THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ARCHITECTURAL ENGINEERING

DESIGN AND CONSTRUCTION ANALYSIS OF THE PERFORMING ARTS CENTER & A PROPOSAL FOR 3D PRINTING ARCHITECTURAL STRUCTURES TO SCALE

ERIC WILDEY LUTTMANN
SPRING 2016

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Architectural Engineering
with honors in Architectural Engineering

Reviewed and Approved by the following:

John Messner
Professor of Architectural Engineering
Thesis Supervisor

Richard Mistrick
Professor of Architectural Engineering
Honors Adviser

* Signatures are on file in the Schreyer Honors College.

ABSTRACT

This report is divided into two sections. The first section consists of a proposal comprised of the design and construction of a multiple story building structure through additive building manufacturing (ABM) techniques made feasible by a concrete-extruding 3D printer. In the second portion of this report, the Performing Arts Center, a premier University music and performing arts facility, is investigated in-depth from a design and construction standpoint. The focus of this section includes three analyses that recommend alternative construction methods and designs to the project team.

Additive Building Manufacturing

Automated construction through a digital fabrication technique known as additive building manufacturing can enhance the building industry by ushering in the next era of architectural design through the emergence of radical geometries and by providing commercial construction the benefits of safety, efficiency control and quality. To illustrate the feasibility of additive building manufacturing, a proposal to 3D print a two-story structure using on-site concrete extrusion is presented. Through a literature review, potential and existing approaches to additive building manufacturing and automated construction are investigated. The review is organized in the following categories: the need for automation of construction; the opportunity digital construction presents to the architectural, engineering and construction industry; the feasibility of the proposal based on the file-to-fabrication process; fabricator and material design; the actual implementation of these categories; and finally gaps in the technology.

The Performing Arts Center

The Performing Arts Center is designed as a state of the art performance and teaching space for the music department, theater, dance, creative and performing arts at a University in New Jersey. In this report, the four building program, consisting of the Theater and Dance building, the Music Building, the Arts Tower and the DRUM theatre, is examined to illustrate the owner's goals, the architectural design intentions, the major building systems, and general construction means and methods. Furthermore, the façade system is examined from a constructability, logistics and production standpoint. Then, project challenges and opportunities are illustrated. After that, a building information modeling (BIM) use evaluation and a sustainability implementation analysis are presented. After presenting the existing, technical details of the project, three major analyses constitute the focus of this section. The first analysis is a Cast-in-Place Concrete Wall Schedule Acceleration analysis in which schedule and cost of using Peri Trio steel wall forms are compared against the proposed Peri Maximo wall forms. Then, the second analysis focuses on implementing Construction Robotics' Semi-Automated Mason (SAM) to install an Alaskan White Velour brick façade in place of a Lecce limestone finish in order to meet the critical path schedule delayed by the façade construction schedule. Finally, in order to improve energy performance, a fan-powered induction unit (FPIU) system is compared to a VAV system based on yearly energy consumption, cost savings and constructability.

Table of Contents

List of Figures

List of Tables

Acknowledgements

Thanks to the University and Turner Construction Company, in particular the entire Performing Arts Center Team, for allowing me to study this project, and for assisting me with pertinent analyses and questions. I'd like to personally thank Don Deakyne for the time he has spent assisting me with this project and a big thanks to Chris Beck for inspiring me to study this project and for introducing me to the project team.

I am also very grateful to have had Dr. John Messner as an advisor and mentor throughout my investigation of 3D printing capabilities in construction, the Performing Arts Center project, and for inspiring me to see the industry from a research perspective. I'd also like to thank Dr. Mistrick for serving as my advisor for this project.

I'd like to thank my friends for inspiring me to dive into the idea of 3D printing a building and for helping me focus on the details from a mechanical, software, hardware and architectural standpoint.

PART 1: PROPOSAL & LITERATURE REVIEW FOR 3D PRINTING ARCHITECTURAL STRUCTURES TO SCALE

Chapter 1

The W: A solution to 3D printing architectural structures to scale

Suppose you are in San Francisco, California where the average building footprint is roughly 5,600 square feet. Along Folsom Street, a street that runs vertically through the Mission District, a local developer is constructing a new, multi-story co-working space that will be home to incubators and start-up technology companies. Since the building itself will be home to ideators, technologists and innovators, the owner has stipulated that the building structure must be constructed through automated technology.

During site investigation, it is determined that the plot of land is 74 ft. x 92 ft. or 6800 square feet, with the shorter side adjacent to the eastern stretch of Folsom St. The integrated project delivery team consisting of the architect, construction management company and engineers decides that the building structure will be constructed on-site through additive building manufacturing (ABM) methods. In particular, 3D concrete extrusion printing is leveraged. In the literature review of this report, the main forms of automated construction investigated include stereolithic printing, concrete extrusion, and assembly using six axis robotic systems. Stereolithic printing may not be scalable to a multi-story architectural scale since a mass of powder is necessary to structurally support the concrete until it solidifies. Containing tons of loose powder in-situ would be extremely difficult with wind and variable conditions. Therefore, additive concrete extrusion through concrete-depositing nozzles proves to be the most viable solution to create scalable architecture. While a six-axis robot should not be the main form of fabrication, this system can serve as an aid in automating construction by moving materials such as metal reinforcement or finish materials. Utilizing a gantry system with multiple end effectors presents the opportunity to leverage a six-axis robot in addition to a deposition nozzle.

Since this is a multiple story co-working space, it is important that the design of the building be configured so that the building can be additively constructed in a seamless, automated manner from floor to floor. As of this writing, it appears that all of the concrete-extruding 3D printers either only reach a single story construction height or additively construct building components and then manually assemble them to multiple floors. The latter technique is essentially glorified prefabrication. As a result, we have W, the solution to constructing multistory building structures solely through automated means.

Building Design

The key design and fabrication goal of this building structure is to create a fluid geometry from the structural walls, to the floor form, to the next set of walls and so on. Essentially, the structure is a single flowing form that can be constructed using the W and with no on-site, manual labor. In contrast to this singular form building, modern building construction has mainly resorted to creating vertical walls that intersect at 90 degrees with a composite floor slab (Figure 1). Rather than designing to this separation of form, the wall and floor can become one.

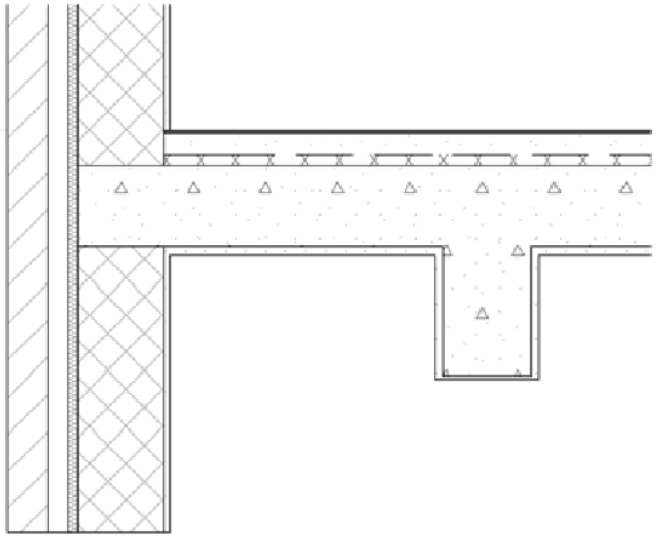


Figure 1: Composite slab intersects structural wall at 90 degree angle

In order to create this fluid transition of form, a bridging arch is created between two structural walls, which can support the additive construction of a flat floor system. This technology is enabled through a slight overhang or cantilever that can be created with each layer of extruded material. Thus, structural walls are first created through additive extrusion.

Structural Wall Construction

In order to create a structural wall, single concrete layers at 30 mm width, 10 mm height and 10 mm depth are laid along the long axis of the building. There are two outer structural walls and one in the center. Each wall runs 84 feet to span the building footprint. It can be assumed that the outer structural walls and interior structural walls are 2 feet thick. The inner structural walls will rise 10 feet as regular, rectangular prism walls, then arches will branch off to each side. For this structure, it is assumed that the walls are solid concrete, rather than single layers with air gaps and steel reinforcement between them. The latter design is leveraged by Contour Crafting, Loughborough University and TotalKustom in their concrete extruded wall construction. Therefore, the width of these walls will be laid with twenty, 30 mm thick concrete extruded strips to reach a 2 foot thickness. Each layer will be laid the entire length of the wall and then the extrusion head will reverse its trip to continue a parallel layer directly next to the previous. Once 10 strips are extruded in parallel, another layer will start. Note that the supporting structural wall below needs to be thicker in size to the one above.

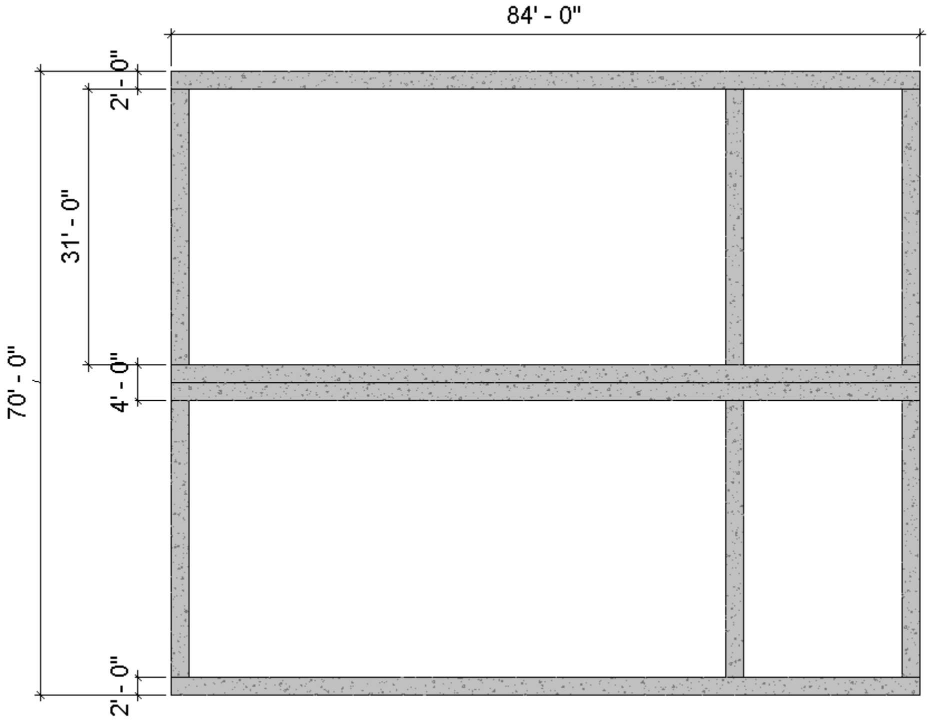


Figure 2 : Floor Plan displaying structural wall layout

Material Design & Overhang Angle Constraint

In order to build the bridging arch, each horizontal layer of the wall is supplemented with an additional strip along the edge that will create an overhang. Eventually this continual overhang creates one-half of a barrel vault arch and if done so on the parallel wall, a full barrel vault can be created between the two walls. It should be noted that the wall structure continues to grow vertically with the overhang, thus creating a bridge-like structure with a horizontal top plane and a curved opening beneath it. As a result, this bridge creates a ceiling and the next story's floor.

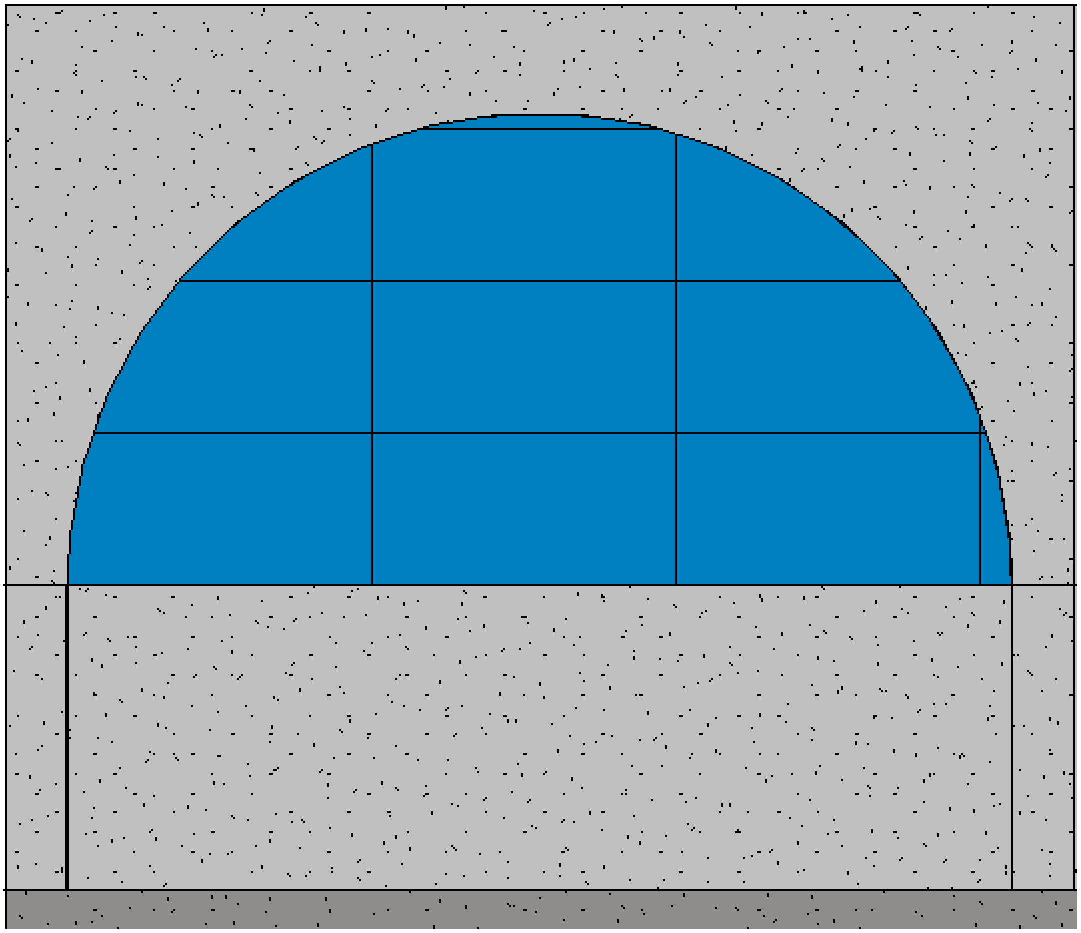


Figure 3: East Elevation illustrating bridging arch, which creates flat floor plane

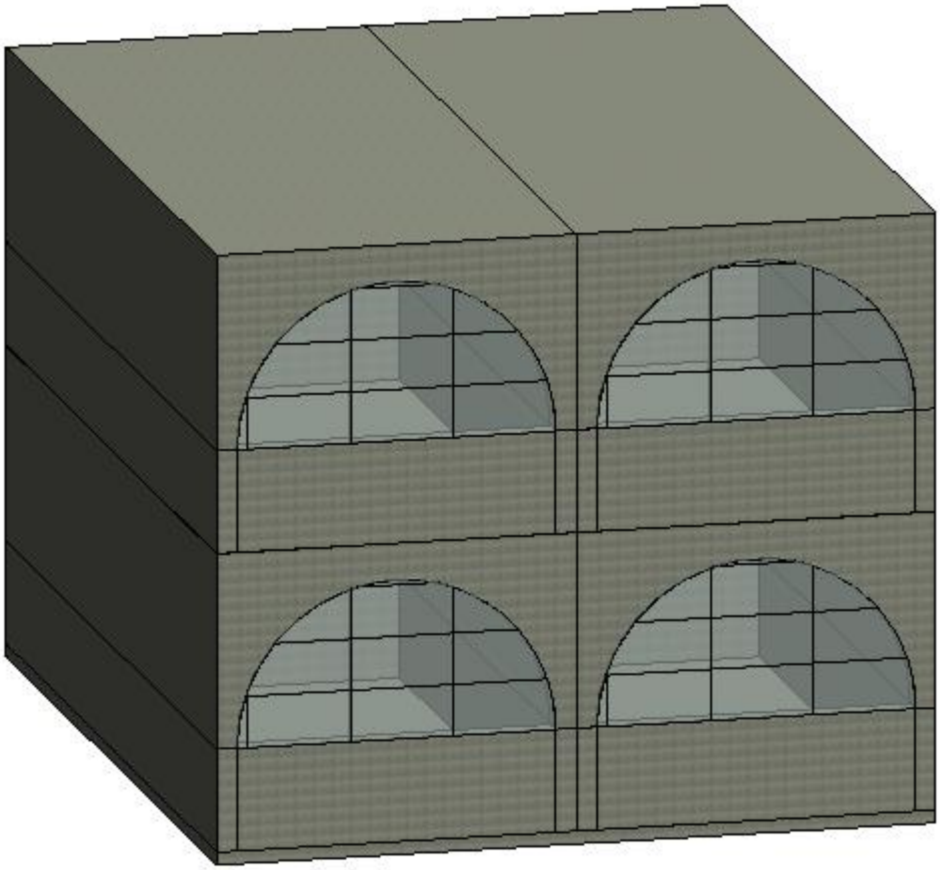


Figure 4: Concept model of multi-story 3D printed concrete structure

Overhang Constraint:

Assume that 10 mm of the extruded layer thickness overhangs from the existing structure. Since the height of the concrete extruded layers are also 10 mm, this creates a consecutive 45-degree angle of incline, which represents an arching geometry similar to that of a Catenary arch. In order to accrue a 45-degree angle of incline utilizing fresh, uncured concrete or composite solution, material property calculations need to be performed.

Although the concrete extrusion strips may have round edges, it is assumed that they can be treated as rectangular solids due to their fast-curing abilities with low deformability, high internal friction and high viscosity. Therefore, the overhang is treated as a cantilever with a fixed end point connection at the location where the base of the extruded layer begins to overhang the structure.

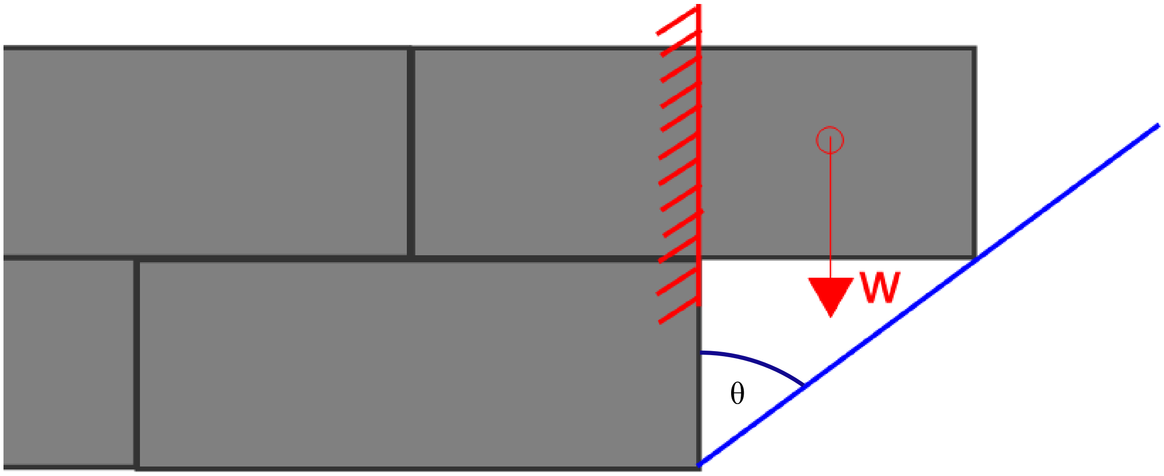


Figure 5: 45 Degree Overhang Extrusion assumed to be rectangular cantilever with fixed end

This type of overhang will rupture due to bending tensile stress in the top portion of the rectangular cross-section caused by self-weight. If the bending stress at the top layer of the strip exceeds the modulus of rupture for this material, the overhang and thus arching geometry is not feasible. For the scope of this material test, the density of a material is related to the modulus of rupture of the material in the following manner:

$$\boldsymbol{\rho > .855 * MOR \ (\frac{lb}{in^3})}$$

The steps to find this formula are illustrated below:

Given: $\sigma_{bending} = \frac{M*y}{I_x}$

$I_x = \frac{bh^3}{12}$

M = moment about neutral axis
σ = bending stress
y = distance to top from neutral axis
I_x = moment of area about neutral axis, x

b = cross sectional base
h = cross sectional height

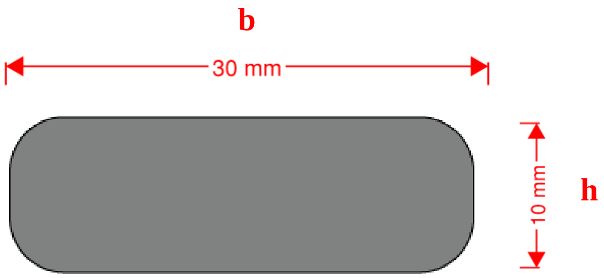


Figure 6: Cross Section of Concrete Extrusion

$$Cross\ Sectional\ Surface\ Area: \boldsymbol{b * h = A'}$$

$$Distributed\ Self\ Weight: \boldsymbol{w = \rho * A'}$$

$$\boldsymbol{w = \rho * b * h} \quad \left(\frac{\text{lb}}{\text{in.}}\right)$$

$$\boldsymbol{Moment = \frac{wl^2}{2} = \frac{(\rho * b * h) * (l^2)}{2}} \quad (in.\,lbf)$$

$$\boldsymbol{\sigma = \frac{\left[\frac{(\rho * b * h) * (l^2) \ * \ \frac{h}{2}}{2}\right]}{\frac{bh^3}{12}} = \frac{3\rho l^2}{h}} \quad (psi)$$

$$\boldsymbol{\sigma_b > Modulus\ of\ Rupture\ (MOR)}$$

$$\boldsymbol{\frac{3\rho l^2}{h} > MOR}$$

$$\boldsymbol{\rho > \frac{(MOR) * h}{3l^2}}$$

$$\boldsymbol{\rho > \frac{(MOR) * (.39\ in.)}{3(.39\ in.)^2}}$$

$$\boldsymbol{\rho > .855 * MOR\ \left(\frac{lb}{in^3}\right)}$$

The concrete or composite material chosen for the printer needs to fit the above constraint in order to create an arched geometry building design. By comparing the density to the modulus of rupture, a specific concrete mixture can be created. While a specific mixture is not in the scope of this proposal, the uncured material needs to have low deformability, fast curing ability, high viscosity, high internal friction and high surface tension. A potential mixture would be to combine around 50% sand, 40 % cementitious compound and 10% water. In the cementitious compound, bases, hydrators and adhesives can be utilized to give the product shape (Rael 2015). The image below illustrates an example of arched geometry 3D printed by overhanging concrete layers.

Figure 7: Cantilevered concrete layers additively extruded by TotalKustom. Source: TotalKustom.com

Gantry Frame

Delta frames, cable-suspended deposition nozzles, and gantry or Cartesian frames were compared in the design of a frame system to additively construct using concrete extrusion. Due to the large scale of the building site, it is important to have multiple deposition heads running independently but also maintain nozzle translational speed and precision as well as robustness in a natural environment. Delta printers do not offer an optimal ratio for a building footprint and also do not offer optimal build-volume compared to printer-volume ratio. Furthermore, delta frames are known to shake when reaching their structure's resonant frequency. The cable-suspended deposition option appears viable since it offers flexibility and ease of movement through pulley systems. However, in order to control the nozzle head from swinging horizontally there needs to be some sort of tensile force to control the head precisely. With a single deposition head, there is still significant room for error in this design, nevertheless, it becomes extremely intricate with multiple deposition heads. As a result, the gantry frame design is most appropriate since it offers the ability to leverage multiple deposition heads with precision, robustness and moderate speed in the x-y-z axes.

With a building footprint of 84' x 70' x 25', W will take form as a rectangular gantry frame with dimensions of 90' x 72' x 30'. The building footprint can be seen in figure 2 and a concept design for the gantry can be seen in figure 8. The frame will be supported by four vertical 3' x 3' steel support columns in the corners of the rectangular plan. These structures will provide the strength and rigidity to support the gantry system and allow for high-speed linear applications. Along the north-south axes, 2' x 2' horizontal truss members with linear guide rails will be attached to these vertical supports at the top (30') and base. However, the east and west stretching truss beams will be strictly for structural support, with no rail capability. As a result a rectangular prism frame is formed.

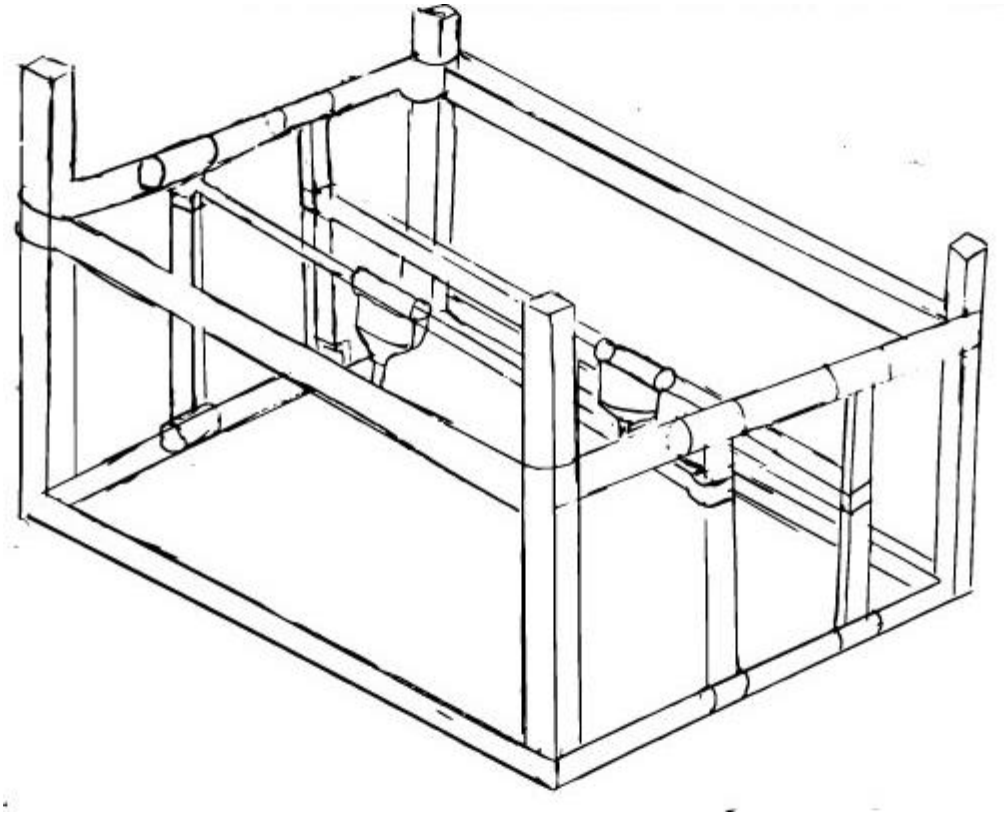


Figure 8: Double Gantry Frame Design

To reach high-speed automation, each printing head will be supported on a gantry system that will also give it x-y-z translation capabilities. A two-gantry system means two printing heads are capable of acting independently over the building site, one operating over the northern spectrum and one operating over the southern spectrum.

On each north-south spanning member, there will be a belt driven linear actuator motor used to drive the carriage attached to a vertical member that spans between the horizontal members. A belt drive is best for the x-y linear translation since it is capable of reaching high speeds for long travel lengths and does not create as much backlash as using lead screws (Dabbletron 2016).

The vertical members in between the north-south horizontal members will contain a planetary roller screw actuator to create linear motion in the z-axis. Using this type of lead screw creates substantial force and is self-locking in case of power source error or controller error. Due to the high stresses that will occur on a scalable printing device, the roller screw is the best option to offer high levels of robustness in natural environments, substantial carrying capacity but still maintain the ability for speed, acceleration and precision in the vertical axis (SKF 2016).

Attached to the nuts on the parallel vertical members will be a horizontal member that allows the extrusion head to translate east-west across the construction site. A belt driven linear actuator will again serve this linear motion. Note that two of these systems will exist in total so that the two printing heads can act independently both horizontally and vertically. Therefore, one extrusion head could be printing at an 8 ft. height in the lower left quadrant of the site, while the other print head operates at maximum height in the upper quadrant.

As an improvement to Contour Crafting’s multiple gantry design, this system has linear guides along the top and bottom of the frame. As a result, stresses created on the base guide rails can be relieved by the guide rail gantries on the top. This allows for faster and more accurate translation of the nozzle head since there will be belt-driven actuators on both horizontal levels, rather than focusing all of the translational motion and stress on the bottom base rail system.

Along the farthest north area of the frame, there will be a dock area off-site where the two-gantry system can rest. This allows for access to the extrusion heads themselves beyond the building footprint so they can be maintained when needed.

File to Fabrication Process & Software

Since the nozzle head tool path and material deposition is completely dependent on the fabrication information model (FIM), construction is the most seamless part of the building lifecycle. FIM represents this lifecycle which runs from the computer aided design (CAD) model to computer aided engineering analysis (CAE) to the computer aided manufacturing model (CAM) which controls the end effector and gantry of the printer (Oxman 2015). Essentially once the model is completed, tested for engineering and design analysis and machine control scripts are created, one only needs to hit print in order to construct the structure of a building.

The goal is to create end-to-end integration from the modeling standpoint to the physical product through a streamlined file-to-fabrication process. A potential solution would be to use Rhino Grasshopper with existing plug-ins for material surface analysis and custom developed plug-ins for machine control. It is essential that during the design process, the building information model incorporates material properties and behavioral constraints. Furthermore, the models cannot have voided geometries, and must be solid similar to an STL file. STL conversion to G Code is a potential solution to controlling the printer. However, to achieve precision in the physically printed material, BIM needs to describe micro-scale physical properties of materials and internal composition based on voxels and finite elements (Oxman 2010). To prevent impact of gantries on the multi-machine system, the buffer zone path cycling algorithm introduced by Contour Crafting is a potential solution. This presents the fastest option to using a multi-gantry solution that created buffer zones between end effectors during fabrication. To see comparison of existing and proposed file-to-fabrication processes, see the *Process* sections in the Literature Review.

Conclusion

This proposal serves as an initial concept for a multi-story 3D printed, concrete structure. While the proposed design concept, material constraints and gantry design are discussed in detail, many aspects of this process are outside the scope of this proposal. Areas to be addressed in the future include material selection, reinforcement capabilities, structural analysis based on material, material pressurization, material extrusion speed, additional finish materials and mechanical, electric and plumbing systems. Considerable hardware portions of the printer itself need to be discussed including the nozzle and end-effector design, the pump system, and the trowel for smoothing material. Process topics that need to be addressed include the speed of the printer, the tool path and the firmware leveraged. Although potential solutions for the software were discussed, an entire lifecycle software process needs to be designed for this printer. Most importantly, a short and long-term cost analysis for using this type of technology is imperative. While many gaps exist for the design of this printer and construction process, the ability to automate construction through additive building manufacturing means exists. The implementation is imminent in the building industry.

Chapter 2

Literature Review: Additive Building Manufacturing & Automated Technology in Architecture

2.1 | Introduction

Building construction will evolve from a labor-intensive industry to one enabled by robotics and algorithmic control. Although other industries have shifted toward automotive assembly and engineering, construction has maintained its traditional methods due to innumerable variables in an uncontrolled environment. Furthermore, the architecture, engineering, construction and owner operator (AECOO) industry's focus is to develop prototyped products, rather than repetitive products produced from a single model. In other words, no two buildings are designed or built the same. Major issues include the "unsuitability of the available of automated fabrication technologies for large scale products" (Khoshnevis 2004) and limitations in the materials to be generated by automated systems. However, these challenges are being overcome as the technological advancement in large-scale robotics, material, and software abilities have put the AEC industry at the brink of creating buildings through digital, automated means.

Digital fabrication represents the process of using a computer aided design (CAD) model to drive material production using subtractive, machining technologies such as computer numerical control (CNC) routers, laser cutters or additive manufacturing, commonly referred to as 3D printing. Moreover, it is the enablement of machine control through computers to perform repeatable and programmable tasks that create a physical end product. "Additive manufacturing, or 3D printing, is the process by which to fabricate three-dimensional structures from digital files. Successive layers of material are deposited according to predetermined tool paths until the final form is completed" (Oxman 2014). In this report, digital fabrication can be defined as the process of creating an occupiable, architectural product through mechanical and robotic measures controlled by computers.

Digital Fabrication in construction is not a new research topic or industry technology. In fact, Japan experimented with automation in housing construction in which they achieved prefabrication success with customization and personalization (Gramazio 95). In addition, Shimizu Corporation setup research initiatives in Tokyo during the 1970s after the general manufacturing "robot boom". First, they created single-task construction robots that completed individual, repeatable tasks but were rarely fully automated. Inferior parallel execution of human work tasks meant productivity gains were often counterbalanced (Gramazio 95). As a result, integrated automated construction sites were initiated by Waseda Construction Robot Group (WASCOR) in which automated cranes, welding, logistics, and alignment occurred under vertically operating, on-site factories which sat above the structure. Unfortunately, this technology never took off due to high initial investment and its capabilities being only constrained to special conditions.

One of the main reasons for the lack of success in early attempts to industrialize the construction site is that construction companies merely tried to leverage existing construction processes using automated measures aligned for industries that build repetitive products. For construction to adopt digital, automated fabrication abilities, a paradigm shift in the entire AECOO process needs to occur in parallel to the automated technologies designed for the building industry. Essentially both the industry and the technologies need to grow together before automated technology will be effective.

The current need for automated construction to replace the labor-intensive construction site is urgent. This is evident by safety risk, jobsite efficiency, and difficulty of management on a jobsite. From a safety perspective, 874 worker fatalities occurred on construction jobsites in 2014 (OSHA). Beyond this need, there is tremendous opportunity that digital fabrication offers in comparison to the traditional architectural design and construction approach. With architectural style evolving to feature "organic, doubly curved surfaces and complex ornamentation" (Rael 2014), digital fabricators have the ability to usher in the next era of building design and construction.

The building construction industry can leverage digital fabrication for the creation of architectural structures with an integrated strategy involving its process from file to fabrication, material usage and optimization, and fabricator design and implementation. At the current stage, gaps are apparent in all of these sectors ranging from scale to durability of material. This analysis will exemplify current proceedings of research and development of digital fabrication and how they contribute to the greater goal of digitally fabricating buildings.

Criteria investigated include: Need for automation of construction; the opportunity digital construction presents to the architectural, engineering and construction industry; the feasibility of the proposal based on the process; design and vision based on constraints such as fabricator, material, and scale; actual implementation based on these constraints; the gaps of the technology; and the future procedures to fill these gaps.

2.2 | The Need for Automated Construction

Through each of the sources investigated, it is apparent that the building construction industry needs to increase its degree of automation due to the inherent risks of construction jobsites, the inefficiencies of the manual construction process and the limitations of human processing powers on large, complex jobs.

Smart Construction Objects, a recent publication linking the “Internet of Things” with construction to create automotive processes, illustrates the limitations of human decision-making on intricate construction jobs. Their logic “resonates with Simon’s (1986) bounded rationality theory, which suggests that rationality of individuals in decision making is limited by the information, their cognitive ability, and the finite amount of time they have to make decisions” (Niu et. al. 2015). Niu et. al. continue to explain that as jobs become increasingly complex, information related to the process of a building lifecycle becomes difficult to manage without comprising for quality defects, delayed delivery and cost spikes. *Smart Construction Objects* illustrates that human processing is nowhere near the power of computers. Although this is critical to changing the processes of the construction industry, this claim does not foster well with current companies grounded in traditional, manual labor and management processes. As the authors continue their discussion, it is evident that Smart Construction Objects, computers imbedded into everyday construction equipment, offer the ability to improve the human powered process through enhanced positioning, logistics and information push and pull, rather than replacing human jobs. *Smart Construction Objects* illustrates that automated construction practices can improve the supply chain process of construction due to the fact that “project managers need real-time information traceability and visibility of materials/ components throughout their logistic and supply chain especially positioning and inventory information” (Niu et al. 2015). The collaboration of “smart” objects and human decision-making marks a significant part of the shift to automated fabrication. To transition from an entirely human process to completely automated becomes unimaginable. However, Behrokh Khoshnevis illustrates that automation will continue to rise in the face of safety risk on the jobsite.

Behrokh Khoshnevis is a professor at The University of Southern California and developer of Contour Crafting (CC), an “emerging technology that uses robotics to construct free form building structures by repeatedly laying down layers of material such as concrete” (Khoshnevis 2012). In contrast to the *Smart Construction Objects* approach to integrate automation with human construction management, Khoshnevis presents a plan to completely automate the entire process once on the jobsite. However, his publication, *Automated construction by contour crafting—related robotics and information technologies,* lacks evidence to prove why construction desperately needs automation to occur. Rather, it lists the issues of the construction industry with “the labor efficiency being alarmingly low, accident rate at construction sites is high, work quality is low and control of the construction site is insufficient” (Khoshnevis 2004).

To reinforce his argument about efficiency being low, a 2009 publication on pre-fabrication of housing in the *Journal of Information Technology in Construction* illustrates that the “building design process generates large amounts of information, and time is often wasted searching for, sharing and recreating information.” (Persson 2009). According to this source, this interoperability between stakeholders including labor and management cumulates to $15.8 billion. Although this source offers insight into the necessity of planning and creating a formal process for a company shifting toward pre-fabrication, it does not offer tremendous understanding for automation of digital fabrication.

Inefficiency and related costs can be associated with wasted time resources but also on-site material waste. Ronald Rael and Virginia San Fratello, fabrication researchers at University of California Berkeley and San Jose State University, respectively, argue that digital fabrication is necessary due to the waste of materials posed by construction job sites. In their publication, *Material Design and Analysis for 3D-Printed Fiber- Reinforced Cement Polymer Building Components,* they reference that "US Construction caused 143.5 million tons of construction waste in 2008" (Rael 2015). In this report they continue to express that major savings through automated construction compared to current construction practices can be in the form of "reduced material cost. If the cost of molding and formwork is 35 to 60 percent of the cost of a concrete structure, then 3D printing in concrete offers tremendous cost saving to the construction industry" (Rael 2015). This is an extremely optimistic view, assuming that additive fabrication presents no room for waste. Using additive fabrication, supportive structures are usually necessary to create irregular geometries. Rael and Fratello counter this argument by illustrating that "excess cement and aggregate can be recycled" (Rael 2015). Reduced costs due to prevention of material and labor waste serves as a fantastic argument for implementing digital fabrication techniques.

