabrication can have many benefits and possibly benefit every aspect of the construction triangle, which is rare. The main benefits include:

- Schedule reduction
- Cost reduction
- Improved safety
- Improved quality
- Waste reduction

Figure 12: Construction Triangle

Implementing a prefabricated system can have many positive impacts on the construction schedule. Since the prefabrication occurs at an offsite location, work can be completed simultaneously at the construction site and offsite which can lead to a schedule decrease (Figure 13).

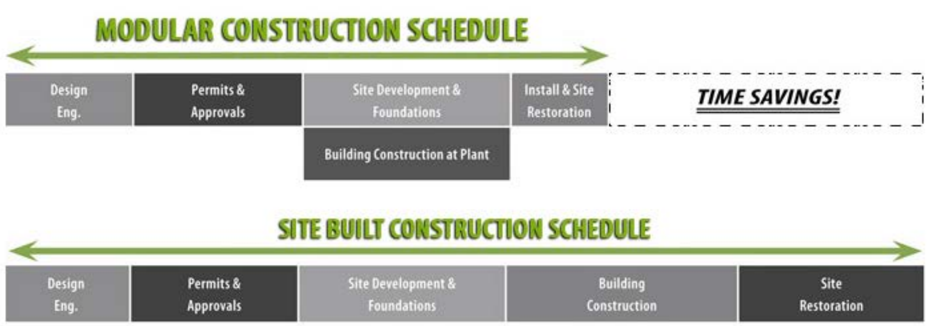


Figure 13: Schedule savings from prefabrication (“Why Build Modular?” n.d.)

By working in a controlled indoor environment, the risk of being delayed by weather is mitigated as well. If the construction site is tight and congested, offsite prefabrication can help decongest the site and maximize productivity and flow. In a 2011 survey conducted by McGraw-Hill Construction, 66% of the respondents said that implementing prefabrication has decreased the project schedule by more than a week. 35% saw schedule decreased of four weeks or more (Figure 14) (McGraw Hill Construction 2011).

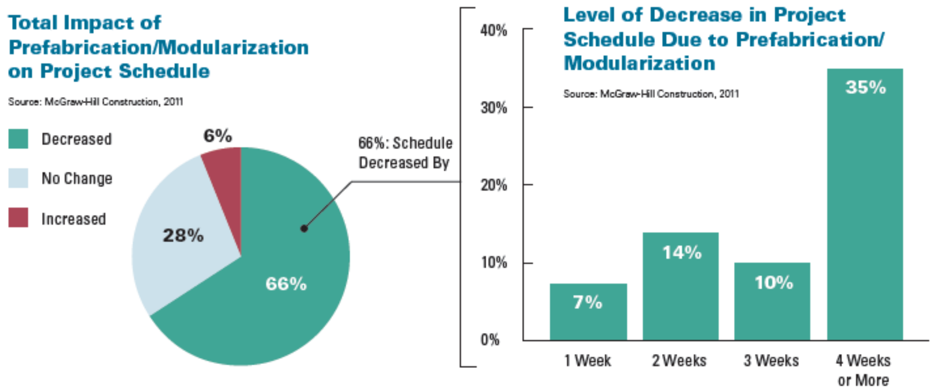


Figure 14: McGraw Hill Construction Survey Results (McGraw Hill Construction 2011)

Cost is always a significant driver in any construction project, especially since the typical GC/CM fee is around 3%. Prefabrication can have a positive impact on construction costs for many reasons. Since prefabrication improves productivity and reduces the schedule, onsite general conditions costs can be reduced. Also, prefabrication may eliminate the need for some onsite resources such as scaffolding and hoists. According to the 2011 McGraw-Hill survey, 65% of the respondents experienced a cost savings (Figure 15) (McGraw Hill Construction 2011). Even if the project cost doesn't decrease, prefabrication can help reduce the chance of critical cost overruns.

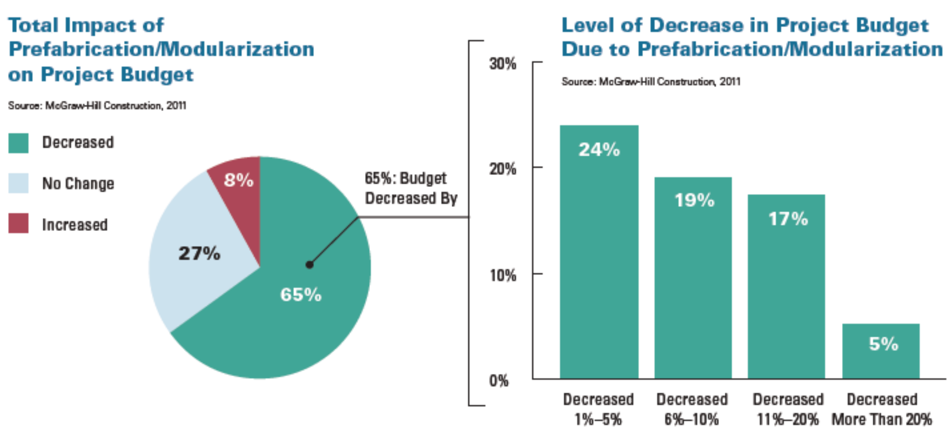


Figure 15: McGraw-Hill Construction Survey Results (McGraw Hill Construction 2011)

Safety is at the center of the construction triangle. It is of utmost importance to the construction industry due to the risks involved on a day to day basis. Incidents can have a negative effect on morale, schedule, and cost to any project. Prefabrication can have positive effects on the overall safety of the workers. Since work is being completed offsite in a controlled environment, worker are able to work at an appropriate working height as opposed to on top of a ladder or hoist. The time spent working in confined spaces onsite can be minimized as well.

Quality of the component can be improved through prefabrication. Prefabrication occurs in a controlled setting, allowing the implementation of more stringent quality control measures compared to onsite construction. Implementing a prefabricated design requires significant collaboration between the designers, subcontractors and CM/GC. The level of detail of design construction documents is much higher than what typical construction documents, resulting in a higher level of quality.

The construction process is notorious for generating waste. Studies have shown that 10-15% of construction materials used on a project are wasted. Construction waste is not ecofriendly, and it can have a significant impact on the cost of the project. Prefabrication in a controlled environment, can minimize waste left over materials can be reused. This may also help keep the construction site more organized and debris free.

PREFABRICATED BRICK PANELS

Exterior walls are one of the most common areas where prefabrication was used (McGraw Hill Construction 2011). (Figure 16). Onsite brick laying is a labor intensive process that has not changed much since brick has been used in building. Prefabrication of brick panels has been around for over a century. The concept of brick prefabrication can be divided into two main categories: automating the process with unskilled labor or maximizing the productivity of skilled labor. Productivity is improved by implementing various means and methods or proprietary mechanical equipment.

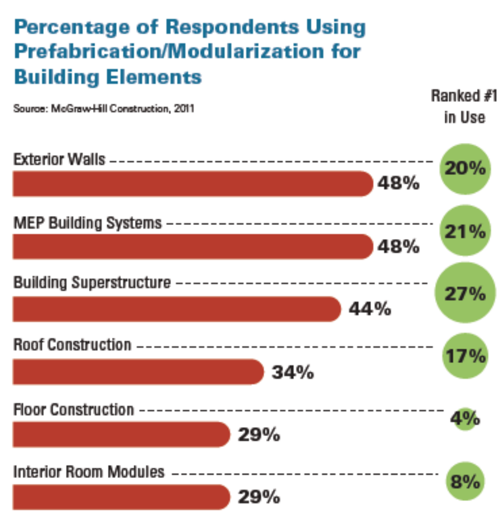


Figure 16: McGraw-Hill Survey Results (McGraw Hill Construction 2011)

As mentioned earlier, the general concept of prefabrication has many advantages. There are a plethora of advantages specific to prefabricated brick panels in an offsite location, along with some disadvantages, as shown in Table 6.

Table 6: Advantages and Disadvantages of Prefabricated Brick Panels

(*Prefabricated Brick Masonry - Introduction* 2001) (Wallace 1990)

Advantages	Disadvantages
Eliminate onsite scaffolding and swing stages	Panel size limited by transportation regulations
Reduce onsite storage of material with delivery schedule	Panel size limited by crane limitations
Create complex patterns and shapes	Limited onsite adjustment capabilities
Mitigate weather effects	Need a higher level of tolerance
Year-around work and multi-shift work days	May need to alter the architectural design
Enclose the building more quickly	
More consistent curing conditions	
Improve quality control	

There are two main methods of prefabricating brick panels: the hand laying method and the casting method. Similar to the traditional onsite laying method, the hand laying method uses skilled labor and traditional tools. The only difference is that it is done offsite. This method is best for a masonry contractor that is acting as a masonry prefabricator on a project, because many of the same tools and the labor force can be used. The casting method is more modern and technological. In this method the process of placing brick, mortar and ground is mechanized and even automated. A skilled masonry labor force is no longer needed and is replaced by unskilled labor. The brick is placed in a mold then grout is added under pressure. The placement of the brick and grout can all be done in an automated fashion using proprietary machinery

Once the panels are fabricated in an offsite location, they are transported to the jobsite then picked directly off the truck by a crane and put into place. Typically the panels are attached to the structure by welding or bolting. One of the disadvantages of prefabricated brick panels is the size limitations due to transportation regulations so this must be considered early in the design phase. On the other hand, prefabrication decreases onsite labor drastically. In order to install prefabricated panels, typically only a crew of six people is needed. (Wallace 1990)

- One worker on the ground for rigging the panels
- A crane operator
- Two workers that align the panels
- One worker to make the connections
- One foreman to supervise the process

ORIGINAL BRICK VENEER ASSEMBLY

The Apartment Building utilizes a couple different façade materials such as brick, architectural concrete masonry units (ACMU), metal panels, and a small amount of decorative cast stone. From Table 7, it is evident that the majority of The Apartment Building's enclosure is comprised of brick veneer with a steel stud back up at roughly 35,300 SF followed next by ACMU at 4,200 SF and lastly metal cladding at 1,700 SF.

Table 7: Facade Material Quantities

Façade Material	Surface Area of Exterior (SF)
ACMU	4,213
Brick	35,322
Metal Cladding	1,733

Within the 35,300 SF of brick, four different brick types and three different mortar types are used (Figure 17). This non uniformity of brick and mortar types makes installation more complex and tedious.

The primary components of the assembly include face brick, rigid insulation, GWB, Batt insulation, and steel studs (Table 8). The entire assembly is to stick built on the construction site.

BRICK TYPE LEGEND
(ALL BRICKS ARE MODULAR)
BRICK TYPE 1 = RED
BRICK TYPE 2 = BLONDE
BRICK TYPE 3 = BLONDE TEXTURED
BRICK TYPE 4 = RED TEXTURED

MORTAR TYPE LEGEND
MORTAR TYPE 1 = FLAMINGO BRIXMENT C-81
MORTAR TYPE 2 = COLOR TO MATCH ACMU TYPE 6
MORTAR TYPE 3 = COLOR TO MATCH ACMU TYPE 3

Figure 17: Brick and Mortar Types Used on The Apartment Building

Table 8: Typical Brick Veneer Assembly

Interior	←				→	**Exterior**
GWB	Steel Stud w/ Batt Insul.	Gypsum Sheathing	Air Barrier	Rigid Insul.	Air Cavity	Brick Veneer
5/8"	3-5/8"	5/8"		1-1/2"	1-1/2"	3-5/8"

Figure 18 depicts a typical elevation of the current brick veneer assembly that is used on the majority of the enclosure. The brick veneer is supported by steel structural relieving angles that are attached to embeds at the concrete slab edge. The concrete slab supports the steel stud back up. The brick veneer is attached to the steel stud backup using adjustable galvanized brick ties.

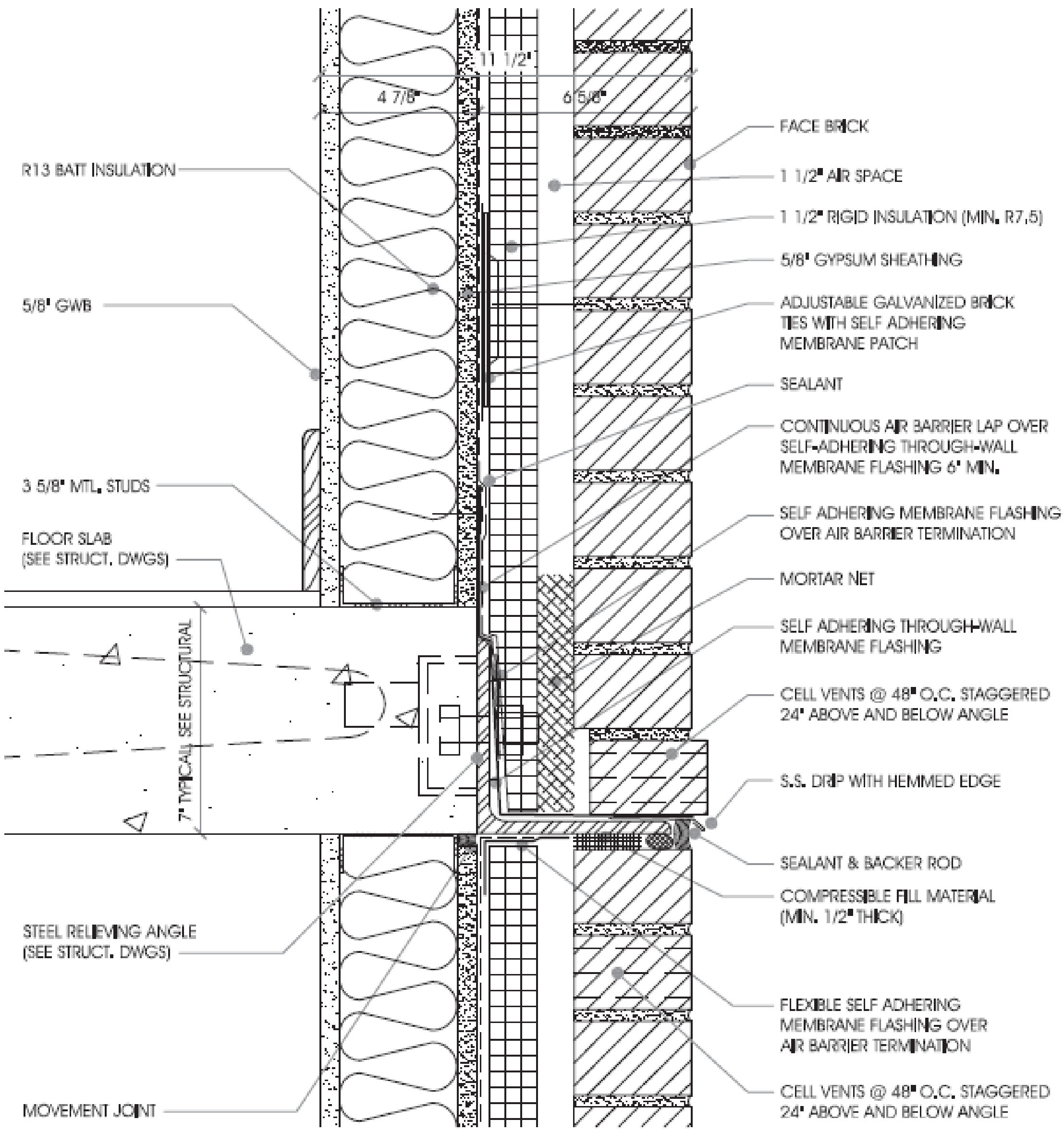


Figure 18: Typical Brick Veneer Elevation

PROPOSED PREFABRICATED SYSTEM

PANELIZED BRICK VENEER ON STEEL STUD SYSTEM (PBVSS) DESCRIPTION

Prefabrication will only be done on the brick veneer because it is the most heavily used. Prefabricated brick veneer will help with repetition and ultimate cost effectiveness of a panelized system. In this analysis, a panelized brick veneer wall system supported by structural steel (PBVSS), created by Penn State, will be used on The Apartment Building. The PBVSS system is comprised of a brick veneer supported by steel studs. This system was developed to address problems with existing brick veneers on steel stud systems. The traditional system is prone to cracking due to the large deflection of the steel studs under wind loads, moisture penetration, corrosion of metal ties, and seismic loading. The PBVSS system addresses these shortcomings by utilizing a rigid steel back up frame that serves as the outer dimensions of the panel, standard steel studs, OSB sheathing, rigid foam insulation, air/vapor barrier, brick veneer, and gypsum wall board (Figure 19).

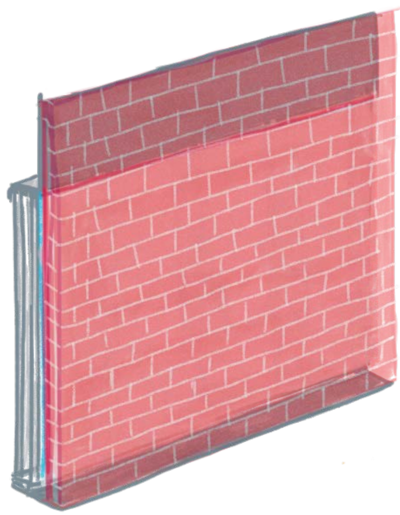


Figure 19: Isometric sketch of PBVSS System

The PBVSS system is supported by a structural steel frame that is comprised of a bottom channel, bottom angle, top channel, two vertical channels, and a top plate (Figure 20). The bottom angle is connected to the bottom channel and supports the brick veneer while the bottom channel supports the steel studs. The top channel is placed below the floor above and the top plate extends up the top of the slab to support the brick veneer. The vertical channels support the gravity loads of the panel during transportation and erection.

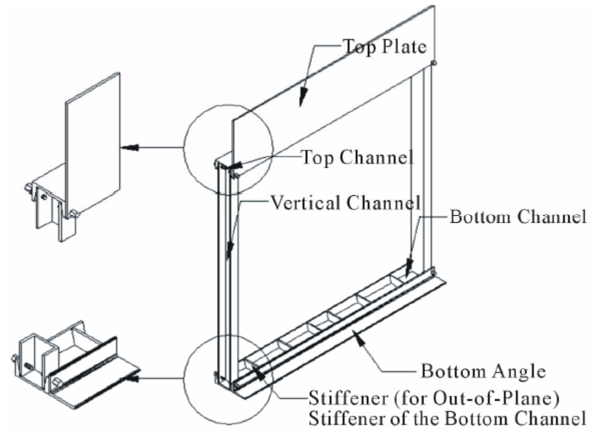


Figure 20: Isometric view of steel support frame (Liang 2012)

Figure 21 highlights a typical elevation detail of the PBVSS system. The brick veneer and steel studs are supported by a bottom channel and angle system. The top of the wall is secured to the concrete slab above by means of an embedded steel angle. The brick veneer continues up the exterior side of the concrete slab and is supported by a top plate.

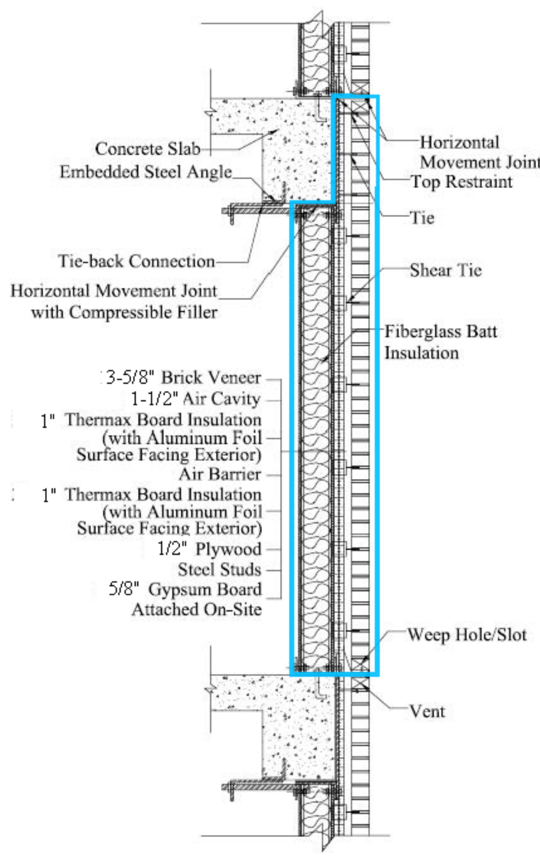


Figure 21: Elevation of PBVSS (Liang and Memari 2011)

The makeup of the wall assembly is very similar to the current assembly designed for The Apartment building. Table 9 shows a typical breakdown of the PBVSS assembly. There are a few differences between the two assemblies. The proposed assembly uses ½" plywood sheathing instead of 5/8" gypsum sheathing. Additionally, the location of the air barrier is altered. In the original assembly, the air barrier is located between the gypsum sheathing and the 1-1/2" rigid insulation. In the proposed PBVSS assembly, two layers of 1" rigid insulation are used instead and the air barrier is located in between. Two layers of rigid insulation are used instead of one to prevent damage from transportation and installation. Since the brick veneer assembly components are being alters, it is vital that the mechanical properties of the system meet or exceed what was originally designed. A mechanical analysis will be completed and discussed later in this analysis.

Table 9: Breakdown of PBVSS assembly

Proposed PBVSS Assembly							
Interior	⟷						**Exterior**
GWB	Steel Stud w/ Batt Insul.	Plywood Sheathing	Rigid Insul.	Air Barrier	Rigid Insul.	Air Cavity	Brick Veneer
5/8"	3-5/8"	½"	1"		1"	1-1/2"	3-5/8"

Adjustable galvanized steel ties were originally specified for The Apartment Building. In the PBVSS system, Stud Shear Connector ties, manufactured by FERO Corporation, are used instead (Figure 22). The benefit of using Stud Shear Connector ties is that the stiffness of the wall system is increased to help reduce cracking in the brick and consequently water infiltration.

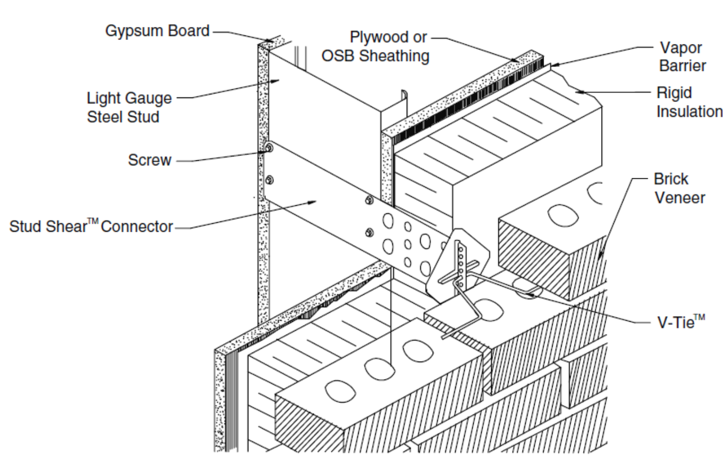


Figure 22: Schematic use of Stud Shear Connector tie (Liang and Memari 2011)

PBVSS PANEL CONSTRUCTION

The original brick veneer system is stick built on site which makes it vulnerable to weather impacts and delays whereas the proposed PBVSS is to be constructed offsite in a controlled environment. In this situation JD Long, the masonry contractor, will be acting as the masonry prefabricator. The same skilled labor and tools that would have been used originally will be used offsite. The design of the PBVSS panel lends itself to the traditional hand brick laying method instead of casting, which is ideal for a masonry contractor acting as a prefabricator. Since four different brick types are being used, the hand laying method will be the most efficient way for skilled masons to construct the panels. Figure 23 shows brick being laid by hand for a mock up for testing (Liang and Memari 2011). Prefabrication will be done in an offsite warehouse that is eight miles from the jobsite. The warehouse will be leased by the masonry contractor and will serve as the prefabrication shop. The PBVSS panels will be constructed in the order in which they will be installed on site. PBVSS Panels can also include opening for windows. In these cases, the steel stud back up must be rearranged to strengthen the opening. Windows can then be installed in the warehouse or onsite by the glazing contractor. When implementing prefabrication on any project, it is essential the proper measures are taken to coordinate with all affected trades to mitigate onsite clashes. PBVSS panels should be coordinated with MEP rough in, embeds, and interior finishes.

Figure 23: PVBSS mock-up during construction (Liang and Memari 2011)

TRANSPORTATION

When a panel is completed it will be transported from the warehouse to the site, which is eight miles away. Flatbed semi-trailers will be used to transport the completed PBVSS panels. Up to four panels can be transported at a time, as shown in Figure 24. If a panel includes a window, the panel is framed with 2 x 4 plants to ensure the window does not crack during transportation.

Figure 24: Transportation similar to Superior Walls (http://www.superiorwalls.com)

CRANEAGE AND INSTALLATION

Once the PBVSS panels are transported to the site, they will be picked directly off the trailer and put into place. Currently, The Apartment Building is using a Potain MDT 412 tower crane (Figure 25). Since the job site is tight due to surrounding existing buildings, picking the panels directly off the trailer and into place will minimize site congestion. The caveat is that the delivery schedule must be properly managed to ensure an efficient process.

Figure 25: Site Photo 11/14/13

SEQUENCING AND LAYOUT

Trucks carrying the completed PBVSS panels will enter the job site from the 2nd Street entrance and exit via the Main Street entrance. The completed panels will be picked directly off the truck and hoisted into place. The panel installation will be sequenced so that one floor is completed at a time, starting at the ground floor and up through the top floor. By enclosing one floor at a time, that particular floor will become weather tight so interior work can begin as soon as possible. On each floor, panel installation will begin on the northwest elevation and work counterclockwise around the building, such that the north elevation is the last to be completed (Figure 26).