Through the array of sources, it is clear that automation of construction would benefit the construction industry. However, why hasn't automation taken hold in the form of digital fabrication or other domains? Khoshnevis continues to illustrate through unsupported reasoning, however, the ethos associated with his name and research group is fairly legitimate considering "Contour Crafting" recently was awarded top prize from NASA for *NASA Tech Briefs Create The Future Contest*. Khoshnevis mentions that the "Implementation of automation in the construction domain has been slow due to: (a) unsuitability of the available automated fabrication technologies for large scale products, (b) conventional design approaches that are not suitable for automation, (c) significantly smaller ratio of production quantity/type of final products as compared with other industries, (d) limitations in the materials that could be employed by an automated system, (e) economic unattractiveness of expensive automated equipment" (Khoshnevis 2004). Although valid points, the design approaches can be manipulated to be suitable for fabrication. Furthermore, many would argue the exact opposite, that fabrication inspires design. Neri Oxman, Jorge Duro-Royo and Steven Keating illustrate that throughout history, "New fabrication technologies have inspired designers and architects to further push the envelope of design" (Oxman 2014).

2.3 | Digital Fabrication Opportunity

The sources selected not only illustrate the need for automation in construction, but the immense opportunity offered with digital fabrication in particular. Throughout the sources, a theme emerges focused on the fact that fabrication technologies can inspire architectural design. In fact Oxman et. al., believe that "robotic construction methods have the potential to usher in the next era of architectural design" (Oxman et. al. 2014).

The concept that design can be influenced through new fabrication techniques tremendously complements digital fabrication's benefits of safety, efficiency, control and quality. To augment their claim of "ushering" in new design, the researchers out of Mediated Matter Laboratories at The Massachusetts Institute of Technology believe that material shapes will be drastically influenced. In comparison, Rael and San Fratello, are similarly optimistic. These two are the founders of Emerging Objects™, an independent, creatively driven, MAKE-tank designing and 3D printing environments for the 21st century—with innovative materials, at unprecedented sizes, and the belief that 3D printing is the medium where good ideas become real (Emerging Objects). Their vision for 3D printing is that the technology presents "New possibilities for shaping materials; the process will reshape the way we think about architectural building components" (Rael 2014).

While many believe that fabrication can influence design, Mediated Matter knows that they have a stake in the future of the AECOO industry. Their source, *Toward Robotic Swarm Printing* can be regarded as connecting digital fabrication to the bigger picture of what it means to be human. In their outlook, it is obvious that digital fabrication will create efficiency, control and quality. However, Mediated Matter stresses the relevance to look deeper. In their vision, there is a difference between fabrication technologies that fundamentally transform the way we see buildings and construction, vs. making the construction of traditional buildings more efficient (Oxman 2014). When researchers illustrate their reasons for pushing the boundaries of the AECOO industry, those that hold higher truths and take a step back to see what they're impacting will be able to achieve greater feats of fabrication, design and connection to why buildings are designed and how they are constructed.

Throughout many of the publications, a common vision exists for the opportunity to strive for an architectural world where buildings resolve to exotic architectural geometries, those characterized by rounded and natural features, rather than brick-by-brick construction. In *Material-based Design Computation,* Neri Oxman elaborately explains that the concept of form making, where forms are created to be expressional, can more readily be tapped through digital fabrication, in contrast to form finding, where the function actually determines the form.

Through a greater balance of form making over form finding, humans can go beyond standard geometry sizes. Oxman breaks down standard geometry components in her assertion, “Points make lines (or curves), lines make surfaces, and surfaces make solids. While such representations of space suffice for basic Euclidean primitives, representation becomes challenging for more complicated spatial elements” (Oxman 2010).

Furthermore, In the book, *Made by Robots: Challlenging Architecture at a Larger Scale*, by Fabio Gramazio and Matthias Kohler, it is stressed that this link to a new design era with more natural geometries is a direct line between the designer’s mind and the physical production because of the capabilities of digital fabrication. This source successfully illustrates the history of attempts to automate construction but focuses in on the power of digital fabrication in architectural design itself. Gramazio states, “Whereas the project to relieve man of painful tasks is by no means original, the quest for a new immediacy based on computation between the designer’s mind and the built reality is without precedent." (Gramazio 2014)

Made by Robots excels at painting a picture of why now is the time to adopt digital fabrication into architecture. Since the technology of robotics, additive manufacturing and materials is ready, “The present moment is thus ripe for revolutionising architectural production; robots are now connecting technology and knowhow, as well as imagination and materialisation, like never before, and have the potential to reveal a radically new way of thinking about and materialising architecture” (Gramazio 2014).

This potential is further elaborated upon as a shift in the process from geometric designs to physical-material in publication that best describes a formal process for digital fabrication, Fabrication Information Modeling (FIM). The study, *Towards Fabrication Information*

*Modeling (FIM): Four Case Models to Derive Designs informed by Multi-Scale Trans-Disciplinary Data***.** In contrast to the Mediated Matter Lab study on Material Design and Analysis, this study presents the process necessary to make the material design and analysis possible. This group expects that the “overlap among and across media will result in more efficient design protocols and will achieve better functionality across length and time scales” (Duro-Royo 2015).

In contrast to the compelling idea of ushering in a new architectural age, many current implementers of digital fabrication in the form of 3D printing and additive manufacturing techniques focus on the construction and building benefits of digital fabrication. For instance, Adam Kushner, president of D-Shape, presents the opportunities such as a safer work environment due to the elimination of human labor, customization without the typical costs for customization, less material waste, the ability to use local materials, cheaper and faster overall construction. Rather than explaining these benefits, the source only lists. Alternatively, this source is unparalleled as it touches upon the opportunity to begin building reefs, repair bridges, bulkheads and other underwater structures that have extremely difficult and expensive current construction techniques.

Likewise, Contour Crafting focuses reasoning to develop digital fabrication techniques to save “considerable time and cost as compared with the traditional way of construction” (CC 2013). Furthermore, Contour Crafting presents that all costs can be estimated more accurately than common construction since the “cost of construction is related to time and energies spent by the machine and the amount of materials consumed for the structure” (Khoshnevis 2004) which can be accurately estimated.

2.4 | Feasibility

Throughout the review of the publications, it is clear why building construction needs to be automated and the benefits of using digital fabrication. In this section, the sources will be analyzed based on the information they present to make the vision of taking a design to fabrication through digital means feasible. When investigating the feasibility of digital fabrication, it is important to first inspect the process design for going from file to fabrication (F2F). File to Fabrication represents the hopeful seamless workflow that is characteristic to digital fabrication where a model can be translated into the physical end product. Throughout the publications, some processes are highly documented with very specific algorithms, while others only touch upon the process to achieve their vision or already built prototypes. Next, it is important to see how they plan to achieve material design and fabrication based on material type, material makeup, and other factors. Furthermore, the fabricator design and infrastructure used to "print" the material needs to be raised to attention.

2.4.1 | Process: File to Fabrication

When discussing the feasibility of digitally fabricating large-scale building structures, it is imperative to start with the process for the lifecycle of the building or building component. Throughout the sources investigated, two sources clearly identify detailed processes for moving from file to fabrication. File to Fabrication illustrates the process of moving from a computer aided design model (CAD) or building information model (BIM) to a physically constructed entity that stems from the original model or file. The representative sources include *Towards Fabrication Information Modeling (FIM) & Optimal machine operation planning for* *construction by Contour Crafting* published by Behrokh Khoshnevis. While the latter publication offers an explicit planning process, it is limited to only simulation staging and testing of algorithms and processes. The former publication details steps “designed to integrate form generation, digital fabrication, and material computation starting from the physical and arriving at the virtual environment” (Duro-Royo 2015). The FIM process offers the most comprehensive process for fabrication identified in this review. While it illustrates the big picture, it does not do a great job of showing details between each stage. Contour Crafting actually presents its entire process with specific algorithms and script. Additional research is necessary to illustrate the most streamlined workflow of file to fabrication.

FIM challenges the traditional architectural design process (which has moved from architectural design to engineering to construction to operation) with an interrelationship between each of these stages so that the future and previous stages share information in the form of trans-disciplinary data. As this source presents, it is sensible to work with the end in mind as FIM “integrate(s) form generation, digital fabrication, and material computation starting from the physical and arriving at the virtual environment (Duro Ruyo 2015). To do so the steps proposed include ideation design, (DES), virtual tracing with computer-aided-design (CAD), to computer aided engineering analysis (CAE) to computer aided manufacturing (CAM), fabrication (FAB) and finally product process (PRD). Through “multi scale trans-disciplinary data” this process can help designers so they can inform the various stages of the process. This document presents four models to translate biological, physical components to trans-disciplinary data. However, through the models, the algorithms are not revealed, only explained in overview. Mediated Matter illustrates that the FIM models are “written in C++ and Java in the Eclipse IDE environment and also C# using the RhinoCommon geometrical kernel” (Duro Ruyo 2015).

When taking a closer look at the models, only Model 3: Construction System Encoding Fab Constraints & Material Curing Scale and Model 4: Water-Based Platform to Encode Material Representation & Trans-disciplinary Data are most relevant. Model 3, *Bots of Babel*, is a "a behavioral protocol for a set of suspended cable robots equipped with extrusion nozzles carrying material" (Duro Royo 2015). The behavior protocol is relevant because it controls how the concrete drops are placed in conjunction with curing-time data. Furthermore, behavior protocol reveals the possibility of bottom-up or top-down formation based on the design geometry. In summary, the algorithm will need to control mechanical properties of the extruder, the material property, the geometrical and time-based Meta info. This can be done with communication between the CAD / PRD cycles.

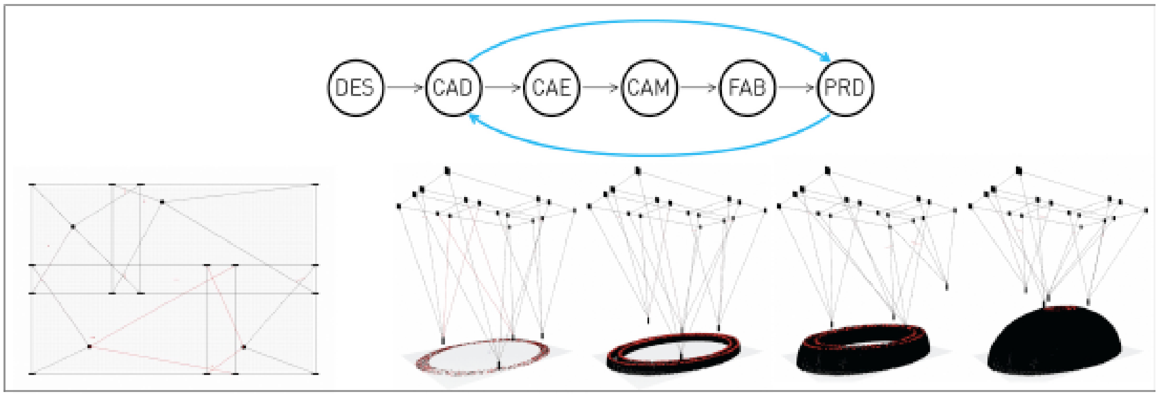


Figure 9: Mediated Matter – Cable Suspended Robots equipped with extrusion nozzles

Model 4 is relevant because this model "generated a seamless workflow to synchronize a portable and customized multi-nozzle deposition tool with an industrial robotic arm" (Duro Royo 2015). Unfortunately, the algorithm and workflow cannot be shared except for three overarching levels of hierarchy. First, "it determines material distribution and material concentration in geometrical primitives. It then transforms the primitives into extrusion geometries by pressure fine-tuning. Finally, it defines geometric and material property maps for the overall shape of the printed structures" (Duro Royo 2015).

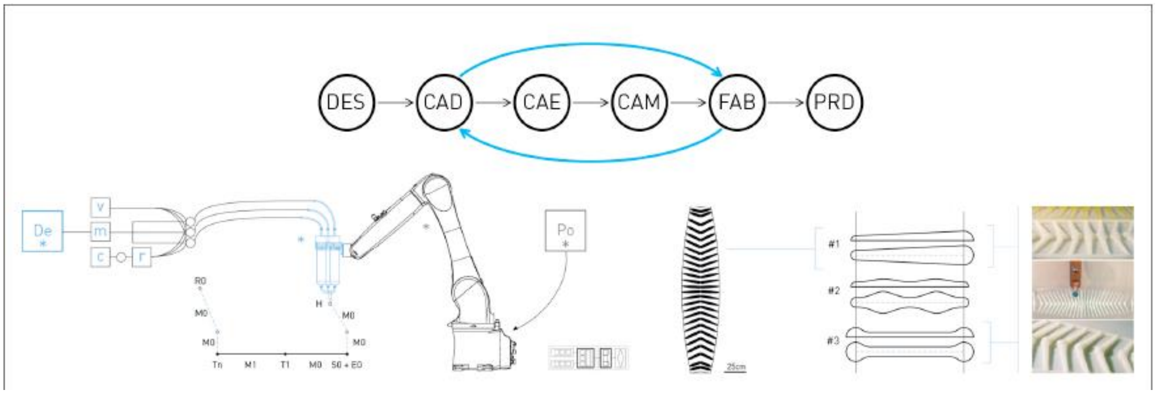


Figure 10: Mediated Matter – Industrial Robotic Arm multi-nozzle deposition tool

The greatest benefit of this article is that is correlates with *Towards Robotic Swarm Printing* in which the processes are actually implemented, such as Cable- Suspended 3D Printing.

Although not as specific in a workflow for fabrication, *Material Based Design Computation*, begins to focus in on the need for end-to-end integration for a process coined variable property rapid prototyping (VPRP). VPRP illustrates an idea where the design prototype is being directly fabricated in prototype form. If the digital medium is instantaneously altered in its digital state, the physical prototype being printing concurrently will be altered based on its material, color, material mixture, etc. Although seemingly irrelevant to this focus of scalable digital fabrication, this publication nicely illustrates the shortcomings of BIM in incorporating "material properties and behavior constraints" (Oxman 2010) or a material-based modeling approach. To do so, this source presents the opportunity to treat voxels as tensors, so that they become geometrical entities with physical parameters. Furthermore, most CAD systems only represent surface protocols and the insides are void, unlike STL, which have geometric coordinates to create solids. Therefore, BIM information needs to describe micro-scale physical properties of materials and internal composition based on voxels and finite elements. This presents an avenue for further research. An extremely relevant portion is the point that this source illustrates that “rapid fabrication technologies are designed as software and hardware packages separate from modeling and analytical environments” (Oxman 2010). However, after reviewing this source it is still unclear how to appropriately embed material properties into the model itself to meet needs such as conductivity and stiffness in the physically printed material.

Rael’s *Material Design and Analysis for 3D-Printed Fiber- Reinforced Cement Polymer Building Components* directly supports the idea of file to fabrication for complex geometry. Although their process is not elaborated on, valuable insight into the software platforms used include Top Mod, to “dynamically change topology of 2-manifold polygonal meshes to explore structural skins”, Blender and Modo to “explore texturing, twisting and deformed surfaces” and Rhino to “explore part to whole relationships, paneling and how 3D printed pieces interlock and connect” (Rael 2015).

While *Towards Fabrication Information Modeling (FIM)* shows the bigger picture of the process, *Towards Robotic Swarm Printing* focuses on the importance of machine control throughout the process. Furthermore, they demonstrate that the ability to additively fabricate at large scales will involve control of material property and variation, material tunability, as well as establishing sufficient communication within and across fabrication nodes or decentralized robotic fabrication. This is presented in three case studies investigating the success of algorithms from FIM: the first, concrete formwork with low tunability with low levels of communication, the second, Cable-suspended foam-printer with low tenability and high communication, and third, templated swarm silk deposit with high tunability and low communication. Through high tunability and high communication, the goal of the MIT research group is the integration of these two strategies to achieve top-down control of large structures combined with bottom-up manipulation of localized material features. *Toward Robotic Swarm Printing* gets into a higher level of detail than *Towards Fabrication Information Modeling*, since it presents the variability between high levels of communication and low material tunability offered by a multi-node fabrication system and low levels of communication and high material tunability offered by a single-node fabrication system. However, Contour Crafting illustrates their process at a greater level with algorithms defined and details specified. As a result, Contour Crafting serves as a more reliable source since their technique can be analyzed and compared against traditional construction practices.

The 2013 Contour Crafting publication, *Optimal machine operation planning for construction by Contour Crafting*, specifies a "systematic methodology for CC machine operations planning and optimization in order to efficiently construct complicated large-scale structures by Contour Crafting systems using single or multiple machines and other hardware configurations" (Zhang 2012). First, they illustrate the tool path, which is a series of positions, orientation, velocity and deposition rate of the nozzle throughout the entire construction period. For a single nozzle tool path, the traveling salesman problem (TSP) is leveraged and machine control is performed through the Lin-Kernighan heuristic Algorithm. Essentially, "the algorithm attempts to find an optimal series of interchange operations between elements of A and which maximizes (T_{old}-T_{new}) and then executes the operations, producing a partition of the graph to *A* and *B" (Zhang 2012).* In this process, the CC-TSP algorithm saved 45% of nozzle path movement time. For a multi-machine system variables include using multiple gantries, or tracks to hold the printer, or having multiple nodes of fabrication. It was determined that the *Buffer*

Zone Path Cycling algorithm found the best paths to prevent collision during fabrication and presented the fastest option. *Buffer Zone Path Cycling* combines *path cycling* and the *auxiliary buffer zone algorithm*.

While Contour Crafting offers value in that they illustrated extreme detail of the series of algorithms developed, the process of choosing the algorithms and the results of simulation, this study can offer the following takeaways to apply to the other reports: The importance of control in a printer is paramount, especially so nozzles do not collide nor do they collide with the existing structure. Furthermore, in comparison to *Toward Robotic Swarm Printing*, this study illustrates the benefits of utilizing multiple nozzles in fabrication. Mediated Matter coins their multiple node printing process, Robotic Swarm Printing (RSP) and has advantages such as "increased footprint, scalability, robustness, efficiency and material tenability" (Oxman 2014).

After review, the FIM process is most representative of the bigger picture and process that can be leveraged for digital fabrication. Contour Crafting's *Optimal machine Operation Planning for Construction* is the best reference for the algorithm design for the fabricator itself and machine control in the actual additive manufacturing stage. Similarly to process of Penn State's BIM Execution Planning Guide, in order to fabricate durable, long lasting components on a building size scale, it is important to start at the end goal and work backwards toward the design of the component. However, the latter two publications reveal greater attention to detail that will be necessary to create a plan for how the process can relate to material and actual fabricators.

Although not mentioned by any reference, the design of the building will seriously impact the process of the digital fabrication method. For instance, in additive manufacturing techniques, there is not a process that translates into the construction of multiple floors without resorting to traditional construction methods such as composite slab design. This is a source for further research.

2.4.2 | Material Design

To investigate the feasibility and conceptual information behind digital fabrication, material design becomes an imperative aspect of the planning and design phase. One of the issues with large- scale digital fabrication is that durable, long lasting construction materials are extremely difficult to fabricate. In rapid prototyping 3D printing, plastic solutions and laminated powders are used to create short lifespan products. These products communicate ideas but usually do not withstand force, UV radiation or temperature extremes. Digitally fabricated material needs to retain structural integrity through various factors if the material is to be used for building components.

While material utilization will be focused on in greater depth in the "Actual Implementation" phase, material design feasibility is revealed in this stage because many publications on digital fabrication and 3D printing focus on theory and design feasibility which is important to recognize in such a bleeding edge aspect of the industry.

Material Based Design Computation by Neri Oxman is a great source that first illustrates the common materials already utilized in the 3D printing and additive manufacturing industry, then associates how these processes can be furthered for the architecture industry through alignment with building information modeling (BIM). Her thesis radically breaks down material representation and says the smallest units of matter must be "small enough to support material property graduation as a function of structural and environmental performance, and yet big enough to be physically constructed" (Oxman 122). Her breakdown of other 3D printing technologies, liquid based stereolithography, powder-based selective laser sintering and solid-based (fused deposition modeling) is very thorough and successfully illustrates her claims to these technologies. Her ultimate proposal to use variable property printing is irrelevant in the sense that her aim is to use as prototyping. However, her data is useful for scalable techniques given the "ability to ability to dynamically mix and vary the ratios of different materials in order to produce a continuous gradient" (Oxman 2010).

Oxman's depth into alternative 3D printing technologies reveals questions as to what type of material is optimal for architectural, scalable components. Using Stratasys PolyJet Matrix technology photopolymers are extruded and zapped with light to harden. Alternatively, Stratasys FDM technology creates soluble thermoplastic polymers for building. Through Stereolithography, D-Shape is able to 3D print structures made up of sand, salt water and magnesium. Essentially, the printer slices up models into 5 mm layers, a blanket of sand-magnesium composite is laid for each layer and then the "printer" deposits seawater based ink through 300 nozzles. The reactant binds the layers into the model's chosen shape.

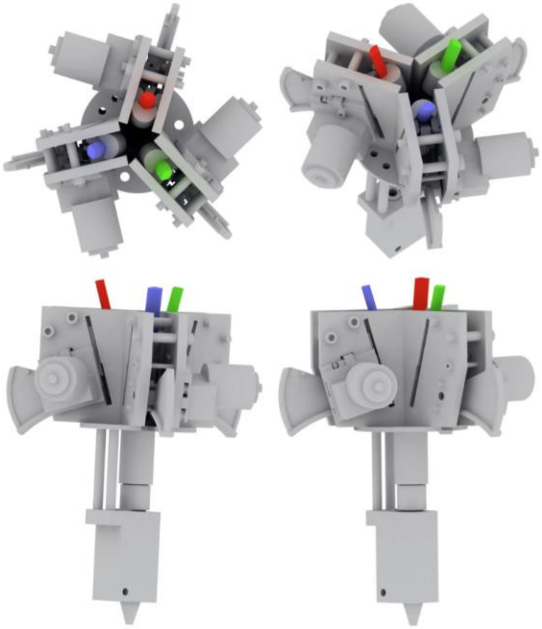


Figure 11: Nozzle design to additively fabricate prototypes with real time material design parameter changes (Oxman 2015)

Many publications and proposals reference traditional wet-concrete as their main material that would be extruded in an additive manufacturing technique. The publication, *Additive Manufacturing Process Development in Construction*, provides a qualitative general backstory as they mention that wet properties of the material are critical to the success of additive manufacturing. This publication illustrates the importance of mix design, particle size and stability of extruded filament's upper bound. However, this publication fails to dive into these accounts. In a press release regarding Dubai's Museum of the Future, WinSun Global, a 3D printing construction firm in China, reveals plans to utilize special reinforced concrete (SRC), Fiber reinforced plastic (FRP) and glass fiber reinforced gypsum (GRG). Although no further details are mentioned, these materials offer room for further review.

In Contour Crafting's *Automated construction by contour crafting—related robotics and information technologies* there is no description of the material makeup of concrete utilized in the machine. Their only allusion to the type of concrete is when they mention it will be "structural concrete" and beads of thick concrete paste will be extruded. To add reinforcement, Contour Crafting proposes creating ducts in the printed material and then post-tensioning metal or FRP wires once additional concrete is poured (Khoshnevis 2004).

Developments in construction-scale additive manufacturing processes proves valuable in illustrating parameter constraints of concrete material. However, Contour Crafting expounds upon these constraints. Primarily, the pumpability of concrete needs to be optimized at a rate to ensure successful time deposition for curing. Furthermore, buildability, or the "resistance of deposited wet material to deformation under load" (Khoshnevis 2004), is essential in the design of the material itself. However, this source does not offer additional value in specifying manners to meet these key characteristics. One of the constraints that arises from Contour Crafting's research is the tool path time constraint that needs to be optimized. This is essential because time between layers cannot be shorter than a "critical limit" or the form cannot dry. If the time between layers exceeds a critical limit, the concrete will not adhere in its desired fashion.

A handful of people are 3D printing architecture using cement-based materials by extruding wet cement through a nozzle. Ronald Rael's research at Berkeley defies this theme by utilizing iron oxide-free Portland cement with fibers and polymers to create "a free-standing pavilion called Bloom to demonstrate the precision of their powder-based cement method of 3D-printed construction" (Williams 2015). With this method, Rael can create a more complex and precisely finished structure. This source is incredibly valuable since it reveals a way to create complex concrete geometries; however, there is no formal literature on its chemistry and material properties. Many publications reviewed have had success using concrete and are further reviewed in the *Actual Implementation* section.

Adam Kushner makes an alternative proposition that in the fabrication of his house in the state of New York, D-Shape's printer will be able to print the house structure using only on-site sand, salt water and magnesium. He then informs that a composite beam construction needs to be emulated with fiberglass strands in the mix because as of this writing, no one has figured out how to 3D print a structure with rebar. Since this story is based on the technology of D-Shape's printer, which has little to no formal literature, it will be necessary to investigate D-Shape's listed patents to fully grasp their material design feasibility.

One instance in which building material and component design is specified for the digital fabrication process is in Contour Crafting's first released report on 3D printing buildings through additive fabrication techniques. This publication, *Automated construction by contour crafting—related robotics and information technologies,* reveals the vision to employ "various materials for outside surfaces and as fillers between surfaces may be used in CC. Also, multiple materials that chemically react with one another may be fed through the CC nozzle system and mixed in the nozzle barrel immediately before deposition" (Khoshnevis 2004). While Khoshnevis presents a range of ideas for how digital fabrication could be feasible to create all the important components of a building, including mechanical, electrical and plumbing equipment, his proposal only includes visuals of the machine with backstory. Is it necessary to blend multiple materials together to formulate a composite material as proposed by Contour Crafting? While it is important to review design propositions, more tangible infrastructure and existing fabricators can be seen in the "Fabricator & Machine Control" section of "Actual Implementation".

Whereas *Contour Crafting* presents the capability to chemically create new materials, *Mediated Matter* reveals the importance of material tunability or material sophistication in fabrication. It is desirable for a material to have the ability to be finitely detailed and organized in similar fashion to how a caccoon's "mechanical properties of the silk vary significantly from the outer stiffer to the inner softer shell" (Oxman 109).

Another trend throughout the publications is the focus on particle size deposition and the ability to create smooth or desired surfaces on the structure itself. Contour Crafting is a reliable source when investigating this aspect. They propose an automated trowel attached to the extruder which creates surface-forming capability in free-form planar surfaces. This is elaborated on in the *Fabricator Design* section.

Although many of the sources reviewed focus on the best design of concrete for nozzle printing, Khoshnevis looks beyond structural material by proposing plans to automate fabrication and digitally fabricate conduit, automated reinforcement, electrical and even material finishes including tiling. For instance, to install reinforcement, "Robotic modular imbedding of steel mesh reinforcement into each layer may be devised. The three simple modular components shown in this figure may be delivered by an automated feeding system that deposits and assembles them" (Khoshnevis 2004). Khoshnevis' infrastructure consists of a gantry system that carries a nozzle and move on two parallel lanes on a construction site. A hybrid nozzle is then able to combine extrusion for forming surfaces and a filling process for injection. Although theoretical Contour Crafting has developed this machinery and is printing 2.5D and 3D shapes of ceramic paste extrusion and concrete filling. See more in actual implementation.

2.4.3 | Fabricator Design

After the overview process for going from file to fabrication, the fabricator design is the most crucial aspect of digital fabrication. Design of the fabricator can set the stage for the footprint of the building, the rate at which material is deployed, how material is deployed and the type of material that is deposited. In this review, one of the goals in the proposal of the design of a digital, automated fabrication of architecture is for the construction to occur on-site with no human, manual labor. Essentially the fabricator should be capable of having a system fully setup, one clicks print and an object emerges.

Throughout this review, the overarching category of digital fabrication for architectural structures resolves into various types of fabricators. For the purposes of this proposal, additive building manufacturing (ABM) or 3D printing techniques are focused on primarily due to the vision of a completely autonomous scalable solution that mitigates reliance on robots for construction. Although leveraging traditional six-axis robots in construction is considered in these sources, it is not a focal point; leveraging multiple robots in a dynamic, outdoor, unpredictable environment creates countless variables and associated complications.

Before investigating the actual printers and technologies leveraged, it is important to step back and realize the overarching goals of the printer itself. The sources reviewed have been considered based on the fabricator's ability to create scalable architectural geometries that redefine what a building form can express in addition to the seamless workflow from model to physical infrastructure.

Two organizations, Contour Crafting and MIT's Mediated Matter, are the most thorough in exemplifying their visions for additive building manufacturing (ABM) fabrication system. In *Toward Robotic Swarm Printing,* Mediated Matter resolves additive manufacturing into two distinct abilities: levels of communication between fabrication units and material tunability or sophistication. In their words, “paradigms to date have been confined to one of these attribute axes, with certain approaches utilising sophisticated tailorable materials, but having limited degrees of freedom and virtually no communication (the silkworm case), and others assembling simple building blocks or prefabricated components in a cooperative fashion with high levels of intercommunication between fabrication nodes (the termite case)” (Oxman 2014). This publication represents the need for both capabilities through common understandings of biological behavior. For instance, a cocoon’s silk mechanical properties vary significantly from the outer layer to the inner layer. This variation in mechanical property is coined material tunability. Furthermore, communication can best be represented through a termite mound, where “nodes” or termites are fully collaborative in their building approach, but offer little tunability since the material is homogenous.

Mediated Matter elaborates on swarm construction fabrication that recent progress has occurred in developing communication and control abilities “to support automated assemblies of basic pre-shaped building components manipulated in predefined paths” (Oxman 2014). To create communication between nodes or fabricating components, the “Deterministic” approach or top-down communication creates robust creations and reduces error. In contrast, bottom up intelligence offers the ability to intervene and respond to error when it happens. While both are beneficial when leveraging robotics to create a product, the deterministic approach is more applicable to this proposal since it leaves the fabricator to a seamless, predetermined path that goes from start to finish without error.

After defining swarm construction capabilities, Mediated Matter presents alternatives to fabricate utilizing cable-suspended systems including the SpiderBot and CableBot. The vision is that cable suspended robots can connect to trees or adjacent buildings. Whereas the SpiderBot is a single-node fabrication system with high tunability, the CableBot is a multi-node fabrication system with superior communication. Although only conceptual, a SpiderBot prototype could reach an area of 30,000 cubic feet with regular winches. The SpiderBot design is composed of "a deposition nozzle, a reservoir of material, and parallel winching electric motors" (Oxman 2014). In the CableBot case, the fabrication technique is to utilize "discrete deposition of soft material drops" (Oxman 2014) through node-to-node communication. This system is made up of various heads programmed by a swarm intelligence algorithm in which the nodes negotiate material deposition in space and time. More than node-to-node communication, the robots are aware of the dimensions of their workspace. By combining these communicative abilities, collision is prevented. Overall, this source offers a great comparison of tunability vs. communicative ability of robots. Although there is not extensive explanation of algorithms utilized to reach this point, the source presents a tremendous starting point for fabricator design capabilities.

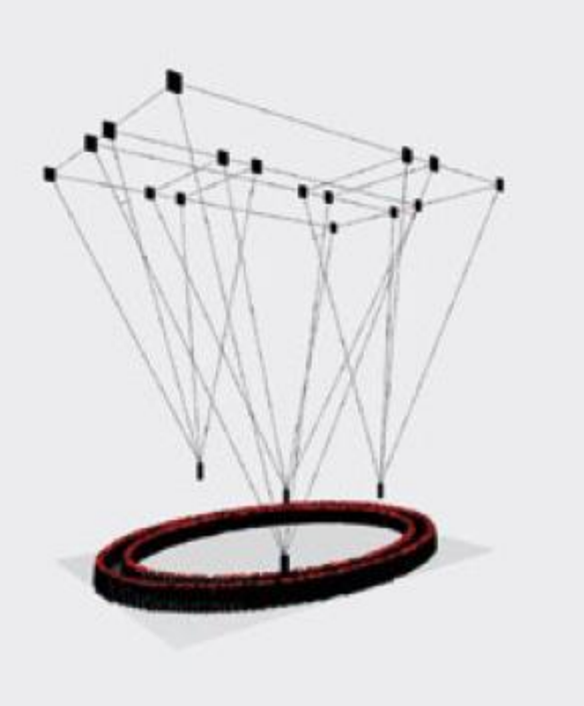


Figure 12: CableBot multi-node fabrication system designed for communicativeness (Oxman 2014)

Contour Crafting presents extremely detailed views at their fabricator designs in order to see the capabilities, components and features of their fabricators. In their first publication on automated construction, *Automated construction by contour crafting—related robotics and information technologies*, they present an on-site additive, concrete fabricator with a hybrid nozzle that combines a trowel and depositor, a gantry system on two parallel lanes. This gantry-rail system that lifts itself up as the structure rises, remains their consistent model for a concrete fabrication system. At this point, it can be assumed that this type of system is viable in alternative to cable based systems similar to what Contour Crafting proposes in their 2007 publication, *Cable-suspended robotic contour crafting system.* One of the main takeaways from Contour Crafting's proposal is that the end-effector has a serial robot arm used for all accompanying tasks aside from producing concrete components. It seems proper that a solution should be proposed to replace this associated robot. Instead, how can the structure be created so that the concrete extrusion fabricator can create as much as possible, and then the rest of the building is completed.

One of the priorities of capabilities is to optimize the tool path of the fabricator since the time and energy spent by the machine can directly be linked to cost. Rather than presenting this short-sighted reason to focus on tool path, the group could have presented the tool path priority due to the importance of preventing collisions and creating a smooth, seamless lay of materials. Nevertheless, the tool path "must describe the position, orientation, velocity, and deposition rate of the nozzle in the entire construction period" (Zhang 2013). Constraints such that the nozzle cannot collide with already deposited material can be resolved through the tool path which relates to the robot's ability to the robot intelligence presented by Mediated Matter. It is unclear whether the tool path collision issue would be resolved using top down or bottom up communication.

The research regarding inter-nodal communication from Mediated Matter and Contour Crafting should be referenced in parallel since Contour Crafting presents a more practical approach to creating a fabricator that uses swarm-printing techniques. In their multi-machine system, the solution is to break down tasks to individually automated machines. It is concluded that multiple gantries is a superior solution to multiple nozzles on a single gantry. Regardless of the tool path between deposition nozzles, one nozzle should traverse each associated edge only once in order to create an optimal tool path by decreasing nozzle airtime. When comparing the systems, the benefits of a multiple gantry system reveal that it is more flexible where "different gantries can simultaneously work on different layers" (Zhang 2013) without collision. To leverage the multi-machine system, a *two-step procedure* divides the original structure into sections based on the nozzles utilized. Contour Crafting's concept of buffer zones and path cycling are introduced to create collision-free tool paths between sections.

One of the key features that Contour Crafting offers in their fabricator is the "superior surface-forming capability of troweling" (Zhang 2013). This makes it possible to create accurate free form and planar surfaces from extruded materials. In their publication, *Optimal machine operation planning for construction by Contour Crafting,* the USC based research group presents a virtual simulation of the entire construction process with their printer. As a result, the tool path can be validated to avoid collisions.

One fabricator design proposal from Contour Crafting is the Climbing System, which allows a gantry to climb above the roof each time a floor is proposed. The issue with this system, which uses tubular segments as anchor points to climb, is that it presents a solution replicates existing building construction with layer-by-layer slab construction.

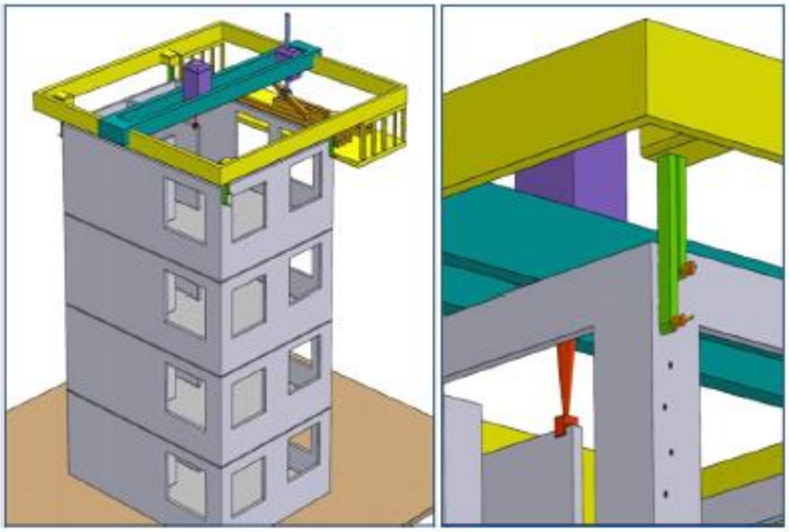


Figure 13: Contour Crafting Climbing System gantry

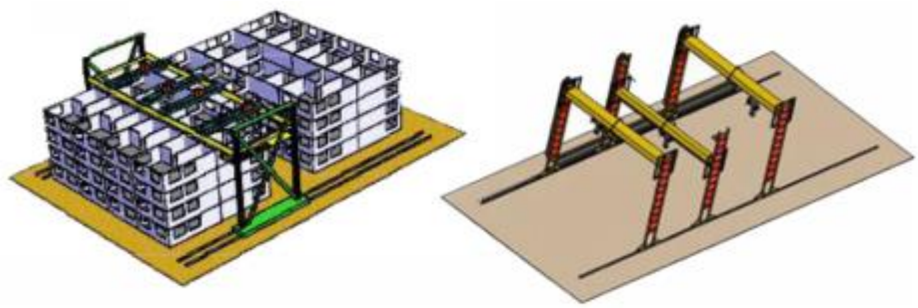


Figure 14: Single Gantry with multiple nozzles (left) vs. Multiple gantry system (right)

Contour Crafting's principle, gantry design is limited in building very large structures since the energy to operate and move such a large manipulator would be excessive. Therefore, a cable-based robot, C^4, is a viable alternative that improves upon the cable suspended design. The solution uses four upper cables to support the end-effector, while three lower sets of parallel cables control the translation motion of the nozzle. The frame of the robot, illustrated in figure 15, only needs to be slightly larger than the building being constructed. Another novel feature is that the end effector is manipulated in an x-y plane by the tension of a cable by motors on "actuated cable mounts that allow on-line reconfiguration of the cable robot to eliminate cable" (Bosscher 2007). A potential improvement to this design is that z-axis control would be controlled from the top actuators and cables, rather than the raising of crossbars, which in turn raises the 4 parallelogram cables above the building structure below. However, Contour Crafting proves the design of their parallel-cable control system printer based on kinematic positioning models and static forces. Similar to other Contour Crafting proposals, an external concrete tank pumps concrete to the extruder through traditional flex hose means. This seems like a trivial resort to already commonplace construction techniques and an opportunity to improve upon. Based on the kinematics and statics constraints that the tension in the cables cannot exceed

10,000 N, the building reaches a 44 x 44 x 40 m area in a 50 m cube machine frame. That reaches a height of 131.234 feet or 12-13 stories!

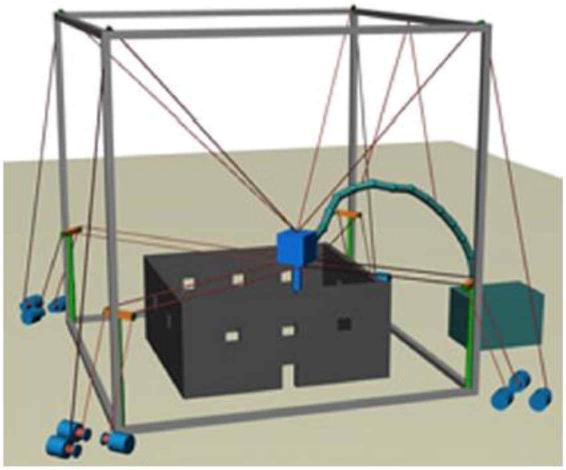


Figure 15: Contour Crafting C4 Cable – Suspended End Effector

Looking at the feasibility and theory behind digital fabrication software processes, material design and fabricator design presents general capabilities and attributes for future additive building manufacturing processes. While these capabilities may have not been developed yet, they offer potential solutions and starting points for the future development of fabrication systems.

2.5 | Actual Implementation

While there are countless publications that illustrate theory, design and vision of where digital fabrication and additive building manufacturing can lead, the actual implementation reviewed offers a much more tangible component where researchers and entrepreneurs share their creations of software processes, actual material utilization in fabrication and the construction and utilization of fabricators to construct scalable buildings or architectural structures.

2.5.1 | Process: File to Fabrication

Based on the publications reviewed, the book, *Made by Robots: Challenging Architecture at a Larger Scale,* presented the most thorough documentation of how a process including end-to-end integration and software standardization needs to occur for digital fabrication. However, this source focuses mostly on utilizing robotics to fabricate, rather than scalable 3D printers or depositing devices. Regardless, the processes presented can be applied to robotic automation, additive deposition or a combined system. The book is broken down into various sections about various companies or research groups and their automated, architecture projects.

The first process described is the Robofold process, which presents a parametric software link from start to finish based out of Rhino Grasshopper platform for a technology that folds metal using industrial robots (Gramazio 2014). The section does a great job at illustrating how the process flow evolves compared to the other publications. A similar type of process should be leveraged for my fabricator design. To ensure the material is viable, material surface analysis is performed with KingKong, a grasshopper plug-in that uses Kangaroo, a physics engine. Next, data is extracted from KingKong as “flat patterns for cutting and as folding animations to drive the robot simulation” (Gramazio 2014). Then, using Unicorn, another Grasshopper plug-in, CNC cuts are made from the flat patterns generated through G-Code CNC programming language. After cuts, GodZilla, a GrassHopper plug-in designed by RoboFold, simulates a six-axis robot production checks occur. After simulation, their software, Mechagodzilla generates robot code on a Raspberry Pi. The simulation process is enacted on real metal using GodZilla. While RoboFold’s process is not specifically relevant to additive building manufacturing, this process presents the opportunity to utilize Grasshopper plug-ins either existing or that can be developed to control the simulation and fabricator device.

Another company in *Made by Robots*, ROB Technologies Process, provides software packages that enable digital fabrication processes. Their platform starts at the design phase and then gives construction companies the ability to exploit manufacturing tasks by giving the ability to leverage the robot and setup the fabrication process. ROB simplifies complex task programming so the user does not need to descent into programming machine code (Gramazio 2014). The design data is leveraged to control the fabrication process so it's a seamless flow between design software and the robot. BrickDesign software was used in 2014 on a large-scale commercial project, Le Stelle di Locarno building in Ticino Switzerland. ROB's CAD software, URStudio, allows bi-directional communication between the design model and the robot itself. ROB software will be useful and can be leveraged in the design of an additive fabrication platform since it offers a bridge between the BIM/CAD model and the fabricator itself. It streamlines the workflow, which is crucial in this proposal.

D-Shape technology, created by Enrico Dini, is a leading 3D printing, stereolithographical process that has constructed large-scale physical structures. As mentioned in the Kushner New York house project, they have developed a viable, current system to actually fabricate architectural structures to scale! From a process standpoint, D-Shape uses a CAD-CAM technology, which operates the plotter during the printing process. Once the model is created, it is converted into an STL file which is used to control the printer head. Using sand in a stereolithography process, the solidification process takes 24 hours to complete. Details on the material makeup, physics and chemistry are discussed in the materials section. Although D-Shape technology is already being utilized, the online documentation is non-existent besides press releases and company published videos that only give glimpses into their technology. To further investigate D-Shape's technology, their patents need to be reviewed and then interviews potentially need to be setup with the company.

The 2011 publication from Loughborough University, *Developments in construction-scale additive manufacturing processes,* presents a minor insight into the process of their "Concrete Printing" technology. Their process can be broken down as follow: First, install the interlayer reinforcement mesh. Unfortunately, they do not mention how this is laid, but its assumed to be laid by hand, which disqualifies the process from being fully automated. After that, the model is designed in solid geometry. This is a crucial change to traditional BIM where most objects are hollow, but solid geometry is necessary to print solid objects. Then, the solid geometry is converted to machine instruction. After printing of the object, post processing involves removal of the support structure and surface finishing. One problem mentioned is that current software tools generate G-Code for each layer of the build, however, this does not address an optimized printing path with a printing and non-printing traverse. The researchers created an in-house script to optimize CNC software to allow for a 30% reduction on build tie with an optimized printing path. While they do not share this script, it is worthwhile to contact S. Lime and R.S. Buswell to see if it is open-source or they are willing to share for future improvements of "Concrete printing" technology.

These sources offer surface overview of the processes leveraged in actual printing operations. Gaining full access to their in-house software and writing plug-in scripts appear to be a viable solution to creating a 3D printing device. Rather than recreating the wheel, these already developed platforms should be pursued and then improved upon.

2.5.2 | Material Utilization

Through press releases and research publications between start-up companies and renowned research institutions, there is a wide array of materials currently utilized in additive manufacturing processes. When investigating the material utilization, the goal is to investigate whether the material presents the ability to construct an architectural component that is structurally capable when scaled. Additional consideration is placed upon whether reinforcement material is integral to the body material itself. This is significant because one of the goals of the printer design is to minimize additional machine interaction through human power or robot beyond the nozzle deposition process. Through review of current fabrication and material technology, it appears that concrete is still a best solution for scalable architectural structures. Loughborough University's *Developments in construction-scale additive manufacturing processes* directly compares current 3D printing concrete in figure 4 below:

Table 1: Existing practice of additive manufacturing in construction (Loughborough University 2011)

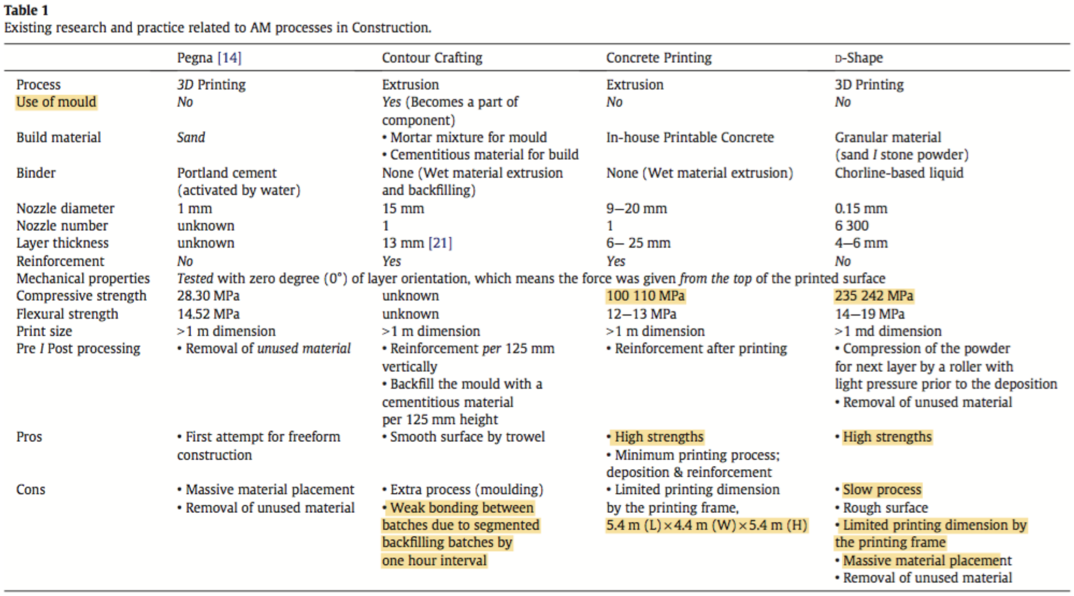


Table 1
Existing research and practice related to AM processes in Construction.

	Pegna [14]	Contour Crafting	Concrete Printing	D-Shape
Process	*3D* Printing	Extrusion	Extrusion	3D Printing
Use of mould	*No*	*Yes* (Becomes a part of component)	*No*	*No*
Build material	*Sand*	• Mortar mixture for mould • Cementitious material for build	In-house Printable Concrete	Granular material (sand *I* stone powder)
Binder	Portland cement (activated by water)	None (Wet material extrusion and backfilling)	None (Wet material extrusion)	Chorline-based liquid
Nozzle diameter	1 mm	15 mm	9–20 mm	0.15 mm
Nozzle number	unknown	1	1	6 300
Layer thickness	unknown	13 mm [21]	6– 25 mm	4–6 mm
Reinforcement	*No*	*Yes*	*Yes*	*No*
Mechanical properties	*Tested* with zero degree (0°) of layer orientation, which means the force was given *from the top* of the printed surface			
Compressive strength	28.30 MPa	unknown	100 110 MPa	235 242 MPa
Flexural strength	14.52 MPa	unknown	12–13 MPa	14–19 MPa
Print size	>1 m dimension	>1 m dimension	>1 m dimension	>1 md dimension
Pre *I* Post processing	• Removal of *unused material*	• Reinforcement *per* 125 mm vertically • Backfill the mould with a cementitious material per 125 mm height	• Reinforcement after printing	• Compression of the powder for next layer by a roller with light pressure prior to the deposition • Removal of unused material
Pros	• First attempt for freeform construction	• Smooth surface by trowel	• High strengths • Minimum printing process; deposition & reinforcement	• High strengths
Cons	• Massive material placement • Removal of unused material	• Extra process (moulding) • Weak bonding between batches due to segmented backfilling batches by one hour interval	• Limited printing dimension by the printing frame, 5.4 m (L) × 4.4 m (W) × 5.4 m (H)	• Slow process • Rough surface • Limited printing dimension by the printing frame • Massive material placement • Removal of unused material

Emerging Objects

Material Design and Analysis for 3D-Printed Fiber- Reinforced Cement Polymer Building Components presents Emerging Objects' existing use of fiber-reinforced concrete to create radical geometric, scalable building components. They best illustrate the difference of their 3D-printing concrete material compared to traditional means by stating that Portland Cement has the same base, purpose, however, in this case, using finely chopped binders and a liquid element are necessary to reinforce the 3D printed material. Material makeup includes Portland cement, bases, hydrators and adhesives to give product shape, binders for reinforcement and a liquid element for binding. In the end, they used a small portion of Portland cement with a large portion of sand that resulted in strong, stable structures. Furthermore, organic adhesives should be limited in mix because they slow hydration, which is detrimental to additive curing. If necessary, an alcohol-based binder is a water-soluble, highly adhesive synthetic polymer with high tensile strength and allows the mix to cure rapidly into a dense material with flexural strength. An infiltration process can be utilized to harden the material and create hybrid concrete polymer that joins fibers into the mix. Is important to note that with this mixture, the binder should be set at .75 to optimize slump. With a nozzle, all binding particles need to fit through a 35-pico liter print head while all aggregate and reinforcement is smaller than 0.010” (Rael 2015).

Emerging Objects uses a stereolithography process to print material. This is similar to D-Shape; however, D-Shape uses strictly sand, rather than a combination of Portland cement and sand in Emerging Objects’ case. The best performance was from a combination of fiber-reinforced and infiltrated material with fiber reinforcement mesh in the Y-axis. After printing, the concrete structure failed at 4537 psi at 14 days strength which above normal strength of concrete. For Emerging Objects the process begins with a powered concrete mix is laid across the plane. Then, an ink jet sprays the binding liquid slice of the object shape. After that, the layer cures through hydration, with no air required for curing. This is repeated for each layer, as a solid concrete object is built up inside dry, powered portion of sand-cement mixture. The object cures in 12 hours and is lifted out of the sand. One of the benefits of this material is that it costs fractions of a cent per cubic inch whereas traditional 3D printing polymer Z Corp ™ polymer / plaster powder, costs $3 / cubic inch.

After a review of Emerging Objects technologies, their solution seems to be an excellent starting point for a concrete mixture if using stereolithography printing. However, their solution may not be scalable to a multi-story architectural scale since a mass of powder is necessary to structural support the concrete until it dries. Containing tons of loose powder in-situ would be extremely difficult with wind and variable conditions.

Contour Crafting:

Similar to Emerging Objects, Contour Crafting has successfully created a concrete, material mixture to 3D print building objects. Through their already mentioned publications and Loughborough University's comparison of their technology to other printers, their material utilization can be evaluated in depth.

Contour Crafting uses a wet, cementitious material that is extruded at 15 mm diameter and 13 mm thickness layers to create walls. Then, layers of reinforcement concrete are laid at 125 mm vertically and then the concrete is backfilled to solidify the still-hollow wall in a CMU like structure. See figure 5 below for a final product depiction. It is unclear between Contour Crafting's *Optimal machine operation planning for construction by Contour Crafting* and Loughborough University's publication how the rebar is laid, therefore patents may have to be investigated for further information. One of the main features of the finished concrete material is that it is smoothed by the trowel intrinsic to the deposition head.

Figure 16: Hollow concrete and reinforcement wall sections from *Optimal Machine Operation Planning for Construction by Contour Crafting*

Loughborough University Concrete Printing

Similar to Contour Crafting, Loughborough University's Concrete Printing technology extrudes concrete material to additively manufacture architectural structures. They successfully printed a 2 m x .9 m x .8 m wall-like bench using concrete material at a rate of 20 min / layer. Their material makeup consists of 54% sand, 36% cementious compounds and 10% water, which result in a material strength of 80-100% of normal concrete casting abilities. The cement utilized is traditional Portland Cement also with oxides of calcium, silicon and aluminum. In this technology, reinforcement mesh is necessary to support overhangs. In addition to the mesh, 23 voids are formed for 8 mm vertical rebar insertion that are then post-tensioned and grouted. The print resolution of Concrete Printing is 4-6 mm, similar to D-Shape, in contrast to Contour Crafting's 13 mm resolution.

This source presents an excellent case for how concrete extrusion can successfully create structurally supportive, scalable architecture. However, this material is weaker in flexural strength tested by the load axis perpendicular to the surface, while the filament is parallel. Also, this material is not smoothed and results in a ribbed finish; therefore, a troweling device or sanding is necessary to achieve a smooth surface. Another flaw and inefficiency is most of the printed material is support structure that needs to removed at the end of production.

Something to note from this project is that internal voids were created that could "acoustic structure, thermal insulation and/or a conduit for building services" (Lim 2012).

Figure 17: Left: Loughborough University 3D Printing process; Right; Final bench usage

D-Shape

After looking at these extruded concrete processes, D-Shape presents a sand-based, stereolithic technology for 3D printing architectural structures, similar to Emerging Objects' technology. D-Shape's material makeup includes sand, mineral dust and inorganic binder. After each layer of sand is laid, the binder is printed in the shape of the object, which allows the sand to harden with micro-crystalline characteristics. Then, the supporting powder material left over at the end can reused to print more material. The material itself is supposed to have resistance and traction superior to Portland Cement (Dezeen 2009). The material is printed in 5-10 mm layers, takes 24 hours to cure and at this point does not utilize steel reinforcement. Similar to other techniques, additional sanding or polishing the surface is necessary to reach a smooth finish.

While the D-Shape material is structurally supportive for structures such as the radiolaria design, it has not been tested to construct a structural building yet. However, current Kushner plans to change that meaning that there are solutions underway to incorporate reinforcement material intrinsically or through integration.

TotalKustom

Another successful implementation of concrete, additive 3D printing is TotalKustom's completion of a castle prototype and the Lewis Grand Hotel in the Philippines. However, there is little to no documentation of these sources. Press releases show a 15 ft. high castle that was printed from a large, concrete extruding printer in Andrey Rudenko's backyard (figure 18). The concrete was extruded using 3 cm x 1 cm layers of concrete, which can be altered based on the scale of the project. Steel reinforcement was placed in the walls when necessary, however, the source does not illustrate in which dimension and of what size.

Figure 18: TotalKustom (Andrey Rudenko) 3D printed concrete castle

After completing this personal project, Rudenko worked with Lewis Yakich to create a 3D printed hotel out of concrete composed of sand and volcanic ash. The local material mix took a month to create. In order to smooth out the walls, a hopper is used during the printing process. Printing progress had to be stopped each time to manually install rebar, plumbing and wiring (Smith 2015). The press release sources on TotalKustom, Rudenko and Yakich do not provide additional insight into material, so these are not viable sources to leverage in material design. However, it can be assumed that these techniques are largely similar to those employed by

Contour Crafting. Furthermore, one can see in figure 19 how the walls are initially constructed, reinforcement, plumbing and wiring is added, and then is backfilled to finalize the structure.

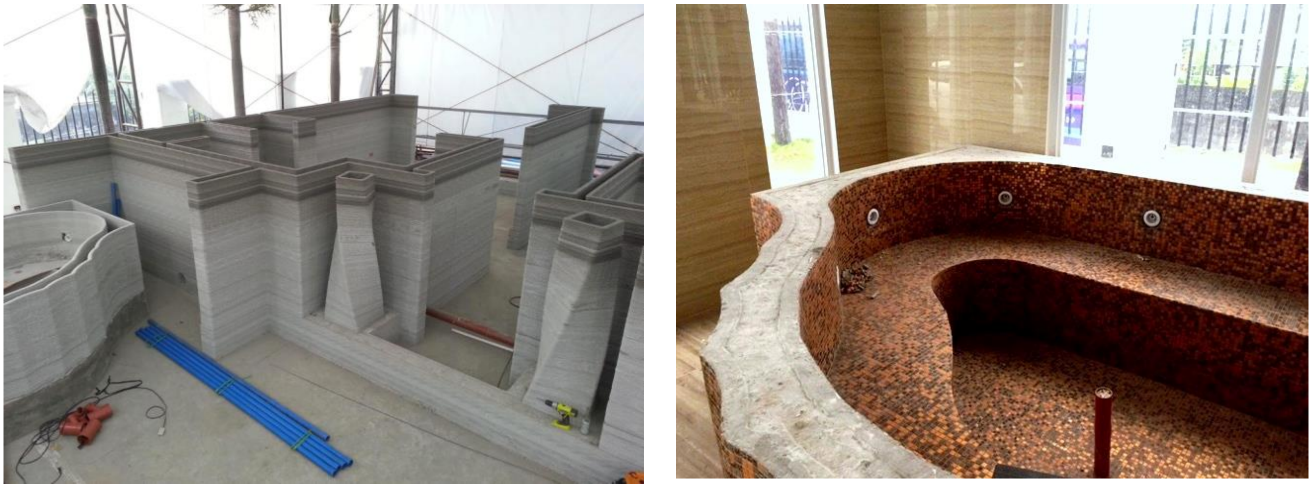


Figure 19: 3D Printed Concrete Villa – Lewis Grand Hotel (Philippines)

Wasp

In contrast to sand and concrete mixtures, WASP (World's Advanced Saving Project), prints scalable structures using aluminosilicate clay reinforced with small amounts of chemical additive. Hemp and kenaf, a reinforcing scaffold to improve the structure's longevity, are additional materials that makeup WASP's mixture. Similar to D-Shape and TotalKustom, this group has limited literature regarding their products, therefore, company websites and patents need to be reviewed to gain additional insight into their technology.

2.5.3 | Fabricator & Machine Control

After reviewing the existing material utilization and processes leveraged in digital fabrication of architecture structures, the various fabricator machines need to be investigated based on whether they utilize additive manufacturing techniques or robotic automation.

Furthermore, their capabilities and design based on material utilization, geometry, scale, cost, and interoperability with additional materials including reinforcement, electric equipment, and plumbing are quintessential parts of this review.

Made by Robots presents various forms of automated, in-situ fabrication machines developed by an array of companies.

Contour Crafting

Contour Crafting's gantry system 3D printing devices can be regarded as the original additive manufacturing fabricator design when it was originally published in 1997. In the 2004 publication, Contour Crafting presents a proposal to utilize a xyz gantry system that translates a concrete depositing nozzle. The nozzle itself extrudes concrete, rotates and has a trowel that creates surface forming capabilities. Moreover, the fabricator "combine(s) an extrusion process for forming the object surfaces and a filling process (by pouring, or extrusion) to build the object core" (Zhang 2013). The nozzles themselves are designed with specific degree of rotation and a mechanical stopper so that cables and wires attached are not harmed. In addition to the nozzle itself, a six-axis mechanical robot aids the extrusion nozzle by insert rebar, and pieces necessary for the floor construction. One of the limitations of the fabricator is that nozzles have to completely finish a layer, and then move to the next which causes an inefficient process compared to stereolithic printing. However, Contour Crafting does propose detailed algorithms and tool paths to optimize this process in addition to proposals for multiple nozzles and gantries for this solution. Although these sources are viable reference sources, the fabricator's construction is not broken down into components beyond the nozzle itself. Furthermore, it is sometimes unclear when Contour Crafting is proposing a design for a fabricator or has actually built and used the fabricator in additive printing. Regardless, the sources, *Automated construction by contour crafting—related robotics and information technologies* and *Optimal machine operation planning for construction by Contour Crafting* are the best sources to investigate the actual fabricator Contour Crafting uses in building construction.

Figure 20: Contour Crafting single-nozzle gantry fabricator (Zhang 2013)

Loughborough University's *Developments in construction-scale additive manufacturing processes* breaks down various additive-manufacturing fabricators in great detail and compare their pros and cons for creating scalable architecture structures. D-Shape, Contour Crafting and Loughborough's Concrete Printing technologies are specifically identified.

D-Shape:

D-Shape's stereolithic sand-based printer is a 10 m x 10 m x 10m gantry device that uses a powder deposition process that is selectively hardened with binder. The gantry contains multiple nozzles in a series that run in a single path per layer. Each layer of build material is laid to the desired thickness, compacted and then the nozzles mounted on a gantry frame deposit the binder where the part is to be solid (Lim 2012). The materials and process that the printer uses to create radical geometric shapes is expressed in the Material Utilization section. To run the printer, a 220 V, 40-amp circuit is needed.

Loughborough University:

The goal of the ‘Concrete Printing’ fabricator is to retain 3D freedom with smaller resolution deposition but allow greater control of internal and external geometry (Lim 2012). Using a single deposition nozzle, the machine extrudes cement mortar. However, the nozzle must traverse the entire build area, which allows for an extremely slow build process. An issue revealed with deposition nozzles is that if the flow rate is not continual, irregular thickness of filaments occurs, there is poor bonding of layers and filament resolve to inaccurate shapes (Lim 2012). While this source presents a significant amount of information for material makeup, it lacks identification for fabricator construction and design.

WASP

WASP, the Italian 3D printer company, unveiled their largest printer, BigDelta, in September 2015. There is little to no information on the printer, except for speculative ideas and videos posted by the company. However, the printer is 12 m high. Doubts for the fabricator itself include its ability to shake when it reaches the structure’s resonant frequency, which is a common issue with delta printer designs. In addition, it may be limited in its ability to move translationally, therefore limiting the footprint of the build.

TotalKustom & Lewis Grand Hotel Fabricator

There is limited information released regarding the actual fabricator used for concrete extrusion. However, it is known that Andrey Rudenko received significant hardware and software support from the RepRap community and Marlin Firmware to build his printer, which cost $500,000.

Made by Robots

While this book offers perspective into robot fabrication machines, it does not present highly detailed reports into the actual construction of automated robots. One of the robotic units, mentioned in the *Stratifications* section has an integrated sensor, laser rangefinder to give the robot environmental awareness. Furthermore, the robot has algorithmic operation strategies or the ability to self-calibrate when deviations in material or environment arise (Gramazio 2014). This positioning and localization technique employed by robotics is an extremely important capability if the proposed printer design will incorporate the use of a six-axis robot assembly. According to Gramazio, local referencing systems allow fabricators to re-calibrate and reposition based on an exchange between the robot and environment. This is useful to prevent collision with construction-site obstacles and reposition with materials built.

Another interesting publication, *Robotic Fabrication in Architecture, Art & Design*, presents a robotic fabricator on a pole that moves up as builds a “high rise” type structure. A Universal Robot UR5, with 6 degrees of freedom, built a structure 4 m high, 1.7 m diameter and 2.7 m in depth. The vertical rise was a Guedel axis system, and the machine can be visualized in figure 9 below. The machine has a safety laser scanning system that registers any changes to the environment around a safety envelope and leverages an in-house, Grasshopper plug-in, YOUR to control the robot. This machine offers new frontiers for building higher story structures. If this type of robot can be scaled and integrated with an extrusion nozzle, there is great potential for additively manufacturing buildings to a significant vertical scale. However, with scale comes the difficulty and high cost of using mechanical components such as actuators and hydraulics.

FIM

Although *Towards Fabrication Information Modeling (FIM)* does not offer significant perspective into the fabricator utilized, it does specifically mention that an Objet Connex 500 and Kuka KR AGILUS robotic arm KR 10 R1100 SIXX WP were leveraged to test the FIM process and additively fabricate components (Duro-Ruyo 2015). Objet500 is a multi-material, desktop 3D printer on the market from Stratasys. Therefore, this does not relate specifically to scalable architectural solutions.

After review, Contour Crafting, TotalKustom, D-Shape and Loughborough University are the best sources to reference for fabricators that have actually constructed scalable architectural structures. Furthermore, the successful robotic machines illustrated in *Made by Robots* should be regarded as a starting point for integrating additive techniques with a six-axis robot. In particular, the robot that can translate vertically on a pole platform proves to be the most valuable source of information since this design can specifically tailor to vertically scaling a structure. At this point in time, the fabricators that have successfully built scalable structures are concrete-depositing nozzles that translate across a risible gantry system. Continued investigation into TotalKustom, Yakich's solution and Contour Crafting would be valuable in designing this type of system. A stereolithic fabricator is also feasible, as illustrated by D-Shape and Emerging Objects, however building actual building structures has yet to be completed using this technology.

2.5.4 | Scale

As mentioned earlier, the scale of the fabricated component(s) is one of the biggest priorities in the design of systems capable of digital fabrication. Based on this review, it appears that additive building manufacturing or 3D printing has successfully been able to create structures of significant scale in comparison to other technologies. For the purposes of this report, significant scale means that the product is in close proximity to one story high or on the scale of providing human shelter. Concrete-depositing nozzles and stereolithic technology have both proven successful in terms of scale, however, the concrete extrusion technique proves to form more structurally adept building components rather than abstract material formations.

Lewis Grand Hotel

As an example of a scalable project constructed with a concrete extruding 3D printer, the construction of a villa in the Lewis Grand Hotel reached 10.5 m x 12.5 m (35 ft. x 45 ft.). This villa contained 2 bedrooms with a living room and Jacuzzi. To print this single-story building, 100 hours of print time were required in addition to manually inserting plumbing, wiring, reinforcement and finish materials.

Contour Crafting

Contour Crafting's printer is designed for full-scale construction. However, throughout the publications, there is no evidence of an actual full building that has been constructed using its technology. Based on images illustrating a woman next to a printed wall in figure 20, it is clear that the fabricator is capable of constructing to scale. One of the gaps of its ability is to scale beyond a single story without using traditional means of construction to create a normal floor slab. This is further elaborated on in Gaps of Digital Fabrication: Scale. Based on the current Contour Crafting technology, "the maximum vertex number in a structure layout would be less than 10,000. This allows for handling fairly large and complex structures" (Zhang 2013). The limit of 10,000 allows for optimization of the tool path for a general structure, however, Contour Crafting does not give a relative size for what 10,000 vertices would deliver.

2.6 | Gaps in Digital Fabrication Technology

Based on the designs and actual implementation of software-hardware processes, materials and fabricating machines, it is possible to digitally fabricate scalable architectural structures utilizing additive building manufacturing, robotic automation or a combination of both of these procedures. Through the projects that already leveraged some of these technologies, it is clear that a new era of the built environment is unfolding due to structures mainly built with a machine. However, significant gaps still exist in leveraging additive building manufacturing, 3D printing, or robotic automated procedures in order to translate a design into a cost-effective, structurally supportive, scalable building.

2.6.1 | Process

One of the first gaps in this technology is the process from the initial design file to the final product since there is not a standardized, streamlined process for a design software and fabricator to communicate seamlessly.

This need for end-to-end integration is one of the major themes that Neri Oxman portrays in *Material Based Design Computation*. Her argument is clear when she mentions, "Rapid fabrication technologies are designed as software and hardware packages separate from modeling and analytical environments" (Oxman 2010). Moreover, this source exemplifies the huge issue that current CAD falls short in incorporating material properties and their behaviors in addition to fabrication and construction process data. In addition to *Material Based Design Computation,* Neri Oxman's research group at MIT, Mediated Matter, is able to point out gaps in digital fabrication more consistently than other sources.

Although *Made by Robots* makes little reference to processes incorporating 3D printing technology, it excels in indicating the process gaps for robotic fabrication systems. In this source, R.O.B. Technologies mentions that a "In reality a gap still exists between the conceiving and planning of a design and its execution by (just in theory) highly flexible industrial robots" (Gramazio 2014). A major theme emerges that robotic manufactures deliver robots that can only be accessed with old-style robotic programming language but they need to accessible by the common architect, engineer, construction engineer or owner. As a result, robots could become easier to control. Moreover, robots need to become more intelligent in perception of their environment.

The limitations in the process ability of achieving a non-standard architecture are best mentioned by Mediated Matter in stating “Limitations associated with computational tools are preventing further progress in the design of non-standard architectures” (Duro Royo 2015).

2.6.2 | Material & Structure

Beyond the process gaps of realizing additive building manufacturing, the materials capable of delivering structurally supportive products through an additive building manufacturing process are significantly limited.

Emerging Objects does a great job in exemplifying how their structures and others generated through 3D printing technology are not sufficient in structural durability and the fact that the current 3D printers only offer single material use, which is highly limiting. While this has largely been dismissed in this review, they elaborate that the expense is still significant to create 3D printing or robotic equipment, material, and customized binder.

Made by Robots illustrates that printing time is excessive to achieve detailed parameters such as a smooth surface. To achieve optimal surface resolution, “the layer height needs to be sufficiently small, which through every layer bisection cubically increases fabrication time “ (Gramazio 2014).

Compared to other sources, Contour Crafting points out the gaps in the structure and materials from a comprehensive standpoint that links these issues to other parts of the process. For instance, one of the reasons the construction industry has not been able to adopt additive manufacturing is because of internal features, which cause complications in automating the process. This is magnified because the technology to additively deposit multiple materials and even switch between them on demand is expensive. Moreover, depositing wet concrete is largely constrained by the material curing time. If the nozzle idles beyond an optimal time, the concrete may solidify. Another limitation associated with optimal timing in terms of curing is the critical limit to achieve lower layer structural support for additive layers on top.

2.6.3 | Scale

If material property, materials utilized, and structural integrity of digitally fabricated structures are concerns, the scale of the architectural structures are naturally going to be affected and thus lead to gaps in this technology.

Toward Robotic Swarm Printing illustrates the gaps throughout history by stating, “Since the mid-1980s, single-node additive rapid fabrication and rapid manufacturing technologies have emerged as promising platforms for building construction automation at the product scale, but with limited applications at the architectural design and building scales” (Oxman 2015). Mediated Matter first points out the limitations in the technology by stating that the layer-by-layer nature of fabrication, the use of non-structural materials, and the “limitation of product size relative to gantry size” (Oxman 2015) prevent methods from being scaled to large architectural systems. However, the source champions additive manufacturing capability by saying that robotic platforms can enable additive fabrication at large scales and overcome the limitations.

2.7 | Further Research & Filling the Gaps

With additive building manufacturing just beginning to become feasible in the last 5-10 years, a paradigm shift in the architecture, engineering and construction world is imminent. After review of the main parties contributing to digital fabrication of architecture components using 3D printing, additive building manufacturing, and automation through robotics, it is evident that an enormous opportunity lies ahead to establish a similar technology that will change the way humans think about buildings, forever.

Some of the areas that need to be focused on in order to fill the gaps of the existing processes, technologies and end-product designs include the material deposition ability, structural ability, and the fabricator itself. More specifically, Emerging Objects calls that materials need to be strengthened through infiltration with additional hardening components. However, the optimal solution would be to deposit a composite material that replicates that of concrete and structural steel to support compressive and tensile forces. It is unclear whether this will be a homogenous material or two integral materials that are deposited simultaneously. To deposit simultaneously, nozzle design needs to be re-evaluated so that full-scale sections of buildings can be co-extruded with mass and structural material. In addition to nozzle design, the fabricator will become increasingly advanced as multiple robots work various sections of the structure and will have to communicate with each other and the surrounding environment. This can be leveraged from other industrial applications where there is already exists such as shipbuilding. Furthermore, as this technology accelerates there will be a necessity to accurately track it in a cost model. For instance, Contour Crafting mentions that one can estimate the construction by analyzing the flow rate of deposition with the velocity of the machine, analyzing the cost of traveling between edges, the cost of moving between end points and the cost of rotation time of the nozzle. To be successfully leveraged in construction and the building industry, the price model is paramount for most owners.

Rather than “filling the gaps” posed by previous technologies, it is important to reevaluate the entire process of designing, engineering, constructing and operating a building altogether given the technology at hand. One of the largest next steps that has not been addressed successfully by any of these organizations or publications is multiple story fabrication. This relates directly to how one visualizes the geometry of architecture. Traditionally, buildings have been constructed from vertical walls with 90 degree intersecting floor slabs. In any publication on 3D printing, the technology, process and end-product being printed revolves around this historical idea of a building. However, when using additive manufacturing techniques or robotic simulation, the floor and the wall begin to blend together so it can be one continual process flow from the wall to the floor to the next wall and so on. As a result, this is the next stage in additive building manufacturing of architectural components. Please see the preceding chapter for a potential design with the purpose of authentically additively manufacturing a building with multiple floors.

PART 2: DESIGN AND CONSTRUCTION ANALYSIS OF THE PERFORMING ARTS CENTER

This section represents an in-depth analysis of the construction management and architectural engineering of The Performing Arts Center. In this report, the four building program, consisting of the Theater and Dance building, the Music Building, the Arts Tower and the DRUM theatre, is examined to illustrate the owner’s goals, the architectural design intentions, the major building systems, and general construction means and methods. Furthermore, the façade system is examined from a constructability, logistics and production standpoint. Then, project challenges and opportunities are illustrated. After that, a building information modeling (BIM) use evaluation and a sustainability implementation analysis are presented. After presenting the existing, technical details of the project, three major analyses constitute the focus of this section. The first analysis is a Cast-in-Place Concrete Wall Schedule Acceleration analysis in which schedule and cost of using Peri Trio steel wall forms are compared against the proposed Peri Maximo wall forms. Then, the second analysis focuses on implementing Construction Robotics’ Semi-Automated Mason (SAM) to install an Alaskan White Velour brick façade in place of a Lecce limestone finish in order to meet the critical path schedule delayed by the façade construction schedule. Finally, in order to improve energy performance, a fan-powered induction unit (FPIU) system is compared to a VAV system based on yearly energy consumption, cost savings and constructability.

Chapter 3 Performing Arts Center Project Overview

3.1 | Architectural Premise: Explanation of Design and Functional Components:

The Performing Arts Center is designed as a state of the art performance and teaching space for the music department, theater, dance, creative and performing arts. It is designed as a portal to the campus that maintains fluidity between its boundaries on all sides. The program is broken down into multiple buildings including a theatre and dance building, music building, arts building and individual rehearsal rooms. In order to enable a powerful courtyard feature, the buildings are integrated into an underground forum. This courtyard feature is intrinsic to the campus' history resembling Oxford University. The towers of the facility create views that are transparent due to curtain wall glass. This is to provoke curiosity and connect the community with the arts and musicians as they perform.

Figure 22: Model rendering of Performing Arts Center

Just as each building shape is unique in itself, each interior holds its own flavor and distinctiveness. The Dance and Theater building contains a black-box theatre made of steel which sits in a concrete frame. The dancing partition is comprised of foamed aluminum, board formed concrete and white washed wood. The Music building is based on suspension of individual practice rooms above a large orchestral room. Unique in its design, this steel rod suspension system creates acoustically separated rooms with superior resonant quality. Suspended practice rooms can be visualized in the graphic below.