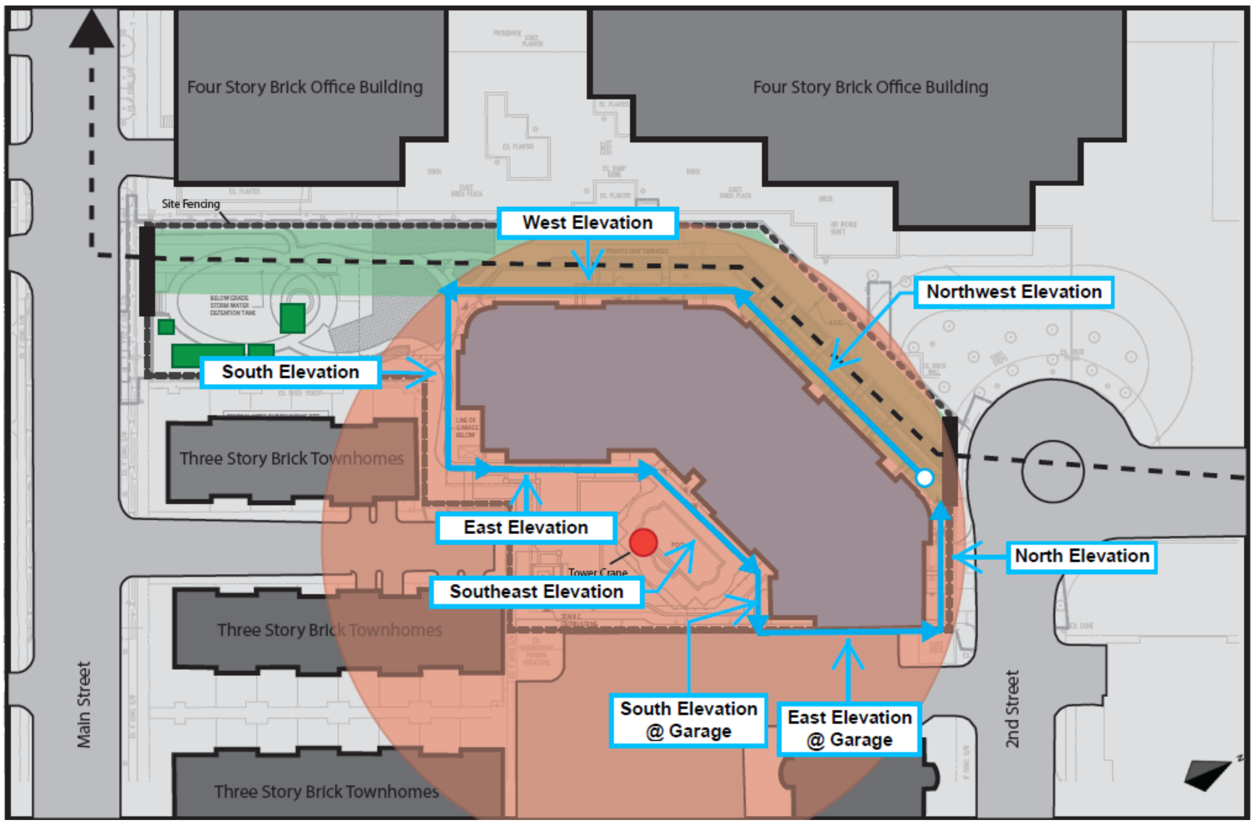


Figure 26: Panel Sequencing

PBVSS PANEL SIZE AND WEIGHT CONSTRAINTS

The dimensions and weight of the PBVSS panels are limited by traffic regulations and the crane capacity since the panels will be constructed offsite then transported to the site and lifted into place. Certain size, weight, and equipment requirements exist for trucks, trailers, and other towed vehicles. These regulations are regulated and enforced by the state's department of transportation. There are many different types of cranes and each has a specific capacity or maximum load that can be lifted safely without failure.

Figure 27: 5-Axel Semi Trailer transporting Panels

According to the Virginia Department of Motor Vehicles, the maximum semi-trailer length, width, and height are 53 ft., 102in, and 13ft 6in, respectively. These constrains dictate the maximum size of each PBVSS panel. For transportation, the maximum weight a 5-axel semi-trailer can carry is 80,000 lbs. As for hoisting, The Potain MDT 412 tower crane has a maximum capacity of 22,000 lbs. and a critical pick of 13,230 lbs. at 196 ft. and no size constraint for the panels (Table 10).

Table 10: Crane Capacity

MDT 412 - L 10 FEM A 3 **POTAIN**

Hoist unit 79 kW SL/WB
Radius and capacity

Update 2-17-05

Jib	Max. capacity		Radius (ft) and capacity (lbs)											
	lbs	ft	91'10"	98'5"	104'12"	114'10'	131'3'	147'8"	164'1"	180'5"	196'10"	213'3"	229'8"	246'1"
L 7 246 ft	22.000	9'6" - 92'6"	22.000	20.507	19.184	17.199	14.774	12.789	11.246	10.143	9.041	8.159	7.497	6.836
L 6 230 ft	22.000	9'6" - 105'4'	22.000	22.000	22.000	20.066	17.199	14.994	13.230	11.907	10.584	9.702	8.820	
L 5 213 ft	22.000	9'6" - 115'2'	22.000	22.000	22.000	22.000	18.963	16.538	14.774	13.230	11.907	10.805		
L 4 196 ft	22.000	9'6" -125'12"	22.000	22.000	22.000	22.000	20.948	18.522	16.317	14.553	13.230			
L 3 181 ft	22.000	9'6" - 133'6"	22.000	22.000	22,000	22.000	22.000	19.625	17.420	15.656				
L 2 164 ft	22.000	9'6" - 137'6'	22.000	22.000	22.000	22.000	22.000	20.286	18.081					
L 1 131 ft	22.000	9'6" - 131'3'	22.000	22.000	22.000	22.000	22.000							

The floor-to-floor height of The Apartment Building is 9'6". The PBVSS panel height will be the floor to floor height plus the thickness of the slab above, making the PBVSS panel height on average about 10ft. The maximum width of the panel is constrained by transportation as well as the capacity of the crane at a specific radius. The accepted weight for a conventional brick veneer on steel stud back up is 50 psf. The PBVSS panel will weigh slightly more due to the steel frame, around 55 psf. The weight breakdown of the proposed PBVSS panel is shown in Table 11.

Table 11: Weight Calculation of PBVSS panel

Weight of Proposed Brick Veneer System				
Item		Quantity	Unit	Weight (psf)
Brick Veneer	3-5/8"		SF	39
Rigid Insulation	1"		SF	0.75
Air Barrier			SF	0.7
Rigid Insulation	1"		SF	0.75
Plywood Sheathing	1/2"		SF	1
Batt Insulation	3-5/8"		SF	1.1
GWB	5/8"		SF	2
Steel Studs	12 gauge 3-5/8"		LF	4
Steel Relieving Angle	6x6x3/8		LF	1.5
Stud Shear Connector Ties			ea	1
Embeds with two stud (1/2" dia)	1/2x8x8			1
Steel Frame				2
		Total Weight		**54.8**

The furthest distance the crane will have to reach for a pick is 130 feet and the capacity at this max distance is 20,948 lbs. (Table 10). Since the PBVSS panel height is 10 ft., the capacity of the crane is 20,948 lbs., and the PBVSS panel weighs 55psf, the maximum length the panel can be is 38 feet. This length is less than 53 ft. limit set by the Department of Transportation (DOT). The maximum dimensions for the panel is summarized in Table 12. Note that the average panel height is given based on the average floor-to-floor height. This dimension may vary by a foot or two which would decrease the maximum panel length.

Table 12: Max PBVSS panel dimensions

Maximum dimensions and weight for PBVSS panel	
Max panel height	10 ft.
Max panel length	38 ft.
Max panel weight	20,948 lbs.

PBVSS PANEL LOCATIONS

The Apartment Building's façade can be broken up into eight main elevations as shown in Figure 26. Using the maximum dimension and weight constraints given in Table 12, the brick portions of each elevation was divided into various panels. In general, the panels span from floor to floor and the width was determined based on the geometry of the building and the transportation and cranage restrictions. In total, the brick portion of the enclosure will comprise of 234 panels (Table 13).

Table 13: PBVSS Panel Count

Total Number of Panels	
Elevation	# of Panels
North Elevation	26
East Elevation	31
East Elevation @ Garage	28
Southeast Elevation	31
South Elevation	17
South Elevation @ Garage	10
West Elevation	35
Northwest Elevation	56
Total	234

NORTH ELEVATION

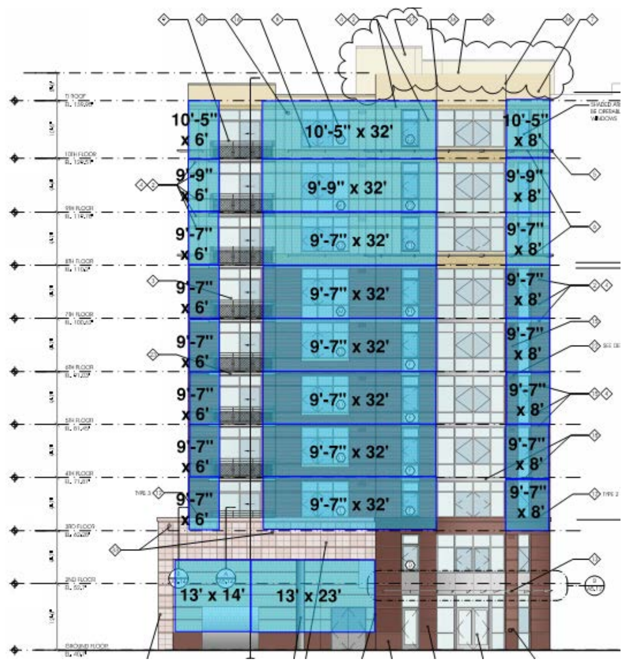


Figure 28: North Elevation Panel Breakdown

Table 14: North Elevation Panel Count

	Panel Height	Panel Length	Quantity
North Elevation	13'	23'	1
		14'	1
	10'-5"	32'	1
		6'	1
		8'	1
	9'-9"	32'	1
		6'	1
		8'	1
	9'-7"	32'	6
		6'	6
		8'	6
		Total	**26**

EAST ELEVATION

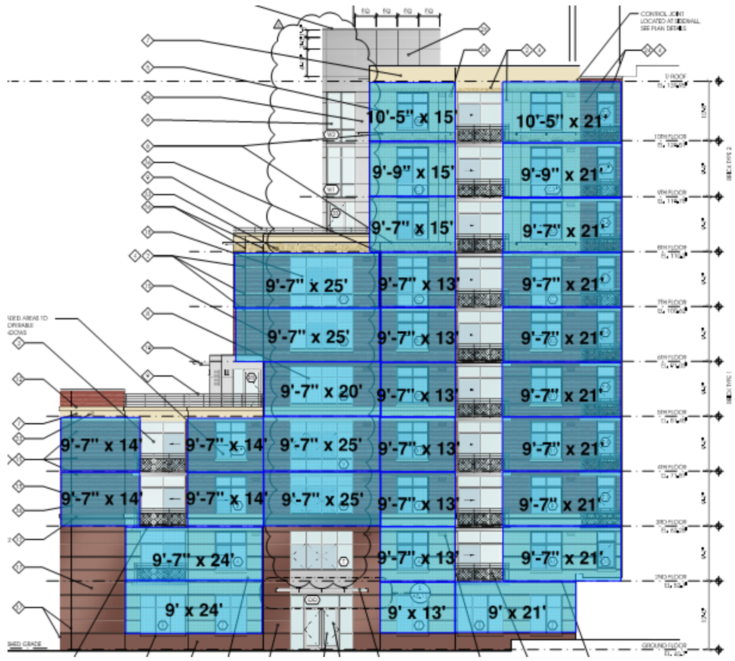


Figure 29: East Elevation Panel Breakdown

Table 15: East Elevation Panel Count

	Panel Height	Panel Length	Quantity
East Elevation	10'-5"	21'	1
		15'	1
	9'-9"	21'	1
		15'	1
	9'-7"	25'	4
		24'	1
		21'	7
		20'	1
		15'	1
		14'	4
		13'	6
	9'	24'	1
		21'	1
		13'	1
		Total	31

EAST ELEVATION @ GARAGE

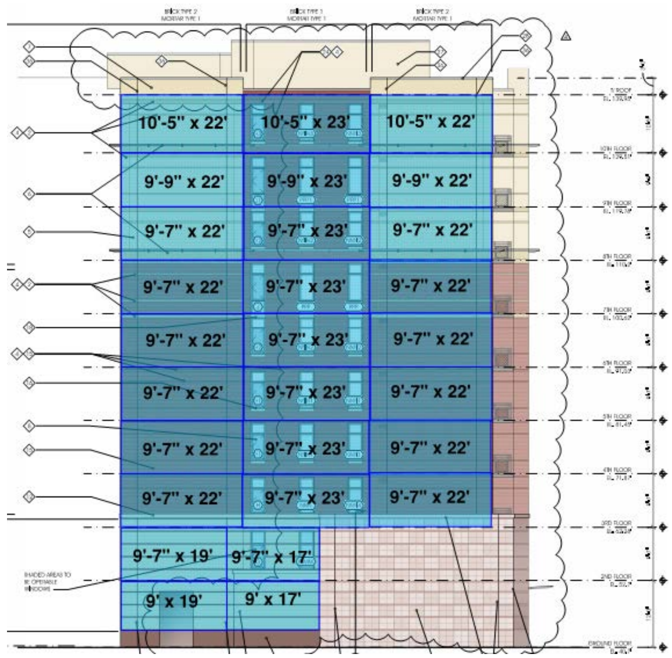


Figure 30: East Elevation @ Garage Panel Breakdown

Table 16: East Elevation @ Garage Panel Count

	Panel Height	Panel Length	Quantity
East Elevation @ Garage	10'-5"	22'	2
		23'	1
	9'-9"	23'	1
		22'	2
	9'-7"	22'	12
		23'	6
		19'	1
		17'	1
	9'	19'	1
		17'	1
		Total	28

SOUTHEAST ELEVATION

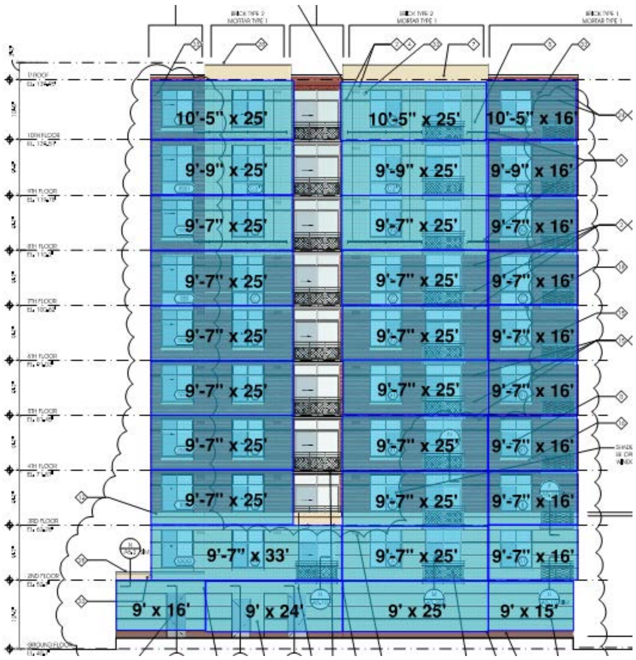


Figure 31: Southeast Elevation Panel Breakdown

Table 17: Southeast Elevation Panel Count

	Panel Height	Panel Length	Quantity
Southeast Elevation	10'-5"	25'	2
		16'	1
	9'-9"	25'	2
		16'	1
	9'-7"	33'	1
		25'	13
		16'	7
	9'	25'	1
		25'	1
		16'	1
		15'	1
		Total	**31**

SOUTH ELEVATION

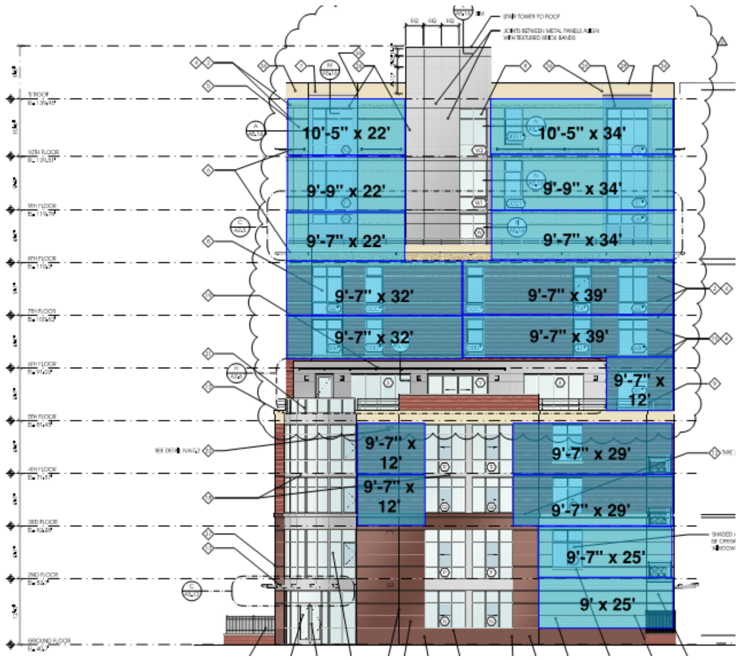


Figure 32: South Elevation Panel Breakdown

Table 18: South Elevation Panel Count

	Panel Height	Panel Length	Quantity
South Elevation	10'-5"	34'	1
		22'	1
	9'-9"	34'	1
		22'	1
	9'-7"	39'	2
		34'	1
		32'	2
		29'	2
		25'	1
		22'	1
		12'	3
	9'	25'	1
		Total	17

SOUTH ELEVATION @ GARAGE

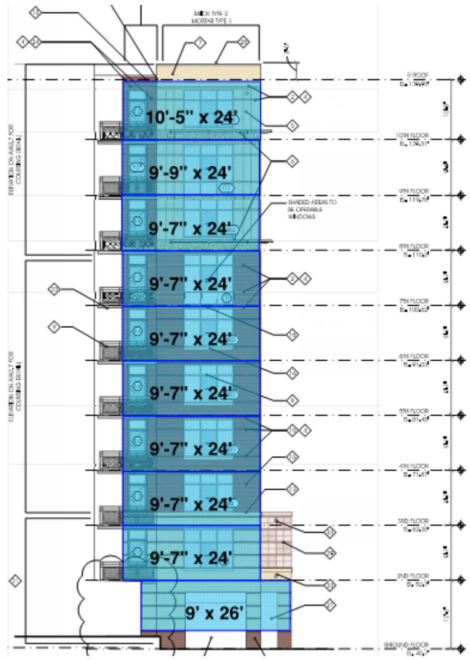


Figure 33: South Elevation @ Garage Panel Breakdown

Table 19: South Elevation @ Garage Panel Count

	Panel Height	Panel Length	Quantity
South Elevation @ Garage	10'-5"	24'	1
	9'-9"	24'	1
	9'-7"	24'	7
	9'	26'	1
		Total	10

WEST ELEVATION

Figure 34: West Elevation Panel Breakdown

Table 20: West Elevation Panel Count

	Panel Height	Panel Length	Quantity
West Elevation	10'-5"	32'	1
		15'	2
	9'-9"	32'	1
		15'	2
	9'-7"	33'	1
		32'	6
		29'	3
		27'	1
		15'	15
	9'	33'	1
		29'	1
		27'	1
		Total	35

NORTHWEST ELEVATION

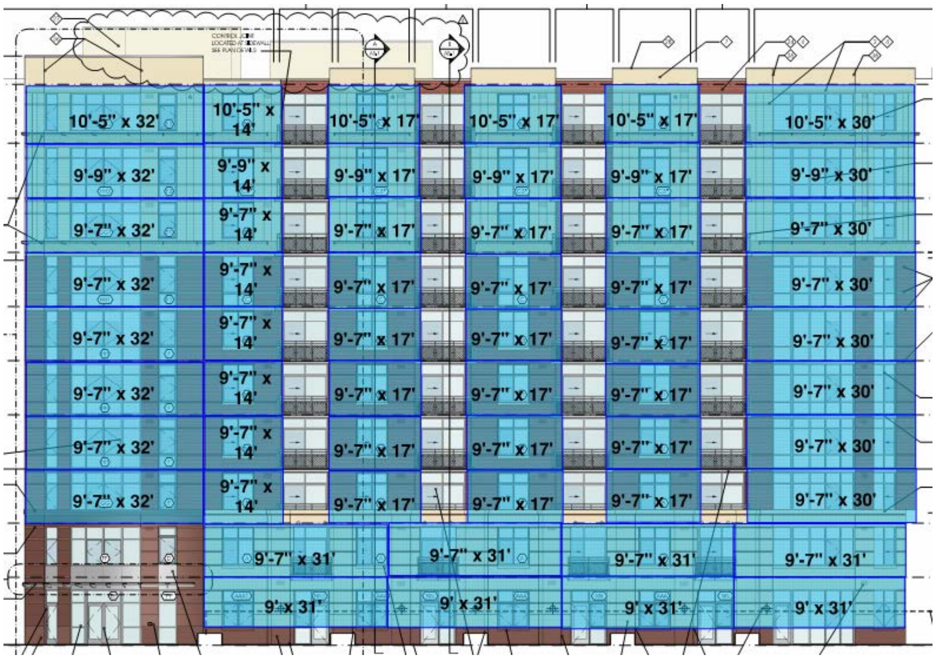


Figure 35: Northwest Elevation Panel Breakdown

Table 21: Northwest Elevation Panel Count

	Panel Height	Panel Length	Quantity
Northwest Elevation	10'-5"	32'	1
		30'	1
		17'	3
		14'	1
	9'-9"	32'	1
		30'	1
		17'	3
		14'	1
	9'-7"	32'	6
		31'	4
		30'	6
		17'	18
		14'	6
	9'	31'	4
		Total	**56**

SCHEDULE IMPACT

According to the baseline schedule, the original brick veneer system was broken up into two main line items, framing/sheathing/Tyvek and brick. Framing/sheathing/Tyvek was scheduled to begin on April 22nd, 2014 and be completed by August 6th 2014 for a total duration of 106 days. Brick construction began on May 6th, 2014 and was scheduled to finish the same time as the framing, sheathing and Tyvek, for a total duration of 77 work days. The two activities were sequenced by floors and follow each other.

Using production rated from Walker's Building Estimator's Reference Book and RS Means the construction duration for an average PBVSS panel can be calculated for both onsite and offsite work. This duration can then be extrapolated for the entire brick veneer. The construction duration is based off on a crew consisting of a welder, two carpenters, three masons, and three laborers. If construction in a linear sequence, a typical PBVSS panel can be constructed in 10.15 hours. This construction duration does assumes that each activity is sequenced in a linear fashion. If certain installation activities are done concurrently the total construction time for one panel can be reduced to 8 hours (Figure 36).

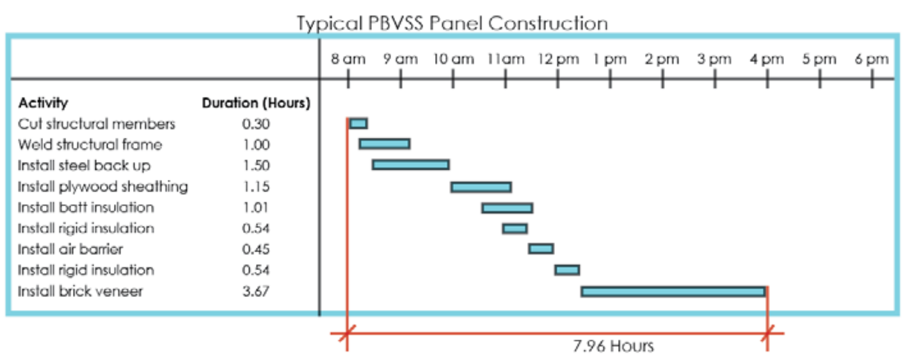


Figure 36: Prefabrication schedule for a typical PBVSS panel

In the offsite shop, two crews can work concurrently on two different panels to produce two panels in an eight hour work day. Since the offsite shop can operate at all hours of the day, two work shifts can be scheduled daily so a total of four panels are constructed a day. By having two shifts the rental period of the warehouse, and various equipment is reduced. It will take 59 work days, or just under three months, to prefabricate the 234 PBVSS panels. Once onsite, it will take 1.2 hours to pick the panel off of the truck, move into place and make the necessary connections. Altogether, it will take 33 days to install the 234 PBVSS panels onsite. The prefabricated panels will be transported as soon as they are completed so that storage space in the warehouse is minimized. Figure 37 shows how the offsite prefabrication and onsite installation activities are overlapped.

Table 22: Construction Duration Calculation for PBVSS System

Construction Duration for a Typical PBVSS Panel				
	Activity	**Quantity**	**Unit**	**Total Duration (Hours)**
Off Site Work	Cut structural members	4	EA	0.30
	Weld structural frame	24	LF	1.00
	Install Steel Backup	150	LF	1.50
	Install Batt Insul	201	SF	1.15
	Install Plywood Sheathing	201	SF	1.01
	Install Rigid Insul	201	SF	0.54
	Install Air Barrier	201	SF	0.45
	Install Rigid Insul	201	SF	0.54
	Install Brick Veneer	201	SF	3.67
	Off Site Duration for One Panel			10.15
	Off Site Duration for One Panel With Sequencing			8
	Total Off Site Duration for all 234 Panels			**59 days**
On Site Work	Hoisting and Installation	201	SF	1.12
	On Site Duration for One Panel			1.12
	Total On Site Duration for all 234 Panels			**33 days**

The total duration for the PBVSS system, including offsite and onsite work, accounting for the overlap of activities, is 63 days (Table 22), which is 14 days more less that the original brick veneer installation duration. However, since the PBVSS system is being prefabricated offsite, this work is not linked to schedule activities that would typically precede the brick veneer installation, making the onsite activity of installing the PBVSS system the only impact of the schedule. Figure 37 depicts the schedule for the proposed PBVSS system compared to the original brick veneer system. Onsite installation starts on the same day the framing, sheathing and Tyvek would have started for the original system. The onsite site activity for the PBVSS system is 33 days which is a 44 day schedule reduction when compared to the original schedule. This 44 day acceleration would make up for the 29 day schedule delay in the superstructure due to bad weather. In fact, the PBVSS system would have put the project schedule 15 days ahead even with the 29 day weather delay.

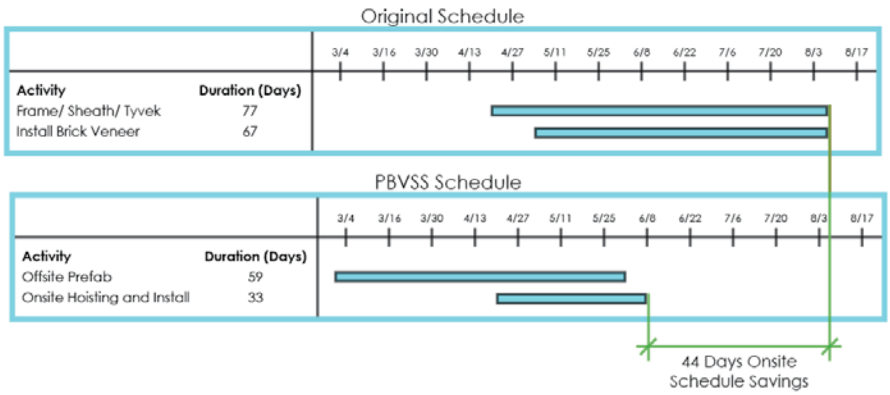


Figure 37: Schedule Comparison

COST IMPACT

In the GMP budget, the masonry scope totals $1,946,150. This includes brick, ACMU, and cast stone. Brick accounts for the majority of façade thus the majority of the cost. The total cost of the original brick veneer system is $1,681,785. This estimate was determined using RSMeans to price a 200 SF section of brick and extrapolating it to the entire brick façade. In addition to the brick veneer assembly cost, the cost of renting swing stages had to be added to the total. The breakdown of the estimate is shown in Table 23.