Figure 23: View of Music Building private practice rooms from east

Building Enclosure

The main enclosure system of the building varies based on the individual building. The Dance building façade is made up of exterior Lecce Limestone cladding and a glazed curtain wall system. With 5 levels of limestone cladding, the east and south walls offer 1,900 and 1,700 square feet of curtain wall, respectively. The limestone exterior cladding system includes 2’ high by 3’ wide limestone panels that are supported by or non-corrosive, stainless steel anchors so the loading is transferred to the secondary steel framing system. Many of the entrances are completely glass entrances with ¾" ultra-clear glass of transparent, fully tempered condition A. Glazed skylights and clerestories allow further permeation throughout the entire project.

While most buildings balance between stone cladding and curtain wall, performance spaces limit transparency into the space. For instance, the round dance theatre drum is made up of 5 levels of stone cladding with only a hint of curved vision glass paneling.

The arts center features a tower with the east side containing all curtain wall system. This system is a four-sided, glazed steel mullion assembly comprised of low-iron insulating glass units. The units are glazed to custom profile steel transoms and frames. All clerestories and glazed skylights are made up of the same system. Along the south side exists one story of typical vision glass curtain wall system while the remaining four stories have translucent curtain wall glass. The east & west sides of the elevation arts tower is all glazed curtain wall, whereas the north & south sides are all stone cladding. Operable window systems include operable vents with weather sensored motorized chain drives.

The music building offers one level of special vision glass outside the rehearsal space with four stories of transparent, rehearsal curtain wall system above. The forum features a glass curtain wall with half of the panels clear and half acid etched along the cantilevered walkway. The graphic below illustrates the balance between curtain wall and stone cladding along the building’s east and south exteriors.

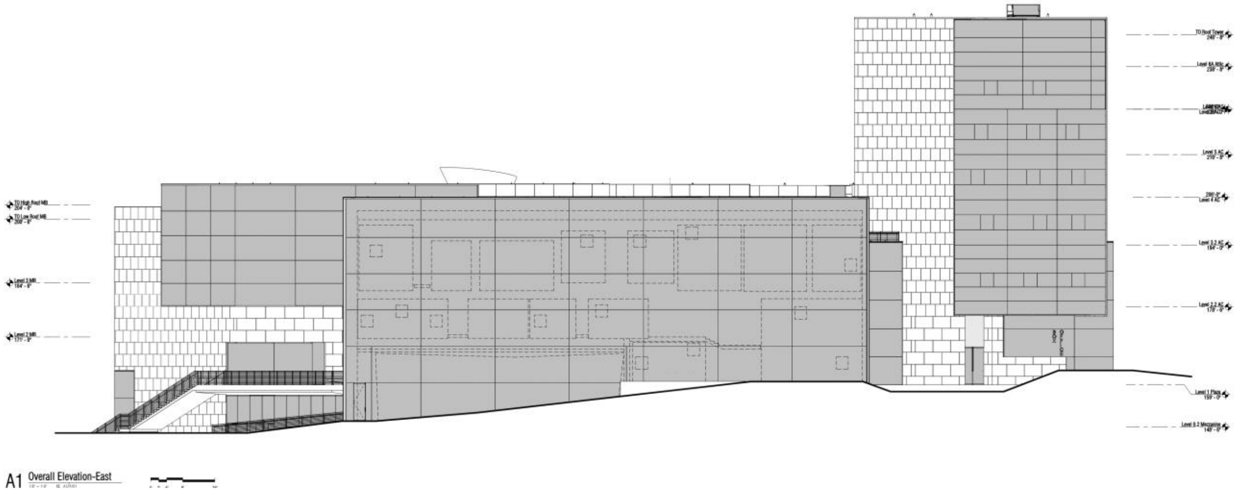


Figure 24: Overall East Elevation: 100 % Contract Documents – Volume 6 – Turner

Roofing

The entire building features a green roof system with a metal coping connection to the glass curtain wall or stone cladding facade. Small square skylights sit atop the vegetated roof assemblies to allow natural lighting into spaces. At some sections, the vegetated roof assembly is mixed with bluestone pavers. At the coping edges, a layer of rock ballast creates a transition from roof vegetation to coping. See the coping below as an example of the roof system.

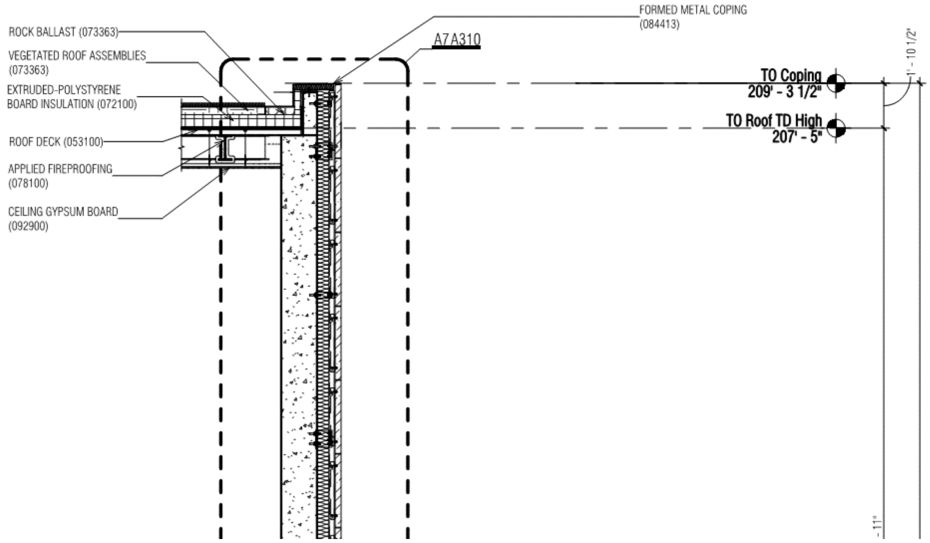


Figure 25: Roof Connection: 100% Contract Documents – Volume 6 – Turner Construction – Exterior Wall Sections – A300

Sustainability Features

The performing arts center is designed to the highest quality of energy efficiency and sustainability. In fact, the "policy is not to pursue LEED, but to go beyond LEED and focus on maximum carbon reduction throughout the design, construction and operation of the facility" (BNIM Architects). The goal is to surpass current energy codes by fifty percent. Sustainability goals are achieved through the implementation of building features including geothermal heating and cooling, green roofs, exterior envelope performance and passive design strategies (BNIM Architects).

Geothermal

The performing arts center can be heated and cooled entirely by an underground geothermal system. The system includes fourteen circuits with 9-11 bores per circuit. The system includes horizontal and vertical ground-loop heat-pump systems composed of U-shaped high-density polyethylene pipe (HDPE). The system operates between 23 and 104 degrees and runs on a propylene glycol antifreeze solution to absorb and exchange heat. The graphics below illustrate the vertical boring holes and circuits that lie under the building structure.

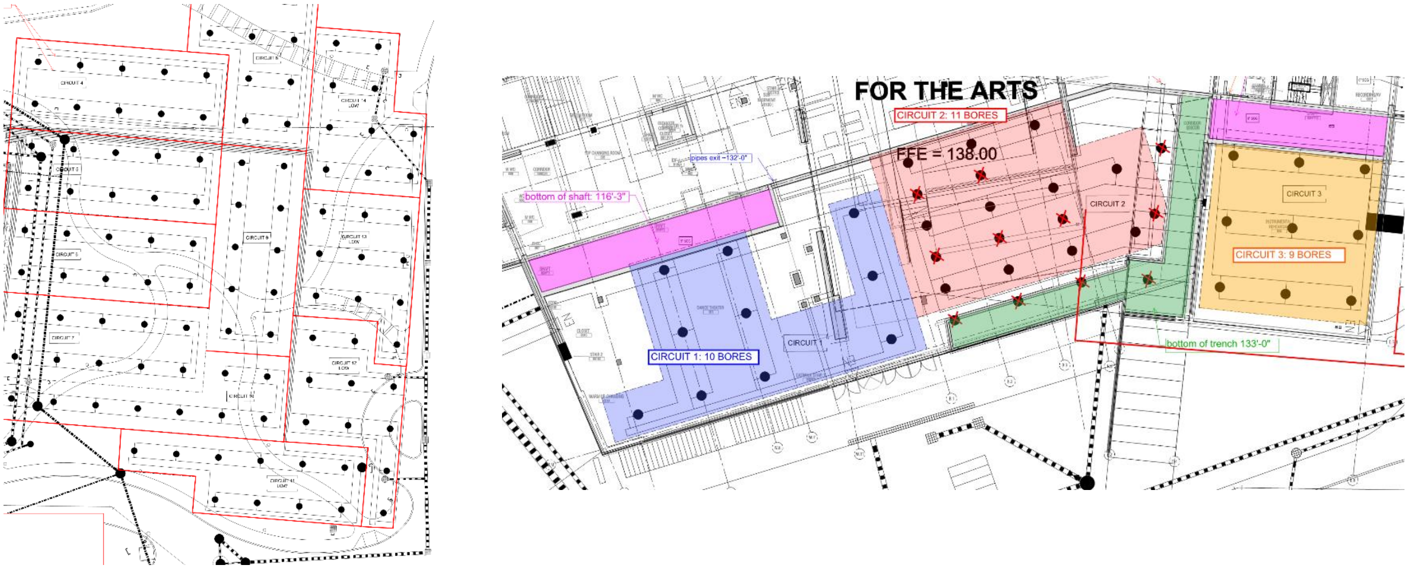


Figure 26: Geothermal heating and cooling boring plans

Roof Garden

A major sustainability feature of the building is the vegetated roof assembly that covers the entire roof area except for the walking forum area. The vegetated roof assembly is made up of moisture retention mats, drainage panels and a Siplast extensive green roof. To encourage local supply, roof garden plants can only be grown in a nursery that is 250 miles from the campus. The flowering plants range from sedum spurium to sedum cauticolum. The roof garden improves heat island effect, air quality and aids in storm water management.

3.2 | Client Information

* Note: The Owner has requested not to disclose the identity and location of the project.
Due to the owner’s desire to set a high precedent on this project, performance and design are paramount. The precedent set in design using geothermal heating and cooling, green roofs and envelope performance is matched with the construction goals and planning between the University and Turner Construction.

The owner needs the Performing Arts Center so that the music, theatre, dance, creative and performing arts departments can be consolidated at a central location. This building will serve as a space for rehearsal and performance from individual to group settings. It will also function as a portal from town to campus with the goal of being a transparent source of learning and experience between the artists and students passing.

For the University, schedule is the main focus of priority so that the campus runs smoothly and effectively around current construction and completion dates. Completion by May 2017 is imperative so that turnover is smooth and final punch list items are eradicated by the time students come back to campus in Fall 2017. Intertwined with the priority of schedule is logistics. To be successful, this project has been planned out to meet the restrictions of both the University and local town ordinances. As seen in Appendix C and discussed in the Site Logistics Section, the site is designed to enable safe and uninterrupted student and faculty pedestrian movement. This becomes especially important because the site is located on the threshold of campus and town. Although logistics and schedule are high priority, this project is extremely focused on maximizing quality. The University will base initial pricing decisions off relationships with contractors and subcontractors that can provide the highest quality work.

3.3 | Project Delivery

Turner Construction has a history of collaborating with The University to meet schedule, quality and budget needs. As familiar project partners, this allows both parties to be confident in their delivery method approach and contractual arrangements. To best complete the project, the delivery system of a CM-At Risk with GMP contract was chosen. Turner holds the risk of performance and must complete the work within the price of $140 Million. Turner obtained the job from an RFP, was chosen for preconstruction services including schedule, budget and constructability advice and then transitioned into general contractor due its competitive bidding, expertise on the job, and quality client driven relationships. This is the traditional system utilized by the University in large projects, especially when working with Turner Construction. A benefit is that the Turner Somerset staff was involved throughout the entire process with early input from design to construction. The difficulties associated with this delivery method is that the relationship between Steven Holl Architects, Turner and the University can become tense and strained once the price is fixed. This system means that the design by Steven Holl Architects and consultant engineers must have been finished with little to no errors in order to maintain The University’s rapid schedule goals.

Both parties excel with this delivery method due to its top-down communication stream from The University to Turner to the subcontractors. The overall contractual arrangement, seen in Appendix A, is organized so the main contract is between Turner Construction and The

University. There are then individual contracts between the general contractor and subcontractors with no unique forms of collaboration or joint ventures.

3.4 | Project Team

**Reference Appendix B*

The staffing plan illustrates the Turner team members from the Somerset, NJ office that all work onsite at the Performing Arts Center. Please reference Appendix B to see a graphical representation of the staffing. It follows a fairly traditional staff plan for large complicated projects. The engineering team is responsible for ensuring that everything is procured and constructed according to the project specifications and architect's design. A notable feature is that a superintendent is hired entirely for quality assurance – quality control. This illustrates the importance of quality and attention to detail for finishes and material on this project. The other two superintendents are hired to lead field operations for the structural system and the MEP system. Please note that as the project progresses through construction, staffing may change to address system focus.

3.5 | Schedule & Cost Summary

Project Schedule Summary

**Reference Appendix E*

Planning and design for the Performing Arts Center began in early 2008. The construction duration began in January 2014 and is projected to be completed earlier than anticipated, by May 2017. The phase of shop Drawings, submittals packages and approvals runs from January 2014 until October 2016. Visual mockups are constructed from July 2015 until October 2015.

Materials are fabricated from June 18th 2015 until January 2016. Physical construction did not begin onsite until May 2015. The University would like the facility to be open by September 2017, therefore temporary certificate of occupancy should be finalized by July 24, 2017 at the latest. The summary schedule (Appendix D) is broken down by the major milestones throughout the entire lifecycle of The Performing Arts Center. The construction sequencing is based around each individual building, the DRUM, the Dance Theatre, the Forum, The Arts Tower, and the Music building.

The overall superstructure is to be complete on December 3rd, 2015 with the superstructure completion of the Lewis Arts Tower. Major milestones for the separate buildings include permanent power being energized on December 7th, 2015, the superstructure of the Theater/Dance building to be completed Oct 28th, 2015, the superstructure of the music building to be completed Oct 20th, 2015 and enclosure of the Forum space on May 24th, 2016.

Project Cost Evaluation

**Reference Appendix D*

While the Performing Arts Center only totals 139,000 square feet, the total construction cost rises to $140 million. This is the equivalent of $1007/SF. When counting the enabling project, the entire project reaches $300 million and an equivalent to $2,158 per square foot. For the Performing Arts Center itself, 60% of the project is material cost which is vastly larger than most jobs because of specialized materials and construction seen in the job. Examples include exterior Lecce Limestone cladding, 100% roof garden and architectural concrete walls seen throughout the building. In addition, a 110 well geothermal ground-coupled heat pump system is installed underneath part of the enabling project. These systems entail large up-front costs, but allow for return on investment over the long term. Another unique feature of the project is that acoustical provisions make up 10% of the entire project cost.

The cost breakdown by system can be seen in Table 2. Appendix D illustrates the square foot estimate of this project based on R.S. Means auditorium model. This model can be assumed because of the zoning designation as theatre/performance space and the focus on acoustical performance throughout the project. Furthermore, the majority of space is utilized for performance or rehearsal space. However, the R.S. Means estimate proves to be extremely low compared to the high actual cost / SF for this project. R.S. Means cost data only reaches 16% of the true cost of this project, a strikingly low estimate because of the usage of basic materials. The complex system choice and high quality material, design and construction enabled by the owner explains the difference in cost compared to the R.S. Means estimate. Furthermore, R.S. Means did not offer a model that resembled the diverse usage or occupancy type of the building that included specialized construction such as acoustical isolation of rooms and structural components that hang individual rehearsal rooms.

Table 2: Major system breakdown costs including material and labor cost

The Performing Arts Center System Breakdown Costs	
Architectural (Carpentry, flooring, paint, etc.)	$70 Million
Structural System	$30 Million
Mechanical (plumbing included)	$25 Million
Electrical System	$15 Million

3.6 | Local Conditions & Site Logistics

Local Conditions

The existing conditions included many existing buildings, paved parking lots and existing NJ Transit lines. Beneath the man-made fill lies residual soil which overlie weathered but intact shale and sandstone bedrock. The Stockton Formation bedrock lies at a shallow depth of 9 to 25 feet. The first stratum soil conditions are described as brown, gray or reddish brown silt with clay. Water conditions indicated by boring logs illustrated dry conditions for the range of 14.1 to 25.1 feet below grade. The highest known water level was at 16.7 feet below grade. For the University, parking is a major concern because the majority of the enabling site was parking space at one time. At the time of construction of the Performing Arts Center, other adjacent facilities such as the train station and Wawa will have limited parking due to the construction site takeover. Local bylaws are strict and allow for significant restrictions to construction. Difficulties include restricted deliveries during University move-in weeks, noise elimination during study periods and final exams, and a no work ordinance after 5 PM and before 7 AM. Based on schedule line items, fire protection, smoke evacuation and elevator permits are most concerning to the project.

Site Logistics Planning

**Reference Appendix C*

The Performing Arts Center is tightly surrounded by two main roads and local University facilities. The highest priority of logistics is to maintain safe and effective pedestrian flow around the project site from town to campus. The green strip on the site logistics plan illustrates the temporary pedestrian sidewalk. (See Appendix C). Due to constricting area, site laydown area is limited. To enable smooth, logistical practice means the team implements Lean practices including all piping being pre-fabricated to minimize clutter onsite.

3.7 | Building Systems Summary

Demolition:

The owner's goal is to salvage and recycle 95% of all nonhazardous demolition materials including but not limited to mechanical equipment, concrete, insulation, roofing, plumbing fixtures and structural steel. Demolition on this job includes clearing the initial site by removing all existing structures and utilities around a 10 foot perimeter space for new building construction. Any asbestos or lead-based paint encountered will require the contractor to stop work immediately and cooperate with the owner and appropriate consultants for removal.

Structural Steel Frame:

The structural steel frame system includes 996 tons of structural steel 100% fabricated from the BIM. A horizontal bracing system is utilized for many of the floors, especially the large courtyard area over the underground forum (See Figure 27). During main superstructure construction, three cranes were on site including the west, east and north. Two cranes are crawler cranes whereas one is a Rough Terrain (RT) truck crane. When the large box girders above the forum were installed, a specialty 600 ton capable crane came to site. The flooring slabs will be composed of composite steel floor deck that range from 2" to 5" thick slab with 18-22 corrugated steel.

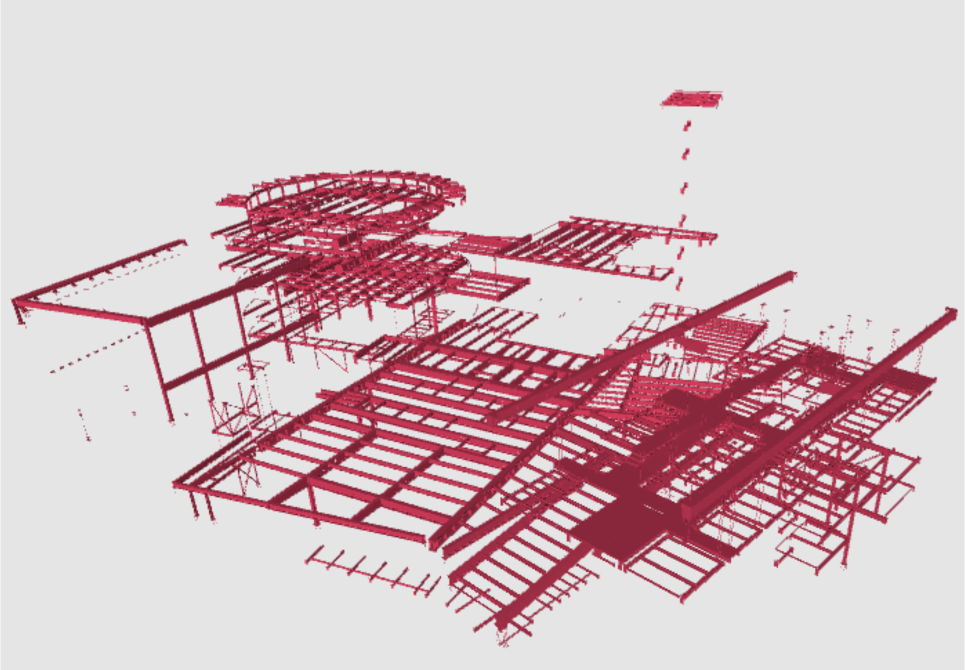


Figure 27: Structural Steel Frame model provided by Turner Construction Company

Cast In Place Concrete System:

The walls, foundation walls, columns and footings of the building are all cast in place concrete. Many beams and structural slabs are post-tensioned, cast-in-place concrete as well. The formwork for most structural elements is traditional timber formwork. For the architectural concrete finish on many interior walls, pre-fabricated board forms are delivered from Massachusetts. This means that the walls have a concrete, ripple finish along the interior which will be the final finish product. All formwork is pre-fabricated. On average, 13 trucks of concrete arrive 3-4 times a week in order to pour 100 yards of concrete a day.

Pre-Cast Concrete System:

All pre-cast concrete is cast within 500 miles of the project site. The concrete specification is to utilize Portland Cement ASTM C 150. Anchorage and connection will be through bolting, welding or grouting. The 2 crawler cranes that are located in the east and north are utilized to install pre-cast elements including beams and slabs.

Mechanical System:

The mechanical system is enabled through the use of the geothermal heating and cooling wells. A ground-coupled heat pump system consisting of heat pumps, circulating pumps and a ground coupled heat exchanger enables the closed loop system. In the majority of the rooms are overhead VAV boxes except for the use of floor supply in select areas. Radiant heat is leveraged in music offices, practice rooms, the forum and the CoLab. Most of the corridors include both overhead VAV boxes and radiant heat to enable the feasibility for completely geothermal dependency or traditional means.

Electrical System:

The power distribution system is delivered from the campus by 4.16kV feeders. These feeder services go directly to the north face of the subbasement level where they meet the main switchgear room at two service tap boxes. Emergency power is supplied to areas that need egress lighting and fire alarm system equipment. Standard dry-type transformers serve all theatrical lighting dimmer racks and LED theatrical lighting. Another major electrical concern is power to the acoustical equipment which will be served from 480-208/120V transformers.

Masonry & Curtain Wall System:

The façade system is composed of Lecce Limestone cladding and a glazed curtain wall system. The masonry façade features 2’ high by 3’ wide limestone panels that are supported by non-corrosive, stainless steel anchors so the loading is transferred to the cast-in-place concrete wall system. (See figure 28 for a connection detail of the wall system). The curtain wall system varies between vision glass curtain wall system and translucent curtain wall glazing. Both are low-iron insulating glass units. These are built to custom profile steel mullions and glazing frames of built-up steel bar stock construction. The design for the vision glass is to allow for students to visualize the rehearsal and practice of students and learn from their exposure. Concrete masonry unit (CMU) walls are utilized as load bearing walls for floor decking. CMU is fully grouted and connected to steel decking through steel angles. Standard board scaffolding with steel tubing is used on this project.

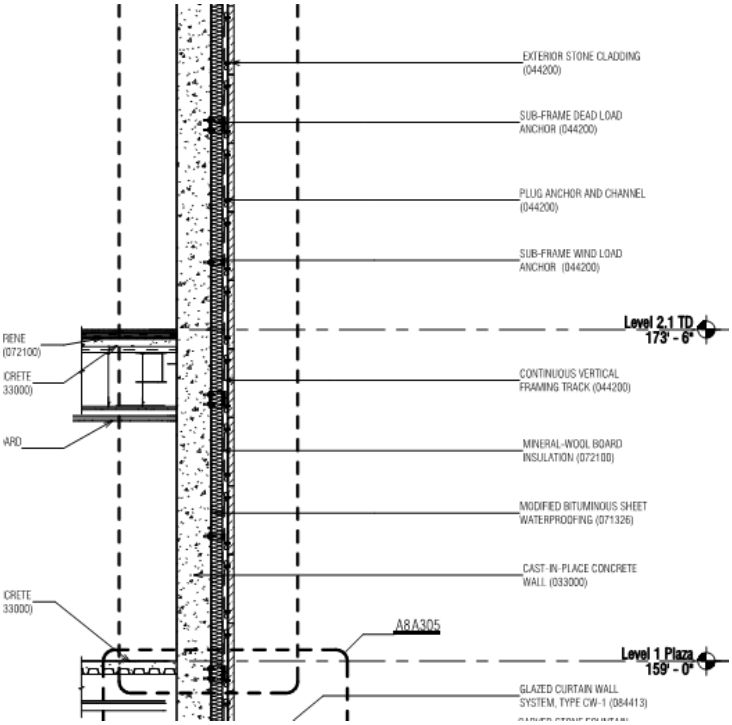


Figure 28: 100% Contract Documents – Volume 6 – Turner Construction – Exterior Wall Sections – A300

Chapter 4 Façade Production Analysis

4.1 | Production Plan

4.1.1 | Façade System Construction Means & Methods

The façade of The Performing Arts Center is a complex system interwoven with specialized material and difficult geometries. As seen in Table 3, the exterior finish system is mainly comprised of Lecce Limestone paneling, curtain wall and glazing system. The balance between solid stone paneling and curtain wall is essential to ensuring Steven Holl Architects' vision of creating a music and visual arts space that promotes campus connection to the musical experience but maintains solidarity for focused rehearsal.

Table 3: Overall Exterior Façade Material breakdown

Façade Exterior Material Breakdown		
Element Type	**Total SF**	**% of Façade**
Lecce Limestone Panel	25503	39%
Curtain Wall System	33277	51%
Glazing Window/Opening	6271	10%

Lecce Limestone Exterior Stone Cladding

The exterior stone cladding system is composed of Lecce Limestone Panels that vary from 2'0" high by 3'0" wide to 3'0" high by 5'0" wide. The panels are 3" thick and are supported by stainless steel anchors which transfer the dead load to the cast-in-place concrete wall and integrated steel structural system. Plug anchors secure the stone to the steel bracket channels in the concrete wall to resist wind and lateral loads. Supporting brackets were installed to test labor efficiency. The project includes 500 brackets with 4 holes that anchor the bracket to the concrete wall. In 1 day, 10 of them were installed in 8 hours. This meant the steel installer drilled 40 holes, installed 40 anchors and hung 10 brackets. At 500 brackets, performing 10 a day means that it will take 50 days of work to drill holes. To install these brackets, workers will be supported by knee-brace scaffolding that is raised by a crane and sits along the wall at a certain height.

Figure 29: Bracket-anchor system to support Lecce Limestone Panels & waterproofing barrier on DRUM Facade

In between the stone panels and the concrete face lies mineral-wool board insulation and a bituminous sheet waterproofing system. The waterproofing consists of 160 millimeter thick fiberglass mat coated with styrene-butadiene-styrene (SBS) bitumen. See figure 29 below to see the initial system of supporting brackets and weather barrier on the Theatre & Dance "DRUM" on the northwest section of the Performing Arts Center.

Joints between the stone panels are .375” thick using non-stain, non-bleed elastomeric sealant and backer. To ensure a smooth façade appearance, these joints have stone dust mixed in with material to provide a soft lime mortar texture. It is crucial for an open ventilation gap to be constructed where stone panel meets glazing sills and windows so that optimal ventilation is provided. All structural performance of this system is designed against ASCE 7 and Uniform New Jersey Construction Code. In addition to the exterior stone cladding system, Lecce limestone makes up the stone benches, sculptures and architectural bollards that populate the courtyard area. See figure 29 below for construction of the façade system.

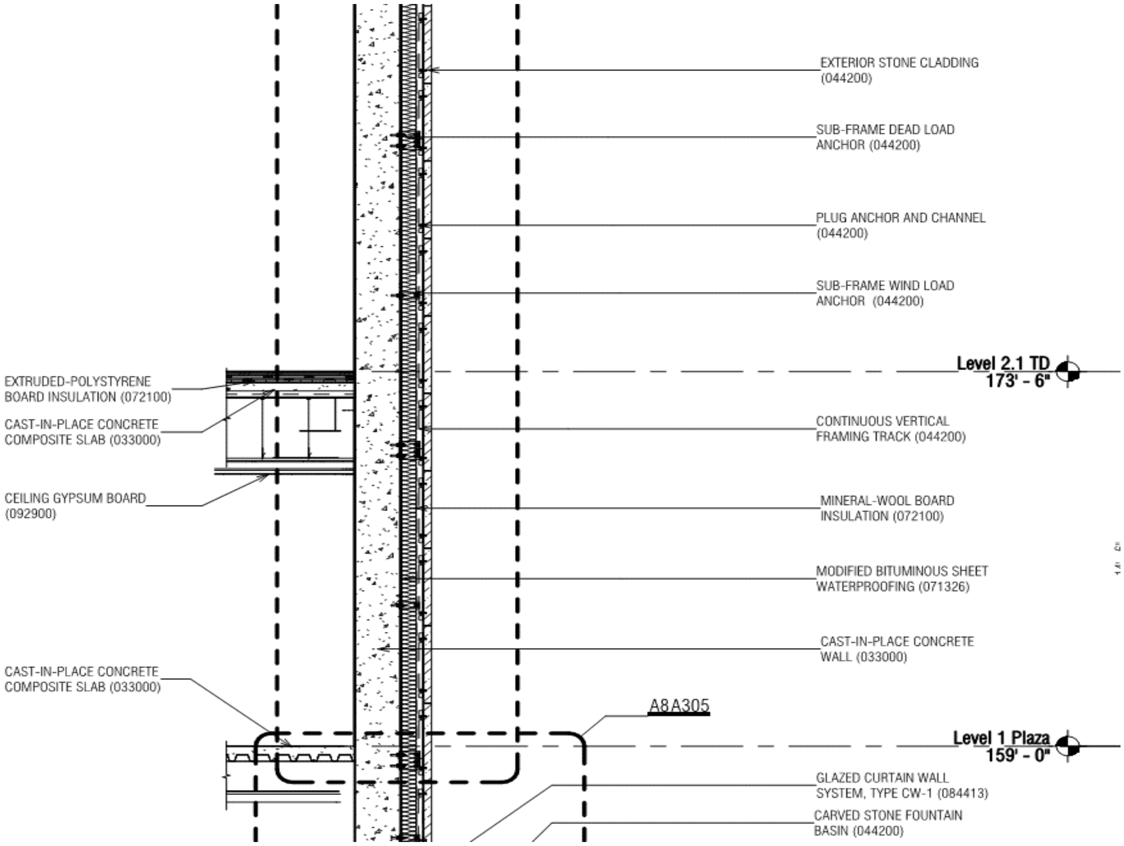


Figure 30: 100% Contract Documents – Volume 6 – Turner Construction – Exterior Wall Sections – A300

Cast-in-Place Concrete Wall Facade

Below the exterior stone cladding, anchoring system, insulation and waterproofing lies the cast-in-place concrete wall system. These walls are composed of 5,000 psi normal-weight concrete that makes up 2,166.81 cubic yard of material. This represents 13% of the total concrete used in the entire building. The overall building system includes straight runs of concrete wall, however the Theatre / Dance DRUM is a radial concrete pour. From a quality assurance standpoint, the highest concern are DRUM concrete pours. The concrete façade walls need to be extremely accurate to the drawing specification so that curtain wall connections and structural truss connections are correctly aligned with the system. These need to be within ¼” for every 10 feet. To ensure the level of quality throughout the project, walls are checked with surveyors. This can be referenced in the Production Schedule as “Layout and field verify façade”. Moreover, many of these straight and radial walls are poured to create an architectural concrete finish that is made possible by prefabricated plywood board-forms. The forms are prefabricated in Norton, Massachusetts. This creates high risk because the specialization of this material can lead to schedule delays due to delivery and laydown logistics.

Concrete is placed on the façade walls 3-4 times a week with 100 – 300 cubic yard poured per day. This equates to an average of 13 trucks a day, necessary to pour façade walls based on a standard 10 cubic yard concrete truck. When pouring concrete, a very unique solution is used as a means of maximizing length of each pour. On a straight run, the entire form will be raised along the length of the wall. The board form is placed inside, along with rebar. Then, the other wall is flown in pieces and stood up next to the wall. To make this work, the wall needs to be slid with the crane and inched over until it fits snug. See figure 4 to see the inside of a form before the second wall is slid into place. In many areas, there will be dowel bar notches in the concrete wall so that re-bar can be screwed in later. In order for this happen, cup-shape metal pieces are attached to the formwork to leave a gap for the re-bar. This is especially effective when it is necessary to add re-bar to an existing wall that will tie into another wall.

Figure 31: Pre-fabricated wooden Board form placed inside steel concrete form with rebar being set.

Curtain Wall System & Glazing

The curtain wall system comprises 51% of the entire building façade. It is made up of two different systems, a four-side supported and two-side supported structural silicone glazed steel mullion assembly. Both are made up of high performance, low-iron insulating glass units that are glazed to custom steel profile mullions to fit the unique geometry of the various buildings of this project. For the four-side supported system, the vertical steel mullions are restrained at the top and are axially slipped at the bottom. The two-sided system's steel transoms and frames are constructed with standard steel shapes and stainless steel spiral wire strand. Both systems are doubly sealed with a continuous primary air and water seal and a secondary water seal, closure and flashing. See the *Field Supervisor Interview* section for constructability issues pertaining to seal quality assurance.

The glazing for clerestories, vision glass, entrances and long stretches of façade glass vary throughout the project to ensure high transparency at points and visual protection at others. This is to create the compelling experience envisioned by Steven Holl Architects and BNIM so that students and faculty can walk through the courtyard and feel at one with the musicians performing in the visible spaces. The design encourages inspiration and education beyond the walls of the performing arts departments. See figure 32 below to visualize the contrast between curtain wall system and vision glass for music building instrument rehearsal. The vision glass is low-e-coated and features sound absorptive lining to ensure acoustical performance STC 56. High forms of transparency in the curtain wall and vision glass elements are contrasted with private, translucent glazing featured on much of the theatre/dance building as well as clerestories and smaller glazing panels. This glass is Low-E coated, insulating laminated glass with an acid etch to create a blurred image visual.

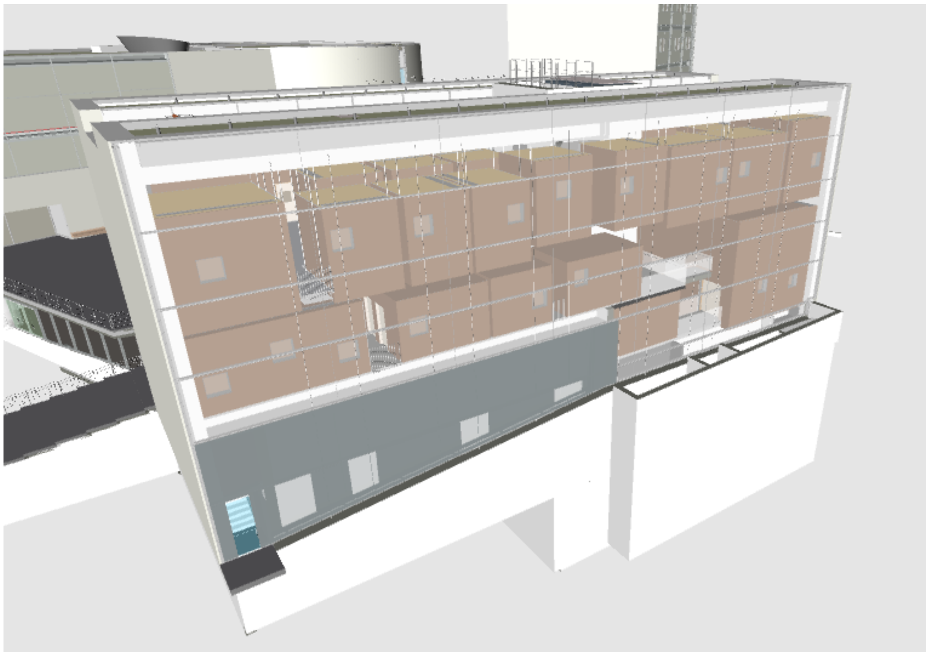


Figure 32: East façade of music building featuring clear visual to hanging cube, practice rooms

Installing the glazing and curtain wall systems is no easy task on the Performing Arts Center. Due to complex and irregular geometries, connections need to be engineered and installed with great detail. For instance, on the DRUM's north façade, the first portion of glazed curtain wall system was being installed with extreme attention to detail so that connections followed up the radial curve of the DRUM and so that the steel paneling would integrate successfully with the steel structure. It took at least 4 hours for glazing subcontractors and surveyors to lay out and field verify connection levels and angles so that the strip of curtain wall would fit correctly. Next, they would install the stainless steel brackets that have been cut out of the waterproofing lining. Anchors will be secured to the base structure and attached to the glazing system. A crane will pick up panels and then crews will secure the steel structure of the glazing to the anchors.

Figure 33: Installation of glazed curtain wall system on north DRUM Façade

4.1.2 | Production Schedule

*Reference Appendix F

The production schedule developed illustrates the detailed schedule of façade construction within the overall milestone schedule of the Performing Arts Center. Note that the façade construction spans from June 2015 until January 2017. During planning stages, it was designed so that sequencing would be staggered on a building-by-building basis. Therefore, the detailed schedule follows the original schedule phasing and plans. Please see *Production Analysis and Field Supervisor Interview* sections to see how this schedule has changed and will continue to change in the future. Façade construction will see the point of the project where total manpower rises to its maximum resource level. Ideally, 200 workers will be onsite at peak production level when façade and interior work will be completed simultaneously on alternate buildings. All schedule values are based on an 8 hour workday.

The labor curve below illustrates the change in crew size and overall manpower in man-hours on site during façade system construction. The initial peak illustrates the high resource demand during cast-in-place concrete pouring throughout the various buildings. Large crew sizes erect board forms, place steel concrete forms, run electrical systems, install rebar and pour concrete to construct quality cast-in-place concrete facades. The dip in manpower during mid-2016 illustrates an overall shift from glazing and curtain wall installation into stone setting toward the end of 2016. Reference Appendix F to see the full detailed schedule with the production curve.

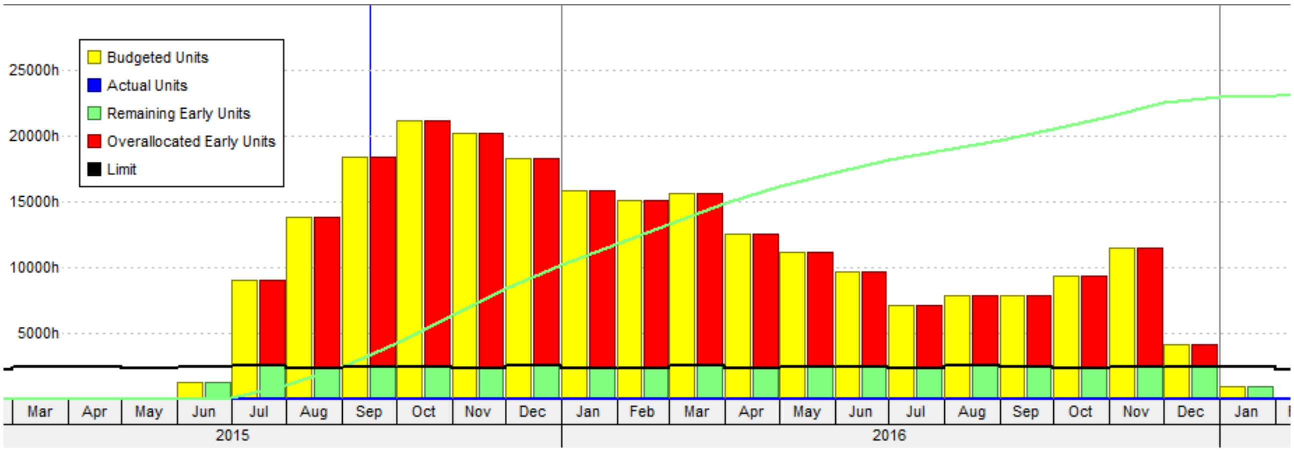
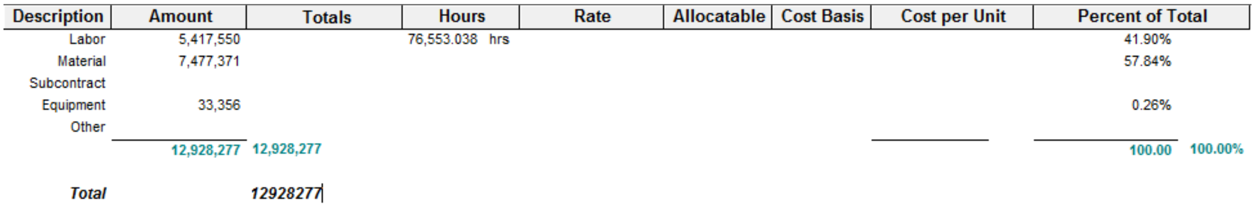


Figure 34: Resource Loading - Installation of glazed curtain wall system on north DRUM

4.1.3 | Detailed Facade Cost Estimate

*Reference Appendix G

The estimated total cost for the Performing Arts Center façade came to $12,928,277. This was calculated using Sage Timberline using MeansDB due to its high complexity of systems included within the item takeoff. Items included in the estimate reflect the major components of the façade system. These contain concrete walls, limestone panel, masonry anchors, waterproofing, insulation, glazing, and curtain wall systems. Takeoffs were completed using the 100% construction drawings provided by Turner Construction Company as well as the BIM 360 Glue concrete and architectural models provided by Turner Construction Company. Please see Appendix G for total estimate, takeoff quantities and illustrations.



Description	Amount	Totals	Hours	Rate	Allocatable	Cost Basis	Cost per Unit	Percent of Total	
Labor	5,417,550		76,553.038 hrs					41.90%	
Material	7,477,371							57.84%	
Subcontract									
Equipment	33,356							0.26%	
Other									
	12,928,277	12,928,277						100.00	100.00%
Total		*12928277*							

Figure 35: Timberline estimate totals for façade system

4.1.4 | Site Plans & Logistics

*Reference Appendix H for full-scale phasing graphics

The 3 phase logistics phasing for the façade is designed around three major steps: cast-in-place concrete façade progress, curtain wall and glazing and setting limestone. Please see Appendix H to see the logistics plans.

The Phase 1 Logistics Plan illustrates the site layouts while the concrete wall façades are being completed. An interesting piece is that the southeast portion of the site is largely empty except for trailers and a concrete pump. Workflow has shifted to the northern portion of the site to accommodate the heavier work taking place on the DRUM. This includes laydown for stone, concrete staging, and steel staging. The scaffolding around the drum is utilized to install limestone panels. In addition, curtain wall shipments arrive. At first the project team staged the curtain wall on top of the wide-open courtyard for quick installation, then they begin to stage toward the east in later logistics plans.

Phase 2 of the logistics phasing illustrates the start of curtain wall installation. Note that the staging area has moved from the courtyard to the southeast portion of the site. Also, workflow is moving into the southeast region for stone installation. Due to the large amount of debris and the shifting of activities from concrete to curtain wall, multiple debris chutes and dumpsters have been brought onsite. Workflow is shifting from the DRUM to the eastern portion of the site to apply curtain wall to the music building.

In the 3rd phase of façade logistics, the entire building is enclosed. Finishing curtain wall installation and hanging limestone are the focuses of manpower. This is illustrated by the heavy amount of laydown area for Lecce limestone and curtain wall staging in the northwest and southeast portion. From this point on, façade material deliveries will diminish and there will be a transition into interior fit out. Another notable milestone is that the main walkway through the project courtyard is being constructed.

4.2 | Production Analysis

4.2.1 | Production

The overall production plan is to stagger the buildings in the order of Theatre / Dance, then the DRUM, then the Music Building, then the LCA Arts Tower. For the façade system, the sequencing of construction will progress from cast-in-place wall pours to waterproofing installation, and then installation of brackets and anchors for glazing. After that, the glazing, curtain wall and glazing system structures will be installed. Finally, stone anchoring system and stone connection will take place.

This production design is extremely efficient, however it is overly idealistic of variable scenarios. It is well suited for a project that does not undergo many design changes or delays since it provides for simultaneous, overlapping work of successive construction activities to occur on different buildings. With the ability to increase crew sizes to a level of 200 workers on site, this becomes a fantastic design to ensure efficiency and meet the demanding schedule needs of The University. Furthermore, the design means that different trades are not on top of each other. For instance, concrete will be on the Theatre / Dance building while glazing is starting on the DRUM. It allows trades to flow from one building to the next while the next trade moves in. This flow cycle is illustrated in Appendix F, the Production Schedule.

However, this project experienced significant delays due to the great attention to detail of the owner in terms of material change decisions as well as the difficulty in obtaining certain specialized items on time. Both are natural, important occurrences to such a unique, specialized project. Therefore, the production is not as efficient as originally planned for the entire project duration. This means that the production cannot be overlapped because the flow is stopped by certain elements. These high risk elements consist of board form equipment procurement and limestone paneling supplier changes late in the project.

Board forms are a critical element to successful sequencing for a largely start-start relationship schedule. These board forms are all prefabricated offsite. The management issue is that not all of the board forms can be delivered simultaneously because of laydown area. When some board forms had to be thrown away due to weather damage, a lack of expected material onsite led to delays in pouring walls. It is an optimization of element quantity while managing risk. The delay in pouring concrete pushes the entire façade schedule back, thus pushing back entire construction because of potential water damage without complete enclosure.

Another major delay is that the supply of Lecce Limestone stone panels was rejected in a go/no go decision in early October. Therefore, fabrication and delivery will be delayed. While anchoring and brackets can still be installed, the stone delay will impact close out items. If there is scaffolding around the outside of the building, then landscaping, sidewalks and courtyard paving are all delayed. These are major milestones which prevent opening the Performing Arts Center by fall 2017.

In future projects, potential solutions include designing a weather protected area for weather-sensitive, critical schedule items. This could be a shelter onsite, an existing facility rented from the owner or a warehouse rented locally. In addition, major material go/no go decisions should not occur this late in the project. The decision was based on a freezing test that failed. This test should be completed at the beginning of the schedule, or materials should only be selected that have been proven to meet the specified freeze/thaw test. See *Field Supervisor Interview* for further solutions and how the schedule will be accelerated to make up for lost time.

4.2.2 | Cost Analysis

The cost analysis resembles the cost nature of the Performing Arts Center based on the systems within the façade. The labor and resources devoted to crew size relate to the estimated work in place for the specific systems included in the overall façade system. When compared to the square foot estimate, this estimate is 300% of the total cost of the exterior enclosure. It was expected that the R.S. Means Square foot estimate would be extremely low due to the unique nature of this project compared to a regular auditorium. If one compared the percentage of the exterior enclosure to the total project cost, this estimate does not follow normal project cost parameters. R.S. Means projects 21.7% of the total cost to be in exterior enclosure. This detailed estimate totals $12,928,277 or 9% of total project cost. This accounts for an error margin of 57%. Explanation for this can be attributed to the extremely expensive interior millwork and finishes in this project. This and other high up-front costs including geothermal wells and 100% green roof allow for such a high total project cost which influences the normal percentage breakdown of systems. In previous hypotheses it was estimated that the façade would be an area of extremely high price, however, after studying the procurement and material costs of the Lecce Limestone material, these projections were determined to be high. After confirmation with project management, other parameters mentioned above impact a higher total cost.

4.2.3 | Logistical Analysis

Logistics and heavy site restrictions present efficiency issues when trying to perform more work in a shorter amount of time. For instance, local ordinances prevent multiple shifts in a day by limiting work from 5 AM – 7 PM. This is to allow students to study at night. Furthermore, the site shuts down during University reunions and exam periods. Finally, no construction can occur on Sunday. These parameters restrict logistics before any planning can occur.

From a planning standpoint, the workflow of material staging and laydown functions very well with the project production flow. While the manpower and type of work shifts from the western portion to the eastern portion (DRUM & Theatre/ Dance to Music and Arts Tower), the material staging and deliveries follow similarly. However it is inefficient to not stage any material in the southeastern portion of the site. Since there are issues with space for board forms onsite, this space can be leveraged to hold the material. Moreover, this space could be utilized to construct a temporary shelter facility to protect high risk lead items such as pre-fabricated board form.

In order to accelerate the schedule to make up for delays mentioned in *Production*, manpower needs to be reorganized so that it is not staggered between trades. Since each building will be waiting for limestone façade, larger crew sizes and more equipment will be required onsite to enable all buildings to be clad at the same time. Therefore, more cranes will be onsite and a higher quantity of limestone will be staged. The limestone should be staged in the courtyard area so that it is in a central location and picks can be performed by two separate crews with cranes. At this point the limestone will be critical to gaining schedule time. The picks can be directed to two separate areas and thus accelerate the schedule. Furthermore, during limestone installation, knee-brace scaffolding should be leveraged so that the flooring below is open. By having more cranes onsite, moving this scaffolding will be easier and having the floor open below allows for courtyard paving, landscaping, sidewalk paving, etc.

4.2.4 | Field Supervisor Interview

The field supervisor interview took place on October 13th, 2015 at 1:30 PM in the Turner On-Site trailer at the University in New Jersey. The interview was conducted with Don Deakyne, General Superintendent of the Performing Arts Center and Sean Tonnesen, enclosure and exterior superintendent.

Schedule Acceleration Scenarios:

Finishing the façade is a major driver to the overall schedule because the building needs complete enclosure to begin interior construction. Moreover, interior construction is proposed to take a year to complete. Therefore, the façade needs to be completed by April or May 2016 so that the interiors can be finished by May 2017. To enclose a building, the curtain wall needs to be completely finished. Consequently, the schedule is riding on Gartner, the curtain wall subcontractor, to finish the work in six months (October 2015 until April 2016). As of October, 2015, the curtain wall construction was one month behind. Turner is strategizing to accelerate the concrete façade and waterproofing areas so that Gartner can follow and install curtain wall after concrete is finished. Turner plans to increase efficiency by increasing the amount of cranes onsite, and increase the amount of material allocation staging onsite. In order to have more curtain wall on hand, Turner has rented local warehouses and the curtain wall provider is storing in their local warehouses. It is ideal for Turner to have Supor use their warehouse because it takes some of the risk off of Turner.

A high risk element that can make or break a schedule is concrete pouring. In this case, the highest risk element is the prefabricated board forms used to create architectural concrete finishes. To accelerate the schedule, delays need to be eliminated by protecting board forms from the weather and optimizing just in time deliveries of the proper board forms. In this case Just-In-Time delivery means 2 days ahead of time for staging and logistics.

A means and methods solution that Turner uses to improve the construction process is an innovative strategy with concrete form placement. One solution for a straight, regular wall is to line one form up the entire side where the wall is to be formed, and then fly the other wall in pieces. These can be slid in with a crane that nudge the wall into the perfect location. This technique is used so board forms can be installed on both sides. However, concrete placement of a wall is limited to 60’ at a time. If concrete is poured on a wall over 60’ there is chance for shrinking and cracking.

Another high risk element is the Lecce Limestone stone cladding that is now going to be heavily delayed due to changing the supplier. The solution will be to assign two crews for each item of work, rather than staggering between the buildings. For instance, the crew installing limestone panels on the DRUM will move to the Arts tower and the crew on dance/theater will transition to the Music building. This breaks the schedule down from 4 steps into only 2 steps. Logistical implications from this include more lulls in labor efficiency, more scaffolding onsite, more Turner staffing and higher overall manpower onsite.

For Turner to accelerate the schedule on a general level, the key is in resource loading. This means adding more equipment, material and manpower to a shift. In this case, Saturdays are the only form of overtime as night shifts and Sundays are restricted by local ordinance. However, another solution is to change the design of a building element so that construction can occur at a faster pace. This is very uncommon to use this strategy in Turner's experience.

Constructability and Logistical Challenges

One of the major constructability issues related to the façade has been the intersection of systems at the southwestern corner of the Dance/Theater building. The issues have been due to drawing coordination issues between the architect and structural engineer. Major schedule delays have resulted. The site team overcame these challenges by coordinating communication at an accelerated level beyond how the engineer and architect were communicating to solve the problem. In the future, the contractor should be involved with the architect and engineer when decisions are made for this aspect of the design. That way the contract will be able to pinpoint issues related to constructability and thus prevent schedule delays.

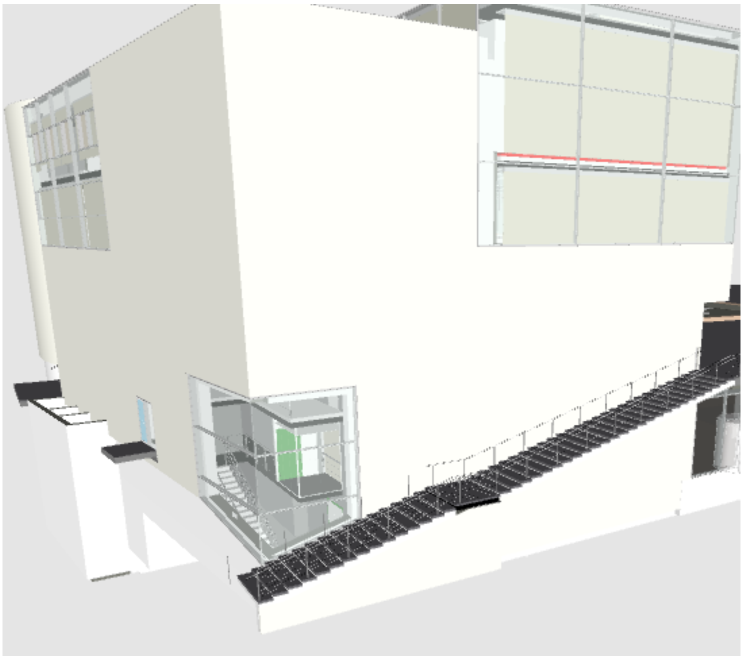


Figure 36: Major constructability issues have been at the Southwestern corner

With a sophisticated geometrical design, there are always opportunities for leaks. The façade's most important role is to prevent leaking to the interior. To ensure that leaks are prevented, the key is monitoring every detail. One needs to remember that the product is only as good as the installer. If an installer has a bad day, this could negatively impact the effectiveness of the product. However, to ensure proper design early on, constructability reviews take place where the contractor will meet with the architect and major stakeholders. When there is going to be a problem, an exterior façade expert will sit down with the sub and pinpoint re-design or onsite changes that need to take place. Holding meetings early on where all relevant subcontractors attend is critical. Therefore, everyone can attest that their system is covered where façade systems intersect. Then, subs can warranty their system. However, with big firms it is important that foremen attend these meetings, rather than executives who will not actually be onsite.

To prevent leaking for this project and ensure cohesiveness of the façade, performance mockups were tested in Germany. The critical systems were tested for water leaks at a basic level. However, these tests did not incorporate interface detailing with flashing details and caulk that are necessary for detailed water leak testing. On many projects, dynamic testing occurs where water is pushed through the façade using an airplane jet. Other techniques include a smoke bomb test where the room is pumped with smoke to see where smoke exits through seams and cracks.

In some examples, caulk is overly utilized. This negatively impacts the façade functionality because water has no way to leave the void. Another solution to prevent leaking might be reevaluating the procedure of construction. If the designer specifies that construction occur in A, B, C sequencing, it may be more effective to build in the rearranged sequence of B, C, A.

Chapter 5 : Project Challenges & Opportunities

Project Manager Interview:

This interview took place on November 9th, 2015. To find key answers on overall project challenges, feedback was collected related to schedule, client requirements, design management, value engineering and delivery method. Overall trends illustrated that due to a CM-At-Risk delivery method, Turner Construction Company was involved in a significant portion of the project, from preconstruction through construction. Preconstruction itself lasted for 5 years with a heavy focus on resolution of constructability issues. Major project challenges have been related to unexpected schedule alterations. During a complex project where construction begins before drawing documentation is finalized, changes occur frequently causing communication challenges where solutions and answers need to be found quickly.

5.1 | Project Management Services

Preconstruction:

The University selected Turner for Preconstruction Services during the design phase. Throughout the 5 year preconstruction process, Turner's priority was to provide any advice that the University needed. Although the services have focused on constructability review decisions and working with the surrounding township, preconstruction services have spanned to logistics planning, phasing design, and scheduling. Due to the unique circumstances of this project, including being located on a major road at the interface of campus and town, much of the advice and consultation was focused on working with the surrounding township. This has been essential so that construction impacts the local population minimally.

During logistics planning, Turner has offered solutions related to optimal site access, material deliveries, and on-site equipment including hoists. During the preconstruction period, Turner designed an eleven-stage site logistics plan that started with earthwork mobilization of the entire enabling site and concluded with the landscaping and unveiling of the Performing Arts Center. In the logistics plan, construction phasing, material delivery allocation and general conditions are illustrated for every three months of the project. This has been valuable to the owner, Turner and subcontractors in visualizing the changes of the site and how it may impact construction and external operations.

Master schedules have been developed including resource-loaded schedules that offer visual projections of material and manpower availability. These have been developed in accordance with the University's highly prioritized guidelines to align with the schedule on a macro scale and micro scale in the form of university schedule and daily road operations, respectively.

5.2 | Major Project Challenges

Schedule Challenges & Solutions

From preconstruction through construction, most of the project challenges have been related to schedule and design management. From a schedule standpoint, the major challenge has been getting the structure ready for the glass and glazing systems. For much of the enclosure phase, roof structure and wall-roof connections have lagged behind schedule expectations. This can be attributed to design management and constructability changes, weather impacts and unfamiliar forms of construction such as board formed architectural concrete. The level of difficulty to implicate board forms to create architectural concrete finish was highly underestimated. When the board forms are on both sides of a wall, this surpasses schedule expectations drastically. Before any windows or curtain wall systems are attached, the structure needs to be complete. In order to resolve this delay in schedule, other construction tasks have begun early including mechanical system construction in the basement and throughout the building in the form of radiant systems. Furthermore, temporary enclosures have been built to ensure dry conditions where necessary. While this prevents moisture, the interior spaces still need to be conditioned from a fully functional mechanical system for millwork and hardwood floors to be installed safely. The costs associated with schedule delay are remediated by the re-sequencing of work so that mechanical system installation takes place. While mechanical system construction was expected to occur after building enclosure, these costs and tasks can be swapped with the now delayed enclosure system construction. In addition, the costs associated with temporary enclosure systems prove viable since it is made up in the form of labor and manpower expenses. Using temporary enclosures can keep the subcontractors onsite at the expected manpower quantity and duration so that additional expenses are not incurred with additional man-hours to the contract.

5.3 | Client Driven Delivery

Throughout preconstruction and construction, Turner works to produce the best overall experience and product for the University. To ensure safety and mitigate impact to the surrounding area, the University presents constraints related to scheduling and phasing of work.

These restrictions are generally related to the student schedule and the overarching University schedule. Turner needs to improvise for the day-to-day schedule changes when deliveries and construction trucks are restricted to roadway travel. However, overarching phasing schedule requirements have been built into the master schedule. These include exam periods, University-wide reunions, etc.

In order to create a great end product, Turner ensures that every element of construction retains the priority of quality. Turner is constantly communicating with the University to protect and ensure preservation of high priority elements through wall protection or wooden floor covering. While this is additional to the budget, it is important so that the University gets the building as it was designed. For example, hardwood floors will be put down a year before the building is finished. These need to be protected to ensure quality while construction still occurs. Other systems that need to be protected include glass and glazing systems and board form concrete walls. For the board form architectural walls, corners need to be protected.

5.4 | Future Solutions

Many of the communication challenges and late, costly changes can be resolved through earlier constructability reviews. In future projects, the project management team envisions performing constructability reviews earlier and more often. It is important to meet with the owner, architect and main subcontractors early on to analyze the drawings based on constructability. On this job, construction started before the constructability reviews were completed. As a result, Turner has been facing difficulties since questions arise late and create hurried, emergency situations where answers come last minute. As a result, changes and RFI’s are demanded on the day of construction, which is unfair to the owner, contractor and designer. Project management is focused on how they can collaborate with the designers or engineers to get answers ahead of time so that solutions and improvements can be implemented easier and more cost effectively. This can be improved by holding constructability reviews in advance.

5.5 | Delivery Method Benefits & Challenges

The CM-At-Risk Delivery Method has proven fruitful for the collaboration of the University and Turner. The University uses this delivery method because they have full control of the budget and have close ties to the contractor from design through construction. This enables the owner to stay heavily involved through every decision making process. In addition, this has allowed the job to start sooner. In a lump sum delivery method, the drawings need to be finalized before construction can begin. For this scenario, delays can be minimalized since construction can begin as documents and drawings are finalized.

5.6 | Value Engineering

For every decision that is made by the owner, value-engineering solutions are proposed by Turner’s project team and reviewed by the architect. The main area of value engineering has been alternative structural elements that were post-tensioned. These changes are based on simplifying the structure and enabling the overall facility to be more constructible. The ideas are not based on creating a cheaper building, but a higher quality and simpler building. Another example of value engineering is that beech wood flooring sourced from Germany has been changed to a material that is closer in proximity and more accessible. From the University's standpoint, there is little constraint related to cost or cutting schedule timeline. Therefore, value-engineering ideas related to faster and easier solutions are not considered.

5.7 | Building Information Modeling (BIM) Use Evaluation

For the Performing Arts Center, this project serves as a case study in which building information modeling is leveraged at a much higher level than previous jobs. One of the University's main goals is to obtain an as-built model with a high level of detail. Naturally the model is transferred from design through operation. Based on University and project team goals, the following potential BIM uses were identified. In summary, the goals represent a high level of detail for the facility management system, improving constructability, enhancing communication, visually communicating design intent and achieving above premium LEED certification.

Table 4: Projected BIM Goals of the Performing Arts Center

PRIORITY (HIGH/ MED/ LOW)	GOAL DESCRIPTION	POTENTIAL BIM USES
High	Enhance efficiency & communication between engineering staff and superintendents	3D Control & Planning, Design Reviews
High	Increase field productivity	Site Utilization Planning, 3D Control & Planning
High	Eliminate design clash & coordinate models	3D coordination (design)
High	Coordinate systems between Turner and subcontractors during construction	3D Coordination (Construction),
High	Integrate As-Built model for facility management system	Asset Management, Record Modeling
High	Align project phasing with campus logistics/schedule	Phase Planning
High	Generate design and construction drawings directly from model	Design Authoring
Med	Adopt Prefabrication for M.E.P. equipment	Digital Fabrication
Med	Present model and design decisions visually to owner	Design Reviews
High	Ensure system constructability for enclosure, joint intersection	Construction System Design
High	Achieve premium energy sustainability level beyond LEED	Facility Energy Analysis, Building System Analysis
Med	Monitor construction progress compared to projections	4D Scheduling
Med	Automated construction of façade	3D Control and Planning, Digital Fabrication

BIM Use Development

After the development of goals, specific BIM Uses were pinpointed to reach these goals throughout the project. To achieve a successful facility management mode, asset management and record modeling was chosen. This will be imperative to store operations, product manuals, equipment specifications and equipment performance information and allow the as-built model to be effective in facility management. Due to the University's high priority for the building efficiency, both Facility Energy Analysis and Building System Analysis were chosen to ensure high energy performance from design through operation. During construction the University has tight constraints on site logistics and phasing. Therefore, the model can be leveraged for optimal site utilization planning and phase planning. Due to the complex geometries of the façade and many structural components, construction system design or virtual mockups can be leveraged to visualize and check constructability. To enable higher level of collaboration and communication between the overall project team, design reviews and 3D Control and Planning were selected. Since Turner used BIM 360 Glue, 3D Control and Planning will be useful to check construction against the construction model. Specific locations can be pinpointed through GPS control so the subcontractor knows where they are in the building related to the model. This can also increase field productivity.

Table 5: Projected BIM Uses

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

5.8 | Sustainability Implementation

The Performing Arts Center is pursuing an energy benchmark of 50 percent less energy than any current energy standards. While LEED is a current energy precedent, the University wants to exceed LEED certification. This can be completed through the reduction of carbon emissions inherent to design, construction and operation. Active features that will provide for an industry leading sustainable building include geothermal heating and cooling, enhanced envelope performance, green roof system, displacement and mixed mode ventilation, and radiant heating and cooling. Passive strategies include shading, natural ventilation and the combination of natural sunlight and thermal mass (BNIM).

Although The Performing Arts Center energy goals are not oriented toward LEED Certification directly, these sustainability guidelines still apply for the facility. LEED™ stands for Leadership in Energy & Environmental Design. The system evaluates environmental performance throughout the building's life cycle. For this project, sustainability focus has been placed on the LEED guidelines of creating a sustainable site, energy usage and atmospheric impact, material selection, indoor environmental quality and innovation processes. To compare the Performing Arts Center to LEED Certification, Penn State University's LEED Policy 2011 will be leveraged. To reference the Penn State University Lead Policy, please see Appendix B: Summary of OPP LEED Policy 2011 Update.

The Penn State LEED Policy prioritizes the level of implementation of sustainable elements in its facilities. In order to customize the LEED process for Penn State University's (PSU) facility design, construction and operation, the credit classification system is broken down into priority classes: Mandatory for all PSU projects, Significant Effort required during lifecycle, Minimal Effort necessary and credit not required.

Based on the comparison of The Performing Arts Center's LEED Project Checklist and Penn State's LEED Policy, the project excels in meeting Penn State's mandatory and significant effort LEED project guidelines. It is an interesting comparison because The University's guidelines for the project must be fairly similar to Penn State's policy. Therefore, for many of the places where Penn State placed priority on an item, The Performing Arts Center meets this point credit. Since the University's goals for sustainable performance are not oriented with achieving a specific LEED certification, the most recent level of certification is acceptable. While the Performing Arts Center may focus on energy performance, it could achieve a broader scale of LEED accreditation.

5.9 | Alternative LEED Proposal Strategy

Since the project goals are highly focused on implementing eco-friendly and renewable resource strategies, the Performing Arts Center should realistically achieve Gold or Platinum accreditation through the LEED system. In order to achieve LEED Gold, it is proposed that this project is designed, constructed and operated to achieve at least 60 LEED accreditation points. In order to achieve 60 points, it is essential that the project lifecycle reaches its potential from an energy and atmosphere, materials and resources, indoor environmental quality and sustainable site benchmark standpoint.

In order to meet the project goals of a high performing energy building, energy and atmospheric LEED initiatives need to be enhanced. The project excels in the energy and atmosphere spectrum from an optimization, and commissioning standpoint. Based on the LEED project checklist, the project could improve on green power implementation and overall on-site renewable energy initiatives. This is extremely surprising due to its onsite geothermal heating and cooling, passive and natural design strategy. However, this lack of accreditation can be explained by failing to provide 35% of the building's electricity through renewable systems.

Another major goal of this project is to reduce carbon and enhance the ventilation. Both of these contribute to the indoor environmental quality of the facility. The Performing Arts Center creates indoor environmental quality through a phenomenal thermal comfort design approach, low-emitting materials and controllable systems. However, in order to achieve a more sustainable interior environment, outdoor air delivery monitoring needs to be leveraged to maintain design requirements. Furthermore, indoor chemical pollutants need to be controlled through design capabilities.

Chapter 6 : Cast-in-Place Concrete Wall Schedule Acceleration

6.1 | Opportunity

One of the greatest concerns for this project has been the schedule delays due to the challenging constructability of the cast-in-place concrete walls on the building façade. Throughout construction, the dynamic structural wall geometry has proven to be more difficult than expected and has fallen behind initial scheduling goals. One of the major contributors to this difficulty includes the implication of board forms to create architectural concrete finish. Board-formed concrete is the name of the process used to create a wood grain pattern finish on concrete. In modern design, board formed finish has become rather popular since it creates a soft, warm application of concrete compared to a cool, smooth finish. On the Performing Arts Center, the board forms are prefabricated in Norton, Massachusetts and follow a just in time delivery schedule to arrive on site 2 days before insertion into the steel, concrete forms. Delivery delays have compounded with the high-difficulty method of utilizing the board forms on a majority of the cast in place concrete areas, which has ultimately delayed the critical path schedule. The board formed areas are displayed in figure 37.

Figure 37: Board formed concrete locations shown in orange. The Mezzanine Level is shown on the left and Level 3 is shown on the right.

When the board forms are on both sides of the wall, concrete placement becomes exceptionally difficult. As a result of these unforeseen constructability challenges, the critical path schedule has been delayed by 30 days. The goal for interior millwork to be fully installed by May 2017 pushes the critical path to stipulating that the enclosure is completed by April 2016. Enclosure needs to be complete by April 2016 because it takes roughly a year to fit-out the interior. With the entire schedule riding on this deadline, it is necessary for the concrete façade construction schedule to be accelerated so that the curtain wall and glazing systems can be installed. To resolve this opportunity, an alternative formwork solution is proposed to significantly enhance the productivity of concrete placement for both regular and board formed concrete walls. As a result of the placement productivity improvement, the schedule will be accelerated.

6.2 | Goals

During this analysis, the overall goal is to meet the critical path schedule so that enclosure can be completed by April 2016. In order to meet the critical path schedule, solutions need to be enacted to save 30 days on the current cast-in-place concrete wall placement schedule. In order to target schedule reduction of 30 days, various solutions were tested with the best solution resulting in leveraging Peri's Maximo formwork technology in place of the existing method of using than Peri's Trio formwork technology.

6.3 | Background

To construct cast in place concrete walls, the project team places concrete 3-4 times per week with at least 13 trucks each day, reaching an average of 130 cubic yards of concrete poured a day. Before placement can begin, steel forms are erected on one side of the wall. When board formed concrete is necessary, the steel panel is first erected, then the wooden board form is inserted. This board formed lining inside the steel panel can be seen in figure 36. After that, electric systems and rebar cages are inserted. When board forms are located on both sides of the wall, the wall needs to be slid in gently with the crane and inched over until the board forms are at the correct dimensions. This process is very unique to this project. In order to expedite the forming process, entire runs of straight, steel wall are lined up on one side. Then, a fly technique is used to bring the other pieces in with a crane to be seamlessly slid in place. However, the project team is restricted to placing concrete walls to 60' at a time. If concrete is poured over 60', there is a chance for shrinking and cracking.

Figure 38: Board formed concrete lining inside Peri Trio form with rebar cages and dowel insertion connectors.

On all of the concrete walls, Trio Panel Peri formwork is used. The Trio model, introduced in 1991, has proven success on a wide range of projects due to its universal system “which places the highest emphasis on uncomplicated forming operations and the reduction of shuttering times” (Peri). One of the major benefits of the Trio panel is that it only has one connection part, the BFD alignment coupler. However, Peri recently introduced the Maximo Panel formwork which uses one-sided MX tie technology to significantly improve upon the Trio system.

Peri’s Maximo formwork is estimated to be 50% faster than conventional formwork used in construction (Peri). Since the MX tie is installed from only one side of the panel system, only one worker is needed to secure the formwork rather than two people. Furthermore, no spacer tubes or cones are necessary when using this formwork which results in material savings in addition to the time savings of leveraging the formwork. Peri presents the Maximo as “fully compatible to the proven TRIO system and fulfils the highest requirements regarding cost-effectiveness and achievable quality of workmanship. All outstanding advantages of the TRIO, e.g. few different panel sizes and the BFD alignment coupler as the only connecting part, were retained for the development of the MAXIMO" (Peri). Therefore, the unique capabilities on this job such as board form insertion are still fully plausible using Maximo rather than Trio formwork.

Figure 39: Peri Maximo Formwork

6.4 | Methodology

To determine if the Peri Maximo formwork should be used instead of the Peri Trio formwork on the construction of the cast in place concrete walls, each product was tested from a schedule and cost standpoint.

Schedule Comparison Procedure

From a schedule standpoint, the two schedules are compared based on their finish date and whether the Maximo finish date is in fact 30 days ahead of the Trio finish date. Each schedule only contains items pertinent to the cast in place concrete wall construction. While this includes forming, reinforcement, placement and curing, it also contains slab construction and shoring items. The base schedule created leverages the Peri formwork and is directly from the Performing Arts Center project.

1) An original base-line schedule is created representing the time to construct the cast-in-place concrete structural system between all four buildings. This schedule can be viewed in Appendix J. It is assumed that this schedule represents the noteworthy 30-day delay in the concrete construction. Since some stages of placement are not included in the schedule provided by the project team, these are interpolated based off Peri Trio's man hour-efficiency of 15 square foot per man-hour. Further information is provided in step 3 of this methodology. Note that this schedule begins March 17th, 2015 and concludes with the superstructure completion on December 11th, 2015.
2) Based on project case study, Peri provides that the concrete placement efficiency of the Peri TRIO formwork is 15.00 sq. ft. per man-hour and that the MAXIMO increases placement efficiency by 16% to reach a productivity of 17.4 square foot per man-hour. This productivity corresponds to the tasks of forming, reinforcing and placing the concrete. Since the time to install forms is directly cut in half when using Maximo formwork, it is logical that a 16% increase in efficiency occurs when applied to the entire process before curing.

3) In order to generate the schedule items as days, the Peri productivity rates were converted into total man-hours necessary to place concrete for each face of each building. For example, on the north wall of the Arts Tower, 3153 square feet of formwork will be leveraged. To determine the total time the TRIO formwork will be used, 3153 SF is divided by 15 (sq. ft. / m-h) resulting in roughly 210 man-hours used to place concrete on that face. This equates to 27 days necessary to place concrete on the north face. Please see Appendix L to see this method applied to the entire project.
4) Based on the analysis in table 6, it is determined that the time of forming, reinforcement and placement using Maximo formwork only took 86% of the time as it would with Peri formwork. This was calculated based on the average total man-hours per face of the Maximo formwork divided by the man-hours per face when using the Trio formwork. For the portions of the building that do not have schedule values on the provided schedule, the duration of concrete placement for both Trio and Maximo were projected based off of the existing rates and the "Total days by building" category. For instance, to determine the duration of placing Mezzanine – Level 1 and Level 1 – Level 2 on Theatre/Dance South, the difference between the "Total Days by Building" and the total building duration on the provided project schedule were subtracted and then an average was taken. Thus, it is projected that concrete wall construction along L 1-2 of T/D South takes 30 days. For the T/D South building, it assumed that slabs not listed in the schedule take 10 days to place, reinforce and cure. Furthermore, on the music building it is assumed that Mezzanine, Level 1 and 2 wall pours are all included in same schedule item.
5) After these rates were determined, the Maximo Schedule could be created for the cast-in-place concrete wall system. Each schedule item including forming, reinforcing and

placing of walls on the baseline Trio schedule is multiplied by .86 to find the Maximo rate. Since the construction a concrete structural system is mainly start-finish between structural slabs and then wall placements, the Maximo schedule could be defined based on the reduced items. Note that the Maximo schedule began on March 17th, 2015 and concluded on December 1st, 2015.