Table 23: Original Brick Veneer Estimate

Original Brick Veneer Estimate										
	Costcode	Item		Quantity	Unit	Unit Material	Unit Labor	Unit Equipment	Extended Total	
04 21 13	132020	Brick Veneer	3-5/8"	201	SF	4.04	7.5		$	2,319.54
07 21 13	102120	Rigid Insulation	1-1/2"	201	SF	0.48	0.49		$	194.97
07 26 10	100700	Air Barrier		201	SF	0.0292	0.097		$	25.37
09 29 10	302250	Gypsum Sheathing	5/8"	201	SF	0.47	0.74		$	243.21
07 21 16	200080	Batt Insulation	3-5/8"	201	SF	0.32	0.27		$	118.59
09 29 10	302090	GWB	5/8"	201	SF	0.37	0.93		$	261.30
05 41 13	305140	Steel Studs	18 gauge 3-5/8"	150	LF	9.55	9.45		$	2,850.00
05 12 23	400476	Steel Relieving Angle	6x6x3/8	20	LF	5.6	21.5	2.53	$	592.60
04 05 19	161100	Adjustable Galvanized Brick Ties		105	ea	0.405	0.34		$	78.23
05 12 23	650400	Embeds with two stud (1/2" dia)	1/2x8x8	6	ea	12.6632			$	75.98
								Subtotal	**$**	**6,759.78**
								Location Factor (0.93)	$	(473.18)
								Time Factor (1.04)	$	270.39
								Tax (6% on Materials)	$	168.63
								Subtotal	**$**	**6,725.62**
								Extrapolated for Entire Brick Veneer	**$**	**1,573,795.12**
01 54 26	500710	Swing Stage		6	mo	18000			$	108,000.00
								Total Cost of Original Brick Veneer	**$ 1,681,795**	

The proposed PBVSS system is estimated to cost $1,751,927. This include the cost of offsite prefabrication and onsite installation. The average panel size of the 234 panels is 9ft-7in by 21ft. The construction cost for an average panel was calculated using RSMeans data then extrapolated for the entire PBVSS system. Since the prefabrication of the panels would be done offsite, the cost of a facility, equipment, and transportation must be taken into account. A breakdown of the PBVSS estimate is shown in Table 24**.**

Table 24: Estimate for a Typical PBVSS Panel

PBVSS Estimate for a Typical Panel									
	Costcode	Item		Quantity	Unit	Unit Material	Unit Labor	Unit Equipment	Extended Total
04 21 13	132020	Brick Veneer	3-5/8"	201	SF	4.04	6		$ 2,018.04
07 21 13	102100	Rigid Insulation	1"	201	SF	0.24	0.36		$ 120.60
07 26 10	100700	Air Barrier		201	SF	0.0292	0.0776		$ 21.47
07 21 13	102100	Rigid Insulation	1"	201	SF	0.24	0.36		$ 120.60
07 46 29	101000	Plywood Sheathing	1/2"	201	SF	1.38	0.824		$ 443.00
07 21 16	200080	Batt Insulation	3-5/8"	201	SF	0.32	0.216		$ 107.74
09 29 10	302090	GWB	5/8"	201	SF	0.37	0.744		$ 223.91
05 41 13	308800	Steel Studs	18 gauge 3-5/8"	150	LF	9.55	7.56		$ 2,566.50
05 12 23	400476	Steel Relieving Angle	6x6x3/8	20	LF	5.6	17.2	2.53	$ 506.60
04 05 19	161100	Stud Shear Connector Ties		105	ea	0.405	0.272		$ 71.09
05 12 23	650400	Embeds with two stud (1/2" dia)	1/2x8x8	6	ea	12.6632	0		$ 75.98
05 12 23	400660	Steel frame		61.6	LF	1.39	8.48	1.25	$ 684.99
								Subtotal	**$ 6,960.52**
								Location Factor (0.93)	$ (487.24)
								Time Factor (1.04)	$ 298.60
								Tax (6% on Materials)	$ 184.75
								Subtotal	**$ 6,956.63**
								Total Onsite Construction Cost for all 234 Panels	**$ 1,627,850.31**
03 41 16	500050	Hoisting and Installation		234	ea		194.97	80.4	$ 64,436.58
		Warehouse Lease		3	month	12750			$ 38,250.00
		Transportation		78	trip	200			$ 15,600.00
		Forklift Rental		3	month	1,930			$ 5,790.00
								Total Offsite Construction Cost for all 234 Panels	**$ 124,076.58**
								Total Cost of PBVSS System	**$ 1,751,927**

Table 25 shows the cost difference if the new PBVSS system is implemented. The PBVSS system will cost just over $70,000 more or 4%. The cost increase is primarily due to the additional steel and the offsite general conditions. This cost increase is compensated by the significant schedule reduction.

Table 25: Cost difference of proposed system

System	Cost
Original Brick Veneer	$1,681,795
Proposed PBVSS System	$1,751,927
Difference	+ $70,132

BREADTH 1: THERMAL AND HYGROTHERMAL ANALYSIS OF PBVSS SYSTEM

It is vital that the proposed PBVSS system performs as well or better than the original brick veneer system in terms of heat transfer and moisture control. In this analysis, two programs will be used to perform various mechanical analyses on the original and proposed system. Two dimensional heat transfer can be analyzed using THERM 7.3 and a hydrothermal analysis can be completed using WOOFI 5. THERM is a program that uses the finite element method to analyze heat transfer through building assemblies in two dimensions. From this analysis, the R value of each assembly can be calculated as well as temperature patterns. Using WOOFI, the moisture transport through an assembly can be analyzed using real weather data for the location of the building.

HEAT TRANSFER ANALYSIS

According to ASHRAE 90.1, the minimum R-value for a steel framed above grade wall assembly is R16 (Appendix C). R-value of the original brick veneer system and PBVSS system can be determined using THERM. Tables 8 and 9 show the components of each assembly. This analysis, was limited to winter boundary conditions.

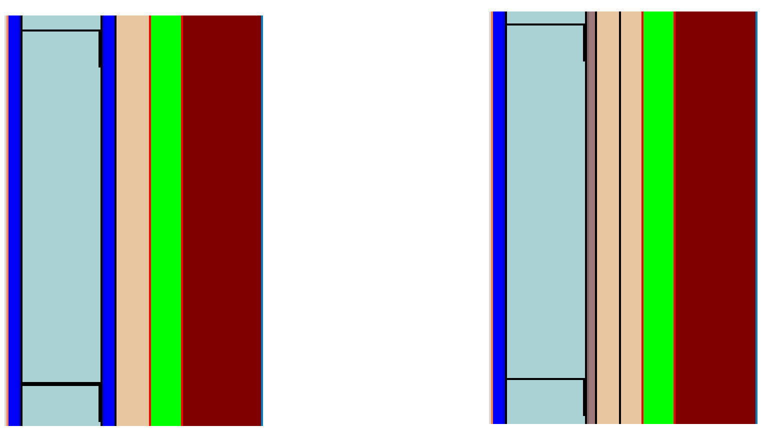


Figure 38: Plan view of Original (left) and PBVSS (right)

The original brick veneer sand PBVSS system were calculated to have an R-value of 20 and 21.1, respectively. Both systems meet the code required R16 (Table 26). The PBVSS system has a higher R-value than the original brick veneer system, consistent with and R-value of 22 determined the building science evaluation in winter conditions (Liang and Memari 2011)

Table 26: Heat Transfer Analysis Results

	Original Brick Veneer	Proposed PBVSS
U-Value	.05	.046
R-Value	20	21.6

Figure 39 shows the thermograph of the original and proposed assembly. Heat transfer is slower through the PBVSS system due to the additional layer of rigid insulation on the exterior side of the metal studs.

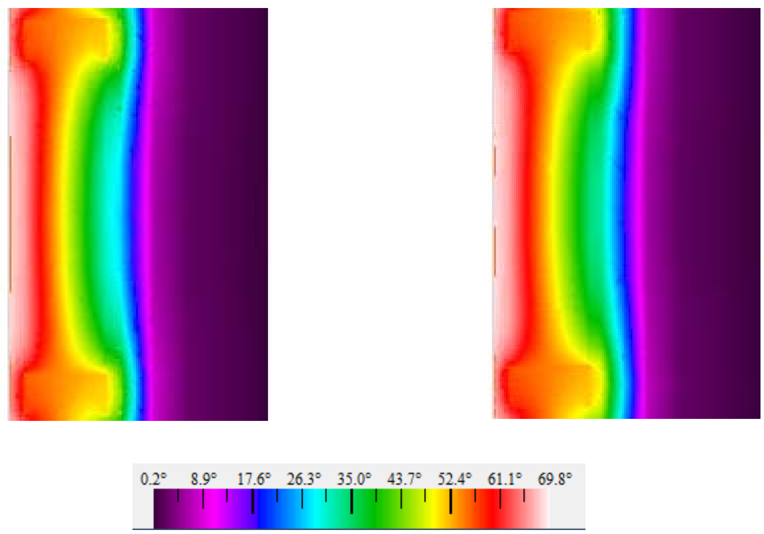


Figure 39: Thermograph of Original (left) and PBVSS (right)

HYGROTHERMAL ANALYSIS

Hygrothermal analysis of the original brick veneer and proposed PBVSS system can be performed using a software called WUFI. Weather data from Oakridge National Laboratory is applied to the assembly and water content and mold growth vulnerability can be calculated. For this analysis, the duration of the calculation was two years, October 2015 to October 2017. This duration represents the first two years of operation of The Apartment Building.

During the two year period of analysis, the original brick veneer system performed better than the PBVSS system in terms of water content. The original brick veneer system reached a maximum and minimum water content of 2.99 lb/ft^2 and 0.05 lb/ft^2 respectively (Table 27). The proposed PBVSS system reached a maximum and minimum water content of 3.1 lb/ft^2 and 0.14 lb/ft^2 respectively

(Table 28). Looking at the water content of the individual materials, it is evident that the increased water content of the PBVSS system is due primarily to the plywood sheathing which reached a maximum water content of 4.05 lb/ft^2. The water content of plywood is 3.64 lb/ft^2 greater than the gypsum sheathing that is used in the original assembly.

Table 27: Water Content Results for Original Brick Veneer

Water Content [lb/ft^2]

	Start	End	Min.	Max.
Total Water Content	0.16	0.13	0.05	2.99

Water Content [lb/ft^3]

Layer/Material	Start	End	Min.	Max.
Brick (old)	0.21	0.20	0.06	9.47
Air Layer 25 mm	0.12	0.16	0.02	0.84
Extruded Polystyrene Insulation	0.02	0.02	0.00	0.04
60 minute Building Paper	0.00	0.00	0.00	0.00
Gypsum Board (USA)	0.39	0.26	0.18	0.41
Fibre Glass	0.12	0.06	0.02	0.12
Gypsum Board (USA)	0.39	0.26	0.10	0.39

Table 28: Water Content Results for Proposed PBVSS System

Water Content [lb/ft^2]

	Start	End	Min.	Max.
Total Water Content	0.3	0.24	0.14	3.1

Water Content [lb/ft^3]

Layer/Material	Start	End	Min.	Max.
Brick (old)	0.21	0.21	0.06	9.47
Air Layer 25 mm	0.12	0.17	0.02	0.84
Extruded Polystyrene Insulation	0.02	0.02	0.00	0.07
60 minute Building Paper	0.00	0.00	0.00	0.00
Extruded Polystyrene Insulation	0.02	0.02	0.01	0.02
Plywood (USA)	4.02	2.87	2.45	4.05
Fibre Glass	0.12	0.06	0.02	0.12
Gypsum Board (USA)	0.39	0.26	0.11	0.39

The mold growth vulnerability of the two systems can be analyzed in WUFI. By plotting the relative humidity against temperature a distribution curve is created. If the isopleth for the interior surface of each system remains below the curve, the assembly is not at risk for mold growth. However, if it exceeds the curve, there is a chance of mold growth. Both the original brick veneer assembly and proposed PBVSS system remain below the curve so they are not at risk for mold growth on the interior surface (Figure 40 and 41). The complete WUFI report can be found in Appendix D.

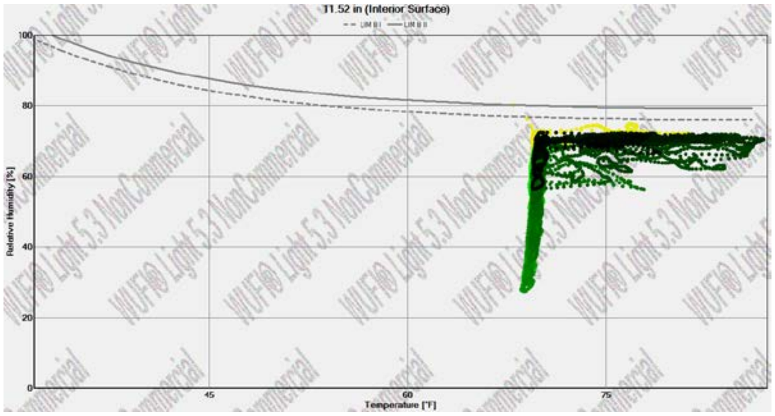


Figure 40: Mold Growth Vulnerability of the Original Brick Veneer Assembly

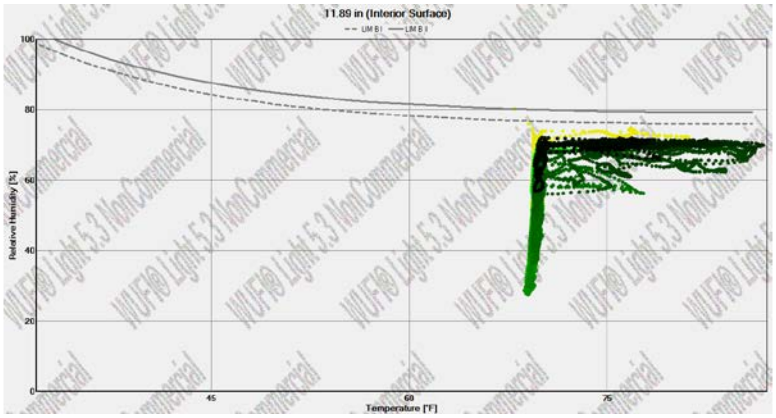


Figure 41: Mold Growth Vulnerability of the Proposed PBVSS Assembly

RECOMMENDATION

Based on a heat transfer analysis, the proposed PBVSS system performs better than the original brick veneer assembly and the R-value increased by 1.6. However, the proposed system performed slightly worse in a hygrothermal analysis, primarily due to the use of plywood sheathing instead of gypsum sheathing. Overall, both assemblies are not at risk for mold growth. Moving forward, gypsum sheathing should be used instead of plywood in the PBVSS system to ensure that it performs as well if not better than the original brick veneer system.

BREADTH 2: STRUCTURAL ANALYSIS OF PBVSS SYSTEM

A structural analysis is essential to ensure the additional weight from the proposed PBVSS system can be supported by the post-tensioned concrete structure. This structural analysis will consist of the following steps:

1. Original brick veneer assembly
   - Use Moment Coefficients to approximate various moments through the beam
   - Use Allowable Stress Analysis to check that the post-tensioned concrete can support the loads
2. Proposed PBVSS system
   - Use Moment Coefficients to approximate various moments through the beam
   - Use Allowable Stress Analysis to check that the post-tensioned concrete can support the loads
3. If the post-tensioned structure cannot support the PBVSS system, redesign the structure

A typical slab edge was used for this analysis, highlighted in Figure 42. For this analysis, since the columns line up with the slab edge, the slab edge will be simplified to a fixed-fixed beam. Figure 43 shows a simplified sketch along the post-tensioning that runs through the slab edge. The post-tensioning is 297K banded and is comprised of 8 sets of ½" diameter tendons.

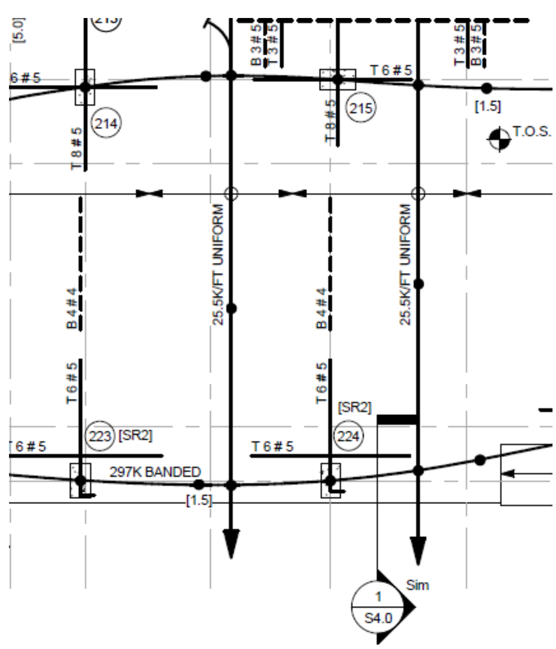


Figure 42: Fourth floor plan view

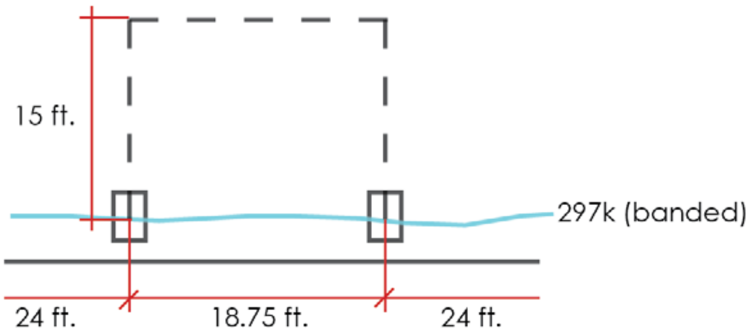


Figure 43: Simplified typical slab edge

ORGINAL BRICK VENEER ASSEMBLY

In order to determine if the structure can support the additional loads imposed by the PBVSS system, the originally design brick veneer system needs to be validated as a baseline.

DESIGN LOADS

The accepted weight for a conventional brick veneer on steel stud back up is 50 psf. Using this load, in conjunction with the original design loads (Appendix E), the loading for this analysis is show in Table 29.

Table 29: Original design loads

Original Design Loads			
		psf	plf
Live Loads	Private Rooms	40	600
		Total	**600**
Dead loads	SW of Conc		1312.5
	Brick Veneer	50	500
	Misc MEP	5	75
		Total	**1887.5**

ACI MOMENT COEFFICIENT

By treating the slab edge between the two columns as a fixed-fixed continuous beam, the moments can be calculated using ACI Moment Coefficients. The slab edge can be simplified to a continuous concrete beam with three spans (Figure 44). The beam of interest is the interior span (Figure 45).

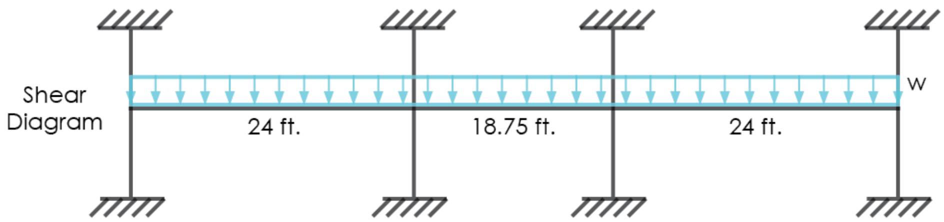


Figure 44: FBD for Moment Coefficients

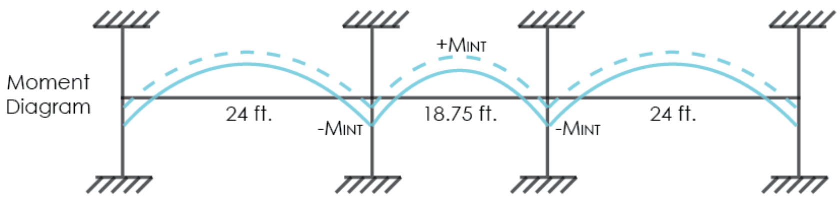


Figure 45: Maximum moment locations for interior span

The maximum positive and negative moments of the interior span can be approximated by the following equations. The maximum positive and negative moments must be determined for two different loading scenarios, which is required to analyze transfer and service calculations with the Allowable Stress Analysis. The two loading scenarios are i) self-weight of concrete only ii) all loads. The results of the moment approximation are shown in Table 30.

$$-M_{int} = \frac{wl_{avg}^2}{11}$$

$$+M_{int} = \frac{wl^2}{14}$$

Table 30: Resulting Moments for Original Brick Veneer

Moment Coefficients		
Selfweight		
w_{sw}	1.3125	klf
-Mint	68.73	ft.k
+Mint	32.96	ft.k
Total		
w_{total}	2.49	klf
-Mint	130.25	ft.k
+Mint	62.47	ft.k

ALLOWABLE STRESS ANALYSIS OF POST-TENSIONED BEAMS

In order to analyze the post-tension concrete beams capacity, the Allowable Stress Analysis method was used to check the original loading as well as the new loading with the PBVSS system. According to the structural drawings, tendons at the slab edge are to be placed at the centroid of the section, meaning no eccentricity (Figure 46).

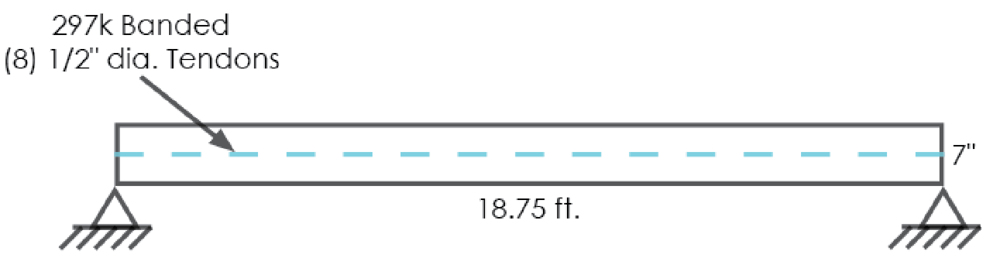


Figure 46: Sketch for Allowable Stress Analysis

Table 31 includes the necessary information to perform an Allowable Stress Analysis. This information was obtained from the post-tension notes in the structural drawings (Appendix F).

Table 31: Variables for Allowable Stress Analysis

Allowable Stress Analysis		
Given		
f'c	3000	psi
f'ci	5000	psi
w_{total}	2.49	klf
SW	1.3125	klf
LL	0.6	klf
f_{pu}	270	ksi
f_{py}	243	ksi
transfer loss	35	ksi
(8) 1/2" dia. Tendons		
Eccentricity	0	in
f_{pi}	**199.26**	ksi
	199.8	ksi
f_{pe}	164.26	ksi
P_e	201.05	kips
P_i	243.89	kips

The capacity of the post-tension beam has to be considered at transfer and at service. In addition the end of the beam as well as mid-point must be checked during transfer and service. The equations to find the stress at the top (f_t) and bottom (f_b) of the beam as well as the maximum allowed compression (σ_{ci}) and tension stresses (σ_t) are listed below.

At Transfer at End of Beam

$$f_t = +\frac{Msw}{S} - \frac{P_i}{A} + \frac{P_i e}{S}$$

$$f_b = \frac{Msw}{S} - \frac{P_i}{A} - \frac{P_i e}{S}$$

$$\sigma_{ci} = 0.6 f'_{ci}$$

$$\sigma_t = 6\sqrt{f'_{ci}}$$

At Service at End of Beam

$$f_t = -\frac{Mtotal}{S} - \frac{P_e}{A} + \frac{P_e e}{S}$$

$$f_b = \frac{Mtotal}{S} - \frac{P_e}{A} - \frac{P_e e}{S}$$

$$\sigma_{ci} = 0.45 f'_c$$

$$\sigma_t = 7.5\sqrt{f'_c}$$

At Transfer at Mid-span of Beam

$$f_t = -\frac{Msw}{S} - \frac{P_i}{A} + \frac{P_i e}{S}$$

$$f_b = \frac{Msw}{S} - \frac{P_i}{A} - \frac{P_i e}{S}$$

$$\sigma_{ci} = 0.6 f'_c$$

$$\sigma_t = 6\sqrt{f'_c}$$

At Service at Mid-span of Beam

$$f_t = -\frac{Mtotal}{S} - \frac{P_e}{A} + \frac{P_e e}{S}$$

$$f_b = \frac{Mtotal}{S} - \frac{P_i}{A} - \frac{P_i e}{S}$$

$$\sigma_{ci} = 0.45 f'_c$$

$$\sigma_t = 7.5\sqrt{f'_c}$$

Table 32: Allowable Stress Analysis Results for Original Brick Veneer Assembly

At Transfer At End				At Service At End			
f_t	-0.15	ksi	compression	f_t	-0.12	ksi	compression
f_b	-0.23	ksi	compression	f_b	-0.21	ksi	compression
σ_t	0.33	ksi		σ_t	0.53	ksi	
σ_{ci}	3.00	ksi		σ_{ci}	2.25	ksi	
$\sigma_{ci} > f_t, f_b$			PASS	$\sigma_{ci} > f_t, f_b$			PASS
At Transfer At Midspan				**At Service At Midspan**			
f_t	-0.17	ksi	compression	f_t	-0.18	ksi	compression
f_b	-0.16	ksi	compression	f_b	-0.19	ksi	compression
σ_t	0.09	ksi		σ_t	0.53	ksi	
σ_{ci}	1.80	ksi		σ_{ci}	2.25	ksi	
$\sigma_{ci} > f_t, f_b$			PASS	$\sigma_{ci} > f_t, f_b$			PASS

The results of the Allowable Stress Analysis show that the beam is in compression at the ends and mid-span both at transfer and service (Table 32). The compression stress are all less than the maximum allowable compression stress. Therefore the post-tensioned structure sufficiently supports the design loads which include the original brick veneer assembly.

PROPOSED PBVSS SYSTEM

Now that it was proven that the original brick veneer assembly can be supported, the proposed PBVSS system can be analyzed using the same procedure

DESIGN LOADS

The weight of the PBVSS is roughly 55psf Table 11. The following table shows the design loads including the PBVSS system. Using the PBVSS system instead of the original brick veneer, the design loads are as show in Table 33.

Table 33: New design loads

New Design Loads			
		psf	plf
Live Loads	Private Rooms	40	600
		Total	**600**
Dead loads	SW of Conc		1312.5
	PBVSS Panels	55	550
	Misc MEP	5	75
		Total	**1937.5**

ACI MOMENT COEFFICIENTS

The maximum positive and negative moments in the span under the new design loads can be calculated using ACI Moment Coefficients (Table 34).

Table 34: Moment Coefficients for PBVSS System

Moment Coefficients		
Selfweight		
w_{sw}	1.3125	klf
-Mint	68.73	ft.k
+Mint	32.96	ft.k
Total		
w_{total}	2.54	klf
-Mint	132.87	ft.k
+Mint	63.72	ft.k

ALLOWABLE STRESS ANALYSIS OF POST-TENSIONED BEAMS

The variables needed to conduct an allowable stress analysis with the additional loading from the PBVSS system are shown in Table 35.

Table 35: Variables for Allowable Stress Analysis

Allowable Stress Analysis		
Given		
f'c	3000	psi
f'ci	5000	psi
w_{total}	2.54	klf
SW	1.3125	klf
LL	0.6	klf
f_{pu}	270	ksi
f_{py}	243	ksi
transfer loss	35	ksi
(8) 1/2" dia. Tendons		
Eccentricity	0	in
f_{pi}	**199.26**	ksi
	199.8	ksi
f_{pe}	164.26	ksi
P_e	201.05	kips
P_i	243.89	kips

Table 36: Allowable Stress Analysis Results for PBVSS system

At Transfer At End				At Service At End			
f_t	-0.15	ksi	compression	f_t	-0.12	ksi	compression
f_b	-0.24	ksi	compression	f_b	-0.21	ksi	compression
σ_t	0.33	ksi		σ_t	0.53	ksi	
σ_{ci}	3.00	ksi		σ_{ci}	2.25	ksi	
$\sigma_{ci} > f_t, f_b$			**PASS**	$\sigma_{ci} > f_t, f_b$			**PASS**
At Transfer At Midspan				**At Service At Midspan**			
f_t	-0.17	ksi	compression	f_t	-0.18	ksi	compression
f_b	-0.16	ksi	compression	f_b	-0.19	ksi	compression
σ_t	0.09	ksi		σ_t	0.53	ksi	
σ_{ci}	1.80	ksi		σ_{ci}	2.25	ksi	
$\sigma_{ci} > f_t, f_b$			**PASS**	$\sigma_{ci} > f_t, f_b$			**PASS**

The results of the Allowable Stress Analysis, including the PBVSS system, are shown in Table 36. Consistent with the original loading scenario with the brick veneer, the slab edge is in compression at ends and mid-span during transfer and service. The compression stresses are all less than the maximum allowable compression stress. Therefore the post-tensioned structure sufficiently supports the design loads which include the original brick veneer assembly. The stresses are in fact the same as the original scenario, meaning the additional weight from the PBVSS system has a minimal impact and can be easily supported by the existing post-tension structure.

RECOMMENDATION

Through a thorough analysis of implementing the PBVSS system, it is recommended that the PBVSS system be implemented on The Apartment Building. The PBVSS system allows for a 44 day reduction of the onsite schedule, which is the ultimate driving force. This system will cost $70,132 more than the original brick veneer assembly but can be justified by not only the schedule reduction, but the quality and safety benefits of offsite prefabrication. Additionally, with slight medication, the thermal and hygrothermal properties of the PBVSS system can surpass the original. A structural analysis showed that the additional loads from the PBVSS system can easily be accommodated by the existing post-tensioned concrete structure.

ANALYSIS 3: SIPS IMPLEMENTATION FOR INTERIOR FIT-OUT

RESEARCH PROBLEM

Schedule is a key driving factor on any project and can ultimately define success. Failure to meet the schedule can be costly in the form of liquidated damages that can eliminate the small profit margin of the contractor. Many forms of scheduling have been developed such as CPM, matrix, linear, and short interval production scheduling (SIPS). Effectively using a schedule requires more than developing the schedule, a process of implementing is required.

PROBLEM STATEMENT

The Apartment Building is being turned over in phases in order to generate revenue before the entire building is complete. With phased turnover comes many caveats; quality and phasing are two critical components. If proper quality control measures are not taken, the extended punchlist and project closeout can result in late turnover which ultimately will impact the owner's financial model and the liquidated damages can impose a financial threat to the contractor as well. During a phased turnover project, construction and occupancy are occurring concurrently such that many factors can impact the experience of the occupant and ultimately their health and safety. It is vital that each floor is turned over on time and at the proper level of quality.

Due to the repetitive nature of apartment units in The Apartment Building, the need for stringent quality control, and the tight schedule constrained by the phased turnover a possible solution is to implement SIPS for interior fit out. In this analysis, a SIPS guide that includes a step-by-step instruction on how to develop and best practice to implement the SIPS for interior fit out with be created.

INTRODUCTION TO SIPS

The main idea behind a successful schedule is the lean concept of flow. As defined in, "Lean Thinking," flow is the process of making value without interruption by eliminating wasteful activities and creating sequential arrangements. In this case, value would be defined as timely turnover of each floor and high quality of work so rework is not necessary. The main principles of flow include lining up the essential steps to get the job done without any waste, interruptions, and batching and queuing. This basic lean concept can be applied to any process.

SIPS is a method of scheduling that elevates the concept of flow by focusing on the interconnections between trades and the movement of trades through the building. SIPS is essentially a detailed production plan and schedule that promotes subcontractor involvement and supplements the CPM schedule.

Traditionally, SIPS has been used for single trades and included very small schedule intervals, down 15 minutes. Hensel Phelps pioneered the concept of SIPS to construction the structure of the Tabor Center in Denver, a $340 million and1.3 million square foot convention center. The SIPS process allowed each floor to be constructed on average in 4 days, which is a day quicker than the original plan. The key to success was close cooperation between the architect, engineer and contractor as well as continuous feedback and follow-up from the subcontractors to ensure the resources and tools were used in the most efficient manner.

SIPS has evolved from a tool for single to multiple trades. The most well-known example of SIPS for multiple trades is the Pentagon Renovation. The Pentagon was built in 1941 and had not been renovated for over half a century. The damage from the 9/11 attacks required wedges 2-5 to be renovated in an extremely accelerated manner. The original plans for renovation was to be completed over a course of 14 years. Through the implementation of SIPS for interior work, the overall duration of the renovation was done in four years, a whole decade earlier.

There are many benefits to using SIPS such as:

- Eliminate the need to stack trades
- Minimize the learning curve
- Increase production due to repetition
- Increase quality control
- Easy to track and communicate
- Improve housekeeping

A key aspect of SIPS is that it is an iterative process that requires continuous communication and feedback between all trades. A SIPS is only successful if it is used effectively and full team buy in exists.

SIPS PROCESS MAP

Burkhart (1989), a member of the Hensel Phelps team that first implemented SIPS, set up a procedure for developing a SIPS schedule. This analysis will building off this procedure and incorporate some lessons learned from previous case studies to create a more complete SIPS process for interior fit out. The SIPS process can be broken into two main parts, schedule development and implementation. Figure 47 depicts an overview of the key steps required for successfully using SIPS. The process map is generalized so that it can be used on various scopes of work other than interior fit out. To demonstrate the process in detail, a SIPS schedule will be developed for interior fit out of The Apartment Building as a working example.

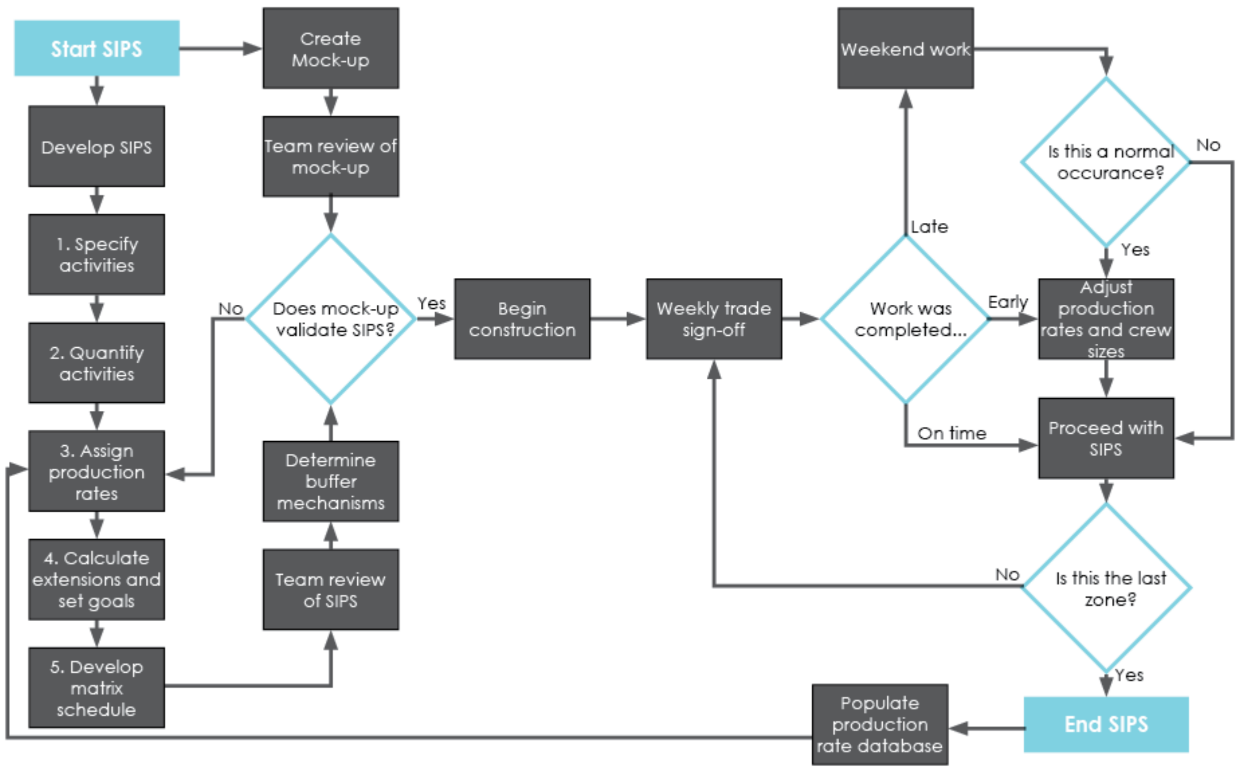


Figure 47: General SIPS Process Map

PART 1: SCHEDULE DEVELOPMENT

Figure 48 includes the schedule development portion of the SIPS process.

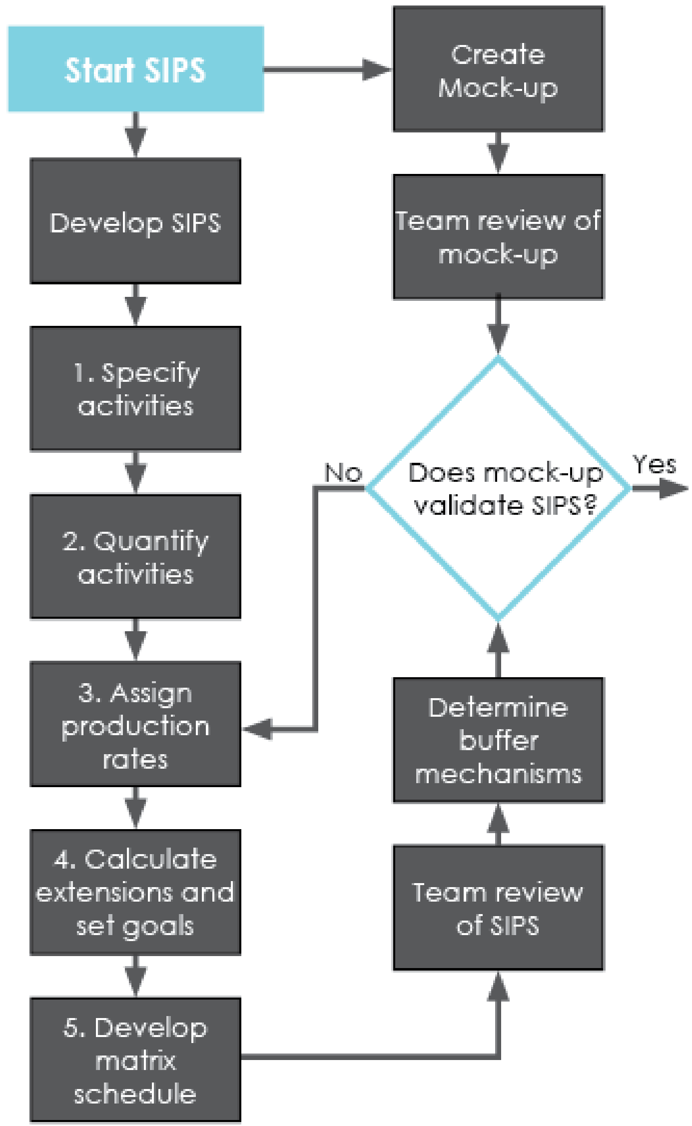


Figure 48: Schedule Development Process Map

DEVELOP THE SIPS

The steps to develop the SIPS schedule are based on the guidelines set by Burkhart (1989)

1. Specify Activities

The first step of developing the schedule is to determine the scope of work and the specific activities that make up the scope. The scope of SIPS for The Apartment Building is interior fit out for the apartment units. The activities for interior fit out are shown in Figure 49. The activities are determined by the construction sequence and subcontractor responsibilities. The breakdown of activities can be as detailed as needed. Since this is a non-traditional SIPS, where multiple trades are included, the level of detail is lower than if a single trade was the focus. For example, if drywall was the primary scope, the activities would be more detailed and include, handling, hanging, mudding, taping, and finishing all as separate activities.

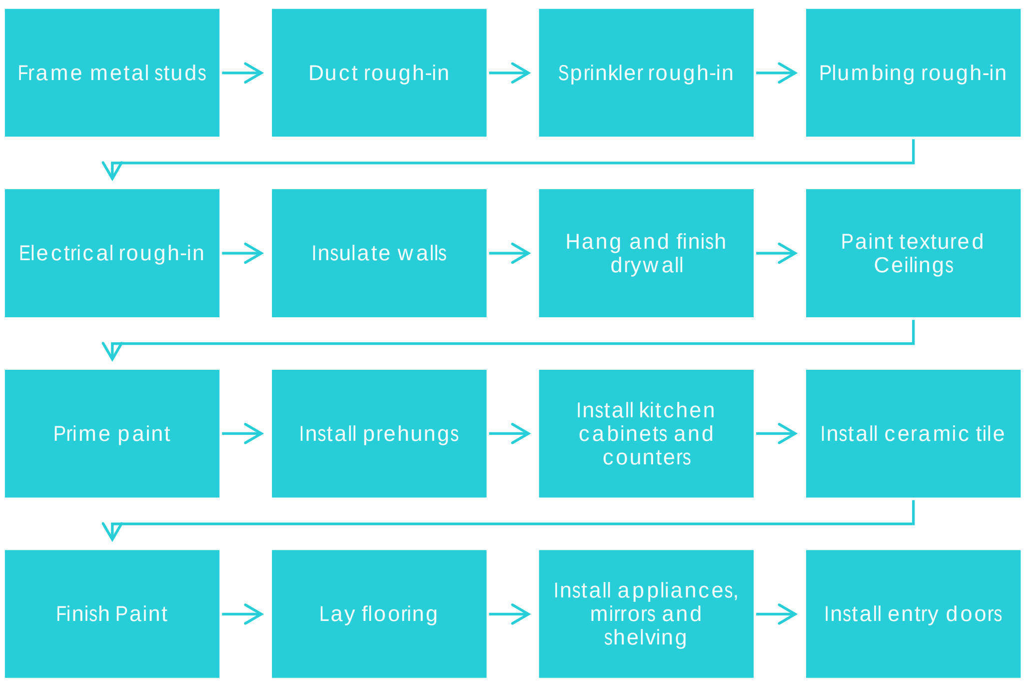


Figure 49: Activity breakdown for interior fit out

The building shape will dictate the overall sequencing. The building footprint of The Apartment Building shrinks as you move up the building due to the southwest end of the building stepping back. At the ground level, The Apartment Building is 16800 square feet and decreased down to 13500 square feet at the tenth floor. This decrease in footprint translates in to the number of apartment units that are on each floor (Table 37). The number of units per floor range from seven to twenty and this will affect the amount of interior fit out needed for each floor. Since SIPS is most successful with high levels of repetition, the ground floor will be omitted. Therefore, SIPS will be used on 157 of the 165 units.

Table 37: Number of units and square footage per floor

Floor	Square Footage	# of Units
Ground	16800	7
2	16800	18
3-4	16800	20
5	15000	16
6-7	15000	18
8-10	13500	16

The next step is to breakdown the building into smaller zones that each crew will sequentially move through. For The Apartment Building, each apartment unit will be considered a zone. Therefore the number of construction zones will vary from floor to floor; this will be addressed later. The sequence through the zones will start at the southwest end and move in a clockwise fashion through the floor (Figure 50). The vertical sequence must now be determined. The Apartment Building is currently being turned over in phases, starting on the lower levels then working vertically. Another alternative is to work from the top down. This way debris and crews will have to track through finished floors. Since it has already been decided by the owner to turnover from the lower levels up, the sequence will be from down up (Figure 51).

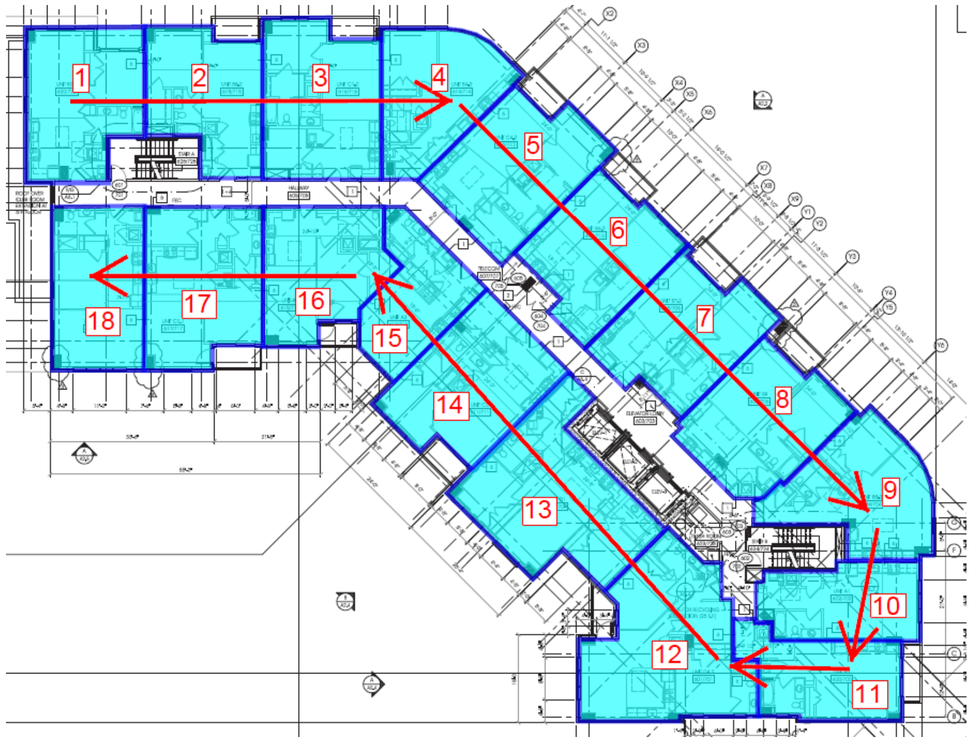


Figure 50: 6th and 7th floor zone breakdown and sequencing

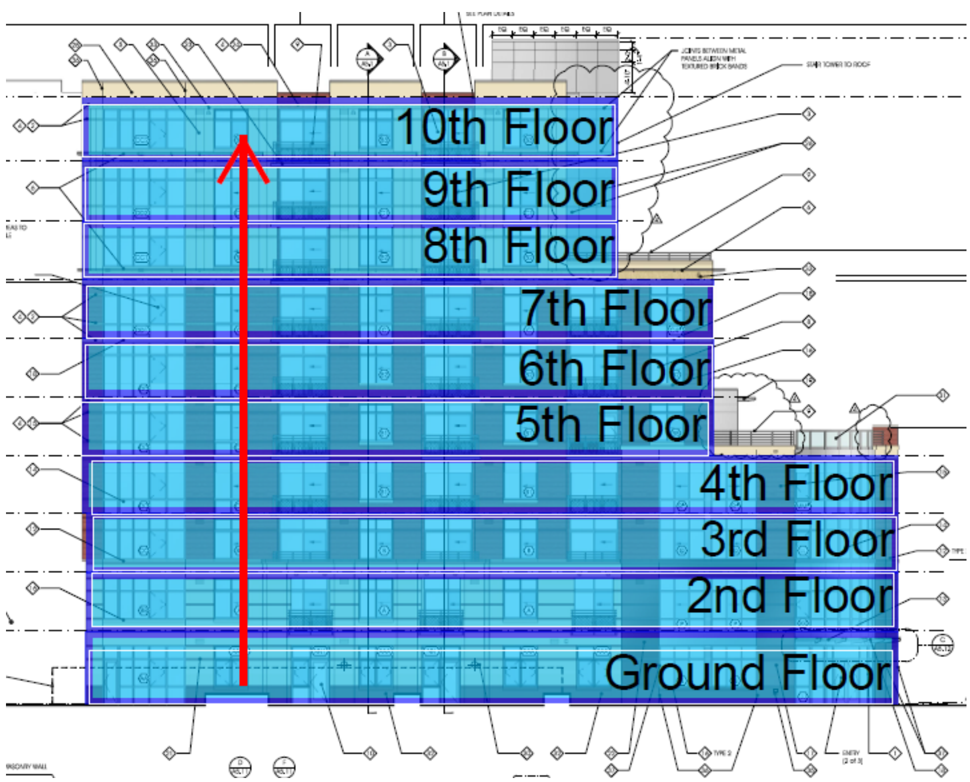


Figure 51: Vertical sequencing (west elevation)

The overall duration that the SIPS must meet has to be determined. According to the CPM schedule, each floor will be turned over per week. Fit out of each floor is to take 16 weeks from framing to final painting

2. Quantify activities

The next step to developing a SIPS schedule is to assign quantities to the activities that were determined in the previous step. According to Burkhart (1989) this is one of the most crucial steps but is often overlooked. Adding quantities to each activity can bring to light the amount of work that is actually required. Brainstorming between all subcontractors can help produce some innovative solutions to improve cost, production, and schedule for each activity.

The Apartment Building has 35 different layouts ranging from studios to two bedrooms. The average square footage of a unit is 741. Quantities were taken off for a one bedroom layout (B9) to represent a typical layout (Table 38). These quantities will then be extrapolated to represent all unit types.

Table 38: Quantities for unit activities (one bedroom B9)

Typical Unit Quantities (one bedroom B9)				
ID		Activity	Quantity	Unit
	A1	Frame metal studs	169	LF
	A2	Duct rough-in	741	SF
	A3	Sprinkler rough-in	741	SF
	A4	Plumbing rough-in	741	SF
	A5	Electrical rough-in	741	SF
	A6	Insulate walls	169	LF
	A7	Hang and finish drywall	2043	SF
	A8	Paint textured Ceilings	741	SF
	A9	Prime paint	2043	SF
	A10	Install prehungs	5	ea
	A11	Install kitchen cabinets and counters	90	SF face
	A12	Install ceramic tile	40	SF
	A13	Finish Paint	2043	SF
	A14	Lay flooring	700	SF
	A15	Install appliances, mirrors and shelving	6	ea
	A16	Install entry doors	1	ea

3. Assign production rates

Once quantities for each activity have been determined, the next step is to determine the required production rate in order to meet the schedule. Production rate is defined as quantity over time. SIPS scheduling utilizes equal time intervals so it is beneficial to have each activity take the same amount of time.

The Apartment Building is currently scheduled to take 16 weeks to fit out a floor from start to finish. There are 16 activities (A1-A16) that leaves one week per activity or five working days. In order to get the quantities for each floor, the quantities taken off in the previous step were multiplied by the number of units on the floor. Using the budget duration of 5 days and the extended quantities, the budget production can be calculated. Table 39 shows a sample calculation for the second floor which consists of 18 apartment units. This process will be repeated for each floor.

Table 39: 2nd Floor SIPS Required Production

2nd Floor SIPS Calculation (18 units)							
ID		Activity	Quantity	Unit	Budget Duration	Units	Budget Production
	A1	Frame metal studs	3042	LF	5	Days	608
	A2	Duct rough-in	13338	SF	5	Days	2668
	A3	Sprinkler rough-in	13338	SF	5	Days	2668
	A4	Plumbing rough-in	13338	SF	5	Days	2668
	A5	Electrical rough-in	13338	SF	5	Days	2668
	A6	Insulate walls	3042	LF	5	Days	608
	A7	Hang and finish drywall	36774	SF	5	Days	7355
	A8	Paint textured Ceilings	13338	SF	5	Days	2668
	A9	Prime paint	36774	SF	5	Days	7355
	A10	Install prehungs	90	ea	5	Days	18
	A11	Install kitchen cabinets and counters	1620	SF face	5	Days	324
	A12	Install ceramic tile	720	SF	5	Days	144
	A13	Finish Paint	36774	SF	5	Days	7355
	A14	Lay flooring	12600	SF	5	Days	2520
	A15	Install appliances and shelving	108	ea	5	Days	22
	A16	Install entry doors	18	ea	5	Days	4

4. Calculate extensions and set goals

After the budget production is calculated for each activity, the crew size can be calculated by assigning known production rates to each activity. Assigning production rates can be difficult to do. The best method is to consult the subcontractors. Other methods include using historical production rates from R.S. Means or Walkers Building Estimators' Reference. If a production rate can't be gathered from any of these sources, an educated guess should be made as a placeholder. These production rates do not have to be perfect the first time around. In addition, subcontractors can determine pricing to ensure that the budget it met. The SIPS process is iterative and production rates will be adjusted as the project moves on.

By knowing the budget production, and the actual work production, crew sizes can be determined for each activity. Table 40 includes a crew size calculation for the fit out of the 2nd floor. Hanging and finishing drywall require the largest crew to complete the work while insulating the walls and installing the entry doors require a single worker. This process will be repeated for each floor.

Table 40: Crew size calculation

2nd Floor SIPS Calculation (18 units)											
ID		Activity	Quantity	Unit	Budget Duration	Units	Budget Production	Worker Production	Units	Required Crew Size
	A1	Frame metal studs	3042	LF	5	Days	608	75	LF/Day	9
	A2	Duct rough-in	13338	SF	5	Days	2668	400	SF floor area/Day	7
	A3	Sprinkler rough-in	13338	SF	5	Days	2668	470	SF floor area/Day	6
	A4	Plumbing rough-in	13338	SF	5	Days	2668	320	SF floor area/ Day	9
	A5	Electrical rough-in	13338	SF	5	Days	2668	300	SF floor area/ Day	9
	A6	Insulate walls	3042	LF	5	Days	608	2000	SF/Day	1
	A7	Hang and finish drywall	36774	SF	5	Days	7355	750	SF/Day	10
	A8	Paint textured Ceilings	13338	SF	5	Days	2668	1000	SF/Day	3
	A9	Prime paint	36774	SF	5	Days	7355	1800	SF/Day	5
	A10	Install prehungs	90	ea	5	Days	18	16	Units/Day	2
	A11	Install kitchen cabinets and counters	1620	SF face	5	Days	324	80	SF cabinet face/ Day	5
	A12	Install ceramic tile	720	SF	5	Days	144	62.5	SF/Day	3
	A13	Finish Paint	36774	SF	5	Days	7355	1800	SF/Day	5
	A14	Lay flooring	12600	SF	5	Days	2520	600	SF/Day	5
	A15	Install appliances and shelving	108	ea	5	Days	22	8	Units/Day	3
	A16	Install entry doors	18	ea	5	Days	4	16	Units/Day	1

5. Develop matrix schedule

Once the duration and crew size for each activity is determined for each floor, a matrix schedule can be developed to visualize the flow of crews through the building. A matrix schedule is a time-scaled, resource loaded bar chart.

A matrix schedule was developed for The Apartment Building (Table 41). Each color represents an activity and a crew to perform that activity. The elimination of stacking of trades is clearly shown. The resources needed (crew size) is identified within each cell. Note how the crew size for each activity fluctuates as each crew moves between floors. In the bottom row the total labor needed each week is shown. The labor peaks on week 8 at 58 workers.