Table 6: Maximo vs. Trio placement rate comparison in days

Building	Face	SF of Formwork	Trio Rate (sq ft / mh)	Maximo rate (sq ft/mh)	Total Trio Time (MH)	Trio in days	Total days by buildin	Accelerated Rate	Total Maximo Time (MH)	Maximo in Days	Total days by building
Arts	North Tower Wall	3153	15.00	17.40	210	26	**56**	0.862068966	181	23	**48**
	South Tower Wall	3516	15.00	17.40	234	29		0.862068966	202	25	
Dance / Theatre	South Wall	3546	15.00	17.40	236	30	**121**	0.862068966	204	25	**105**
	East Wall	2352	15.00	17.40	157	20		0.862068966	135	17	
	West Wall	5073	15.00	17.40	338	42		0.862068966	292	36	
	North Wall	3590	15.00	17.40	239	30		0.862068966	206	26	
Music Building	South Wall	3877	15.00	17.40	258	32	**53**	0.862068966	223	28	**46**
	North Wall	2522	15.00	17.40	168	21		0.862068966	145	18	
DRUM	East Wall	8069	15.00	17.40	538	67	**117**	0.862068966	464	58	**101**
	West Wall	5939	15.00	17.40	396	49		0.862068966	341	43	
Totals		**41637**		**Total**	**2776**	**347**			**2393**	**299**	

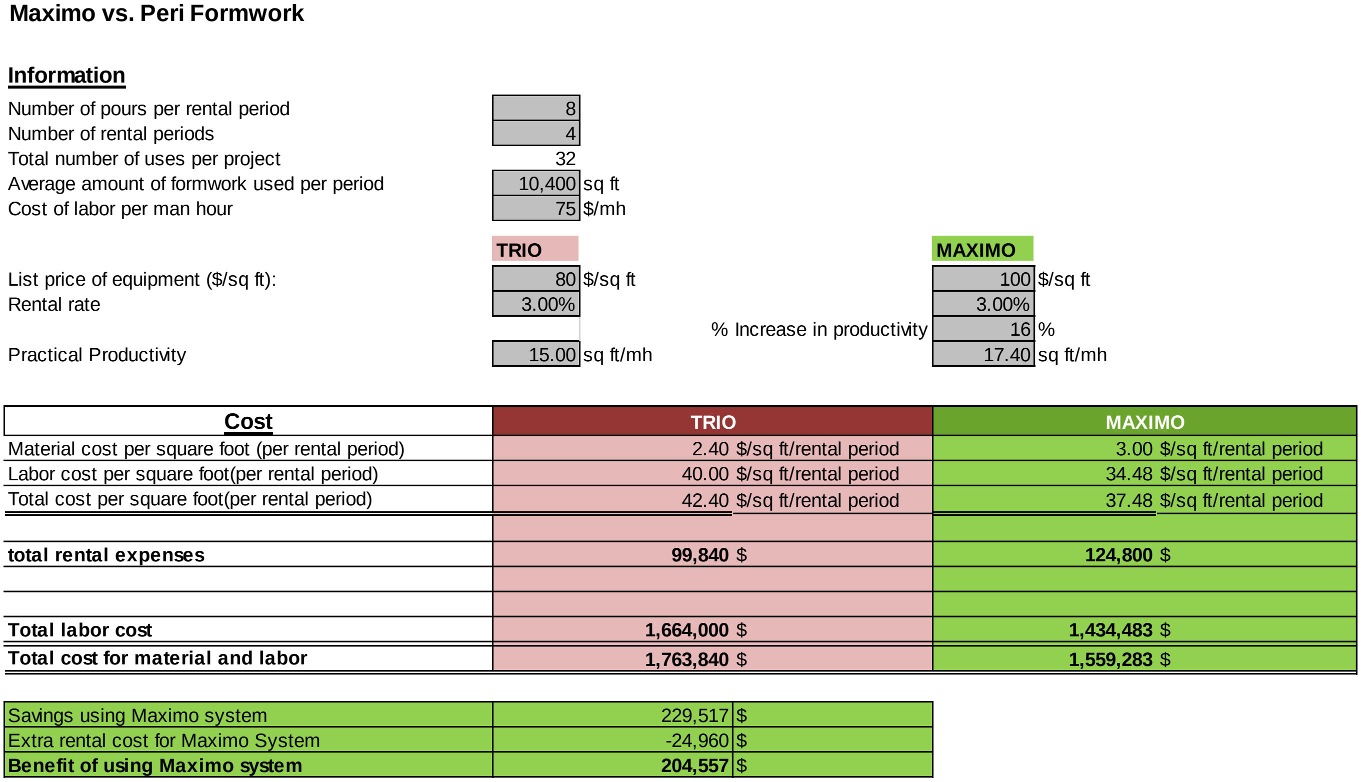
Cost Comparison Procedure

From a cost standpoint, the two schedules are compared based on total cost to construct the cast-in-place concrete wall system. The total cost includes the material cost to rent the Peri formwork and also the labor cost to form, reinforce and place concrete wall sections. The spreadsheet utilized to generate the Maximo cost savings values can be seen in table 7.

1) Peri's list price to buy the Trio formwork system is $80 / sq. ft. and $100 / sq. ft. Their rental rate for this job is 3% of their list price, therefore, Trio rental is $2.40 / sq. ft. / rental period and the Maximo is $3.00 / sq. ft. / rental period.

2) Based on Peri’s projections, a rental period is defined as having 8 pours per each rental period. Since four buildings create the Performing Arts Center, there are four rental periods. This is important in the calculation of material rental expense and labor expense.
3) To calculate the material rental expense, the material cost per square foot (per rental period) is multiplied by the average amount of formwork (SF) per rental period and the total number of rental periods which is 3 in this case. Since the total square footage of concrete formed is roughly 41,600 square feet, the average square footage per period is 10,400 square feet. Therefore, the total rental expenses for the Trio formwork sum to $99,840 and the total rental expenses for the Maximo formwork sum to $124,800.
4) Before calculating the total labor cost, one needs to calculate the labor cost per square foot per rental period. It is assumed that the cost of labor per man hour is $75. To differentiate the labor costs between the Trio and Maximo, this cost is divided by the productivity to get the labor cost per square foot. This is then multiplied by the number of pours per rental period.
5) To calculate the total labor cost, the procedure is similar to calculating the total material cost. The labor cost per square foot per rental period is multiplied by the square footage of formwork used per period by the total number of periods. As a result, the total Trio labor cost sums to $1,664,000 and the total Maximo labor cost sums to $1,434,483.
6) After summing the total labor and material cost for each system, the overall cost savings of using the Maximo formwork are determined to be $204,557.

Table 7: Maximo vs. Trio Cost Comparison Breakdown illustrating Maximo cost savings



Maximo vs. Peri Formwork

Information

Number of pours per rental period	8	
Number of rental periods	4	
Total number of uses per project	32	
Average amount of formwork used per period	10,400	sq ft
Cost of labor per man hour	75	$/mh

	TRIO			MAXIMO	
List price of equipment ($/sq ft):	80	$/sq ft		100	$/sq ft
Rental rate	3.00%			3.00%	
			% Increase in productivity	16	%
Practical Productivity	15.00	sq ft/mh		17.40	sq ft/mh

Cost	TRIO		MAXIMO	
Material cost per square foot (per rental period)	2.40	$/sq ft/rental period	3.00	$/sq ft/rental period
Labor cost per square foot(per rental period)	40.00	$/sq ft/rental period	34.48	$/sq ft/rental period
Total cost per square foot(per rental period)	42.40	$/sq ft/rental period	37.48	$/sq ft/rental period
total rental expenses	**99,840**	$	**124,800**	$
Total labor cost	**1,664,000**	$	**1,434,483**	$
Total cost for material and labor	**1,763,840**	$	**1,559,283**	$

Savings using Maximo system	229,517	$
Extra rental cost for Maximo System	-24,960	$
Benefit of using Maximo system	**204,557**	$

6.5 | Conclusions & Recommendations

After comparing the cost and schedule implications of leveraging the Maximo formwork system vs. the Trio formwork system, it is determined that the Maximo should be rented instead of the Trio system. Due to the 16% productivity increase in using the Maximo system instead of the Trio system, the cast-in-place concrete wall schedule completion can be reduced from December 11th, 2015 to December 1st, 2015. However, this means that the Maximo system failed to meet the 30 day schedule acceleration goal. While the Maximo system projects a total forming, reinforcing and placing time reduction of 48 days, this does not necessarily translate to a similar over schedule reduction based upon the sequencing of the Performing Arts Center concrete schedule. This is due to relationships unaffected by the wall formwork within the schedule such as start-start items involving structural slab placement, slab curing times, shoring of slabs and walls. Nevertheless, the Maximo system is still a more efficient alternative to the Trio formwork system.

Based on the cost comparison, it is clear that the Maximo system provides a more cost-effective solution than the Trio system. Although the Maximo material list price is 25% greater than the original Trio material list price, its labor efficiency makes it cost-effective throughout the rental period. After accounting for the total labor cost in using the Maximo system, it is determined that the alternative offers an 11% cost savings compared to the original Trio total cost for rental and labor. Therefore, the Peri Maximo formwork system is recommend as a more efficient and cost effective solution to the Peri Trio formwork for this job and future jobs.

Chapter 7 : Alternative Façade Schedule Acceleration Using Semi-Automated Mason (SAM)

7.1 | Opportunity

On the Performing Arts Center, the main enclosure system consists of Lecce Limestone cladding and glazed curtain wall system. Due to a Go / No go decision late in the project, the existing Lecce Limestone was determined to be inadequate stone material due to local weather condition testing on the stone itself. As a result, the supplier for this vital component of the façade was changed to the supplier, PiMar Pietra Leccese out of Lecce, Italy. For PiMar to resubmit approval for shop drawings for 3,000 stones, test the stone, fabricate them and then ship them from Italy would delay installation until summer 2017, which is the end of the project. This is a daunting issue because it impacts the final stages of construction and punchlist period for scheduled opening of the Performing Arts Center by the end of August, 2017. The University's highest priority is to meet the academic schedule. In order to meet this schedule goal, Turner would have to reschedule the project so that limestone panels could be installed while late tasks occur including closeout items, courtyard construction and landscaping. Therefore, this presents a significant site logistics and a schedule reorganization challenge. This analysis proposes to accelerate the veneer installation to finish ahead of schedule so that scrambling and overlapping of trades does not occur during project punch list and turnover. In order to do so, a Semi-Automated Mason (SAM) can be leveraged to increase schedule efficiently and install local, traditional masonry that is substituted for the Lecce limestone finish.

7.2 | Goals

The main objective of this analysis is to determine a solution that allows the façade finish to be completed by the original January 2017 schedule goal, even with the realignment process that occurs after the Go / No Go decision made on October 1st, 2015. The University's highest priority is to meet the schedule projection to open the Performing Arts Center in August 2017. To drastically accelerate the construction schedule, Construction Robotics' Semi Automated Mason (SAM) is proposed which can increase productivity of masonry installation by 3-5 times compared to solely manual installation. Another major objective is to maintain the particular design intent that the Lecce Limestone panels created as the major finish of the Performing Arts Center. Therefore, a fireclay brick material with an Alaskan white velour finish is proposed as an alternative finish. Overall, the two systems and installation procedures are compared from a schedule and cost perspective to see if the proposed alternative is a viable solution.

7.3 | Background

Construction Robotics' Semi-Automated Mason (SAM)

To rapidly accelerate the construction schedule, Construction Robotics' Semi-Automated Mason (SAM) is proposed with an alternative masonry façade system. SAM, is the "first commercially available bricklaying robot for onsite masonry construction" (Construction Robotics 2016) and is designed specifically to work alongside the mason, not to replace the mason. By leveraging SAM on a jobsite, construction teams increase productivity by 3-5 times which results in a 50% reduction in labor costs. Using SAM, one mason and one laborer, the team can lay 280 bricks an hour. Furthermore, lifting is reduced 80% which means a safer jobsite and masonry workforce.

In order for a masonry team to integrate SAM into their construction process, the machine and software platform costs $500,000 to purchase, but has a return on investment in 3 years (Construction Robotics 2016).

Figure 40: Semi-Automated Mason laying brick at Fort Lee Barracks in Virginia

However, SAM only works with traditional brick including modular and utility bricks. Therefore, in order to secure SAM as a solution to the schedule delays on the project, the façade needs to be changed to brick. SAM can only be used on select jobsites consisting of long, straight runs of brick façade. If the Performing Arts Center's façade is changed to brick, most of its faces can apply SAM since they are straight runs ranging from 50-100 linear feet. However, the DRUM cannot use SAM due its radial geometry. The only other major constraint to use SAM on a project is that the robot only works with the Hydro-Mobile M2 Mast Climber System at this time so that it can be raised gradually and run long spans of wall footage. To fit around the corners of the Performing Arts Center and allow seamless progress from SAM, the bridge extension can be inserted to reach 60' span. On the west and east wall of the Dance / Theatre building, two units will need to be linked together to reach a length of 144 feet long. With these capabilities in place and with a redesign of the brick façade, SAM can be leveraged to dramatically enhance the project schedule.

Figure 41: Semi-Automated Mason laying brick at Fort Lee Barracks in Virginia

Original System - Lecce Limestone Façade

The original Lecce Limestone paneling system makes up roughly 40% of the Performing Arts Center façade. Each stone averages 3’ in height by 5’ in width with a thickness of 4 inches. In total there is roughly 40,000 square feet of limestone façade finish created by 3,000 individual stones. The stone panels are supported by non-corrosive, stainless steel anchors, which transfer the dead load to the cast-in-place concrete wall system. In addition, plug anchors secure the stone to the steel bracket channels in the concrete wall to resist wind and lateral loads. Beneath the façade cladding is insulation and waterproofing. The Lecce limestone façade integration to the structural system can be visualized in figure 42.

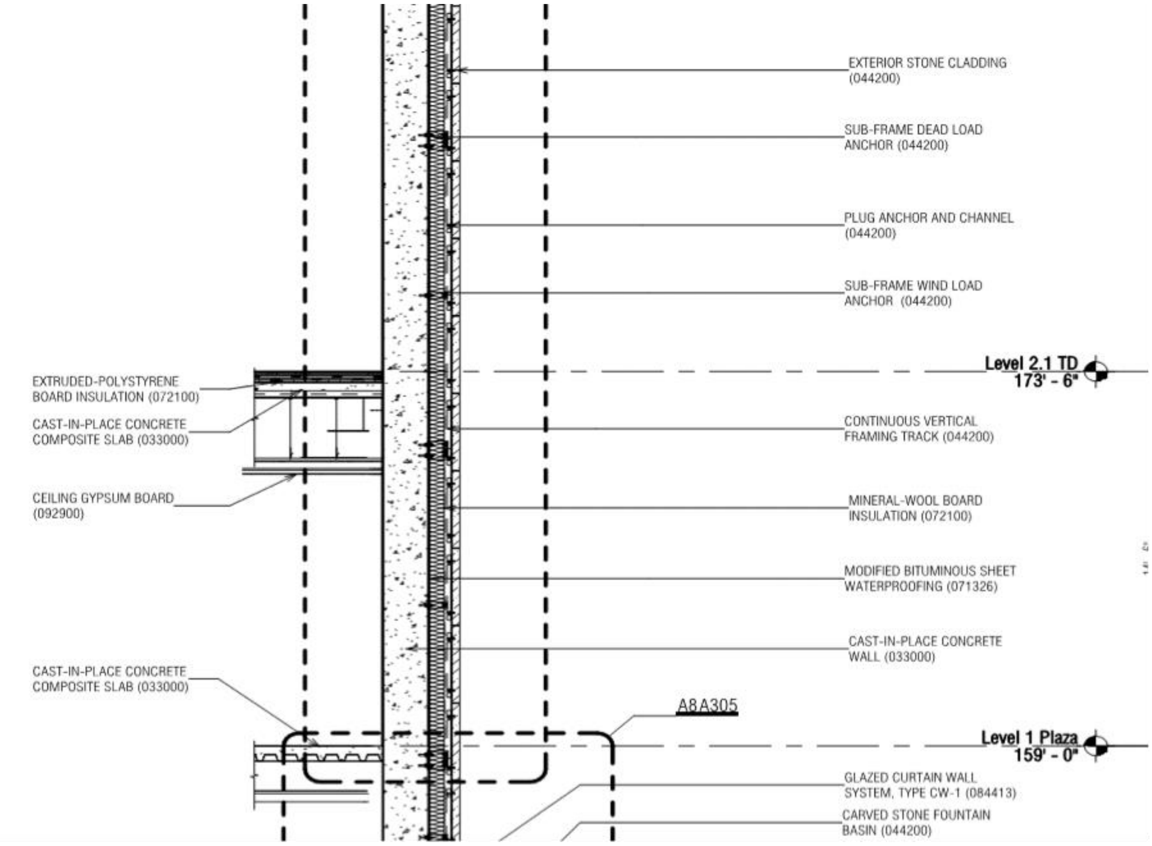


Figure 42: Exterior wall section illustrating connection and support of Lecce Limestone Paneling

Alternative System - Alaskan White Velour Brick Façade

In order to maintain the design intent of the owner, the alternative brick façade proposed is intended to match the original limestone finish. To best match the original finish, an Alaska White Velour utility brick will be used. Figure 43 illustrates a comparison of the original lecce stone cladding finish to the proposed brick finish.

Figure 43: The original, Lecce Limestone finish on the left is juxtaposed next to the proposed brick façade finish on the right

The new façade solution will be an anchored masonry veneer that is composed of a wythe on the exterior. To vertically support the veneer, a steel angle can be attached to the building structural system. Steel angles are embedded to the floor slab at each floor level to limit differential movements. For lateral support of the veneer, 3/16” metal ties can be leveraged at a spacing of 4.5 square feet (Masonry Magazine). It is assumed that the same insulation and waterproofing will be used along the cast-in-place concrete structural wall.

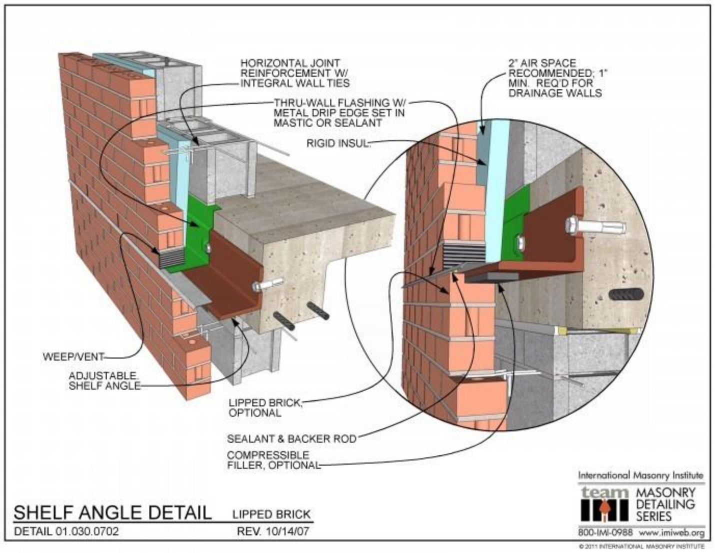


Figure 44: Brick veneer detail illustrating steel angle and wire ties

7.4 | Analysis Implementation Methodology

In order to compare whether the alternative system and construction method is a viable solution, SAM and the brick façade construction were compared to the existing system from a cost and schedule standpoint. In this section a schedule is created to resemble the delayed Lecce Limestone procurement and construction schedule for each building of the Performing Arts Center. A procurement and construction schedule is also created for the alternative SAM solution. Then, detailed cost estimates are composed for the original and alternative system, allowing a clear cost and schedule comparison on the two systems.

Original System - Lecce Limestone Façade Construction

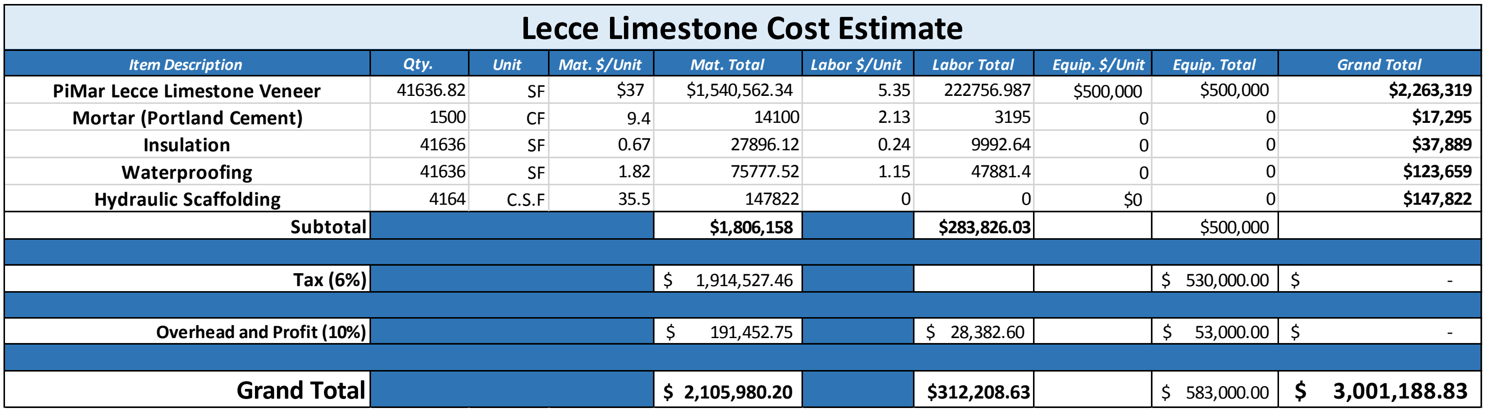
Schedule

Using Microsoft Project Professional, the delayed façade construction schedule is created based on overall procurement for the project and then the construction process for each building. Based on the documentation provided by the project team, the original duration of "Exterior Stone Shop Drawings, Approvals, Fabrication and Delivery" is 210 days but is extended to 314 days once the Go / No Go decision is enacted. The tasks included in the construction schedule for the original façade can be seen in Appendix N: Delayed Lecce Limestone Façade Schedule. Crew sizes used to install the Lecce limestone are assumed to be R.S. Means size D-8 which consists of 3 bricklayers and 2 laborers. After the Go / No Go decision on October 1st, 2015, material procurement until December 27th, 2016 and façade construction, the schedule concludes on August 10th, 2017. This seriously impacts the completion of construction and punch list period of the project with opening of the University facilities scheduled for the end of August, 2017.

Cost

The material, labor and equipment costs of construction for the limestone façade totals $3,001,188. This includes the PiMar Lecce Limestone material and shipping, the masonry anchors, Portland cement mortar, insulation, waterproofing and scaffolding. It can be assumed that the limestone paneling and the masonry anchors are included in the "PiMar Lecce Limestone Veneer" item line. The overall cost breakdown can be seen in table 8. A larger scale view of this estimate is available in Appendix D as well as the R.S. Means 2016 Building Cost Data takeoffs for this estimate.

Table 8: Lecce Limestone Cost Estimate



Lecce Limestone Cost Estimate

Item Description	*Qty.*	*Unit*	*Mat. $/Unit*	*Mat. Total*	*Labor $/Unit*	*Labor Total*	*Equip. $/Unit*	*Equip. Total*	*Grand Total*
PiMar Lecce Limestone Veneer	41636.82	SF	$37	$1,540,562.34	5.35	222756.987	$500,000	$500,000	**$2,263,319**
Mortar (Portland Cement)	1500	CF	9.4	14100	2.13	3195	0	0	**$17,295**
Insulation	41636	SF	0.67	27896.12	0.24	9992.64	0	0	**$37,889**
Waterproofing	41636	SF	1.82	75777.52	1.15	47881.4	0	0	**$123,659**
Hydraulic Scaffolding	4164	C.S.F	35.5	147822	0	0	$0	0	**$147,822**
Subtotal				**$1,806,158**		**$283,826.03**		$500,000	
Tax (6%)				$ 1,914,527.46				$ 530,000.00	$ -
Overhead and Profit (10%)				$ 191,452.75		$ 28,382.60		$ 53,000.00	$ -
Grand Total				**$ 2,105,980.20**		**$312,208.63**		$ 583,000.00	**$ 3,001,188.83**

Alternative System - Alaskan White Velour Brick Façade

Schedule

In order to see if the alternative brick façade will accelerate the schedule to a completion date of 2017, two project schedules are created in Microsoft Project Professional. The first project schedule assumes a procurement timeline of 3 months of 90 days for the Alaska White Velour brick material from The Belden Company in Canton, Ohio. In order to directly compare the construction schedule of SAM and the brick veneer versus the limestone veneer installation, the second schedule allows a 314 day procurement period before construction can begin. Both schedules have the same sequencing and duration times, only different start dates of construction. However, both of these schedules begin exactly the same as the limestone schedule with a Go/No Go decision on October 1st, 2015.

After material procurement, construction of the brick veneer façade follows the sequence of the T/D South building, to the Music Building, to the Arts Tower and concluded with the DRUM. Since SAM can only be purchased from Construction Robotics for $500,000, this analysis only considers utilizing one robot at a time. Thus, each face of each building is constructed independently, in a start-finish sequence using 1 semi-automated mason, a single mason and a single laborer. It is necessary to sequence the work to the adjacent face since the scaffolding system needs to be setup for a seamless transition of SAM. This is because SAM works best in straight runs. Delays caused by corners can be mitigated with wrap-around scaffolding using the Hydro-Mobile M2 Mast Climber System.

SAM Schedule Rate Methodology

Since SAM's rate of bricklaying is 280 bricks-per-hour, multi-story faces take only 4-7 days to complete using one team. The rate of laying brick was created based on the following rationale:

1. The total square footage of each face is calculated
2. The square footage is multiplied by (3 Utility Brick Units / square foot) to get total bricks per face
3. To get installation time in hours, the amount of bricks per face is divided by the rate of 280 bricks per hour.

4. The laser adjustment time for SAM to calibrate the level at which he is laying brick is calculated. This is calculated based on a 15 second re-adjustment time to move to a new layer of brick and then multiplied through the entire vertical span of the face.
5. The total installation in hours is calculated by adding the laser adjustment time for each face to the brick installation time. This is converted to days for a total installation time in days per each face

Schedule Item Duration Determination

The time to install wall ties is based off of the assumption that there will be a wall tie every 4.5 square feet. In total only 38 days were spent laying brick on the entire brick façade portion. Based on the R.S. Means provided rate of 1080 ties per day, the total time to install wall ties per face is calculated. The time to install steel angles is based off of the R.S. Means rate that 550 lbs of steel angle can be installed a day. If a steel angle weighs 1.65 lb. / LF on average (FarWest Steel Corporation), the linear footage of each face can determine the total poundage of steel angle and thus the installation rate in hours and days can be calculated. It is assumed installation of waterproofing and insulation are both 10 days based on the provided schedule from the project team. It is assumed that all construction activities are start-finish.

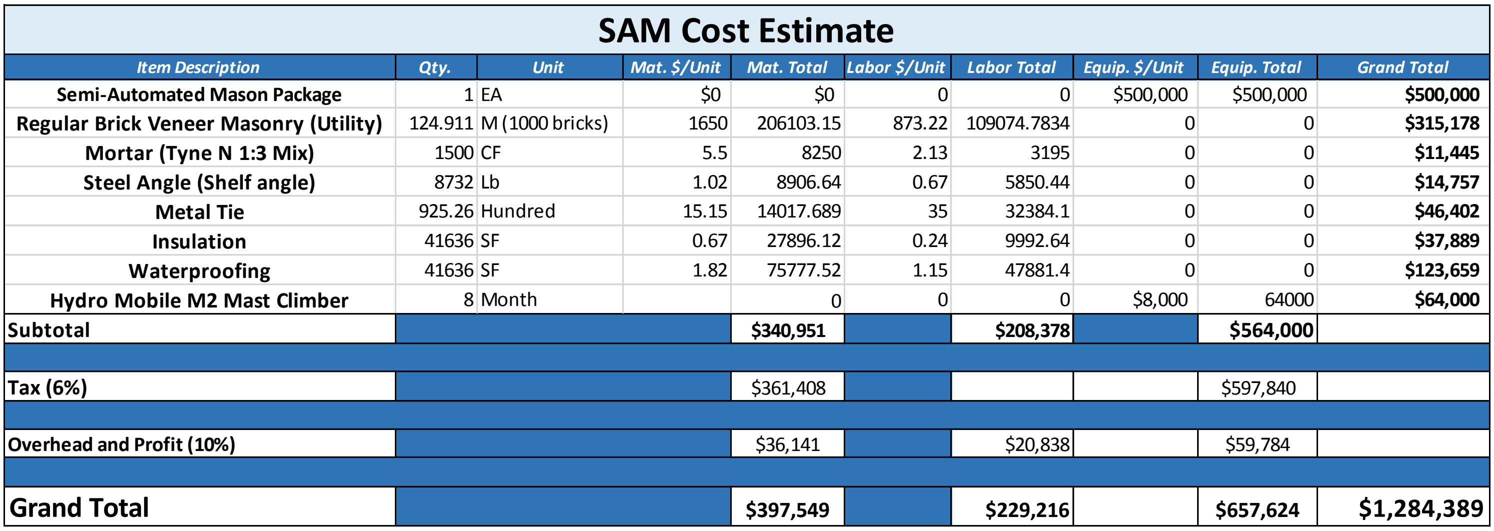
SAM Façade Schedule Completion

The schedule using the brick façade 90 day procurement will be completed on October 19th, 2016 and the schedule that begins construction at the same time frame as the Lecce Limestone panels would be starting completes construction on June 1st, 2017. Using SAM, the construction of the T/D south building façade will take 61 days, the Music building façade will take 29 days and the Arts tower façade will take 29 days.

SAM Detailed Cost Estimate:

The initial cost to implement SAM and construct the brick façade totals $1,284,389. This includes the initial purchase of SAM, all materials, equipment and labor necessary to build this system.

Table 9: SAM Detailed Cost Estimate



SAM Cost Estimate

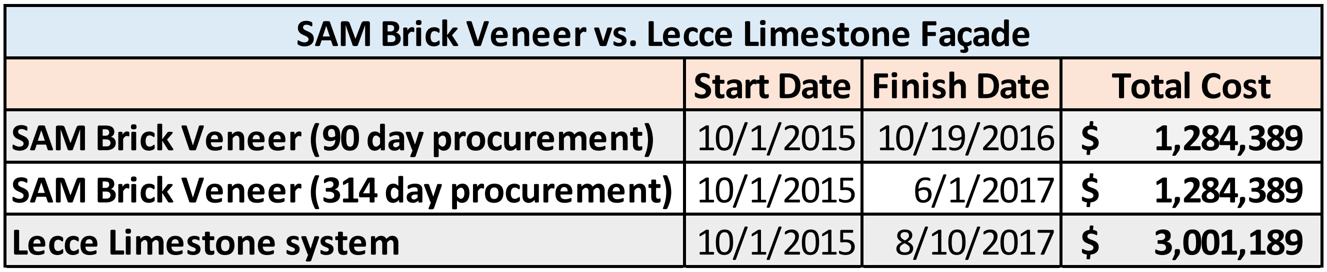
Item Description	Qty.	Unit	Mat. $/Unit	Mat. Total	Labor $/Unit	Labor Total	Equip. $/Unit	Equip. Total	Grand Total
Semi-Automated Mason Package	1	EA	$0	$0	0	0	$500,000	$500,000	**$500,000**
Regular Brick Veneer Masonry (Utility)	124.911	M (1000 bricks)	1650	206103.15	873.22	109074.7834	0	0	**$315,178**
Mortar (Tyne N 1:3 Mix)	1500	CF	5.5	8250	2.13	3195	0	0	**$11,445**
Steel Angle (Shelf angle)	8732	Lb	1.02	8906.64	0.67	5850.44	0	0	**$14,757**
Metal Tie	925.26	Hundred	15.15	14017.689	35	32384.1	0	0	**$46,402**
Insulation	41636	SF	0.67	27896.12	0.24	9992.64	0	0	**$37,889**
Waterproofing	41636	SF	1.82	75777.52	1.15	47881.4	0	0	**$123,659**
Hydro Mobile M2 Mast Climber	8	Month		0	0	0	$8,000	64000	**$64,000**
Subtotal				**$340,951**		**$208,378**		**$564,000**	
Tax (6%)				$361,408				$597,840	
Overhead and Profit (10%)				$36,141		$20,838		$59,784	
Grand Total				**$397,549**		**$229,216**		**$657,624**	**$1,284,389**

7.5 | Conclusions & Recommendations

Conclusions

It is determined that leveraging the Semi-Automated Mason to construct a brick veneer façade as an alternative to manual labor of the Lecce Limestone façade system will allow the schedule to be completed before January 2017 when assuming the 90 day procurement process. Moreover, due its cost-effective model, the alternative system and construction method can be recommended strictly based on schedule cost goals. It accelerates the schedule more than 2 months ahead of the original façade completion goal. Furthermore, when assuming the 314 day procurement or alignment with the Lecce Limestone construction start time, SAM still accelerates the schedule by 2 months and 9 days. Furthermore, the Alaskan White Velour Brick Façade realizes cost savings of 57% compared to the original Lecce Limestone system. This is largely due to the fact that the custom, Lecce limestone contract is roughly $2,000,000 whereas brick is a much cheaper commodity. Furthermore, the labor costs to use SAM are greatly reduced. Based on R.S. Means data and crew size for masonry installation compared to the proposed crew size in this report, labor cost savings reach 45% by using SAM rather than traditional manual brick laying. Therefore, initial schedule and cost-effectiveness goals are reached by using the semi-automated mason with the Alaskan White Velour Brick Façade alternative.

Table 10: SAM Brick vs. Lecce Limestone Cost & Schedule Totals



SAM Brick Veneer vs. Lecce Limestone Façade			
	Start Date	**Finish Date**	**Total Cost**
SAM Brick Veneer (90 day procurement)	10/1/2015	10/19/2016	**$ 1,284,389**
SAM Brick Veneer (314 day procurement)	10/1/2015	6/1/2017	**$ 1,284,389**
Lecce Limestone system	10/1/2015	8/10/2017	**$ 3,001,189**

However, the greatest barrier to using this alternative is the change in finish material. Even if the brick veneer can closely match the limestone panel finish, it cannot replace the experience created by the large limestone panel façade designed by Steven Holl Architects and BNIM Architects.

Recommendations

Due to its cost-effective model and significant schedule acceleration, the alternative brick façade system and SAM construction method can be recommended strictly based on schedule and cost goals. Since a high priority of the University is to open the facility in time for the 2017 Fall Semester, this alternative solution is feasible. However, the finish material and quality of the final product are a higher priority in the long term for the Performing Arts Center. If the University does not approve of the brick façade, then it is not a suitable option in the long term quality of the building to the owner.

Potential Sources of Error

A significant barrier to using SAM on the Performing Arts Center is that the entire project uses Union-based contractors. Before implementing SAM, it is necessary to discuss with the unions regarding the goals of using SAM in order to avoid any conflict. Since the masonry trade and the rest of the project consists of union contractors, the semi-automated mason will potentially create significant tension and disruptions. After defining goals with the masonry trades, a 2-gate system is recommended to prevent disruptions to the Performing Arts Center project site. Since the unions have a right to picket and block the entrance gate to the jobsite, an alternative gate is setup so that the trades can enter the project site without disruption in work. Still, in a heavily dominated union market and geographical location, using a robot on a construction jobsite will cause severe disruption.

Chapter 8 : FPIU Mechanical System Evaluation

8.1 | Opportunity

The Performing Arts Center is designed at a caliber to exceed energy expectations and design codes by utilizing 50% less energy that current energy standards. However, the LEED Project Checklist illustrates a rating of Silver level of certification for this project. Based on the “Energy & Atmosphere” category, the Optimization of Energy Performance could be enhanced to provide improved cost savings for the University. In order to optimize long-term energy performance, an alternative mechanical system can be evaluated based on energy consumption in BTU/year, if it fits current building design and does not require dramatic re-design, and if it is cost effective both initially and in the long term. The current mechanical system is designed around leveraging radiant heating and cooling for circulation and public space, with VAV boxes or the combination of VAV boxes and radiant heating and cooling in performance and occupied zones. An opportunity to improve the optimization of energy performance in select spaces is to upgrade the VAV terminal units to the fan powered induction units (FPIU). This analysis focuses on the feasibility of making this change in the Instrument Rehearsal Room based on long term energy optimization, initial cost, cost savings due to energy efficiency and constructability of the system given the existing building and system design.

8.2 | Goals

In this analysis, the overall goal is to meet the needs of the University by recommending whether an alternative mechanical energy system will optimize energy performance in the long term.

Since one of the University’s highest priorities is to produce a building with superior quality, it is appropriate to analyze whether an upgraded mechanical system will prove effective given the existing design, initial cost and long-term cost. In order to meet this goal, a fan powered induction unit (FPIU) will be designed for the space and run through an energy model analysis in Trane Trace 700. To see if the alternative system is cost effective for the University, the two systems will be compared through initial construction cost in addition to yearly energy savings costs. Since major design changes to the building structure and systems cannot be made this late in the process, constructability of the alternative will be evaluated. Furthermore, as a performing arts center, this space is sensitive to acoustic performance. Through an acoustical breadth analysis, it will be determined whether the alternative, FPIU system meets sound transmission class (STC) requirements for the Instrument Rehearsal Room, the space designed to the have the highest acoustical performance in the entire project.

8.3 | Background

Existing Mechanical Design

The existing mechanical system serving the instrument rehearsal rooms consists of two variable air volume (VAV) terminal units, an air handling unit (AHU), an Ebtron Grid Controller, linear diffusers, supply ductwork and return ductwork. A single-zone VAV system uses a temperature sensor to “vary the cooling or heating capacity and the airflow delivered by the supply fan to maintain supply-air temperature at a desired setpoint” (Trane). A VAV unit’s fan speed will vary to meet the design temperature of the space. This system works well for the Instrument Rehearsal Room since it is a large, densely occupied zone, with variable cooling and heating loads.

However, with a VAV unit, the AHU is responsible for dehumidification, primary air modulation and cooling capacity. This results in excessive ductwork between the VAV terminal Unit and the AHU. In the case of the Performing Arts Center, the air handling and VAV units are located in the sub-basement level. Then, all of the supply and return ductwork branch out the Instrument Rehearsal Space. The schematic below illustrates the existing system supply and return air ductwork. The area marked by the white rectangle illustrates the Instrument Rehearsal Room area. Note that the white units circled in red illustrate the two VAV boxes that serve the ductwork above.