Table 41: Matrix schedule for interior fit-out

SIPS Schedule for Interior Fit-Out (2nd - 10th floor)																								
Floor	Week																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
2	9	7	6	9	9	1	10	3	5	2	5	3	5	5	3	1								
3		10	8	7	10	10	1	11	3	5	2	5	3	5	5	3	1							
4			10	8	7	10	10	1	11	3	5	2	5	3	5	5	3	1						
5				8	6	6	8	8	1	9	3	4	1	4	3	4	4	3	1					
6					9	7	6	9	9	1	10	3	5	2	5	3	5	5	3	1				
7						9	7	6	9	9	1	10	3	5	2	5	3	5	5	3	1			
8							8	6	6	8	8	1	9	3	4	1	4	3	4	4	3	1		
9								8	6	6	8	8	1	9	3	4	1	4	3	4	4	3	1	
10									8	6	6	8	8	1	9	3	4	1	4	3	4	4	3	1
Total labor	9	17	24	32	41	43	50	52	58	49	48	44	40	37	39	29	25	22	20	15	12	8	4	1

SIPS Legend	
	Frame metal studs
	Duct rough-in
	Sprinkler rough-in
	Plumbing rough-in
	Electrical rough-in
	Insulate walls
	Hang and finish drywall
	Paint textured Ceilings
	Prime paint
	Install prehungs
	Install kitchen cabinets and counters
	Install ceramic tile
	Finish Paint
	Lay flooring
	Install appliances, mirrors and shelving
	Install entry doors

TEAM REVIEW OF SIPS

The entire team, including all affected trades should meet and review the SIPS after the first pass of the SIPS has been developed. Sequencing, production rates, and crew sizes should be reviewed. In addition, the exchanges and interconnection between trades should be studied in detail. This is a primary step towards achieving team buy in and elevating communication. Team buy in is crucial to the success of the SIPS and can be hard to achieve. Subcontractors may be traditional and skeptical of accepting new means and methods. It should be communicated early on that the same benefit for the general contractor exist for the subcontractor.

Since all activities in the schedule are dependent on the predecessor activity, any problems that are encountered early may impact all future activities. Buffers are used to accommodate any variability in the schedule. Homan et al. (2003) described four types of buffers:

1. Resource variation
2. Progress management
3. SIPS time buffers
4. Trade time buffers

Resource variation is the ability of each trade to be able to ramp up and ramp down their resources at direction of the general contractor. Progress management is any method of keeping track of progress. For example, weekly subcontractor sign offs to validate completion of work. SIPS time buffer is allowing time in the schedule to make up work. Typically this is in the form of weekend work. Trade time buffers are including a small time buffer at the trade level.

Since turnover of each floor is critical to the success of The Apartment Building, all four buffer mechanisms should be used. Trades should be able to ramp up or ramp down resources as needed. Weekly sign offs should be used when each floor is completed. A SIPS buffer in the form of weekend work should be used, but sparingly. If trades fail to sign off for completion by end of the day on Friday, weekend work can be used to make up this time. At the trade level, trades should plan to complete work slightly ahead of schedule to ensure their work gets completed on time.

CREATING THE MOCK-UP

A mock- up of the planned work should be created and reviewed. The aesthetics, design, budget quality and production rates should all be included in the review. This is the first chance at catching any major issues that can be costly to address during construction.

Since the ground floor of The Apartment Building is not included in the SIPS, the units on this floor can be used for a mock up, or a trial run. This is a chance for the architect, owner, and contractor to review final quality and aesthetics of finishes and construction.

VALIDATION OF SIPS PRODUCTION WITH MOCK UP

In the process of constructing the mock up can be used to validate the production rates that were estimated to build the SIPS. If the production rates match the real time production rate of building the mock up, construction is ready to begin. If the real time production rates do not match the estimated rates, the production rates must be updated in the SIPS. Once the production rates have been finalized, construction is ready to commence.

PART 2: IMPLEMENTATION

The second part of the SIPS process is implementing the SIPS that was developed in part one. SIPS is an iterative process so feedback, communication and flexibility are the key to success. The general process for implementing the SIPS is described in Figure 52.

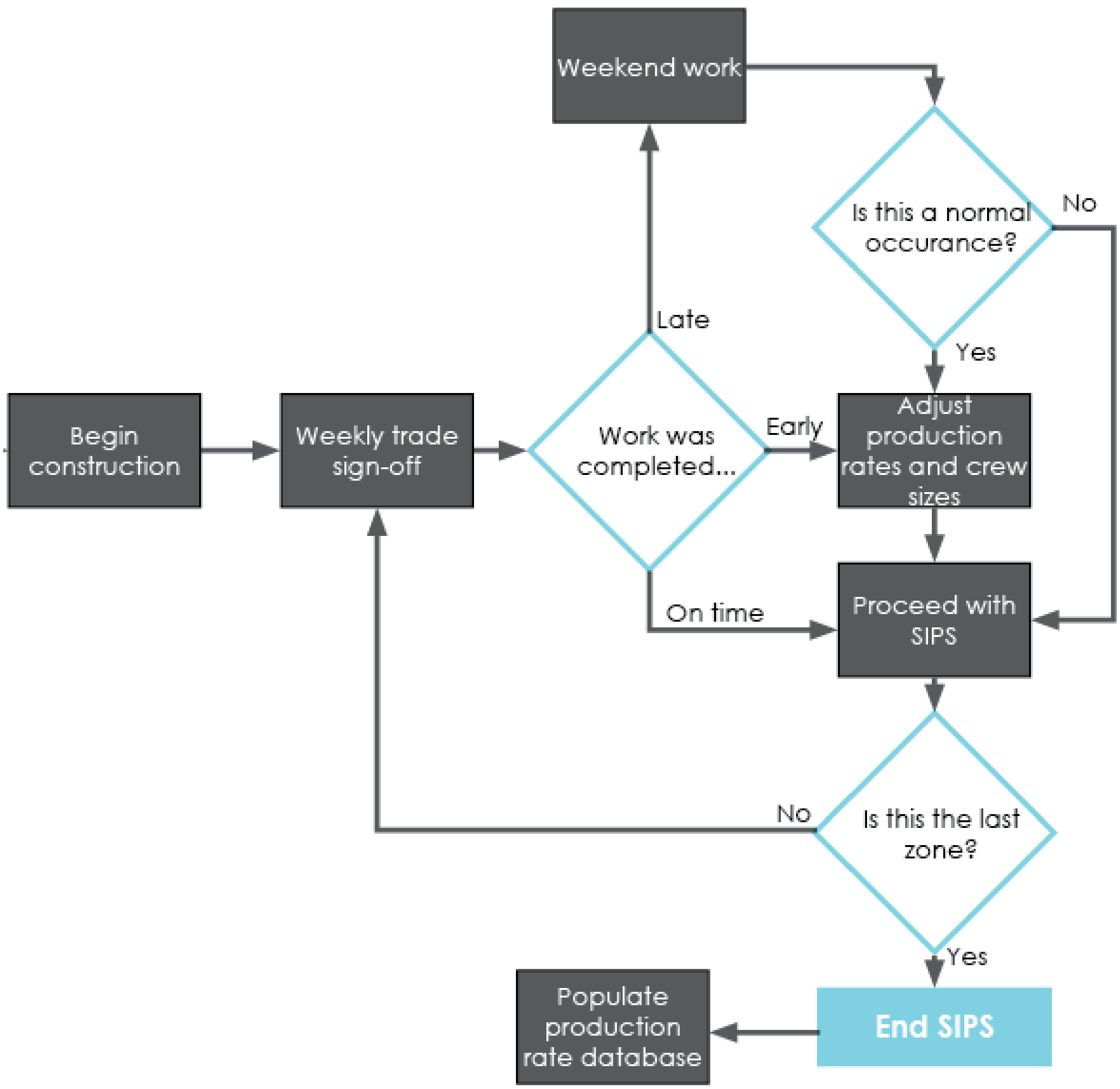


Figure 52: SIPS Implementation process map

BEGIN CONSTRUCTION

Once a SIPS is created and the production rates are validated by the mock-up, the plan can be put into action. The work should be completed according to the plan, no late no earlier. Any deviations from the plan can throw the entire SIPS out of sync since activity are so tightly coupled. Since interior fit out requires a high level of quality to ensure owner and tenant satisfaction, punchlists are common and can make or break the project schedule. By implementing SIPS, quality control is built into the process so in theory punchlist items should be minimal.

WEEKLY SIGN OFF

Once a trade has finished their floor for the week, the foreman should sign off the completed area to communicate to the GC that the work is complete. These sign offs would then be used by the GC as a production tracking tool and will trigger necessary feedback that may lead to another iteration of the schedule. For The Apartment Building, each trade will have one week on each floor beginning on Monday. Sign offs will be done of Friday when work on that floor is complete

FEEDBACK AND ITERATIONS

If the trade finishes their activity on time and are able to sign off their area, then they can move on to the next zone and proceed with the SIPS. However this is not always the case. If work is not competed on time, that trade must perform weekend work to get back on schedule. If this is a normal occurrence, then the SIPS logic must be reworked to determine the proper production rate and crew sizes before moving on to the next floor. Similarly, if a trade consistently completes their zone early, the production rate and crew size should be adjusted before moving on to the next floor. These iterations continue during the entirety of the schedule can only be completed if communication between trades is prompt and effective. This iterative process can also account for an inherent learning curve at the beginning of the project.

POPLATE PRODUCTION RATE DATABASE

Once the SIPS process is complete, the actual production rates for each activity should be populated into a database. As part of the continuous improvement process, this data base of production rates can be used on future SIPS projects, specifically step 3 of developing the schedule. Having actual production rates will help make the SIPS more accurate and require less iterations.

RECOMMENDATION

It is recommended that SIPS is used for interior fit out activities from the 2nd through 10th floor of The Apartment Building. SIPS has no cost impact and provides many benefits to the project team and the owner. By eliminating the need to stack trades, production can be better managed and quality control is improved as it is now part of the process. SIPS requires strong communication between all parties and can create a collaborative work environment as well as a more successful project. SIPS for interior fit out can help ensure that the planned phased turnover of floors is met.

ANALYSIS 4: TOOLS TO SUPPORT SIPS IMPLEMENTATION

RESEARCH PROBLEM

In the construction industry, many tools have been developed to help meet the need of faster, cheaper and higher quality construction. These tools range from manual production tracking to building information modeling. The usage of a specific tool does not guarantee project success, it must be appropriate implemented into the design and construction process.

PROBLEM STATEMENT

As mentioned in Analysis 3, The Apartment Building is being turned over in phases. During a phased turnover project, construction and occupancy are occurring concurrently and there are many factors that can impact the experience of the occupant and ultimately their health and safety. It is vital that each floor is turned over on time and at the proper level of quality. The need for a high level of quality control, in association with a stringent SIPS for interior fit out, lends itself to various tools: both technical and non-technical. This analysis, the House of Quality, the basic tool of Quality Function Deployment (QFD), will be used to determine target criteria and metrics to aid in the tool selection process.

INTRO TO THE HOUSE OF QUALITY

The House of Quality, the basic tool of the QFD approach to management created by the Japanese company, Mitsubishi. The goal of QFD is to better understand the customer, predict how customers will judge a product's value, and obtain customer buy in. The House of Quality can serve many different purposes such as determining if a product meets the customer's needs, translating customer requirements into engineering targets for production.

There are many variations of The House of Quality, but at its core it can be broken up into six main areas (Figure 53).

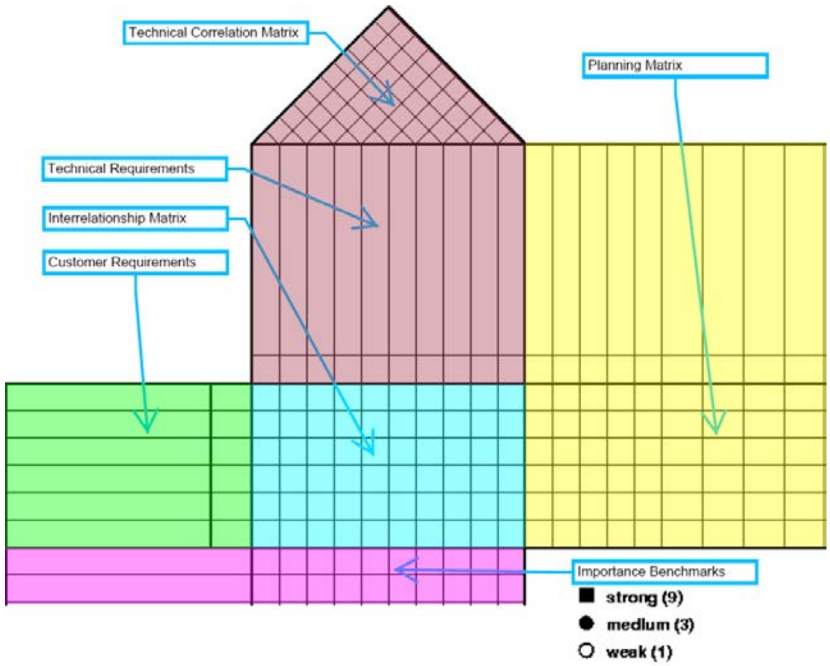


Figure 53: Basic components of the House of Quality

1. Customer Requirements: The left most portion of the house is the customer requirements. Customer requirements are essentially just what the consumers want. These requirements can be derived from market research and studies such as surveys, opinion polls, or interviews. It is important that the producer communicates well with the customer in order to produce accurate customer requirements, which are often misidentified. An importance level on an arbitrary scale is assigned to each of these customer requirements. From the scale, an importance percentage is determined for each requirement.

2. Technical Requirements: The upper roof portion of the house is where measurable technical requirements and engineering parameters are listed. These technical requirements are determined by management, designers, and engineers. In the triangular section of the roof, the technical correlation matrix, the tradeoffs and interrelationships between technical requirements are determined. This does not factor into the overall calculations but helps the designer to determine how much parameters can be pushed at the cost of another.

3. Interrelationship Matrix: Located as the main body of the house. A relationship between the customer requirements (step 1) and the technical requirements (step 2) is determined. An arbitrary rating scale is created, (typically using numbers 1, 3, and 9). A symbol is assigned to each of these values and used to populate the interrelationship matrix.

4. Importance Benchmarks: The two rows located at the bottom of the house are used to determine the weighted importance and percent importance of each technical requirement. This is done by multiplying the percent importance from step 1 by the ratings from step 3 then each column is summed up to determine the weighted importance for each technical requirement. From here the percent importance for each technical requirement can be calculated.

5. Planning Matrix: Located to the right of the house, is the planning matrix. This matrix is used to measure how well current products meet the customer's needs. Each column represents a product that is currently in existence. Each product is given a rating on an arbitrary scale for each customer requirement. These ratings can be determined from surveys or other research methods. The planning matrix can help the designers determine the strengths of different products and use this information to design a product that meets all of the customer requirements.

HOUSE OF QUALITY FOR THE APARTMENT BUILDING

The House of Quality will be used on The Apartment Building to identify criteria and requirements that a tool that complement the SIPS process should meet or address. The owner typically would be the customer but since JMAV will be the main user of the tool and has aligning goals with the owner, JMAV will be considered the customer. The customer requirements are outlined in Table 42. These customer requirements will later be given an importance rating.

Table 42: Customer Requirements

Customer Requirements	
Finish under budget	Increased communication between trades
Finish on budget	Easily integrated with SIPS
Finish on time	Easy to use (GC and subs)
Efficient phased turnover of floors	Easy to learn (GC and subs)
Improved quality control	Tool is cost effective

Next, the measurable technical requirements must be determined (Table 43). These requirements relate to measurable parameters that are associated with a tool.

Table 43: Technical requirements

Technical Requirements	
Cost of technology	Training required
Management labor cost	Visuals produced to aid communication
Time spent prior to construction	Labor efficiency and production
Time spent during construction	Wasted labor time
Learning curve of process	Problem areas of construction process identified
Design issues prevented	Intervals of iterations
Rework time saved	Time spent per iteration
Quality issues prevented	

The interrelationship matrix is used to establish the relationships between the customer requirements and technical requirements. The legend below shows the rating scale that will be used to depict the relationships. The symbols correspond to a rating between 1 and 9 (Figure 2).

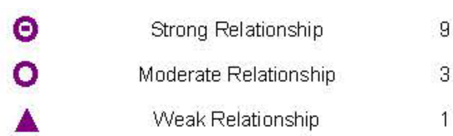


Figure 54: House of Quality Legend

A completed House of Quality is shown in Figure 56. The importance benchmark section of the house shows a weighted importance of each technical requirements. The higher the weighting, the more focus should be on that technical requirement. These weighting ensure that the technical requirements align with the customer requirements. The five technical requirements with the highest rating are listed in Table 44. The tools should increase labor efficiency and production, help identify problem areas, prevent design issues and should not be too time consuming to use. The lower weighted technical requirements must not be ignored as they are still important.

Table 44: Technical Requirements

Importance Benchmarks		
Technical Requirement	**Relative Weight**	**Direction of Improvement**
Labor efficiency and production	11.6	Increase
Intervals of iterations	9.1	-
Problem areas of construction process identified	9.1	Increase
Design issues prevented	8.9	Increase
Time spent during construction	8.5	Decrease

In order to optimize each technical requirements, the relationship between each technical requirment is necessary. The technical correlation matrix, the "roof" of the house, is used to show these correlations (Figure 56). Figure 55 shows the meaning of the symbols used in the "roof".

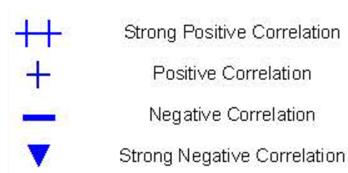
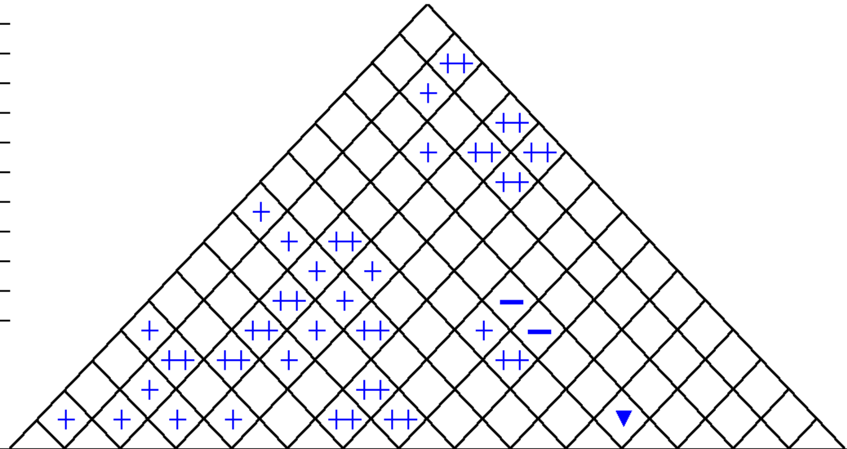


Figure 55: Technical correlation matrix legend

Criteria of Tools to Compliment SIPS

B. Kerem Demirci



Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▼	▼	▼	▲	▲	▲	▼	x	▲	▼	▲	▲	▼
		Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Cost of technology	Management labor cost	Time spent prior to construction	Time spent during construction	Learning curve of processs	Design issues prevented	Rework time saved	Quality issues prevented	Training required	Visuals produced to aid communication	Labor effieciency and production	Wasted labor time	Problem areas of construction process identified	Intervals of iterations	Time spent per iteration
5.5	4.0	Finish under budget	⊙	⊙				▲	○	○	▲		⊙	▲		▲	▲
12.3	9.0	Finish on budget	⊙	▲				▲	○	○	▲		⊙	▲		▲	▲
13.7	10.0	Finish on time			○	⊙	○	⊙	⊙	▲	○		⊙	⊙	⊙	⊙	⊙
13.7	10.0	Efficient phased turnover of floors			⊙	⊙	○	⊙	⊙	▲	○		⊙	⊙	⊙	⊙	⊙
8.2	6.0	Improved quality control			○			○	○	⊙					▲	▲	
5.5	4.0	Increased comunication between trades				▲		▲		○	▲	⊙			⊙		
13.7	10.0	Easily integrated with SIPS					▲	⊙	▲			○	⊙	○	⊙	⊙	○
8.2	6.0	Easy to use (gc and subs)		○	⊙	⊙	⊙				⊙	○	▲			○	▲
8.2	6.0	Easy to learn (gc and subs)		○	⊙	⊙	⊙				⊙	▲	▲			▲	▲
11.0	8.0	Tool is cost effective	⊙	▲													
		Target or Limit Value															
		Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)															
		Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
		Weight / Importance	258.9	121.9	337.0	400.0	243.8	417.8	338.4	171.2	253.4	123.3	546.6	305.5	427.4	428.8	321.9
		Relative Weight	5.5	2.6	7.2	8.5	5.2	8.9	7.2	3.6	5.4	2.6	11.6	6.5	9.1	9.1	6.9

Figure 56: House of Quality for SIPS Tool

AVAILABLE TOOLS

The next step in selecting tools that can complement the SIPS is to conduct background research on existing tools while keeping in mind, the technical requirements highlighted in the House of Quality for The Apartment Building. For this analysis, two major groups of tools were researched: building information modeling (BIM) tools and data collection tools.

BIM TOOLS

In Technical Report 3, a BIM execution plan was developed for The Apartment Building. In the execution plan, specific BIM uses were identified based on feasibility, cost and overall benefit to the owner. The following BIM uses in Table 45 were selected.

Table 45: BIM uses from Technical Report 3

X	PLAN	X	DESIGN	X	CONSTRUCT	X	OPERATE
	PROGRAMMING	X	DESIGN AUTHORING	X	SITE UTILIZATION PLANNING		BUILDING MAINTENANCE SCHEDULING
	SITE ANALYSIS		DESIGN REVIEWS		CONSTRUCTION SYSTEM DESIGN		BUILDING SYSTEM ANALYSIS
		X	3D COORDINATION	X	3D COORDINATION		ASSET MANAGEMENT
		X	STRUCTURAL ANALYSIS		DIGITAL FABRICATION		SPACE MANAGEMENT / TRACKING
		X	LIGHTING ANALYSIS		3D CONTROL AND PLANNING		DISASTER PLANNING
		X	ENERGY ANALYSIS		RECORD MODELING	X	RECORD MODELING
		X	MECHANICAL ANALYSIS				
			OTHER ENG. ANALYSIS				
			SUSTAINABLITY (LEED) EVALUATION				
			CODE VALIDATION				
	PHASE PLANNING (4D MODELING)		PHASE PLANNING (4D MODELING)	X	PHASE PLANNING (4D MODELING)		PHASE PLANNING (4D MODELING)
	COST ESTIMATION	X	COST ESTIMATION	X	COST ESTIMATION		COST ESTIMATION
X	EXISTING CONDITIONS MODELING		EXISTING CONDITIONS MODELING		EXISTING CONDITIONS MODELING		EXISTING CONDITIONS MODELING

The BIM uses were selected to be utilized throughout the planning, design, construction and operation of The Apartment Building. Some of the selected BIM uses would not be directly applicable to the SIPS for interior fit-out. The BIM uses that may compliment the SIPS process are:

DESIGN AUTHORING

Design authoring is the use of 3D software, such as Revit, to develop a model. This is the first step towards BIM and is necessary in order to use subsequent BIM tools. Design authoring adds transparency to the design process for all stake holders through visualization and communication. Quality is better controlled during the design process. A weakness to design authoring is the amount of time it takes to develop a detailed model. In addition, the software and technology must be acquired and stakeholders must be trained to properly use the technology. In this day in age, majority of design firms and contractors have the technical capability. The architect of The Apartment Building, Rust Orling, used Revit for design as well as construction documentation. However, the model was not carried over into construction by JMAV. Design authoring is necessary if other BIM uses are selected to compliment SIPS for interior fit-out.

DESIGN REVIEWS

Design reviews is the process of reviewing the 3D model with key stakeholders and providing feedback on design and construction. This process helps with transparency and increases communication between the owner, design and construction teams so that design decisions can be made more efficiently. Design reviews do not require any more software than design authoring, just a large enough space to hold meetings. Design reviews are typically done prior to construction and are not used during construction.

4D MODELING

By incorporating the schedule into the 3D model, a 4D model can be created. A 4D model can be used to effectively visualize construction phases and give project stakeholders a better understanding of construction milestones. Labor, equipment, and materials can be included in the model. The software needed to create a 4D model include: scheduling software, design authoring software, and 4D modeling software. A 4D model can be created prior to or during construction. For The Apartment Building, a 4D model can be used in two ways. First, a 4D model can be made for the interior fit-out of a single apartment units to visual the sequencing of construction. This can help validate production rates for the activities in the SIPS as well as identify any major sequencing issues. Secondly, a 4D model can be created in conjunction with the SIPS to show the sequence of construction through an entire floor. This visual tool can help communicate the SIPS more effectively than to a matrix schedule.

3D COORDINATION

One of the most commonly used BIM use is 3D coordination, also known as clash detection. The purpose of 3D coordination is to identify spatial conflict by comparing 3D models of the major systems of the building prior to construction. Designs are then changed to eliminate the conflict then the process is repeated. The main benefit of 3D coordination is identifying issues prior to construction, which can be costly to address during construction. 3D coordination is a collaborative process that incorporates major trades and can increase overall quality. The downside of clash detection is that it can be a time consuming process if the process is not properly managed. In addition each trade must have the technical capabilities. During the construction of The Apartment Building, many coordination issue arose. For example, sleeves were missed or incorrectly placed during the placement of the concrete floors. Missed sleeves pose a major issue in a post-tensioned concrete slab. The only solution for a missed sleeve is to core drill through the slab, which is extremely risky. If a steel tendon is hit, the tendon could snap and whip through the concrete slab and cause structural damage and become a safety hazard. Since SIPS for interior fit-out is so tightly coupled and design conflicts can easily throw the schedule off track, performing clash detection prior to construction can help mitigate any issues that may delay the SIPS.

SITE UTILIZATION PLANNING

Site utilization planning is the process of using the 3D model to generate a site utilization plan. The model can include material delivery, labor, equipment and temporary utilities. A 3D site utilization plan model can minimize the time typically spent developing 2D site utilization plans. Site utilization planning is ideal for constrained jobsites. Effective site utilization can minimize safety risks and increase productivity. Since the construction site for the Apartment Building is tight due to the neighboring existing buildings, site utilization planning can be used to efficiently plan out the site layout for each phase of construction in a visual manner. This planning will minimize overall site congestion, improve safety, and minimize spatial conflicts between trades. For interior fit-out, a 3D site utilization plan can incorporate material location for each trade in order to maximize productivity. For example, materials can be preloaded on each floor in a manner that minimizes the moving material multiple times.

FIELD AND MANAGEMENT TRACKING

Field and management tracking is the use of field software for quality control measure in the field. Personnel in the field can access the 3D model and construction drawings and have the ability to make changes or comments instantly. This can speed up the process of finding a solution if any issues arise. By optimizing quality the first time around, rework and punchlist time will be minimized. This BIM tool has the most technical requirements compared to the previous tools. In addition to design authoring software, field management software is necessary as well as a tablet and internet connection to access information while on site.

On The Apartment Building, field and management tracking can help optimize quality of interior fit-out work. This can help minimize the rework time and ultimately punchlist items that can prevent a timely turnover of each floor.

DATA COLLECTION TOOLS

In construction, productivity is the man hours required to complete a task. With a tightly coupled SIPS, it is important that the construction process is productive. Worker productivity can be affected by many factors as, shown in Figure 57. The SIPS process for interior fit-out assumes an ideal productivity that is likely not reached. Figure 58 shows the actual productivity vs ideal productivity. It is important that productivity is tracked and problem areas are identified. This section will cover various tools that can be used by management to track productivity and improve the process.

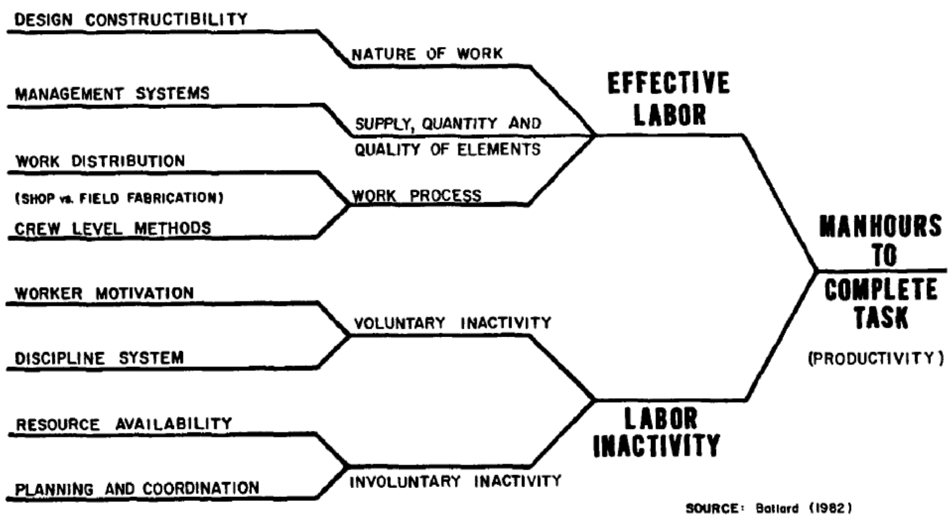


Figure 57: Factors that affect productivity (Bollard 1992)

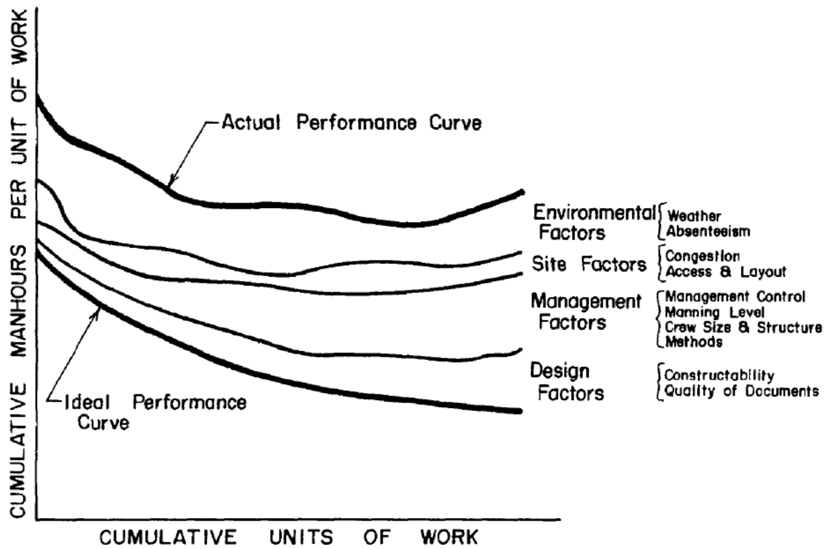


Figure 58: Ideal vs. Actual Productivity (Bollard)

CREW BALANCE CHART

A crew balance chart is a production tracking tool that is used to identify the relationships between individual crew members. Crew balance charts create a graphical representation of the sequential activities with time durations of individual crew members. The process requires detailed observation of a specific crew where each member's contribution is recorded. From this information a segmented bar chart is created that breaks down the contribution of each crew member. The time of observation is located on the vertical axis and each crew member is listed on the horizontal axis. The goal is to minimize the time spent waiting by adjusting labor, resequencing activities or combining activities. An example of an original and revised crew balance chart is shown in Figure 59 and 60. Crew balance charts have many benefits (Kuprenas and Fakouri 2001):

- Elevate awareness of crew activities
- Establish a performance mindset
- Create a visual tool that can easily be communicated and evaluated
- Iterative process

This tool can help balance crew sizes and ultimately improve productivity. It can be easily implemented into the SIPS process for interior fit-out on The Apartment Building. A crew balance chart can be made for each of the 16 crews on each floor to help adjust production rates, as part of the iterative process, for the following floor.

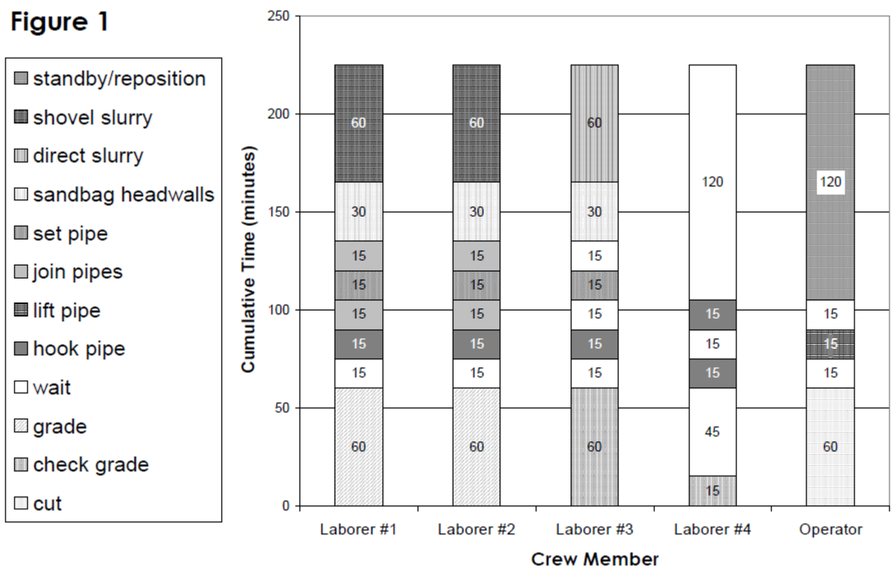


Figure 59: Example of a crew balance chart (Kuprenas and Fakouri 2001)

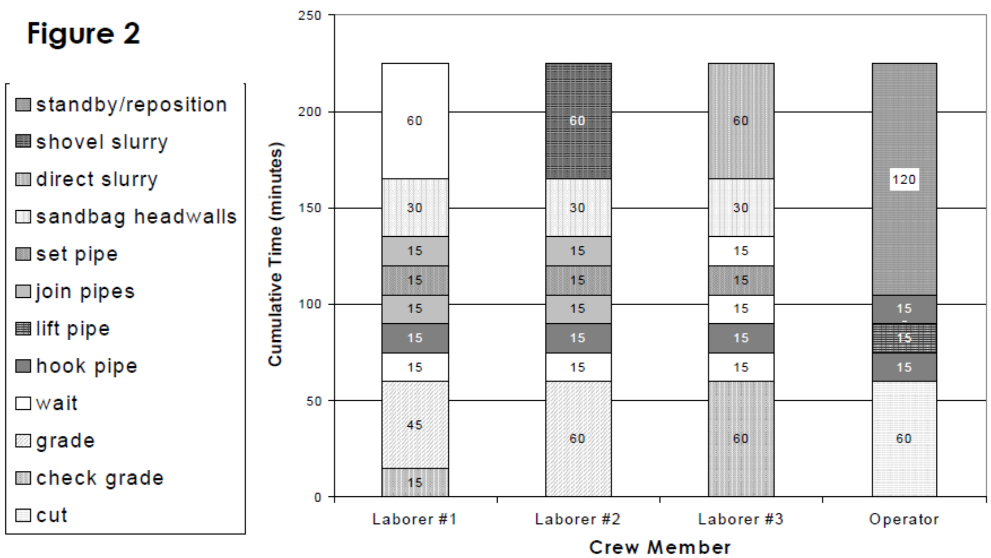


Figure 60: Example of a revised crew balance chart (Kuprenas and Fakouri 2001)

FLOW DIAGRAM AND PROCESS CHART

Flow diagrams, in conjunction with process charts can be used to identify inefficiencies of a crew. This graphical tool looks at the movement of the crew within a space. To create a flow diagram, first a process chart (Figure 61), that lists all construction activities in chronological order, must be developed. The flow diagram consists of a line sketch of the movement of a crew member (Figure 62). This tool can help sequence activities as well as increase productivity by mitigating double handling or excessive travel distance. This tool could be implemented on The Apartment Building during mock up construction for interior fit-out. By identifying inefficiencies, material storage and equipment location can be modified to increased productivity.

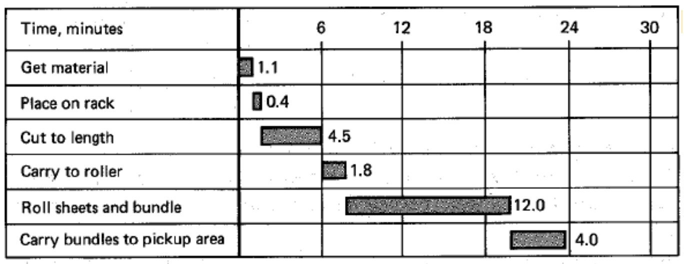


Figure 61: Example flow diagram and process chart

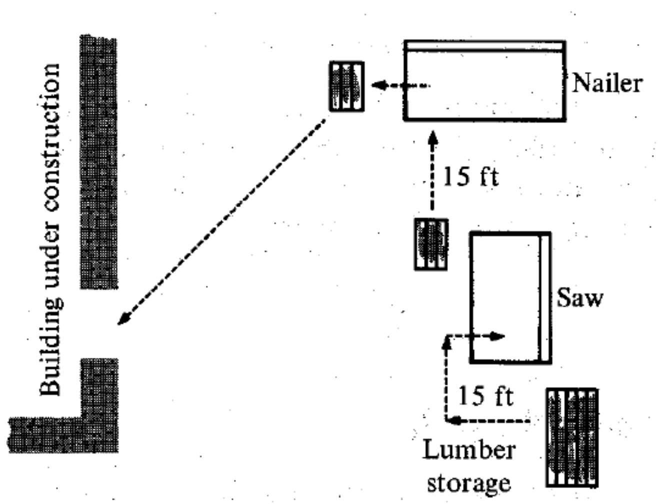


Figure 62: Example flow diagram and process chart

ACTIVITY SAMPLING

Another tool to identify inefficiencies is activity sampling. Activity sampling consists of random observations, conducted at various times of day and different location, to create a production snap shot by recording work. Work is categorized into three categories (*Productivity Measurement and Analysis* 2004). Table 5 includes a sample of activity sampling observations.

- Effective work – work that leads directly to the work in place
- Contributory – work that is not directly effective but is necessary
- Non-contributory – Work that does not fall in either of the other two categories

Table 46: Sample activity sampling results (*Productivity Measurement and Analysis* 2004)

	Effective Work	Contributory Work	Non-Contributory Work
Day1	72	66	20
Day 2	55	35	22
Day 3	57	55	27
Sum	184	156	69

A benefit to this tool is that it gives a sense of the productivity of an entire site. However, a large number of observations are needed for statistically significant outcome. This process can be very time consuming. This tool can be used periodically throughout interior fit-out of The Apartment Building to track productivity on a larger scale.

LABOR UTILIZATION FACTORS

Labor Utilization Factors (LAF)can be used to analyze the activity sampling data. Using the following equations a LAF can be calculated.

$$LUF = \frac{(effective\ work + 0.25\ \times contributory\ work)}{total\ observed}$$

$$LUF = \frac{effective\ work}{total\ observed}$$

The LUF can then be compared to the acceptable LUF values for different trades (Table 47).

Table 47: Acceptable LUF values

Trade	Effective	Contributory	Non-Contributory
Carpenter	29	38	33
Electrician	28	35	37
Insulator	45	28	27
Laborer	44	26	30
Painter	46	26	28

FOREMAN DELAY SURVEY

Foreman delay surveys can be used to identify problems that are outside of a foreman's control. This tool is beneficial because it identifies problems specific to a crew. The survey should be given periodically to all trades and results should be communicated between all trades. Figure 63 depicts a sample foreman delay survey for interior fit out activities. This survey can help improve collaboration between trades and solve issues that are hindering production. On The Apartment Building, weekly foreman delay surveys, as part of the sign off process, can help identify issues that may have prevented timely completion of work for that floor. Information from these surveys can be incorporated into the next iteration of the SIPS.

	Electrical	Mechanical	Framing	Drywall	Insulator	Casework	Flooring	Total	Percent
Changes/ redo (design error or change)									
Changes/ redo (fabrication error))									
Changes/ redo (field error or damage)									
Waiting for materials (warehouse)									
Waiting for materials (vendor delay)									
Waiting for tools									
Waiting for construction equipment									
Construction equipment breakdown									
Waiting for information									
Waiting for other crews									
Waiting for fellow crew members									

Figure 63: Sample foreman delay survey

RECORD WORKFORCE ACTIVITIES

By recording workforce activities, a general work evaluation can be made regarding spatial layout and movement of crews and productivity. Two common methods of recording workforce activities are through photographs and video time lapses. Photographs can be used to analyze production in a snap shot and evaluating spatial layout. Time lapses can be used to perform a detailed analysis of an activity and factors that affect productivity. Time lapses are more beneficial since an observer is not needed. A benefit of recording is that the information can reviewed and analyzed at a future date. On The Apartment Building, cameras can be set up for each trade so production can be documented. If signification production issues turn up, the video can be reviewed to identify issues. Other analysis such as crew balance charts can later be made by reviewing the recordings,

TOOL SELECTION USING HOUSE OF QUALITY

The planning matrix section of the House of Quality can now be populated and used to see how each tool meets the customer requirements. From this comparison and the importance benchmarks, a tool or combination of tools can be selected to complement the SIPS process for interior fit-out. In the planning matrix, each existing tool is given a rating between 0 and 5, based on how well each customer requirement is met.

In Figure 64, BIM tools are compared to the customer requirements in the planning matrix section of the House of Quality. The completed House of Quality can be found in Appendix G. The graphic on the right shows which BIM tools best address the customer requirements. In general, BIM uses do not rank very high when it comes to ease of learning and using. However they rank high in categories related to budget, schedule and quality control. 3D coordination and 4D modeling consistently have the highest scores in the majority of the categories.

	Competitive Analysis (0=Worst, 5=Best)					
	Design Authoring	Design Reviews	4D Modeling	3D Coordination	Site Utilization Planning	Field and Management Tracking
Finish under budget	3	3	3	4	2	1
Finish on budget	4	3	3	5	3	2
Finish on time	4	2	5	5	3	2
Efficient phased turnover of floors	2	2	5	5	3	3
Improved quality control	4	4	2	4	1	5
Increased comunication between trades	3	3	4	5	4	1
Easily integrated with SIPS	3	3	5	5	3	5
Easy to use (gc and subs)	3	2	4	4	3	3
Easy to learn (gc and subs)	2	2	3	3	3	3
Tool is cost effective	4	4	3	3	3	2

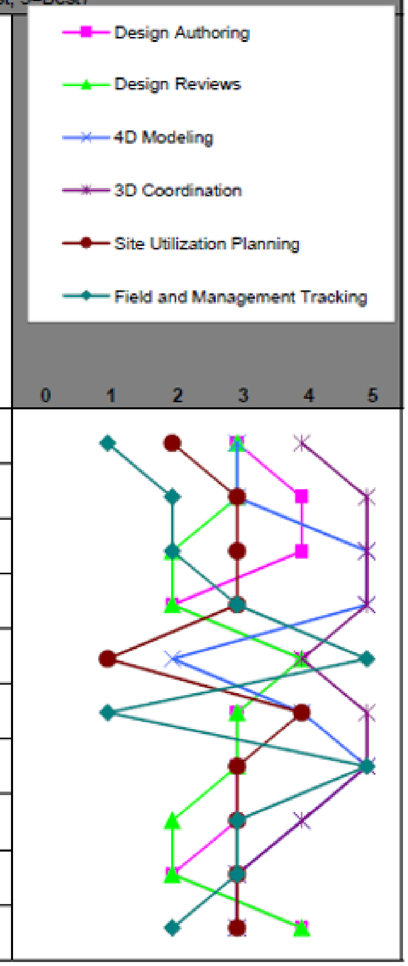


Figure 64: BIM tools planning matrix

Figure 65 compares data collection tools to the customer requirements in the planning matrix section of the House of Quality. For the completed House of Quality refer to Appengix G. The graphic on the right shows which BIM tools best address the customer requirements. Most data collection tools are easy to use and learn except activity sampling and labor utilization factors. Data collection tools do not address quality control as well as BIM tools. Crew balance chart, foreman delay survey, and flow diagram and process chart have the highest scores in the majority of the categories.

Competitive Analysis (0=Worst, 5=Best)

	Flow Diagram and Process Chart	Activity Sampling	Labor Utilization Factors	Foreman Delay Survey	Record Workforce Activities
Finish under budget	4	2	2	3	2
Finish on budget	4	2	2	3	2
Finish on time	5	2	2	4	2
Efficient phased turnover of floors	4	1	1	5	1
Improved quality control	1	1	1	2	2
Increased comunication between trades	3	1	1	5	2
Easily integrated with SIPS	5	1	1	5	5
Easy to use (gc and subs)	3	1	1	5	5
Easy to learn (gc and subs)	3	2	2	5	5
Tool is cost effective	4	1	2	5	4

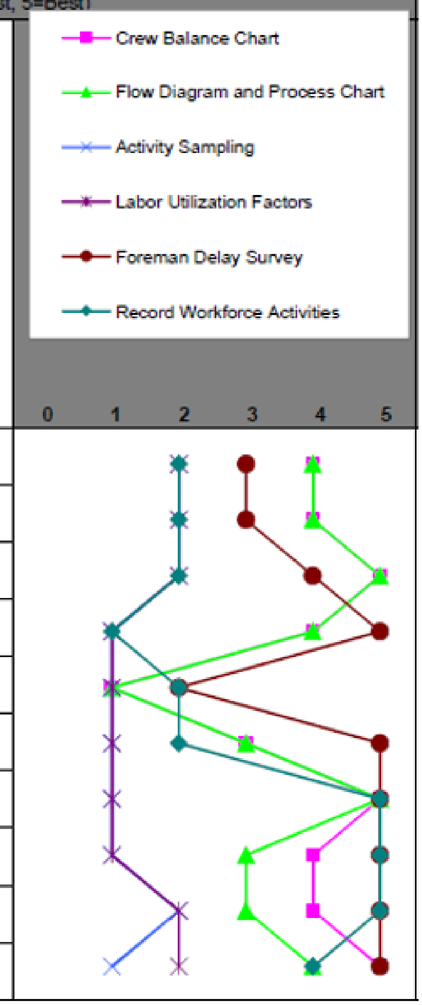


Figure 65: Data collection tools planning matrix

The planning matrix show that in general BIM tools effectively address requirements regarding budget, schedule and quality control while data collection tools are easier to use and learn and also effectively address the schedule. Using a combination of BIM tools and data collection tools, all the customer requirements can been met and an effective compliment to the SIPS for interior fit out can be achieved. The ideal combination of tools is as follows:

- Design authoring
- 3D coordination
- Crew balance charts
- Flow diagram and process charts
- Foreman delay surveys
- Time lapse

UPDATED SIPS PROCESS MAP FOR INTERIOR FIT OUT

The SIPS process map developed in Analysis 3 must be updated to accommodate the selected tools. Design authoring and 3D coordination will occur prior to developing the SIPS. The goal of 3D coordination is to identify major design clasher prior to construction, which derail the SIPS process. In the schedule development phase, flow diagrams and process charts will be used during the construction of the mock up. This is a chance to eliminate excessive travel distances and double handling of work by rearranging material storage and work stations. In the implementation phase video time lapse will begin to document productivity of a typical room on each floor. In addition crew balance charts will be created for ever floor. If there is excessive wait time, the crew size and production rates should be adjusted. Weekly foreman delay surveys will be completed weekly, at the same time as weekly trade sign offs. This will help identify factors that affected the productivity of the trade. Figure 66 includes an updated SIPS process map.

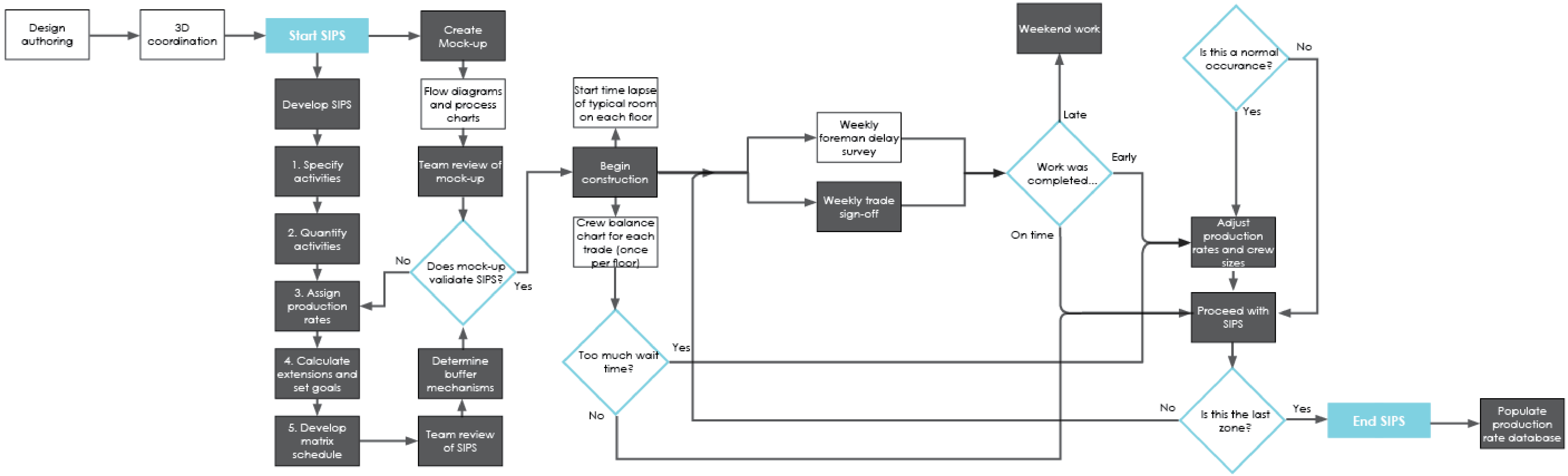


Figure 66: Updated SIPS Process Map

RECOMMENDATION

Through a thorough decision making analysis using a House of Quality, a combination of tools was selected to complement the SIPS process for interior fit out of The Apartment Building. The recommended combination of tools is as follows.

- Design authoring
- 3D coordination
- Crew balance charts
- Flow diagram and process charts
- Foreman delay surveys
- Time lapse

Implementing these BIM and data collection tools can help elevate worker productivity and quality which will ultimately result in project that is on schedule, on budget and of high quality.

CONCULSION

Analysis 1: Effect of Eco Certifications on Marketability

As part of the critical industry research for this course, a literature review was completed to determine if a rent premium existed for buildings with eco-certifications, such as LEED. Rent premiums exist and range anywhere from 0.1% to 20%. It is recommended that The Apartment Building upgrades to LEED Silver by the addition of three LEED Points that are feasible to achieve at this point in construction, green power and a mechanical system flush.

Analysis 2: Exterior Enclosure Acceleration

Due to a harsh winter, the overall construction schedule was delayed 26 days. By implementing a panelized brick veneer system (PBVSS), a 44 day reduction of the onsite schedule, which is the ultimate driver of the project. This system will cost $70,132 more than the original brick veneer assembly but can be justified by the reduction in schedule as well as the increased quality and safety benefits of offsite prefabrication. In addition, the thermal and hygrothermal properties, with slight modification, of the PBVSS system can surpass the original. A structural analysis showed that the additional loads from the PBVSS system can easily be accommodated by the existing post-tensioned concrete structure.

Analysis 3: SIPS Implementation for Interior Fit-Out

Due to the stringent schedule dictated by the phased turnover of the building, high level of quality and the repetitive nature of the apartment units, short interval production scheduling (SIPS) was implemented for interior fit out of apartment units on the 2nd through 10th floor. A guide was produced that outlines the schedule development process as well as keys to proper implementation.

Analysis 4: Tools to Support SIPS Implementation

Building off Analysis 3, a combination of tools was selected to complement the SIPS process for interior fit out. Tools were selected using the House of Quality, a decision making tool that ensures the customer's requirements are met. The recommended combination of tools are: design authoring, 3D coordination, crew balance charts, flow diagram and process chars, foreman delay surveys, and video time lapse. The tools were then added to the guide that was created in Analysis 3.

FINAL RECOMMENDATION

It is recommended that The Apartment Building achieves LEED Silver, institutes a prefabricated brick veneer system and implements SIPS for interior fit-out. Each analyses has the potential to improve schedule, cost, quality and safety on The Apartment Building.

MAE REQUIREMENTS

Many of the analyses incorporate various tools and concepts that were obtained in through MAE courses at Penn State. Some of the MAE courses were complete prior to these analysis and some were taken concurrently. Below is a list of some of the courses and the relevant material from these courses that will be used various analysis.

AE 542: Building Enclosure Science and Design

This course was taken in the spring of 2015. The PBVSS system that was used in Analysis was brought up in this course. Thermal and hygrothermal analysis using software such as THERM and WOOFI were taught in this course and implemented on Breadth 1 for thermal and hygrothermal analysis of the PBVSS system.

AE 543: Research Methods in Architectural Engineering

In this course, research skills were developed that indirectly effected each analysis. For example, the literature review that was part of Analysis 1 was based on guidelines and best practices that were presented in this class.

AE 570: Production Management in Construction

This course covered the concept of prefabrication and modularization which was used to analyze the prefabrication PBVSS system. SIPS and production tracking tools were introduced in this course. Analysis 3 and 4 used information from this course heavily.

AE 598C: Sustainable Construction Project Management

The Law of Three framework that was used in this thesis was obtained from this course. This course also helped in Analysis 1 when looking into various green rating systems.

All in all, the MAE courses taken, helped me conducted high level analyses. Because of these courses I focused more into the high level process that were involved to successfully implement a prefabrication brick veneer system and SIPS.