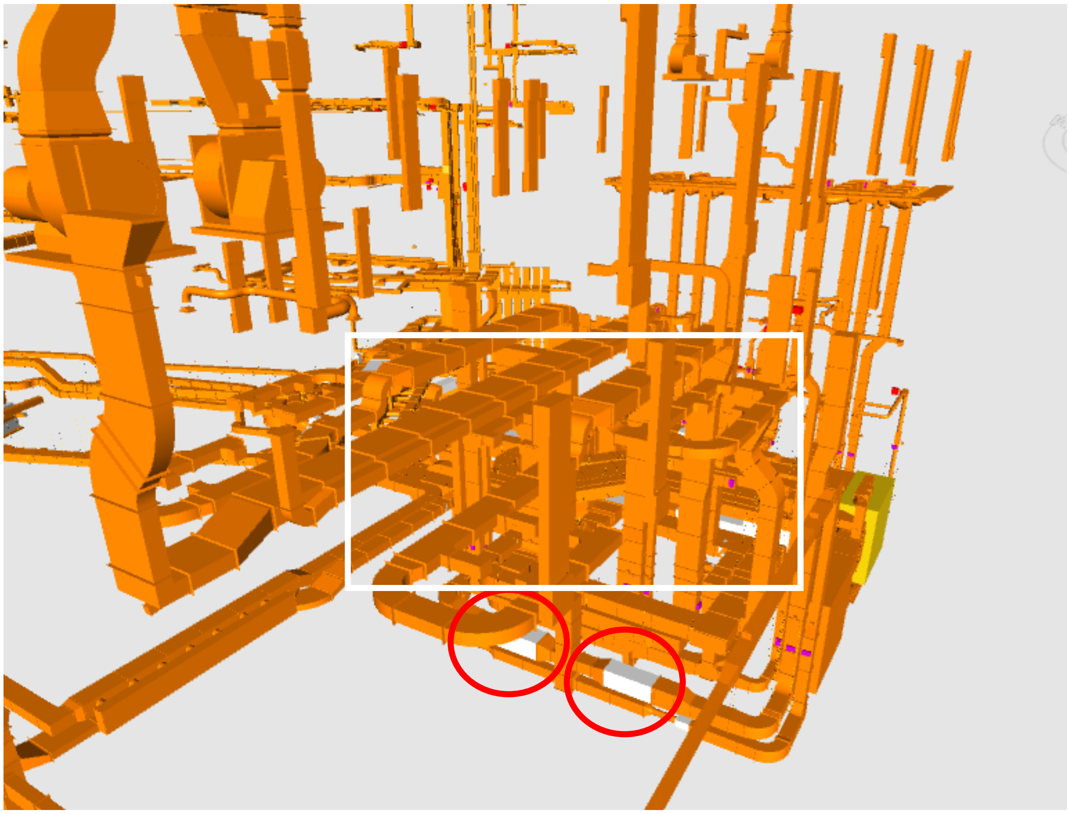


Figure 45: Instrument Rehearsal Room Ductwork & VAV Boxes

FPIU Alternative Mechanical System

The main premise of the fan powered induction unit system is that it delivers cooling and heating to occupied spaces through a dedicated outdoor air system (DOAS) consisting of a cooling coil, heating coil and fan to condition individual spaces. These components, inherent to the terminal unit itself, can be seen in figure 46. The two main differences between an FPIU and VAV box is that on a FPIU system, the “primary air inlet typically delivers ventilation air and handles latent loads in the space” (Southland Industries) and a cooling coil on the air inlet includes heating capabilities. The FPIU system is paramount over the air handler for sensible load since each FPIU has its own sensible chilled water-cooling coil which modulates to space conditions. On a VAV system , the air-handling unit is responsible for dehumidification, air distribution, cooling capacity, outdoor air control and primary air modulation. However, the DOAS air handler only needs to supply filtered air and the FPIU does the rest of the work. Since the FPIU unit does the work rather than the air handler, ductwork is reduced to 20% of what a VAV box requires. Instead, there is increase in sensible chilled water piping, however, but overall reduction in infrastructure and volume occupied (Southland Industries). Since VAVs only use a percentage of outdoor air and FPIU’s send outdoor air directly to each zone, FPIU’s have higher control and precision in meeting design temperature which leads to long term energy savings.

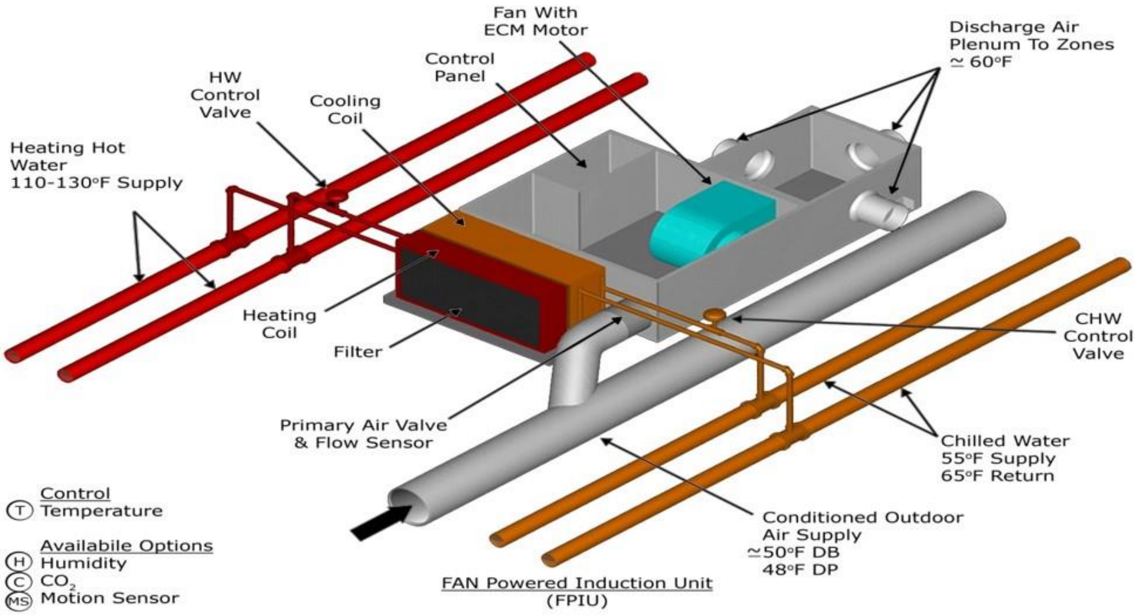


Figure 46: Fan Powered Induction Unit Schematic

8.4 | Mechanical Breadth: Mechanical Breadth: TRACE Energy Model to compare FPIU System Design & VAV

In order to decide whether the FPIU system will serve as a long term energy optimization solution for the University, Trane Trace 700 is used to design and test the alternative system. In Trace the space design criteria is entered including summer and winter environment conditions, interior temperature design ranges, humidity range, lighting gains, and ventilation rates. For this comparison, all of the known parameters of the existing VAV system are leveraged in addition to the design criteria to calculate cooling and heating design loads. For the FPIU system, the closest resembling system in Trace is a 4-pipe induction system. To meet the design criteria for the overall Performing Arts Center and Instrument Rehearsal room, an alternative system was created in Trace and an accompanying energy model was calculated based on cooling and heating design loads.

8.4.1 | Energy Model Results

The VAV energy model resulted in a total energy consumption of 457 MBTU/year to serve the instrument rehearsal room. The total cooling coil load summed to 405 kBtu/h with 90% sensible and 10% latent load. In addition, the annual operating cost to meet this load is calculated to be $9,107. The induction unit energy model resulted in a total energy consumption of 592 MBTU/year with an annual operating cost of $11,228. The total cooling coil load summed to 414 kBtu/h with 87% sensible load and 10% latent load. The average yearly cost and breakdown by month for each system can be seen in figure 47. Shockingly, the design loads and energy usage indicated for the FPIU vs VAV system are the exact opposite of the expected results for the systems. Based on engineering design and previous case study, the FPIU system should outperform the VAV system and present cost savings in the long term. However, the Trace Energy Model does not indicate so. Potential sources of error are discussed in the conclusions section of this chapter.

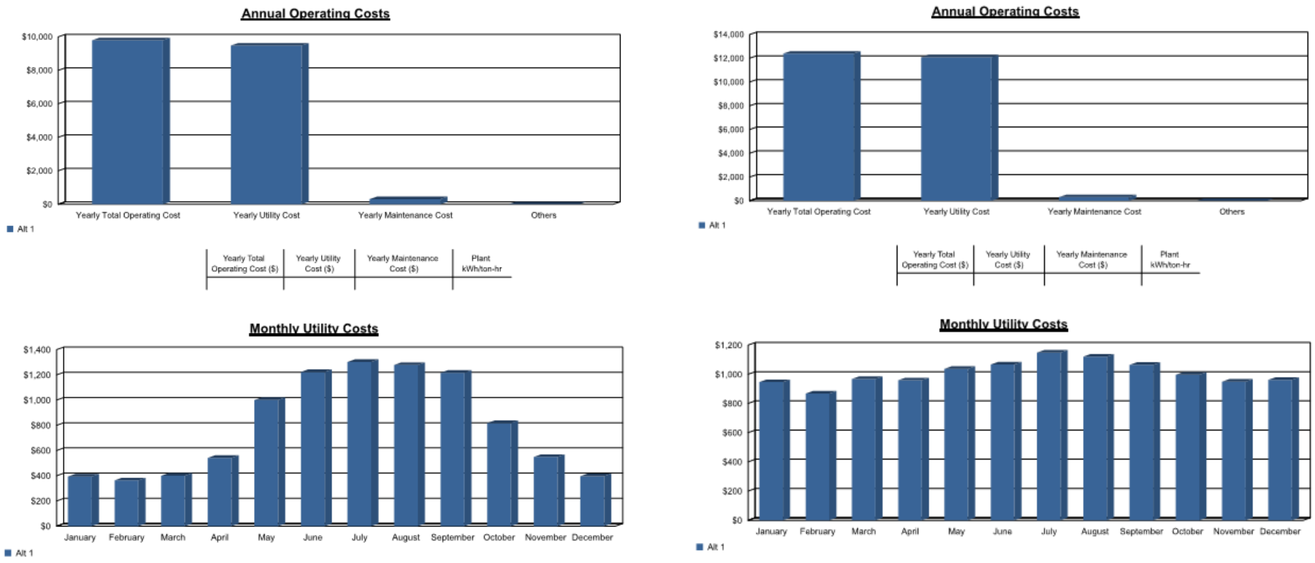


Figure 47: Annual cost data and monthly utility costs for VAV system (left) and induction system (right) generated through Trace 700

8.4.2 | FPIU System Design

In order to analyze constructability and generate initial costs for the FPIU system, the system components were selected for the Instrument Rehearsal Room. FPIU units, a dedicated outdoor air supply (DOAS) AHU, and controller were selected to formulate a FPIU system that would meet the airflow requirements and design standards of the Instrument Rehearsal Room. For the FPIU unit itself, a Krueger KLPS-D unit 5 with inlet size 8 is selected to meet the primary airflow max of 1000 CFM. Please see product details in Appendix P: Krueger KLPS-D Fan Powered Induction Unit. In order to serve the entire instrument rehearsal room, two identical units are needed, similar to the dual VAV box usage in the existing design. For the DOAS unit, a single Trane Horizon OAKD is selected because it can handle the maximum 9,000 CFM needed from the initial supply. The Siemens OpenAir GDE Series Electric Damper Actuator is chosen as a controller since it is a suggested pair with the Kruger unit. It should be noted that the FPIU terminal units will be placed in the ceiling plenum since the main return air duct is not necessary with the FPIU unit. By placing the terminal unit here, the supply ductwork is drastically reduced, rather than running all the way from the sub-basement level to the linear diffusers. However, two hot water pipes and two cold water pipes need to run from the DOAS unit in sub-basement to the terminal unit above the instrument rehearsal room. The FPIU system redesign can be visualized in the following isometric and section view of the Instrument Rehearsal room in figure 48 and 49.

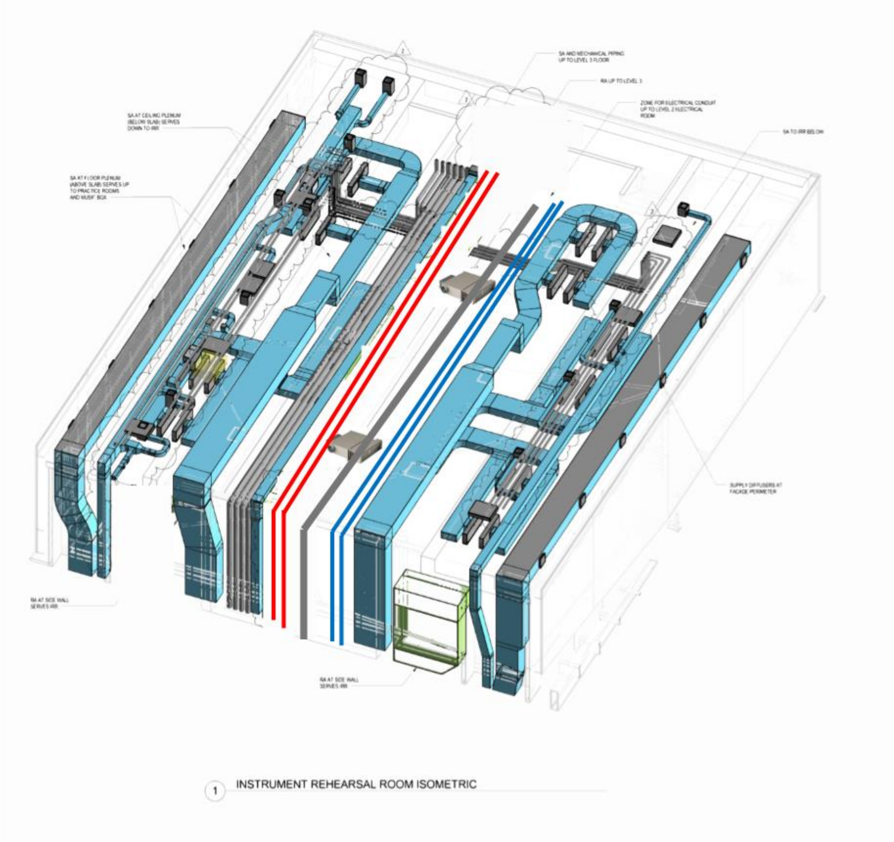


Figure 48: Instrument Rehearsal Redesign Isometric with Fan Powered Induction Unit

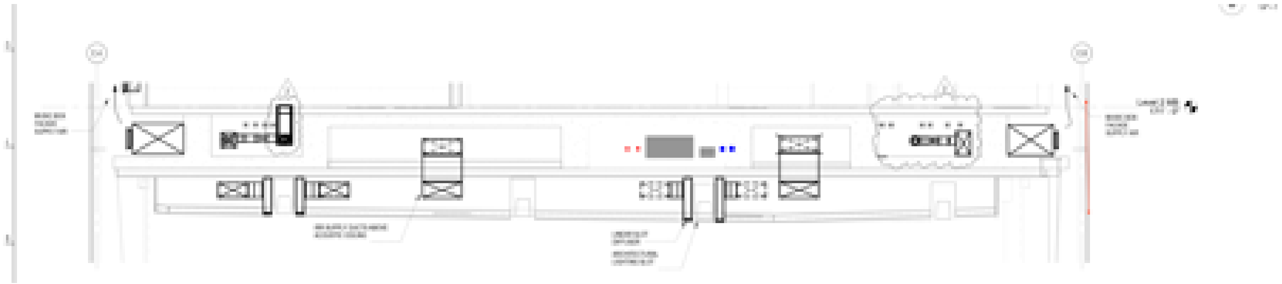


Figure 49: Instrument Rehearsal Redesign Section with Fan Powered Induction Unit

8.5 | Initial Construction Cost

In order to compare the FPIU design to the VAV design, a detailed estimate is created based on construction material and labor cost data. The total cost to build the VAV system in the instrument rehearsal room is $117,961 and the total cost to build the FPIU system is $78,985. The reduction in cost is explained largely due to the decrease in ductwork from the DOAS AHU to the FPIU compared to the original AHU to the VAV. Construction cost data is determined based on R.S. Means Mechanical Cost Data as well as supplier pricing. Supplier pricing was provided by Krueger, Trane and Siemens for the components in the FPIU estimate. To compare the estimates please see table 10 below. Additional information including HVAC duct takeoff can be seen in Appendix Q.

Table 11: VAV vs. FPIU Detailed Cost Estimate

Instrument Rehearsal Room Estimate (VAV)

Item Description	*Qty.*	*Unit*	*Mat. $/Unit*	*Mat. Total*	*Labor $/Unit*	*Labor Total*	*Grand Total*
Sheetmetal	**10269.93**	lb	$2.93	$ 30,090.90	$0.00	$0.00	$ 30,090.90
Sheetmetal Labor	**761.77**	LF	0	0	$34.77	$ 26,486.60	$26,486.60
Insulation	5922.68	SF	$0.19	$ 1,125.31	$2.10	$12,437.63	$13,562.94
Hangers	253.92	EA	$0.00	$ -	$3.26	$827.79	$827.79
Linear Diffusers	24	LF	$92.00	$ 2,208.00	$19.10	$458.40	$2,666.40
VAV	2	EA	$840.00	$ 1,680.00	$103.00	$206.00	$1,886.00
Ebtron Thermal Dispersion Grid	1	EA	$975.00	$ 975.00	$197.00	$197.00	$1,172.00
Trane AHU-1	1	EA	$25,500.00	$ 25,500.00	$1,350.00	$1,350.00	$26,850.00
Subtotal				**$61,579**		**$41,963**	**$103,543**
Tax (6%)				$65,274			
Overhead and Profit (10%)				$6,527		$4,196	$0
Grand Total				**$71,801**		**$46,160**	**$117,961**

Instrument Rehearsal Room Estimate (FPIU)

Item Description	*Qty.*	*Unit*	*Mat. $/Unit*	*Mat. Total*	*Labor $/Unit*	*Labor Total*	*Grand Total*
Sheetmetal	**3423.31**	lb	$2.93		$0.00	$0.00	
Sheetmetal Labor	**253.92**	LF	0	0	$34.77	$ 8,828.87	$8,828.87
Insulation	1974.23	SF	$0.19	$ 375.10	$2.10	$4,145.88	$4,520.98
Hangers	84.64	EA	$0.00	$ -	$3.26	$275.93	$275.93
Linear Diffusers	24	LF	$92.00	$ 2,208.00	$19.10	$458.40	$2,666.40
Hot & Cold Water Supply Piping (50' Each)	8	EA	$615.00	$ 4,920.00	$33.50	$268.00	$5,188.00
FPIU	2	EA	$4,200.00	$ 8,400.00	$150.00	$300.00	$8,700.00
DOAS AHU	1	EA	$35,000.00	$ 35,000.00	$1,350.00	$1,350.00	$36,350.00
Controller	2	EA	$1,000.00	$ 2,000.00	$50.00	$100.00	$2,100.00
Subtotal				**$52,903**		**$15,727**	**$68,630**
Tax (6%)				$56,077			
Overhead and Profit (10%)				$5,608		$1,573	$0
Grand Total				**$61,685**		**$17,300**	**$78,985**

8.6 | Constructability Review

The 2 Krueger KLPS-D units can be placed in the air plenum above the Instrument Rehearsal Room since the unit is 17” high and the plenum is 24” in height. Furthermore, the FPIU system does not require ductwork, therefore, the entire central area that was taken up by main return air duct is now open. The hot and cold water piping as well as the outdoor air supply ductwork can run through this central area in place of the pre-existing return duct. Since the DOAS air handling unit is much smaller than the pre-existing air handling unit for the VAV system, there will be no issues with spacing in the sub-basement level. As a result, the alternative system is determined to be a viable solution from a coordination and constructability standpoint. No design changes or system rearrangement is necessary.

8.7 | Acoustical Breadth: Design of Sound Attenuating Device to Handle FPIU Sound Transmission

At a rating of 15 PNC, the Instrument Rehearsal Room is designed to have the lowest background noise criteria from HVAC systems in the entire Performing Arts Center. This is because the room is used for university groups such as the University Orchestra, Concert Jazz Ensemble and Sinfonia ranging from 20 to 100 musicians. Furthermore, the space is designed for substantial reverberance and loudness for orchestral rehearsal, so any leaked sound from the HVAC system will be naturally amplified. Therefore, acoustical performance is paramount to the space. In order to maintain minimal sound transmission into the Instrument Rehearsal room, the original HVAC design is to place all of the terminal units in the sub-basement level with only supply and return ductwork and linear diffusers in the plenum above the space.

The existing acoustical design is created by material selection on the floors, ceiling, walls and variable absorption banners. To create optimal acoustics, the wooden floor is placed on battens, and the ceiling contains a fixed 4” thick sound-absorbing treatment over 60% of the area. This treatment is concealed behind an acoustically transparent wooden layer. In addition, the walls have an acoustically transparent architectural facing with motorized sound-absorbing banners consisting of wool serge panels behind them.

FPIU Acoustics Introduction

Based on the Krueger KLPS-D product data, found in Appendix P, at a maximum fan flow rate of 1400 CM, the sound pressure level (Lp) reaches a noise criterion (NC) rating of 38. However, the preferred noise criterion (PNC) for the Instrument Rehearsal Room is 15. In order to provide the necessary transmission loss, a 5 ft. long standard pressure drop duct silencer is recommended from PCI industries. This silencers can be placed directly upstream and downstream from each FPIU unit instead of ductwork. Upstream will mitigate noise coming from the DOAS to the FPIU and downstream will prevent noise between the FPIU unit and diffusers. It is assumed that the transition of noise directly from the FPIU to the space is absorbed by the 4” thick sound-absorbing treatment system concealed by wood facing.

To design for the particular silencer used, the required transmission loss (TL) is calculated. Using the FPIU noise criterion and the desired instrument rehearsal room noise criterion, the octave band sound pressure levels (dB) for frequencies 125, 250, 500, 1000, 2000, and 4000 Hz were determined. The difference in these sound pressure levels results in the required noise reduction (NR) in dB. The required transmission loss can be calculated using the formula: TL = NR – 10log(A_{rec}/S). Here, A_{rec}, represents the total absorption of the receiving room, in this case the instrument rehearsal room, in sabins. Assuming the absorptive coefficient of the room is .60, with a surface area of 9650 square feet, the A_{rec} is calculated to be 5790 sabins. S represents The surface area of the barrier between the plenum and the space which is equal to 3100 ft^2.

In order to ensure that sound transmission is diminished to the preferred noise criterion, the transmission loss of the silencer needs to exceed the required transmission loss. As seen in table 9, a 5-foot silencer will exceed transmission loss requirements and is recommended to maintain desired acoustical performance. Figure 50 illustrates the transmission loss at each frequency for the silencer.

Table 12: Duct Silencer sound Transmission Loss (TL) compared to required transmission loss (TL)

	Acoustical Breadth: IRR Sound Barrier Design						
		Octave Band Sound Pressure Level (dB)					
	Frequency (Hz)	125	250	500	1000	2000	4000
	NC						
FPIU Noise level	**38**	47	48	43	38	35	31
Desired IRR Noise level	**15**	35	28	21	15	10	8
Required NR (dB)	**23**	12	20	22	23	25	23
Required TL (dB)		**9.304871**	**17.30487**	**19.30487**	**20.30487**	**22.30487**	**20.30487**
PCI Industries 5 ft. Silencer Tranmission Loss (dB)		10	25	40	55	55	50

FIGURE 14.8 Silencer Dynamic Insertion Loss Data (PCI Industries, 1999)

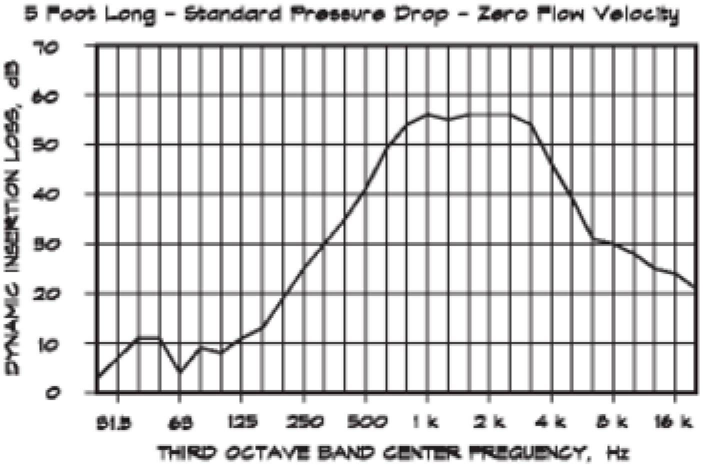


Figure 50: Duct Silencer sound Transmission Loss (TL) compared to required transmission loss (TL)

Cost of Duct Silencers

The cost to install the (4) 5’ silencers that can handle the 9000 CFM flow from the DOAS, sums to $7,012. Each silencer is $860 in material and labor costs $16.50. This is a 9% increase in price to the original FPIU total, however it is still cheaper than the VAV price.

8.8 | Conclusions & Recommendations

Although the Trane Trace Energy Model reveals that the FPIU does not optimize energy performance and cost savings in the long run, it can still be recommended to use the FPIU for the Performing Arts Center, in particular, the Instrument Rehearsal Room. Since Trane Trace did not have a Fan Powered Induction Unit (FPIU) with DOAS air supply, the recommendation can not be solely based off of the resulting yearly energy consumption and yearly cost from this program. Moreover, after discussions with Senior Design Engineer personnel at Southland

Industries regarding previous case studies in which FPIUs were used instead of VAV boxes, it was confirmed that FPIUs do in fact provide long term energy savings and thus long term cost savings for the owner. Furthermore, the detailed construction estimate of the FPIU as 33% cheaper than the VAV system provides another reason to utilize the FPIU system. After constructability review, the FPIU is a better solution than the VAV box due to its ability to save 20% ductwork due to inherent technology and after placing it in the plenum above the instrument rehearsal room. Finally, the acoustical design addition of (2) 5 foot long duct silencers to maintain the preferred noise criteria (PNC) of 15 in the Instrument Rehearsal Room is only a 2% price increase in the overall FPIU system. Therefore, it can be concluded that the FPIU system is a viable alternative for the University to use in the Performing Arts Center.

Table 13: General Energy and Cost comparison of VAV vs. FPIU

	VAV	FPIU
Construction (Material + Labor) Cost	$117,961.12	$ 78,984.80
Long Term Cost ($/year)	$9,107	$11,228.00
Long Term Cost Savings	$2,121	$0.00
Yearly Energy Consumption (MBTU) / (year)	457	405

Potential Sources of Error

In the Mechanical breadth, the main goal was to compare the long-term energy consumption of the Fan Powered Induction Unit (FPIU) versus the original VAV system in BTU/year. One of the issues when running the energy model was that Trace 700 is limited to a 4-pipe Induction system rather than a Fan Powered Induction Unit. After running the energy model in Trace 700, the Induction system proved to have a higher yearly energy consumption and yearly cost compared to the VAV system. This can be explained by potential errors with the VAV energy model. The VAV energy model only showed using 12% of Outdoor Air, which significantly limited the heating load that went into the design of the system. Therefore, the VAV system represented in the Trace 700 Energy Model illustrates much lower levels of energy consumption and total yearly cost than it should.

Chapter 9: Overall Conclusions for the Performing Arts Center

The Performing Arts Center will be the premier space for music and performing arts in higher education. The unique design includes superior acoustical performance standards, board formed architectural concrete, exquisite finish materials and irregular geometries. As a result, the task to construct The Performing Arts Center at the University's high standard is no easy task. Moreover, the University places extraordinary priority on meeting the academic driven schedule and superior quality of work. The goal of this report is to assist the project team by investigating alternatives to the construction and design of the building based on the data collected and the three analyses completed.

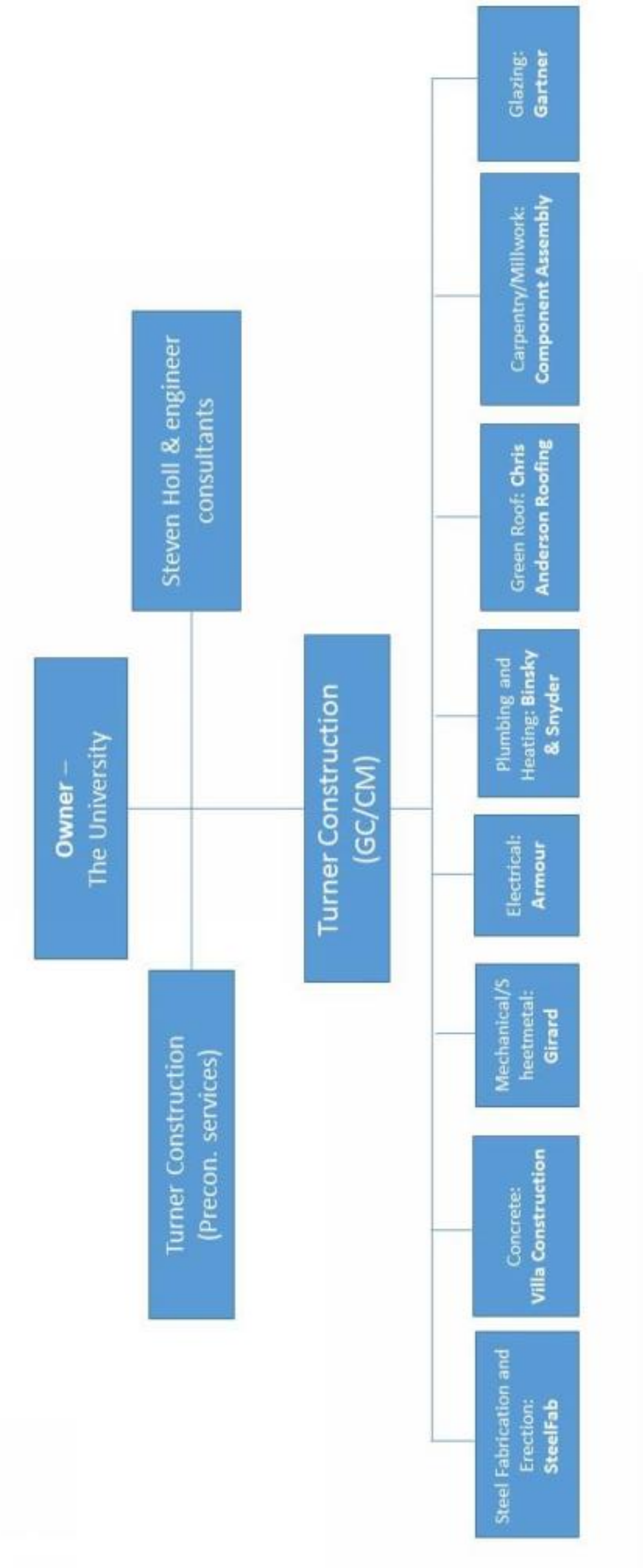
In the first analysis, the Cast-in-Place Concrete Wall Schedule Acceleration, it is concluded that the Peri Maximo system should be rented instead of the Trio system for the cast-in-place concrete walls on this job. Even though the Maximo did not meet the 30-day schedule acceleration goal, the 16% productivity increase allowed for an overall 10-day, 5% schedule reduction and an 11% cost savings.

In the second analysis, the Alternative Façade Analysis constructed using Semi-Automated Mason (SAM), it is recommended that SAM and the alternative Alaskan White Velour brick façade finish are leveraged based on the cost-effective model and significant schedule reduction. Compared to the delayed Lecce Limestone schedule, the SAM alternative has a 43% schedule reduction when considering the brick veneer procurement and 10% reduction when only strictly considering construction rates. Moreover, the SAM alternative provides 57% cost savings compared to the original Lecce Limestone system.

In the third analysis, the FPIU Mechanical System Evaluation, the fan powered induction unit (FPIU) system is recommended over the original VAV system for the Instrument Rehearsal Space. In order for the University to optimize energy performance in the long term, the FPIU system is a viable alternative. In order to leverage the FPIU system, it is recommended to install the system above the instrument rehearsal room, but to invest in duct silencers to meet the recommended noise criterion of 15.

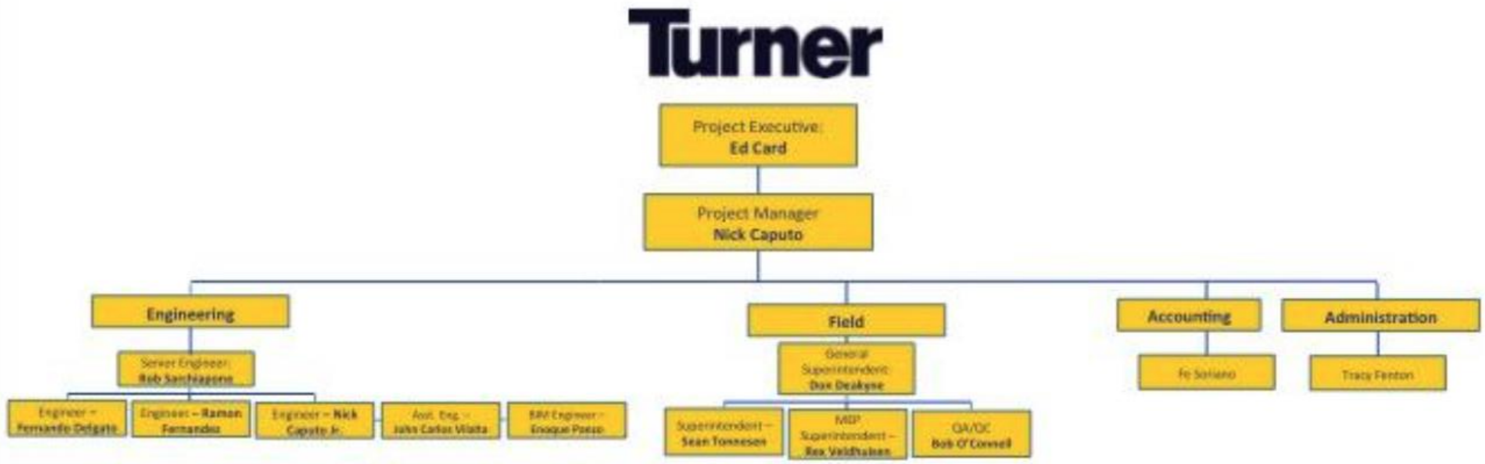
Appendix A

Organization Structure



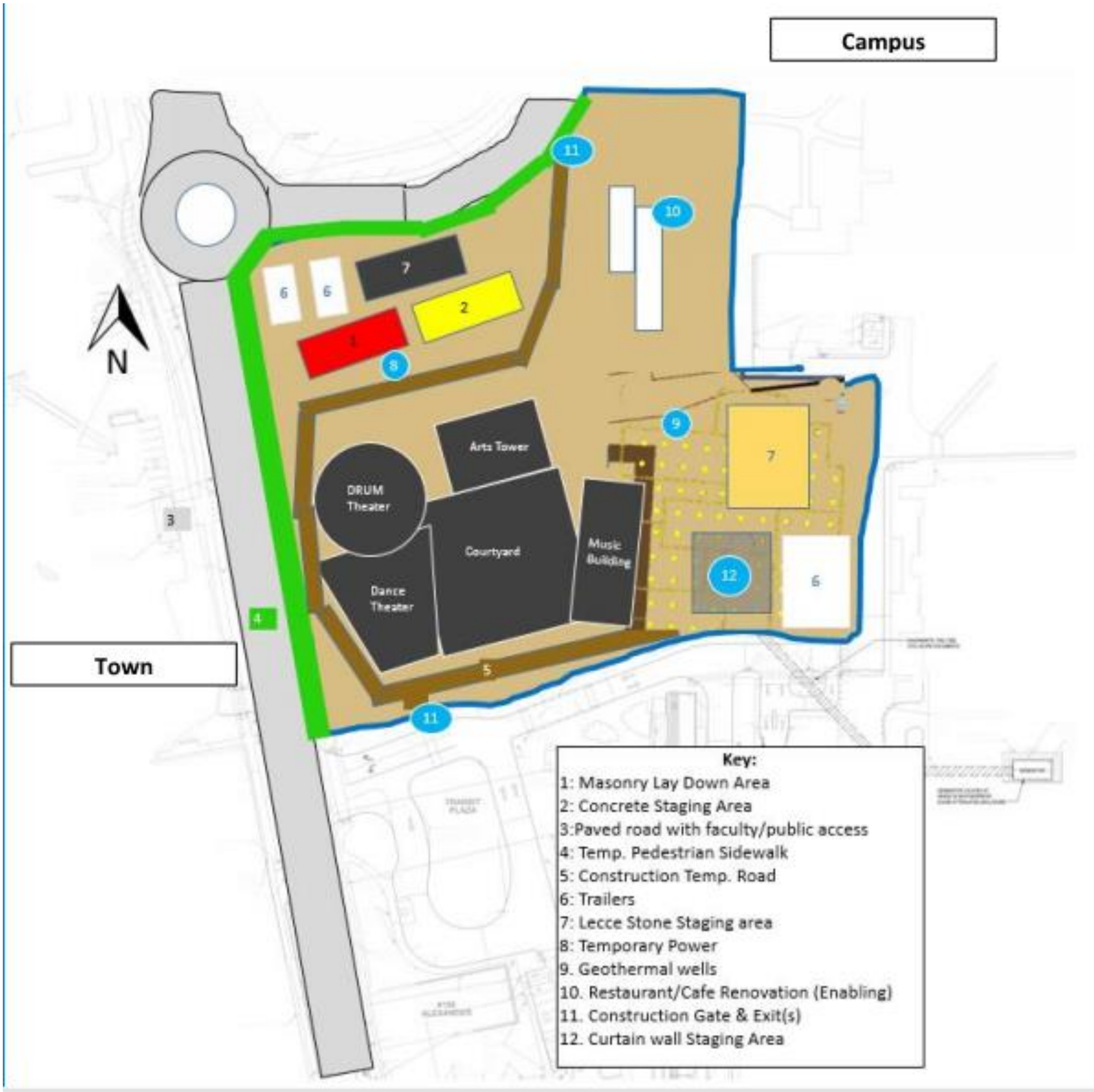
Appendix B

Staffing Plan



Appendix C

Site Logistics Plan



Appendix D

Square Foot Estimation Data

The Performing Arts Center – Square Foot Schematic Estimate

Cost Data based off of:

Phelan, Marilyn, AIA. R.S. Means Square Foot Costs 2015. N.d. Construction Cost Data. Norwell, Massachusetts.