APPENDIX A: LEED SCORECARD

Category	Credit	Description	Possible Points	Currently Proposed	Additional Suggested
Sustainable Sites	Prereq 1	Construction Activity Pollution Prevention			
	1	Site Selection	1	1	
	2	Developent Density & Community Connectivity	5	5	
	3	Brownfield Redevelopment	1		
	4.1	Alt. Transportation, Public Transportation Access	6	6	
	4.2	Alt. Transporation, Bicycle Storage & Changing Rooms	1	1	
	4.3	Alt. Transporation, Low Emitting & Fuel Efficient Vehicles	3	3	
	4.4	Alt Transporation, Parking Capacity	2	2	
	5.1	Site Development, Protect or Restore Habitat	1		
	5.2	Site Development, Maximize Open Space	1	1	
	6.1	Stormwater Design, Quantity Control	1		
	6.2	Stormwater Design, Quality Control	1		
	7.1	Heat Island Effect, Non-Roof	1	1	
	7.2	Heat Island Effect, Roof	1	1	
	8	Light Pollution Reduction	1		
Water Efficiency	Prereq 1	Water Use Reduction - 20% Reduction			
	1	Water Efficient Landscaping	2 to 4	2	
	2	Innovative Wasewater Technologies	2		
	3	Water Use Reduction - 30% Reduction	2 to 4	2	
Energy and Atmosphere	Prereq 1	Fundamental Commissioning of Building Energy Systems			
	Prereq 2	Minimum Energy Performance			
	Prereq 3	Fundamental Refrigerant Management			
	1	Optimize Energy Performance	1 to 19	2	
	2	On-site Renewable Energy	1 to 7		
	3	Enhanced Commissioning	2	2	
	4	Enhanced Refrigerent Management	2		
	5	Measurement and Verification	3		
	6	Green Power	2		2

Materials and Resources	Prereq 1	Storage and Collection of Recyclables			
	1.1	Building Reuse - Maintain Existing Walls, Floors and Roof	1 to 3		
	1.2	Building Resue - Maintain 50% of Non Structural Elements	1 to 3		
	2	Construction Waste Management	1 to 2	2	
	3.1	Material Reuse	1 to 2		
	4	Recycled Content	1 to 2	2	
	5	Regional Materials	1 to 2	2	
	6	Rapidly Renewable Materials	1		
	7	Certified Wood	1		
Indoor Environmental Quality	Prereq 1	Minimum IAQ Performance			
	Prereq 2	Environmental Toacco Smoke (ETS) Control			
	1	Otdoor Air Delivery Monitoring	1		
	2	Increased Ventilation	1		
	3.1	Construction IAQ Management Plan - During Construction	1	1	
	3.2	Construction IAQ Management Plan - Before Occupancy	1		1
	4.1	Low-Emitting Materials - Adhesives and Sealants	1	1	
	4.2	Low-Emitting Materials - Paints and Coatings	1	1	
	4.3	Low-Emitting Materials - Flooring Systems	1	1	
	4.4	Low-Emitting Materials - Composite Wood and Agrifiber Products	1		
	5	Indoor Chemical & Pollutant Source Control	1		
	6.1	Contrallability of Systems - Lighting	1	1	
	6.2	Contrallability of Systems - Thermal Comfort	1	1	
	7.1	Thermal Comfort - Design	1		
	7.2	Thermal Comfort - Verification	1		
	8.1	Daylight and Views - Daylight	1		
	8.2	Daylight and Views - Views	1	1	
Innovation in Design	1.1	Innovation in Design: Exemplary Performance in SSc4.1 Public Transportation Access	1	1	
	1.2	Innovation in Design: Exemplary Performance in SSc7.1	1	1	
	1.3	Innovation in Design: Education Program	1	1	
	1.4	Innovation in Design: Exemplary Performance in EAc6 Green Power	1		
	1.5	Innovation in Design: Energy Star Appliances	1	1	
	2	LEED Accredited Professional	1	1	
Regional Priority	1.1	Regional Priority: EAc1	1		
	1.2	Regional Priority: SSc5.1 - Restore Habitat	1		
	1.3	Regional Priority: SSc6.1 SW Quantity	1		
	1.4	Regional Priority: MRc1.1, WEc2	1		
			Total	47	3
				50 (Silver)	

APPENDIX B: GREEN POWER CALCULATIONS

Baseline energy usage for a multifamily building according to Energy Star: 78.8 kBtu/ft^2 per year

ENERGY STAR® PortfolioManager®

Technical Reference

Broad Category	Primary Function	Further Breakdown (where needed)	Source EUI (kBtu/ft²)	Site EUI (kBtu/ft²)	Reference Data Source - Peer Group Comparison
Healthcare	Ambulatory Surgical Center		155.2	63.0	CBECS - Outpatient Healthcare
	Hospital	**Hospital (General Medical & Surgical)***	389.8	196.9	CBECS - Inpatient Healthcare
		Other/Specialty Hospital			
	Medical Office*		116.7	44.4	CBECS - Medical Office
	Outpatient Rehabilitation/Physical Therapy		155.2	63.0	CBECS - Outpatient Healthcare
	Senior Care Community*		243.2	125.7	CBECS - Nursing
	Urgent Care/Clinic/Other Outpatient		182.7	66.8	CBECS - Clinic/Outpatient
Lodging/Residential	**Barracks***		114.9	73.9	CBECS - Dormitory
	Hotel*		162.1	73.4	CBECS - Hotel & Motel/Inn
	Multifamily Housing*		127.9	78.8	Fannie Mae Industry Survey
	Prison/Incarceration		169.9	93.2	CBECS - Public Order and Safety
	Residence Hall/Dormitory*		114.9	73.9	CBECS - Dormitory
	Senior Care Community*		243.2	125.7	CBECS - Nursing
	Single Family Home		N/A	N/A	None Available
	Other - Lodging/Residential		155.5	73.4	CBECS - Lodging
Manufacturing/Industrial	Manufacturing/Industrial Plant		N/A	N/A	None Available
Mixed Use	Mixed Use Property		123.1	78.8	CBECS - Other
Office	**Medical Office***		116.7	44.4	CBECS - Medical Office
	Office*		148.1	67.3	CBECS - Office & Bank/Financial
	Veterinary Office		182.7	66.8	CBECS - Clinic/Outpatient
Parking	Parking		N/A	N/A	None Available

Square footage of The Apartment Building= 150,000 SF

Energy usage per year= 78.8 kBtu/ft^2 x 150,000 SF =11,820,000 kBtu per year = 3,464,100 kWh per year

35% of total energy usage must be green power: 3,464,100 kWh per year x 0.35 = 1,212,435 kWh per year

Cost of green energy: 1,212,435 kWh per year x $0.15 = $181,865 per year

Cost of green energy for two year period = $181,865 per year x 2 years = $363,730

Owner cost (assuming 50%) = $363,730 x 0.5 = **$181,865**

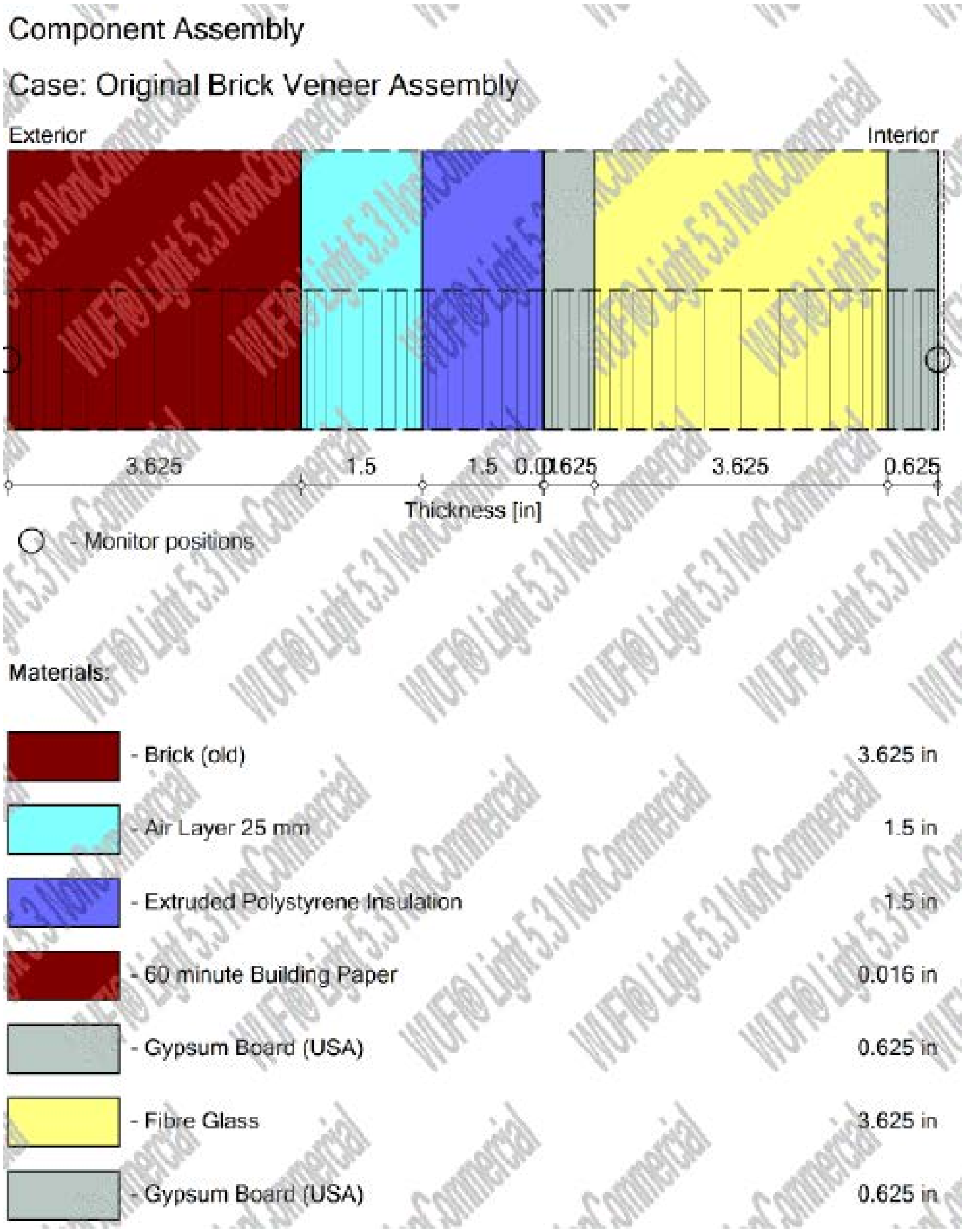
APPENDIX C: ASHRAE 90.1 BUILDING ENCLOSURE REQUIREMENTS

Table 5.5-4 Building Envelope Requirements for Climate Zone 4 (A,B,C)*

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.032	R-30 c.i.	U-0.032	R-30 c.i.	U-0.093	R-10 c.i.
Metal Building[a]	U-0.037	R-19 + R-11 Ls or R-25 + R-8 Ls	U-0.037	R-19 + R-11 Ls or R-25 + R-8 Ls	U-0.082	R-19
Attic and Other	U-0.021	R-49	U-0.021	R-49	U-0.034	R-30
Walls, above Grade						
Mass	U-0.104	R-9.5 c.i.	U-0.090	R-11.4 c.i.	U-0.580	NR
Metal Building	U-0.060	R-0 + R-15.8 c.i.	U-0.050	R-0 + R-19 c.i.	U-0.162	R-13
Steel Framed	U-0.064	R-13 + R-7.5 c.i.	U-0.064	R-13 + R-7.5 c.i	U-0.124	R-13
Wood Framed and Other	U-0.064	R-13 + R-3.8 c.i. or R-20	U-0.064	R-13 + R-3.8 c.i. or R-20	U-0.089	R-13

APPENDIX D: WUFI HYGROTHERMAL REPORTS

ORIGINAL



Boundary Conditions

Exterior (Left Side)

Location: Baltimore, MD; cold year
Orientation / Inclination: South / 90 °

Interior (Right Side)

Indoor Climate: ASHRAE 160P
Heating only; 5.04 °F; 69.98 °F
M.Rate 0.83 lb/h; A.Ch.Rate 0.2 1/h; Vol. 17657.3334 ft³
Humidity Ratio Wo -1.0000 lb/lb

Surface Transfer Coefficients

Exterior (Left Side)

Name	Description	Unit	Value
Heat Resistance - includes long-wave radiation	External Wall	[h ft² °F/Btu]	0.3339 yes
Permeance	No coating	[perm]	----
Short-Wave Radiation Absorptivity	Brick, red	[-]	0.68
Long-Wave Radiation Emissivity	Brick, red	[-]	0.9
Adhering Fraction of Rain	Depending on inclination o	[-]	0.7
Explicit Radiation Balance			no

Interior (Right Side)

Name	Description	Unit	Value
Heat Resistance	External Wall	[h ft² °F/Btu]	0.7098
Permeance	Gypsum board	[perm]	32.8

Status of Calculation

Calculation: Time and Date	2/27/2015 5:57:21 PM
Computing Time	13 min,57 sec.
Begin / End of calculation	10/1/2015 / 10/1/2017
No. of Convergence Failures	4

Check for numerical quality

Integral of fluxes, left side (kl,dl)	[lb/ft^2]	11.08 -11.0
Integral of fluxes, right side (kr,dr)	[lb/ft^2]	3.8E-9 0.11
Balance 1	[lb/ft^2]	-0.03
Balance 2	[lb/ft^2]	-0.03

Water Content [lb/ft^2]

	Start	End	Min.	Max.
Total Water Content	0.16	0.13	0.05	2.99

Water Content [lb/ft^3]

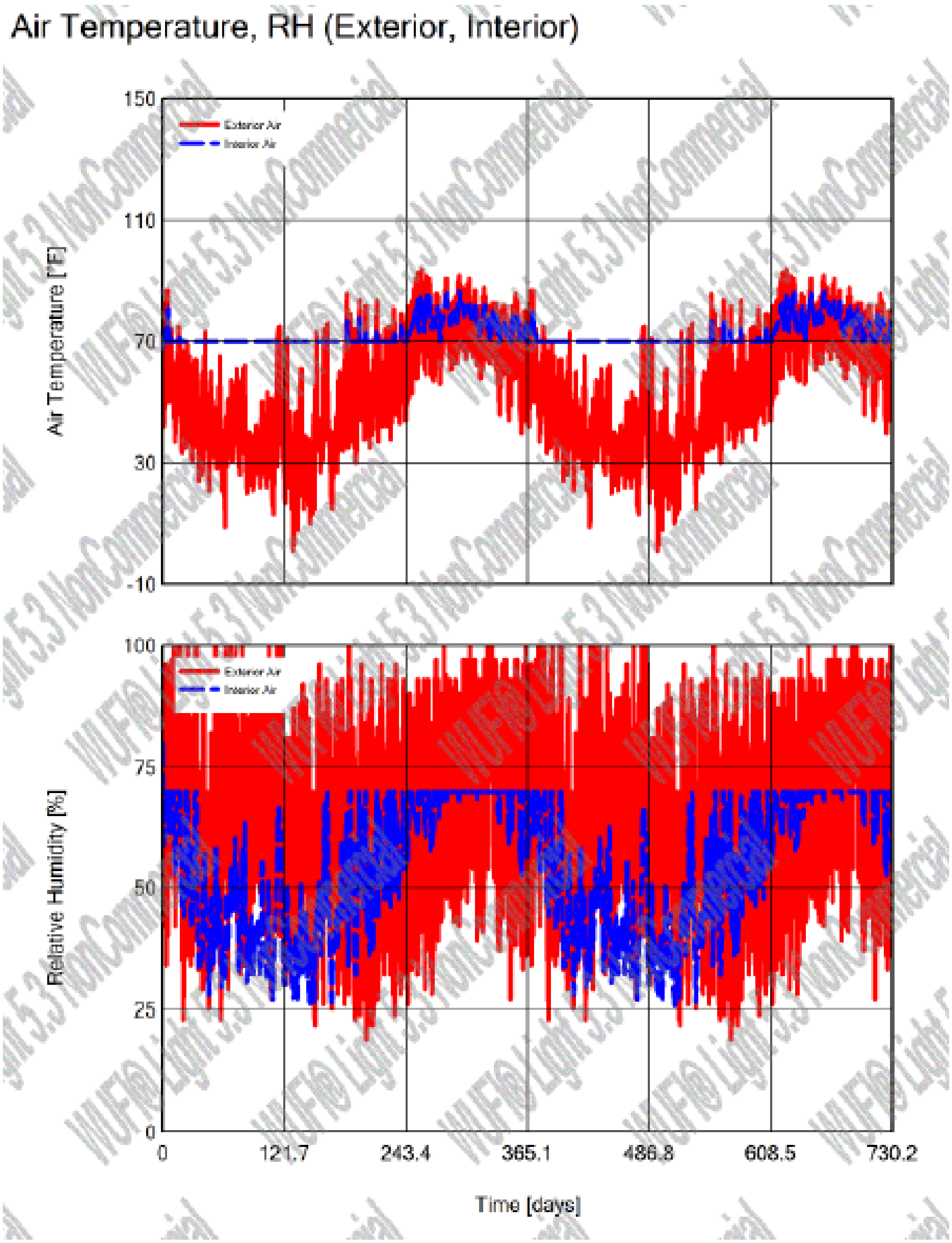
Layer/Material	Start	End	Min.	Max.
Brick (old)	0.21	0.20	0.06	9.47
Air Layer 25 mm	0.12	0.16	0.02	0.84
Extruded Polystyrene Insulation	0.02	0.02	0.00	0.04
60 minute Building Paper	0.00	0.00	0.00	0.00
Gypsum Board (USA)	0.39	0.26	0.18	0.41
Fibre Glass	0.12	0.06	0.02	0.12
Gypsum Board (USA)	0.39	0.26	0.10	0.39

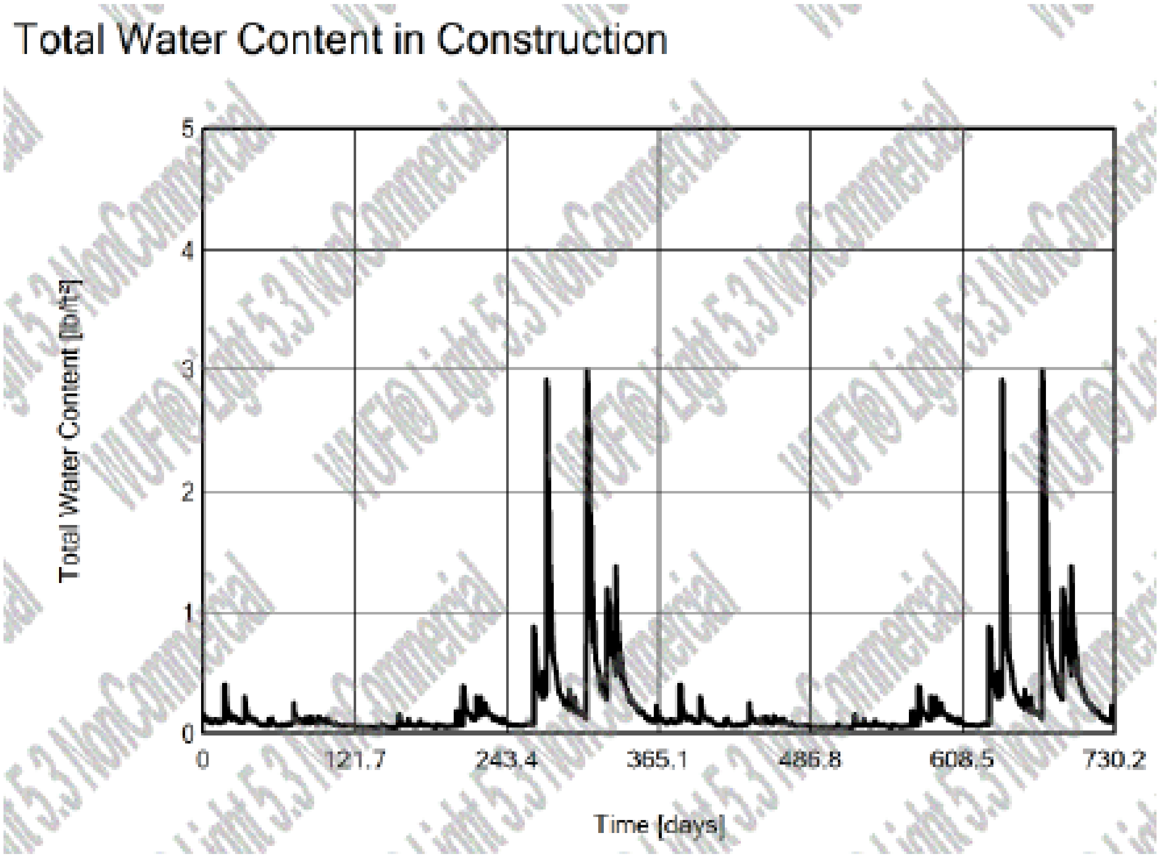
Time Integral of fluxes

Heat Flux, left side	[Btu/ft^2]	-6766.11
Heat Flux, right side	[Btu/ft^2]	-6678.31
Moisture Fluxes, left side	[lb/ft^2]	0.08
Moisture Fluxes, right side	[lb/ft^2]	0.11

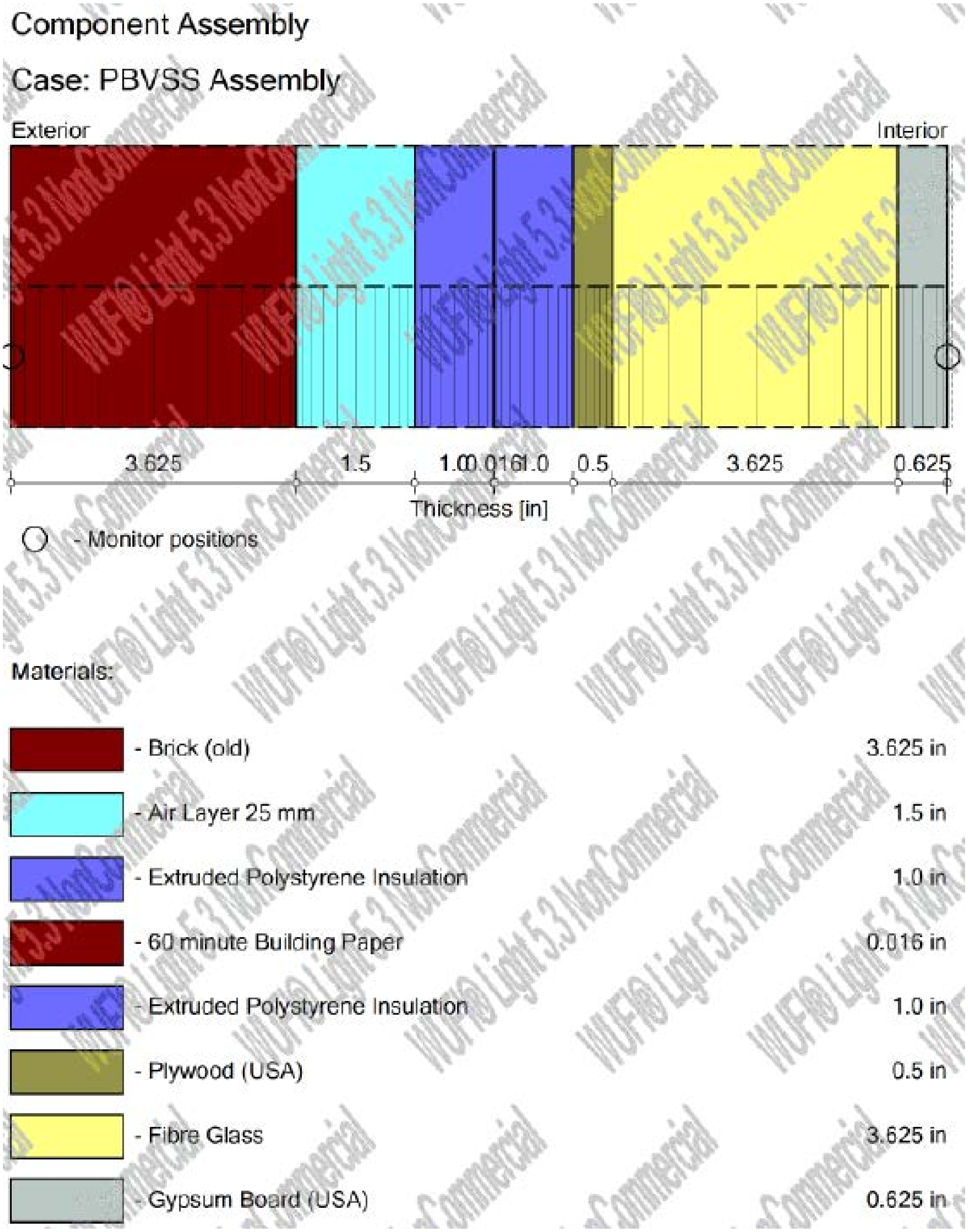
Hygrothermal Sources

Heat Sources	[Btu/ft^2]	0.0
Moisture Sources	[lb/ft^2]	0.0
Unreleased Moisture Sources (due to cut-off)	[lb/ft^2]	0.0


Air Temperature, RH (Exterior, Interior)
Exterior Air
Interior Air
Air Temperature [°F]
150
110
70
30
-10
Exterior Air
Interior Air
Relative Humidity [%]
100
75
50
25
0
0
121.7
243.4
365.1
486.8
608.5
730.2
Time [days]


Total Water Content in Construction
Total Water Content [lb/ft³]
5
4
3
2
1
0
0
121.7
243.4
365.1
486.8
608.5
730.2
Time [days]

PBVSS


Component Assembly
Case: PBVSS Assembly
Exterior
Interior
3.625
1.5
1.0
0.016
1.0
0.5
3.625
0.625
Thickness [in]
- Monitor positions
Materials:
- Brick (old) 3.625 in
- Air Layer 25 mm 1.5 in
- Extruded Polystyrene Insulation 1.0 in
- 60 minute Building Paper 0.016 in
- Extruded Polystyrene Insulation 1.0 in
- Plywood (USA) 0.5 in
- Fibre Glass 3.625 in
- Gypsum Board (USA) 0.625 in

Boundary Conditions

Exterior (Left Side)

Location: Baltimore, MD; cold year
Orientation / Inclination: South / 90 °

Interior (Right Side)

Indoor Climate: ASHRAE 160P
Heating only; 5.04 °F; 69.98 °F
M.Rate 0.83 lb/h; A.Ch.Rate 0.2 1/h; Vol. 17657.3334 ft³
Humidity Ratio Wo -1.0000 lb/lb

Surface Transfer Coefficients

Exterior (Left Side)

Name	Description	Unit	Value
Heat Resistance - includes long-wave radiation	External Wall	[h ft² °F/Btu]	0.3339 yes
Permeance	No coating	[perm]	----
Short-Wave Radiation Absorptivity	Brick, red	[-]	0.68
Long-Wave Radiation Emissivity	Brick, red	[-]	0.9
Adhering Fraction of Rain	Depending on inclination o	[-]	0.7
Explicit Radiation Balance			no

Interior (Right Side)

Name	Description	Unit	Value
Heat Resistance	External Wall	[h ft² °F/Btu]	0.7098
Permeance	Gypsum board	[perm]	32.8

Results from Last Calculation

Status of Calculation

Calculation: Time and Date	2/27/2015 6:28:46 PM
Computing Time	4 min,51 sec.
Begin / End of calculation	10/1/2015 / 10/1/2017
No. of Convergence Failures	9

Check for numerical quality

Integral of fluxes, left side (kl,dl)	[lb/ft²]	10.86 -10.78
Integral of fluxes, right side (kr,dr)	[lb/ft²]	2.9E-9 0.13
Balance 1	[lb/ft²]	-0.07
Balance 2	[lb/ft²]	-0.05

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	0.3	0.24	0.14	3.1

Water Content [lb/ft³]

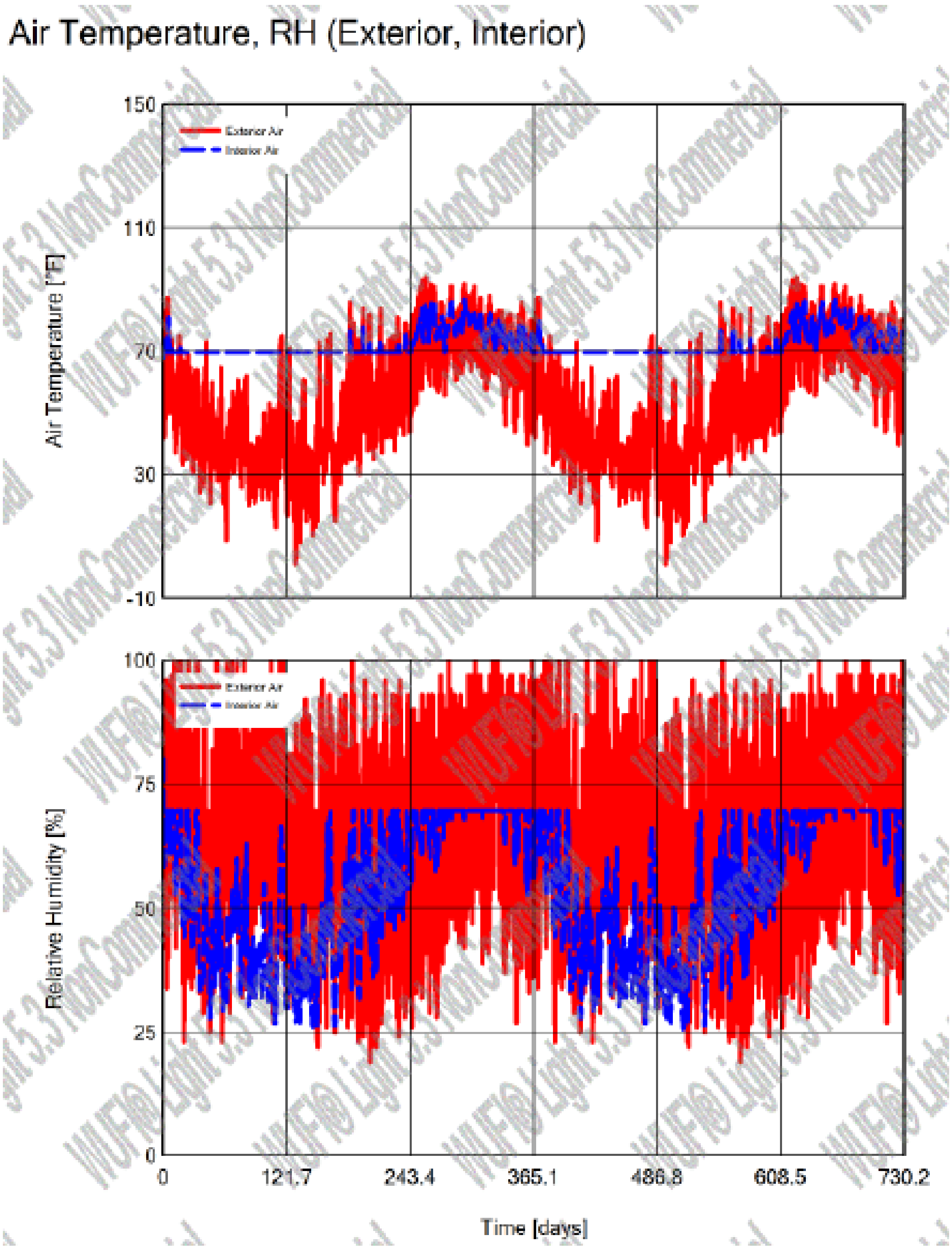
Layer/Material	Start	End	Min.	Max.
Brick (old)	0.21	0.21	0.06	9.47
Air Layer 25 mm	0.12	0.17	0.02	0.84
Extruded Polystyrene Insulation	0.02	0.02	0.00	0.07
60 minute Building Paper	0.00	0.00	0.00	0.00
Extruded Polystyrene Insulation	0.02	0.02	0.01	0.02
Plywood (USA)	4.02	2.87	2.45	4.05
Fibre Glass	0.12	0.06	0.02	0.12
Gypsum Board (USA)	0.39	0.26	0.11	0.39

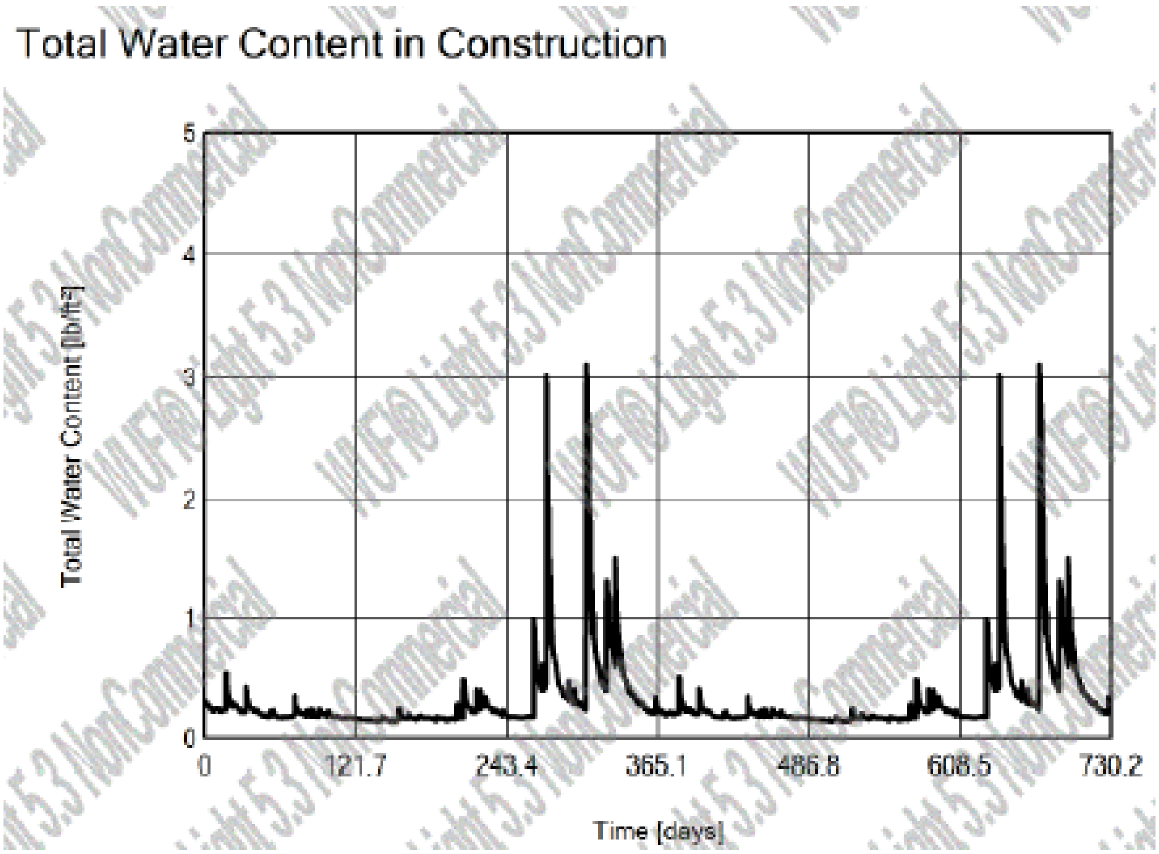
Time Integral of fluxes

Heat Flux, left side	[Btu/ft²]	-6082.6
Heat Flux, right side	[Btu/ft²]	-5991.49
Moisture Fluxes, left side	[lb/ft²]	0.07
Moisture Fluxes, right side	[lb/ft²]	0.13

Hygrothermal Sources

Heat Sources	[Btu/ft²]	0.0
Moisture Sources	[lb/ft²]	0.0


Air Temperature, RH (Exterior, Interior)
Exterior Air
Interior Air
Air Temperature [°F]
150
110
70
30
-10
Relative Humidity [%]
100
75
50
25
0
0
121.7
243.4
365.1
486.8
608.5
730.2
Time [days]


Total Water Content in Construction
Total Water Content [lb/ft³]
0
1
2
3
4
5
0
121.7
243.4
365.1
486.8
608.5
730.2
Time [days]
WUFI® Light 5.3 NonCommercial

APPENDIX E: DESIGN LOADS

DESIGN CRITERIA

BUILDING CODES AND REGULATIONS

INTERNATIONAL BUILDING CODE (IBC) 2009
VIRGINIA CONSTRUCTION CODE (VCC) 2009

LIVE LOADS:
SECTION 1607 IBC
CHAPTER 4 ASCE 7

RESIDENTIAL MULTIFAMILY DWELLINGS:

- PRIVATE ROOMS AND CORRIDORS SERVING THEM: 40PSF
- PUBLIC ROOMS AND CORRIDORS SERVING THEM: 100PSF

- STAIRS AND EXIT WAYS: 100PSF
- YARDS AND TERRACES, PEDESTRIAN: 100PSF
- GARAGES, PASSENGER VEHICLES: 40PSF, 3000LB CONCENTRATED
- VEHICULAR DRIVEWAYS, LOADING: 250PSF, 3000LB CONCENTRATED
- FIRE TRUCK LOADING: 350PSF, 30,000LB CONCENTRATED

MINIMUM LOADS:

- ROOF: 30 PSF
- ALL INTERIOR WALLS AND PARTITIONS SHALL BE DESIGNED TO RESIST A MINIMUM HORIZONTAL LOAD: 5 PSF

APPENDIX F: POST-TENSION NOTES

E 0' 4' 8'

TYPICAL PT NOTES:

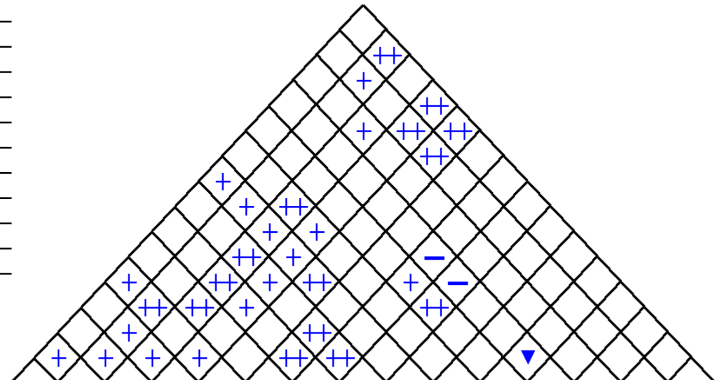
1. UNLESS NOTED OTHERWISE SLAB THICKNESS IS 7" WITH A GENERAL BOTTOM REINFORCING MAT OF #4 @ 24" O.C. IN BOTH DIRECTIONS.
2. "XXX K" BANDED - INDICATES THE TOTAL EFFECTIVE TENDON FORCE (KIPS) IN BANDED TENDONS.
3. "XXX K/FT" UNIFORM - INDICATES THE TOTAL EFFECTIVE TENDON FORCE (KIPS PER FOOT) IN UNIFORMLY SPACED TENDONS.
4. UNLESS OTHERWISE NOTED ON PLAN, TENDON PROFILE HEIGHTS SHALL HAVE A 1.0" TOP COVER OVER SUPPORTS, A 1.0" BOTTOM COVER AT MID-POINTS OFSPANS, AND BE LOCATED AT THE CENTROID OF THE SLAB/DROP/BEAM SECTION AT SLAB EDGES (TOTAL SECTION THICKNESS/2).
5. PROVIDE CONTINUOUS BRICK SUPPORT AT EVERY FLOOR (REFER TO TYPICAL DETAILS FOR BRICK SUPPORT ASSEMBLY INFORMATION).
6. PROVIDE 2#5 X CONTINUOUS ADDITIONAL BARS TOP AND BOTTOM AROUND THE PERIMETER OF ALL SLAB EDGES. SPLICE TOP BARS AT MID SPAN AND BOTTOM BARS AT COLUMNS.
7. AT ALL BALCONIES PROVIDE EPOXY COATED REBAR FOR TOP AND BOTTOM STEEL, PROVIDE A BOTTOM MAT OF #4@12 FOR THE EXTENTS OF THE BALCONY.
8. [SRX] INDICATES SHEAR STUD REINFORCEMENT, SEE SHEET S5.4 FOR ADDITIONAL INFORMATION.
9. PROVIDE ADDITIONAL LATERAL SLAB REINFORCING PER TYPICAL DETAILS, SEE DETAIL 6/S5.3 FOR ADDITIONAL INFORMATION.

1. POST-TENSIONING TENDONS SHALL BE LOW-RELAXATION STRAND CONFORMING TO THE FOLLOWING:
- SEVEN WIRE STRAND ASTM A416
- MINIMUM ULTIMATE STRENGTH OF 270KSI
- 1/2" DIAMETER TENDON AREA = 0.153 in2

2. END ANCHORAGE DEVICES SHALL MEET THE MINIMUM REQUIREMENTS OF POST-TENSIONING INSTITUTE (PTI) AND ACI.
3. TENDONS SHALL BE SUPPORTED ON REINFORCING BARS SPACED AT A MAXIMUM OF 4 FT. ON CENTER AND SHALL BE SECURED TO POSITIONING DEVICES AT EACH TENDON/SUPPORT BAR INTERSECTION TO ENSURE THAT THE CORRECT VERTICAL AND HORIZONTAL LOCATION IS MAINTAINED DURING PLACING OF CONCRETE.
4. CONCRETE SHALL REACH A MINIMUM COMPRESSIVE STRENGTH OF fc'=3000 PSI OR 75% OF SPECIFIED 28 DAYS CONCRETE STRENGTH PRIOR TO STRESSING. THE MINIMUM CONCRETE STRENGTH SHALL BE ESTABLISHED BY BREAKING CONCRETE TEST CYLINDERS. STRESSING SHALL NOT COMMENCE UNTIL THE CONCRETE REACHES THE SPECIFIED STRENGTH.
5. POST TENSIONED BEAM STIRRUPS SHALL CONFORM TO ASTM-A615, GRADE 60.
6. AFTER STRESSING TENDONS, SHALL BE CUT SUCH THAT A MINIMUM COVER OF 1" IS ACHIEVED.
7. DETAILED SHOP DRAWINGS SHOWING LAYOUT OF ALL TENDONS STRESSING SEQUENCE AND EXTENT OF CONCRETE POUR ARE TO BE SUBMITTED FOR APPROVAL.
8. CONTRACTOR SHALL SUBMIT RECORDS OF ELONGATION & JACK FORCE TO ENGINEER. FIELD READINGS OF ELONGATIONS AND OR STRESSING SHALL NOT VARY BY MORE THAN ± 7% FROM CALCULATED REQUIRED VALUES SHOWN IN SUBMITTALS.
9. GROUT ALL POST TENSIONED GIRDERS AFTER ALL TENSIONING IS COMPLETED AND APPROVAL RECEIVED FROM THE ENGINEER WHERE NOTED/SCHEDULED ON DRAWINGS.
10. ALL INSERTS FOR SUSPENDED MECHANICAL AND ARCHITECTURAL WORK SHALL BE CAST IN PLACE. POWER DRIVEN FASTENERS WILL BE PERMITTED ONLY AFTER SPECIFIC APPROVAL FROM THE STRUCTURAL ENGINEER IS RECEIVED.
11. ANCHORAGE DEVICES SHALL BE RECESSED A MIN. OF 2". TWO (2) CONTINUOUS #4 BACKUP BARS SHALL BE PLACED BEHIND ALL ANCHORAGES AT SLABS UNLESS NOTED OTHERWISE.
12. TENDONS SHALL BE SHOP FABRICATED WITH PRE-ASSEMBLED FIXED END ANCHORAGES. PLASTIC POCKET FORMERS SHALL BE USED AT ALL STRESSING ENDS TO RECESS THE ANCHOR CASTING SO THAT THE REQUIRED COVER IS ACHIEVED.
13. FORCES SHOWN ON STRUCTURAL DRAWINGS ARE EFFECTIVE FORCES AFTER ALL LOSSES.
14.VERTICAL PROFILE SHALL CONFORM TO CONTROL POINTS SHOWN ON THE DRAWINGS AND SHALL BE AN APPROXIMATE PARABOLIC DRAPE BETWEEN SUPPORTS UNLESS NOTED OTHERWISE. LOW POINTS SHALL BE AT MID-SPAN UNLESS NOTED OTHERWISE. HARPED TENDONS SHALL BE STRAIGHT BETWEEN HIGH AND LOW POINTS.
15. WHEN TENDONS CURVE HORIZONTALLY,TENDON GROUPS SHALL BE FLARED SUCH THAT A MINIMUM OF 2 INCHES OF SEPARATION IS MAINTAINED BETWEEN EACH INDIVIDUAL TENDON. TENDONS SHALL BE FLARED A MAXIMUM OF 1:6. IF TENDONS ARE FLARED AT MORE THAN 1:12, #3 HAIRPINS @ 12" ON CENTER SHALL BE USED TO TRANSFER THE HORIZONTAL RADIAL FORCE TO THE CONCRETE UNLESS NOTED OTHERWISE.
16. ALL DIMENSIONS SHOWING THE LOCATION OF PRESTRESSING TENDONS ARE TO THE CENTER OF GRAVITY OF THE TENDON UNLESS NOTED OTHERWISE.
17. BLOCKOUTS/POCKETS REQUIRED FOR ACCESS TO ANCHORAGE IN BEAMS AND SLABS SHALL BE REINFORCED SO AS NOT TO DECREASE THE STRENGTH OF THE STRUCTURE. ALL BLOCKOUTS AND POCKETS SHALL BE SEALED IN SUCH A MANNER AS TO ELIMINATE WATER LEAKAGE THROUGH OR INTO THE BLOCKOUT OR POCKET. LOCATIONS OF ALL BLOCKOUT AND POCKETS SHALL BE APPROVED BY THE ENGINEER.
18. THE POST-TENSIONING SUPPLIER SHALL PROVIDE LOSS AND ELONGATION CALCULATIONS FOR APPROVAL BY THE ENGINEER.
19. OPENING, PENETRATION AND EMBED LOCATIONS SHALL BE DETERMINED PRIOR TO TENDON LAYOUT. NO CHANGES SHALL BE MADE IN THE FIELD WITHOUT PRIOR APPROVAL OF THE ENGINEER.
20. FOR SLABS, UNBONDED TENDONS SHALL BE ENCASED IN A SLIPPAGE SHEATHING (MIN. THICKNESS = 50mil.) PROVIDING WATERTIGHT ENCASEMENT OF THE CORROSION INHIBITING COATING MATERIAL (P-T COATING) SO AS TO PREVENT THE INTERNAL MIGRATION OF ANY WATER. SHEATHING SHALL BE OF SUFFICIENT STRENGTH AND DURABILITY TO RESIST DAMAGE DURING NORMAL FABRICATION, INSTALLATION, AND CONCRETE PLACEMENT OPERATIONS.
21. IN TWO-WAY SLAB CONSTRUCTION, A MINIMUM OF TWO TENDONS SHALL BE PLACED DIRECTLY OVER THE SUPPORTING COLUMN (WITHIN THE COLUMN CAGE), IN EACH ORTHOGONAL DIRECTION.
22. CONCRETE MIX DESIGN SHALL BE SUCH THAT THE SPECIFIED MINIMUM CONCRETE STRENGTH FOR STRESSING IS ACHIEVED WITHIN 72 HOURS. SLAB TENDONS SHALL BE STRESSED WITHIN 24 HOURS OF ACHIEVING MINIMUM SPECIFIED CONCRETE STRENGTH FOR STRESSING.
23. STRESSING JACKS AND GAUGES SHALL BE INDIVIDUALLY IDENTIFIED AND CALIBRATED TO KNOWN STANDARDS.
24. TO MINIMIZE MOISTURE ACCESS TO THE TENDONS, ANCHORAGE POCKETS SHALL BE FILLED WITH NON-SHRINK GROUT AS SOON AS POSSIBLE AFTER STRESSING.

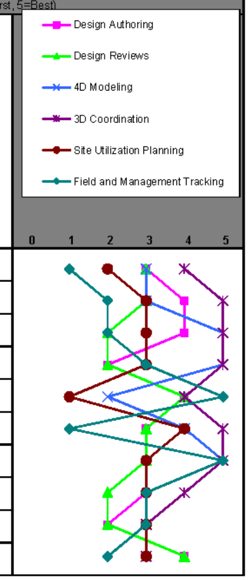
APPENDIX G: HOUSE OF QUALITY WITH BIM TOOLS

Title: BIM tool for SIPS for Interior Fit-out
Author: B. Kerem Demirci
Date:
Notes:



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	1 Cost of technology	2 Management labor cost	3 Time spent prior to construction	4 Time spent during construction	5 Learning curve of processs	6 Design issues prevented	7 Rework time saved	8 Quality issues prevented	9 Training required	10 Visuals produced to aid communication	11 Labor effieciency and production	12 Wasted labor time	13 Problem areas of construction process identified	14 Intervals of iterations	15 Time spent per iteration	Design Authoring	Design Reviews	4D Modeling	3D Coordination	Site Utilization Planning	Field and Management Tracking
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▼	▼	▼	▲	▲	▲	▼	x	▲	▼	▲	▲	▼						
1	9	5.5	4.0	Finish under budget	Θ	Θ				▲	O	O	▲		Θ	▲		▲	▲	3	3	3	4	2	1
2	9	12.3	9.0	Finish on budget	Θ	▲				▲	O	O	▲		Θ	▲		▲	▲	4	3	3	5	3	2
3	9	13.7	10.0	Finish on time			O	Θ	O	Θ	Θ	▲	O		Θ	Θ	Θ	Θ	Θ	4	2	5	5	3	2
4	9	13.7	10.0	Efficient phased turnover of floors			Θ	Θ	O	Θ	Θ	▲	O		Θ	Θ	Θ	Θ	Θ	2	2	5	5	3	3
5	9	8.2	6.0	Improved quality control			O			O	O	Θ					▲	▲		4	4	2	4	1	5
6	9	5.5	4.0	Increased comunication between trades				▲		▲		O	▲	Θ			Θ			3	3	4	5	4	1
7	9	13.7	10.0	Easily integrated with SIPS					▲	Θ	▲			O	Θ	O	Θ	Θ	O	3	3	5	5	3	5
8	9	8.2	6.0	Easy to use (gc and subs)		O	Θ	Θ	Θ				Θ	O	▲			O	▲	3	2	4	4	3	3
9	9	8.2	6.0	Easy to learn (gc and subs)		O	Θ	Θ	Θ				Θ	▲	▲			▲	▲	2	2	3	3	3	3
10	9	11.0	8.0	Tool is cost effective	Θ	▲														4	4	3	3	3	2
				Target or Limit Value																					
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)																					
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9						
				Weight / Importance	258.9	121.9	337.0	400.0	243.8	417.8	338.4	171.2	253.4	123.3	546.6	305.5	427.4	428.8	321.9						
				Relative Weight	5.5	2.6	7.2	8.5	5.2	8.9	7.2	3.6	5.4	2.6	11.6	6.5	9.1	9.1	6.9						

Competitive Analysis (0=Worst, 5=Best)



Legend

Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

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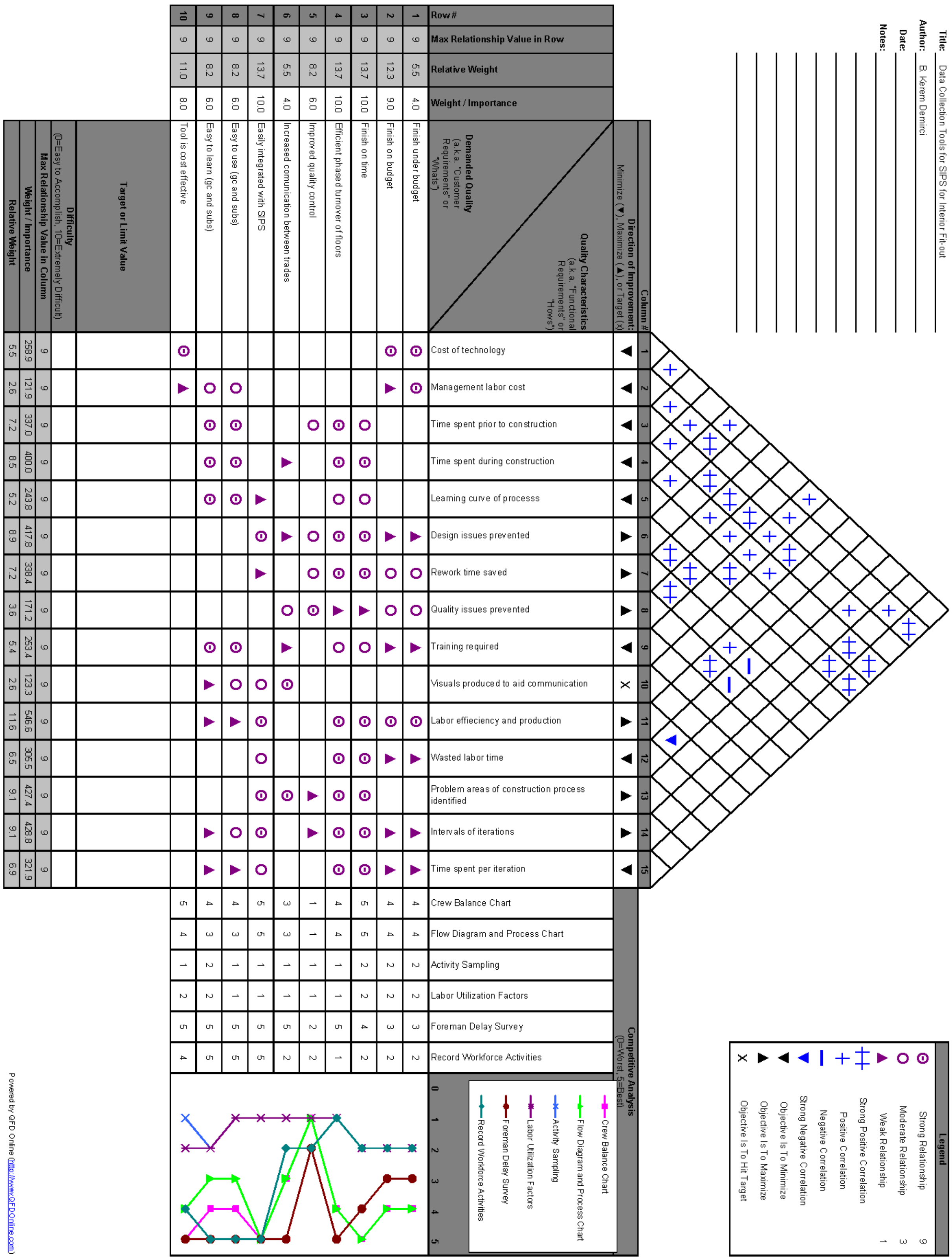
APPENDIX H: HOUSE OF QUALITY WITH DATA COLLECTION TOOLS



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