The Performing Arts Center - Square Ft. Schematic Estimate

RS Means Source	R.S. Means Square Foot Costs 2015		**Model #**		M.040 Auditorim
Page(s)	86-87		**Ext Wall Type**		Face Brick with Concrete
Area	125,900		**Frame**		Steel Frame
Area Falls Between	125,900		and	+	
			Base cost per SF		**$137.40**
Cost Adj Type:	Perimeter			**Per SF Adj**	$45.35
Cost Adj Type:	Story Height			**Per SF Adj**	-$10.00
			Adj Base cost per SF		**$172.75**
Base Bldg Cost	172.75	x	125,900	=	$21,749,225.00
	Adj Base Cost / SF		FloorArea		
Basement Cost	30.15	x	30,023	=	$905,193.45
	Basement Cost / SF		Basement Area		
			Total Base Bldg Cost		**$22,654,418.45**
Additive Source	**Type**	**Quantity**	**Price/Unit**		**Total**
RS Means Additions	Closed Circuit Sur	3	1975	Amount	$5,925.00
RS Means Additions	Seating	200	320	Amount	$64,000.00
RS Means Additions	Emergency Lighting	100	$780	Amount	$78,000.00
RS Means Additions	Sound System	2700	$130	Amount	$351,000.00
			New Subtotal Cost		**$23,153,343.45**
Multiplier Type	Time			Value	1.05
Multiplier Type	Location			Value	0.94
			New Subtotal Cost		**$22,852,349.99**

	Assembly	% of Total	Cost per SF	Total Cost
A	Substructure	7.50%	$13.61	$1,713,926.25
B	Shell		$45.71	$0.00
B10	Superstructure	8.80%	$19.41	$2,011,006.80
B20	Exterior Enclosure	21.70%	$20.46	$4,958,959.95
B30	Roofing	4.60%	$5.84	$1,051,208.10
C	Interiors	18.80%	$26.19	$4,296,241.80
D	Services		$0.64	$0.00
D10	Conveying	2.70%	$6.90	$617,013.45
D20	Plumbing	9.50%	$23.33	$2,170,973.25
D30	HVAC	9.60%	$2.91	$2,193,825.60
D40	Fire Protection	2.90%	$15.69	$662,718.15
D50	Electrical	13.90%	$2.93	$3,176,476.65
E	Equipment & Furnishings	0.00%	$0.00	$0.00
F	Special Construction	0.00%	$0.00	$0.00
G	Building Sitework	N/A	N/A	N/A
	Additions	N/A	N/A	N/A
			Subtotal	**$22,852,349.99**
	Jobsite OH & GC's	20.00%		$4,570,470.00
	Contractors Fee	5.00%		$1,142,617.50
	Designer's Fee	5.00%		$1,142,617.50
			Total	**$29,708,054.98**

Assumptions and Clarifications:

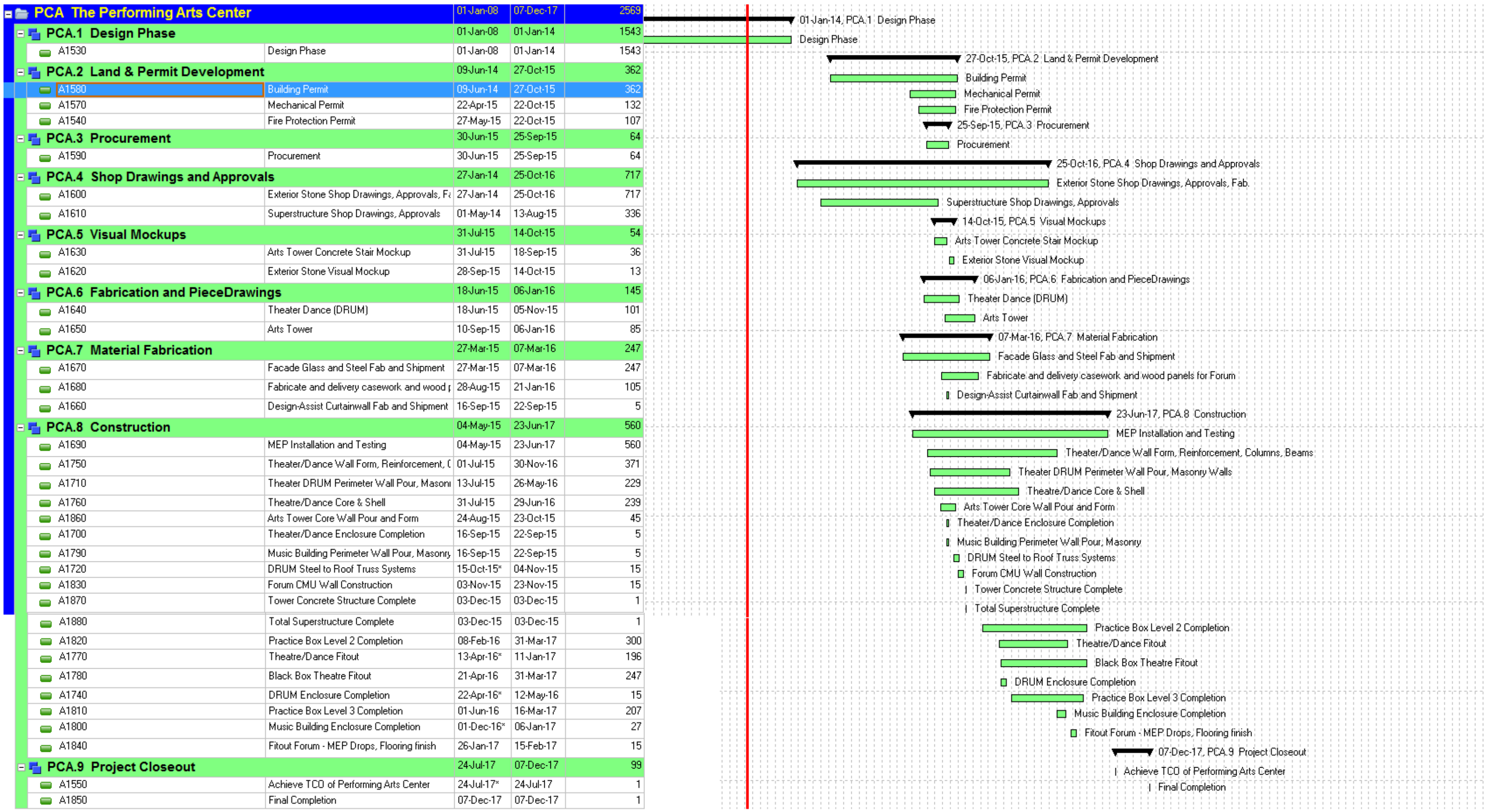
Assume building type is M.040 Auditorium
Assume Face Brick Concrete Block Back Up based on the given parameters and actual Lecce Limestone façade.
Assume steel frame structural system
Assume maximum ceiling height of 16'

Square Foot Takeoff and Calculations:

	Perimeter	Area	
Forum Level	996.75'	49,860	SF Takeoffs
Mezzanine Level	(All from above)	16,705	3,751
			891
			630
			11,433
Plaza Level		16,262	4,711
			2,345
			4,369
			3,065
			1,772
Level 2 Plan		24,715	532
			4,447
			15,522
			4,214
Level 3 Plan		18,357	13,565
			1,532
			3,260
	Total Area:	**125,899**	
	Perimeter:	**996.75'**	

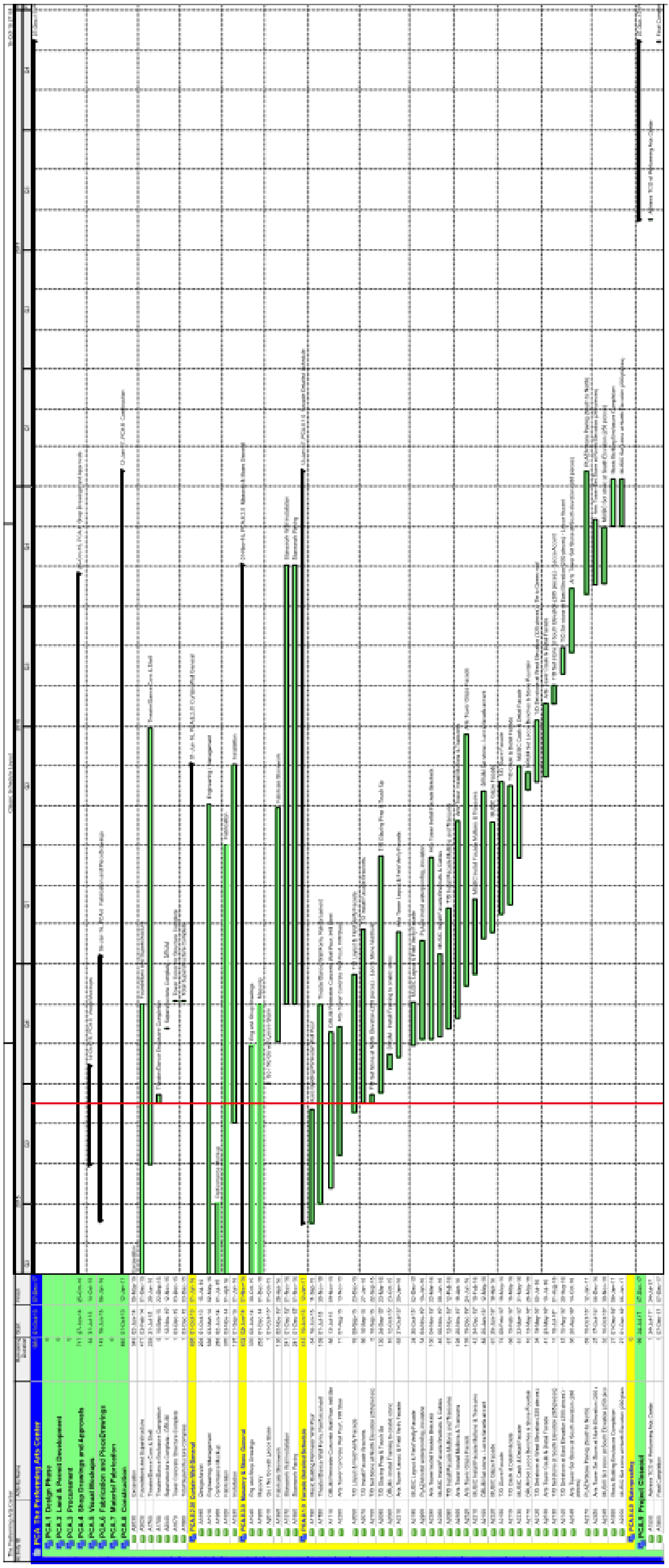
Appendix E

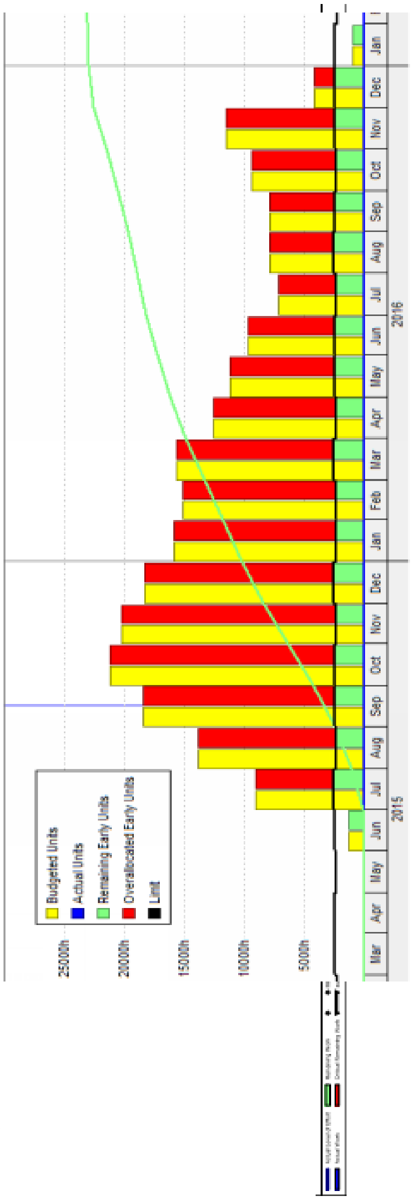
The Performing Arts Summary Schedule



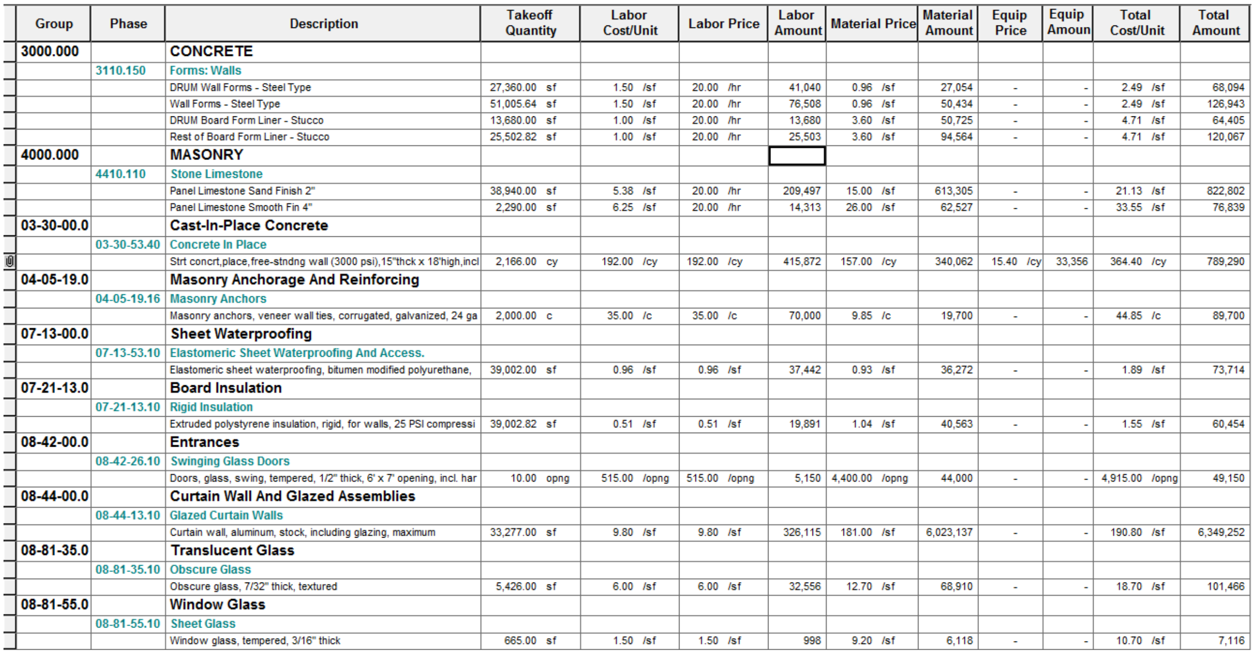
PCA The Performing Arts Center		01-Jan-08	07-Dec-17	2569
PCA.1 Design Phase		01-Jan-08	01-Jan-14	1543
A1530	Design Phase	01-Jan-08	01-Jan-14	1543
PCA.2 Land & Permit Development		09-Jun-14	27-Oct-15	362
A1580	Building Permit	09-Jun-14	27-Oct-15	362
A1570	Mechanical Permit	22-Apr-15	22-Oct-15	132
A1540	Fire Protection Permit	27-May-15	22-Oct-15	107
PCA.3 Procurement		30-Jun-15	25-Sep-15	64
A1590	Procurement	30-Jun-15	25-Sep-15	64
PCA.4 Shop Drawings and Approvals		27-Jan-14	25-Oct-16	717
A1600	Exterior Stone Shop Drawings, Approvals, F	27-Jan-14	25-Oct-16	717
A1610	Superstructure Shop Drawings, Approvals	01-May-14	13-Aug-15	336
PCA.5 Visual Mockups		31-Jul-15	14-Oct-15	54
A1630	Arts Tower Concrete Stair Mockup	31-Jul-15	18-Sep-15	36
A1620	Exterior Stone Visual Mockup	28-Sep-15	14-Oct-15	13
PCA.6 Fabrication and PieceDrawings		18-Jun-15	06-Jan-16	145
A1640	Theater Dance (DRUM)	18-Jun-15	05-Nov-15	101
A1650	Arts Tower	10-Sep-15	06-Jan-16	85
PCA.7 Material Fabrication		27-Mar-15	07-Mar-16	247
A1670	Facade Glass and Steel Fab and Shipment	27-Mar-15	07-Mar-16	247
A1680	Fabricate and delivery casework and wood	28-Aug-15	21-Jan-16	105
A1660	Design-Assist Curtainwall Fab and Shipment	16-Sep-15	22-Sep-15	5
PCA.8 Construction		04-May-15	23-Jun-17	560
A1690	MEP Installation and Testing	04-May-15	23-Jun-17	560
A1750	Theater/Dance Wall Form, Reinforcement,	01-Jul-15	30-Nov-16	371
A1710	Theater DRUM Perimeter Wall Pour, Mason	13-Jul-15	26-May-16	229
A1760	Theatre/Dance Core & Shell	31-Jul-15	29-Jun-16	239
A1860	Arts Tower Core Wall Pour and Form	24-Aug-15	23-Oct-15	45
A1700	Theater/Dance Enclosure Completion	16-Sep-15	22-Sep-15	5
A1790	Music Building Perimeter Wall Pour, Masonr	16-Sep-15	22-Sep-15	5
A1720	DRUM Steel to Roof Truss Systems	15-Oct-15*	04-Nov-15	15
A1830	Forum CMU Wall Construction	03-Nov-15	23-Nov-15	15
A1870	Tower Concrete Structure Complete	03-Dec-15	03-Dec-15	1
A1880	Total Superstructure Complete	03-Dec-15	03-Dec-15	1
A1820	Practice Box Level 2 Completion	08-Feb-16	31-Mar-17	300
A1770	Theatre/Dance Fitout	13-Apr-16*	11-Jan-17	196
A1780	Black Box Theatre Fitout	21-Apr-16	31-Mar-17	247
A1740	DRUM Enclosure Completion	22-Apr-16*	12-May-16	15
A1810	Practice Box Level 3 Completion	01-Jun-16	16-Mar-17	207
A1800	Music Building Enclosure Completion	01-Dec-16*	06-Jan-17	27
A1840	Fitout Forum - MEP Drops, Flooring finish	26-Jan-17	15-Feb-17	15
PCA.9 Project Closeout		24-Jul-17	07-Dec-17	99
A1550	Achieve TCO of Performing Arts Center	24-Jul-17*	24-Jul-17	1
A1850	Final Completion	07-Dec-17	07-Dec-17	1

Appendix F Façade Production Schedule





Appendix G Façade Detailed Cost Estimate



Group	Phase	Description	Takeoff Quantity	Labor Cost/Unit	Labor Price	Labor Amount	Material Price	Material Amount	Equip Price	Equip Amoun	Total Cost/Unit	Total Amount
3000.000		**CONCRETE**										
	3110.150	Forms: Walls										
		DRUM Wall Forms - Steel Type	27,360.00 sf	1.50 /sf	20.00 /hr	41,040	0.96 /sf	27,054	-	-	2.49 /sf	68,094
		Wall Forms - Steel Type	51,005.64 sf	1.50 /sf	20.00 /hr	76,508	0.96 /sf	50,434	-	-	2.49 /sf	126,943
		DRUM Board Form Liner - Stucco	13,680.00 sf	1.00 /sf	20.00 /hr	13,680	3.60 /sf	50,725	-	-	4.71 /sf	64,405
		Rest of Board Form Liner - Stucco	25,502.82 sf	1.00 /sf	20.00 /hr	25,503	3.60 /sf	94,564	-	-	4.71 /sf	120,067
4000.000		**MASONRY**										
	4410.110	Stone Limestone										
		Panel Limestone Sand Finish 2"	38,940.00 sf	5.38 /sf	20.00 /hr	209,497	15.00 /sf	613,305	-	-	21.13 /sf	822,802
		Panel Limestone Smooth Fin 4"	2,290.00 sf	6.25 /sf	20.00 /hr	14,313	26.00 /sf	62,527	-	-	33.55 /sf	76,839
03-30-00.0		**Cast-In-Place Concrete**										
	03-30-53.40	Concrete In Place										
		Strt concrt,place,free-stndng wall (3000 psi),15"thck x 18'high,incl	2,166.00 cy	192.00 /cy	192.00 /cy	415,872	157.00 /cy	340,062	15.40 /cy	33,356	364.40 /cy	789,290
04-05-19.0		**Masonry Anchorage And Reinforcing**										
	04-05-19.16	Masonry Anchors										
		Masonry anchors, veneer wall ties, corrugated, galvanized, 24 ga	2,000.00 c	35.00 /c	35.00 /c	70,000	9.85 /c	19,700	-	-	44.85 /c	89,700
07-13-00.0		**Sheet Waterproofing**										
	07-13-53.10	Elastomeric Sheet Waterproofing And Access.										
		Elastomeric sheet waterproofing, bitumen modified polyurethane,	39,002.00 sf	0.96 /sf	0.96 /sf	37,442	0.93 /sf	36,272	-	-	1.89 /sf	73,714
07-21-13.0		**Board Insulation**										
	07-21-13.10	Rigid Insulation										
		Extruded polystyrene insulation, rigid, for walls, 25 PSI compressi	39,002.82 sf	0.51 /sf	0.51 /sf	19,891	1.04 /sf	40,563	-	-	1.55 /sf	60,454
08-42-00.0		**Entrances**										
	08-42-26.10	Swinging Glass Doors										
		Doors, glass, swing, tempered, 1/2" thick, 6' x 7' opening, incl. har	10.00 opng	515.00 /opng	515.00 /opng	5,150	4,400.00 /opng	44,000	-	-	4,915.00 /opng	49,150
08-44-00.0		**Curtain Wall And Glazed Assemblies**										
	08-44-13.10	Glazed Curtain Walls										
		Curtain wall, aluminum, stock, including glazing, maximum	33,277.00 sf	9.80 /sf	9.80 /sf	326,115	181.00 /sf	6,023,137	-	-	190.80 /sf	6,349,252
08-81-35.0		**Translucent Glass**										
	08-81-35.10	Obscure Glass										
		Obscure glass, 7/32" thick, textured	5,426.00 sf	6.00 /sf	6.00 /sf	32,556	12.70 /sf	68,910	-	-	18.70 /sf	101,466
08-81-55.0		**Window Glass**										
	08-81-55.10	Sheet Glass										
		Window glass, tempered, 3/16" thick	665.00 sf	1.50 /sf	1.50 /sf	998	9.20 /sf	6,118	-	-	10.70 /sf	7,116

Estimate Company

Estimate Totals

Performing Arts Center Fa

10/16/2015 3:20 AM

Page 1A

Description	Amount	Totals	Hours	Rate	Cost Basis	Cost per Unit	Percent of Total
Labor	1,288,565		19,027.056 hrs				14.64%
Material	7,477,371						84.98%
Subcontract							
Equipment	33,356						0.38%
Other							
	8,799,292	8,799,292					100.00
Total		***8,799,292***					

Detailed Cost Estimate Takeoffs

Element	**Building**	**Area**	**Quantity (Unit)**
Lecce Limestone Veneer	Dance/Theatre	West Elevation	320
	Dance/Theatre	South Elevation	265
	Dance/Theatre	East Elevation	200
	Dance/Theatre	North Elevation	250
	Dance/Theatre	Clerestory	20
	Music	South Elevation	250
	Music	North Elevation	200
	LCA Tower	South Elevation	280
	LCA Tower	North Elevation	260
	DRUM		170
	DRUM		210
	DRUM		170
	All		2595

Element	**Quantity**	**Dimension**	**Unit**
Lecce Limestone Bench	60'	9" deep x 1' wide	LF
	60'	8" deep x 1' wide	LF
	228'	9" deep x 1' wide	LF
	228'	8" deep x 1' wide	LF
Lecce Limestone Bollard	7 each	45" x 62" x 47"	

Concrete Board Formed Wall

Element	**Quantity**	**Dimension**	**Unit**
Dance Theatre South Wall	Wall Area	3546	SF
Dance Theatre East Wall	Wall area	2351.83	SF
Dance Theatre West Wall	Wall Area	5073	SF
DRUM	**Height**	**60'**	**LF**
	Circumfrence	**228**	**LF**
Breezeway	Wall Area	790	SF
	Wall Area	674	SF
LCA Arts Tower	North Tower Wall	3153.32	SF
LCA Arts Tower	South Tower Wall	3515.67	SF
Music Building	South Wall	3877	SF
Music Building	North Wall	2522	SF
	Total SF (not DRUM)	**25502.82**	

Concrete Wall Item

Wall Thickness	1.5'		
Total SF	39002.82		
Total CF	**58504**		
Total CY	2166.814815		

Curtain Wall System Takeoff

Element	Quantity	Dimension	Unit
Music East Curtain Wall	Wall Area	5624.89	SF
Music West Curtain Wall	Wall Area	5885	SF
Arts Tower West Wall	Wall Area	2425.59	SF
Arts Tower East Wall	Wall Area	3234.95	SF
Breezewall South Wall	Wall Area	3113.56	SF
Arts Tower and Breeze North	Wall Area	3090.05	SF
Breezeway north Wall	Wall Area	551.7	SF
DRUM South Wall	Wall Area	2555	SF
T/D West Curtain Wall	Wall Area	1231.26	SF
T/D SW Curtain Wall	Wall Area	451.69	SF
T/D South Curtain Wall	Wall Area	1474.18	SF
T/D East Curtain Wall	Wall Area	2391	SF
T/D North Curtain Wall	Wall Area	57.9	SF
Forum Entrace	Wall Area	1191	SF
	Total	**33277.77**	SF

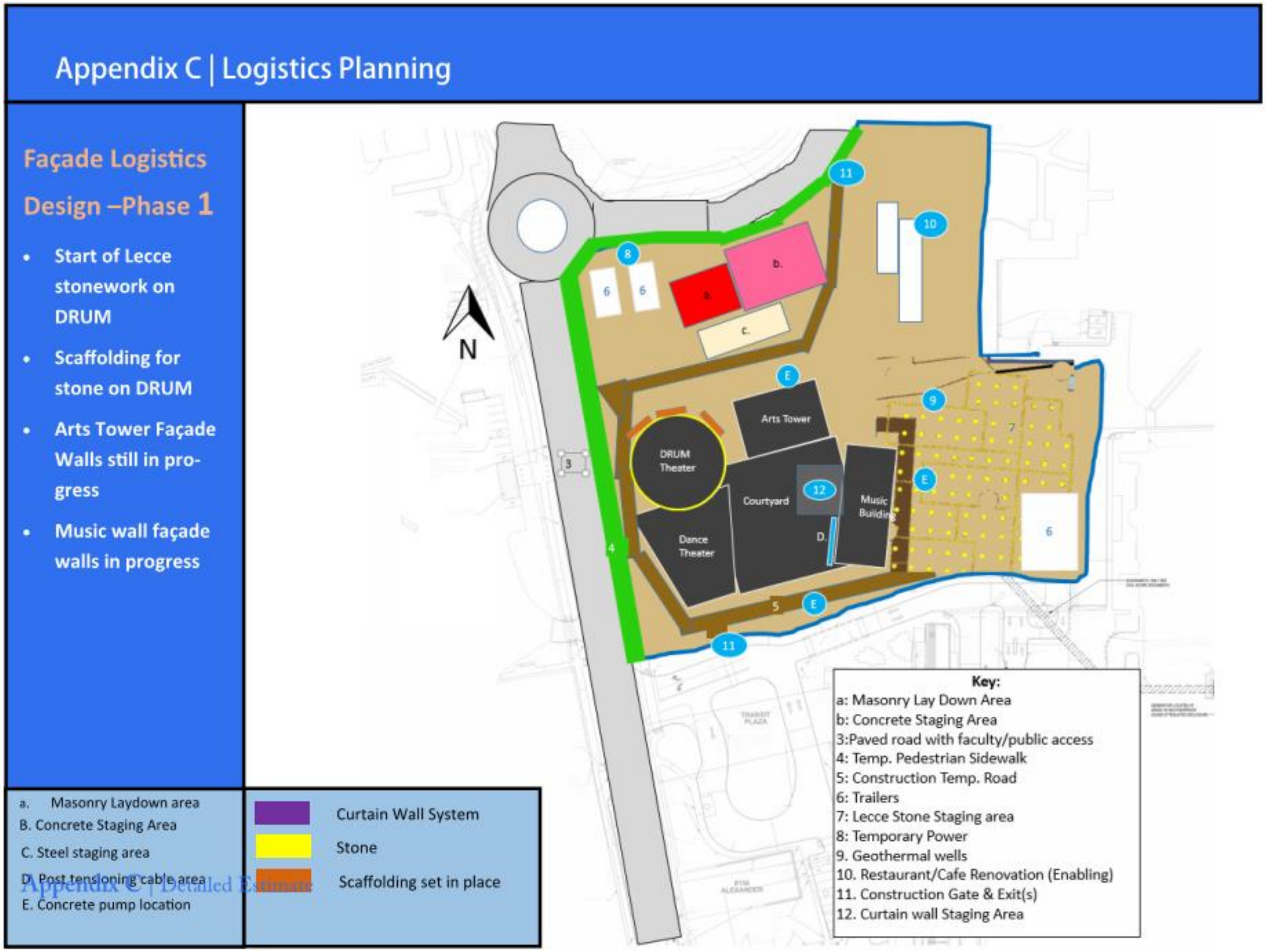
Translucent Glass Takeoff

Music Building West Wall	Wall Area	1006.59	SF
Music Building West Wall	Wall Area	1121.47	SF
Clerestories (EG-2.2)		142.87	SF
		272.79	SF
		153	SF
		163	SF
		290.8	SF
		236	SF
		2040	SF
	Total	**5426.52**	SF

Vision Glass Takeoff

Element	Quantity	Dimension	Unit
DRUM EG-1C (west)	Wall Area	665	SF

Appendix H Façade Logistics Design



Appendix C | Logistics Planning

Façade Logistics Design –Phase 1

- Start of Lecce stonework on DRUM
- Scaffolding for stone on DRUM
- Arts Tower Façade Walls still in progress
- Music wall façade walls in progress

a. Masonry Laydown area
B. Concrete Staging Area
C. Steel staging area
D. Post tensioning cable area
E. Concrete pump location

Appendix C | Detailed Estimate

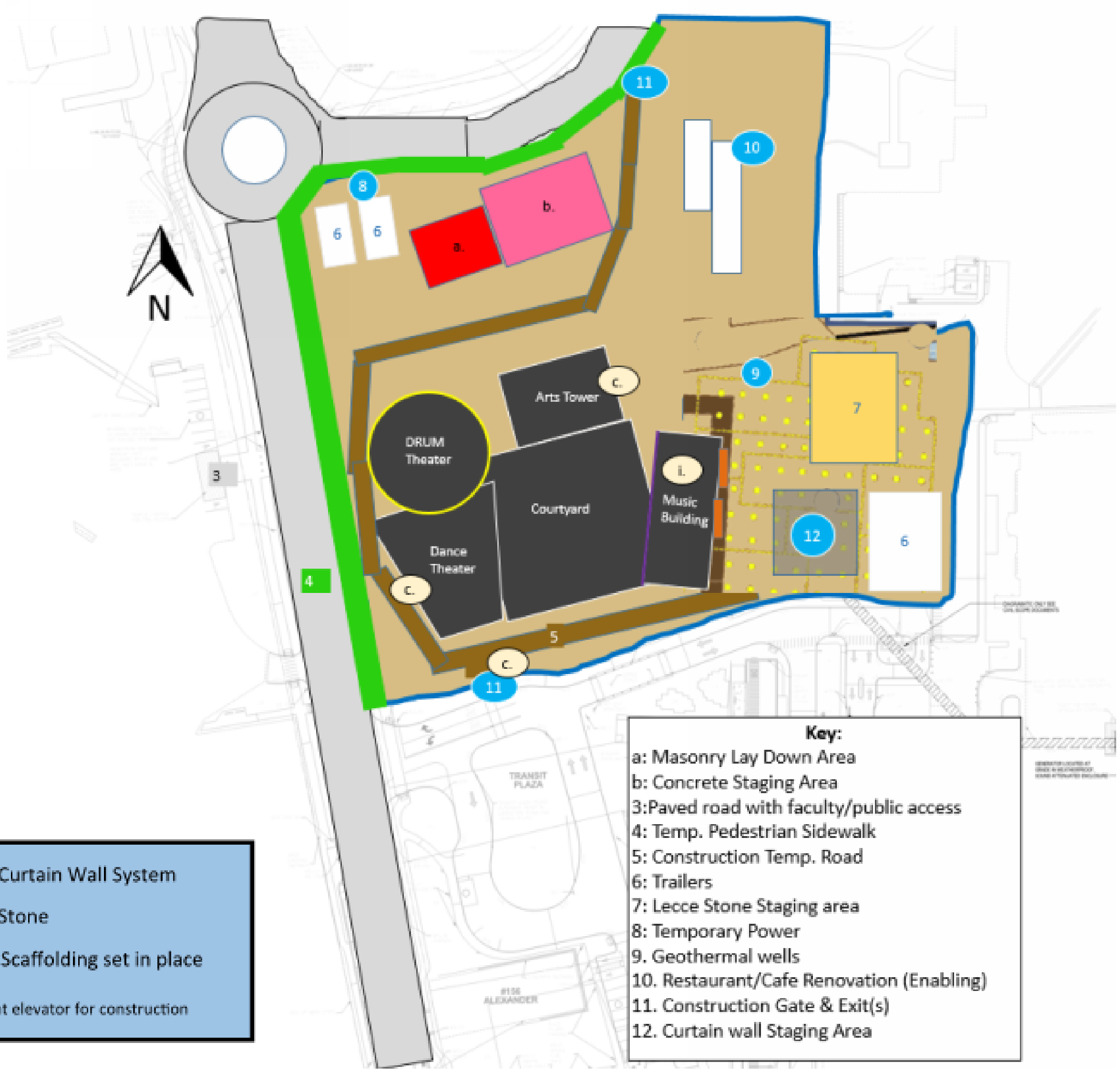
🟪 Curtain Wall System
🟨 Stone
🟧 Scaffolding set in place

Key:
a: Masonry Lay Down Area
b: Concrete Staging Area
3:Paved road with faculty/public access
4: Temp. Pedestrian Sidewalk
5: Construction Temp. Road
6: Trailers
7: Lecce Stone Staging area
8: Temporary Power
9. Geothermal wells
10. Restaurant/Cafe Renovation (Enabling)
11. Construction Gate & Exit(s)
12. Curtain wall Staging Area

The Performing Arts Center | Logistics

Façade Logistics Design –Phase 2

- Superstructure complete
- All board-formed concrete façade walls poured
- Start of Curtain Wall



Key:
a: Masonry Lay Down Area
b: Concrete Staging Area
3:Paved road with faculty/public access
4: Temp. Pedestrian Sidewalk
5: Construction Temp. Road
6: Trailers
7: Lecce Stone Staging area
8: Temporary Power
9. Geothermal wells
10. Restaurant/Cafe Renovation (Enabling)
11. Construction Gate & Exit(s)
12. Curtain wall Staging Area

a. Masonry Laydown area
b. Concrete Staging Area
c. Debris Chute & dumpster

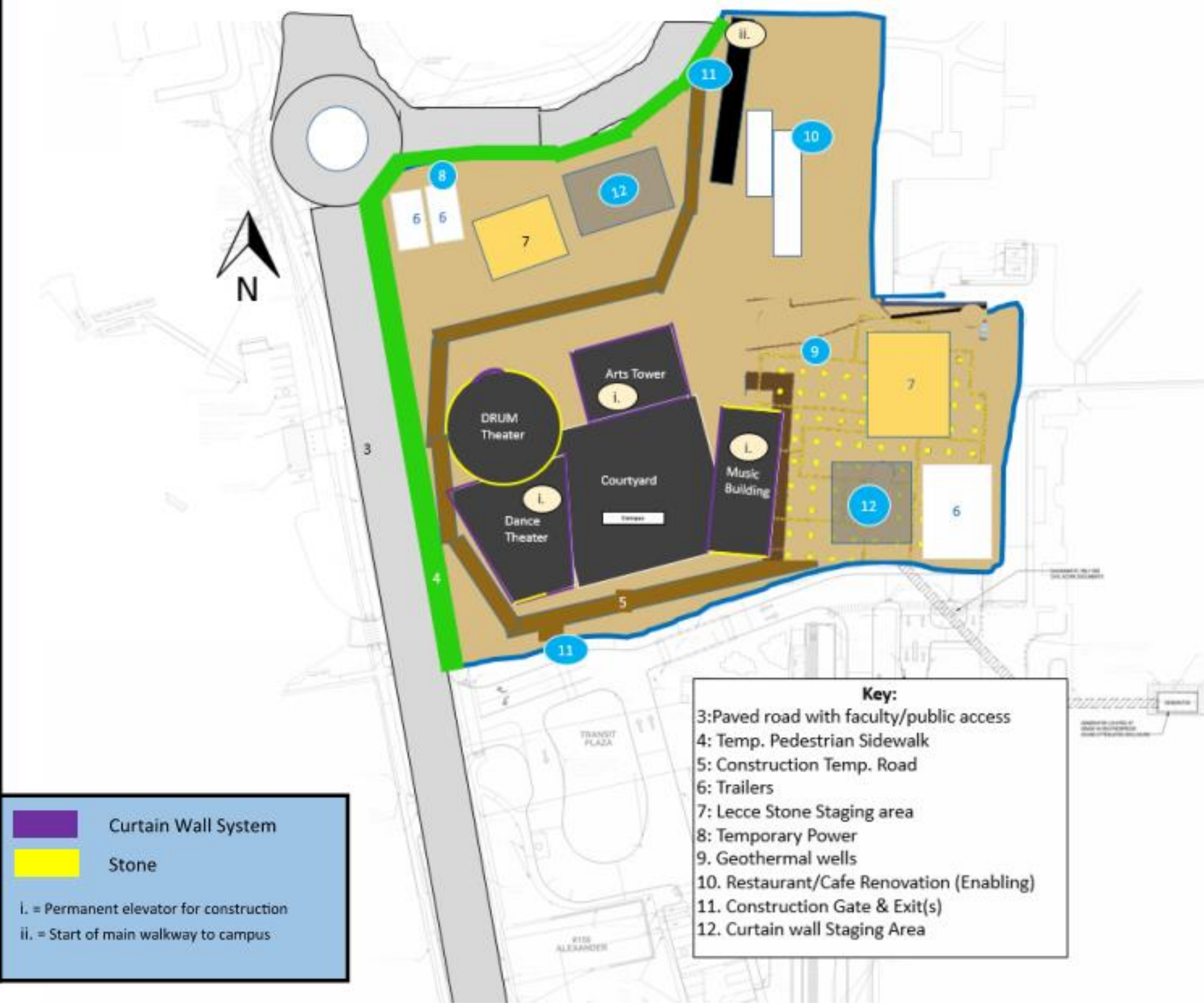
🟪	Curtain Wall System
🟨	Stone
🟧	Scaffolding set in place

i. = Permanent elevator for construction

The Performing Arts Center | Logistics

Façade Logistics Design –Phase 3

- Building Enclosed
- Curtain Wall Framing Complete
- Skylight and glazing complete
- Lecce Limestone—80% Complete



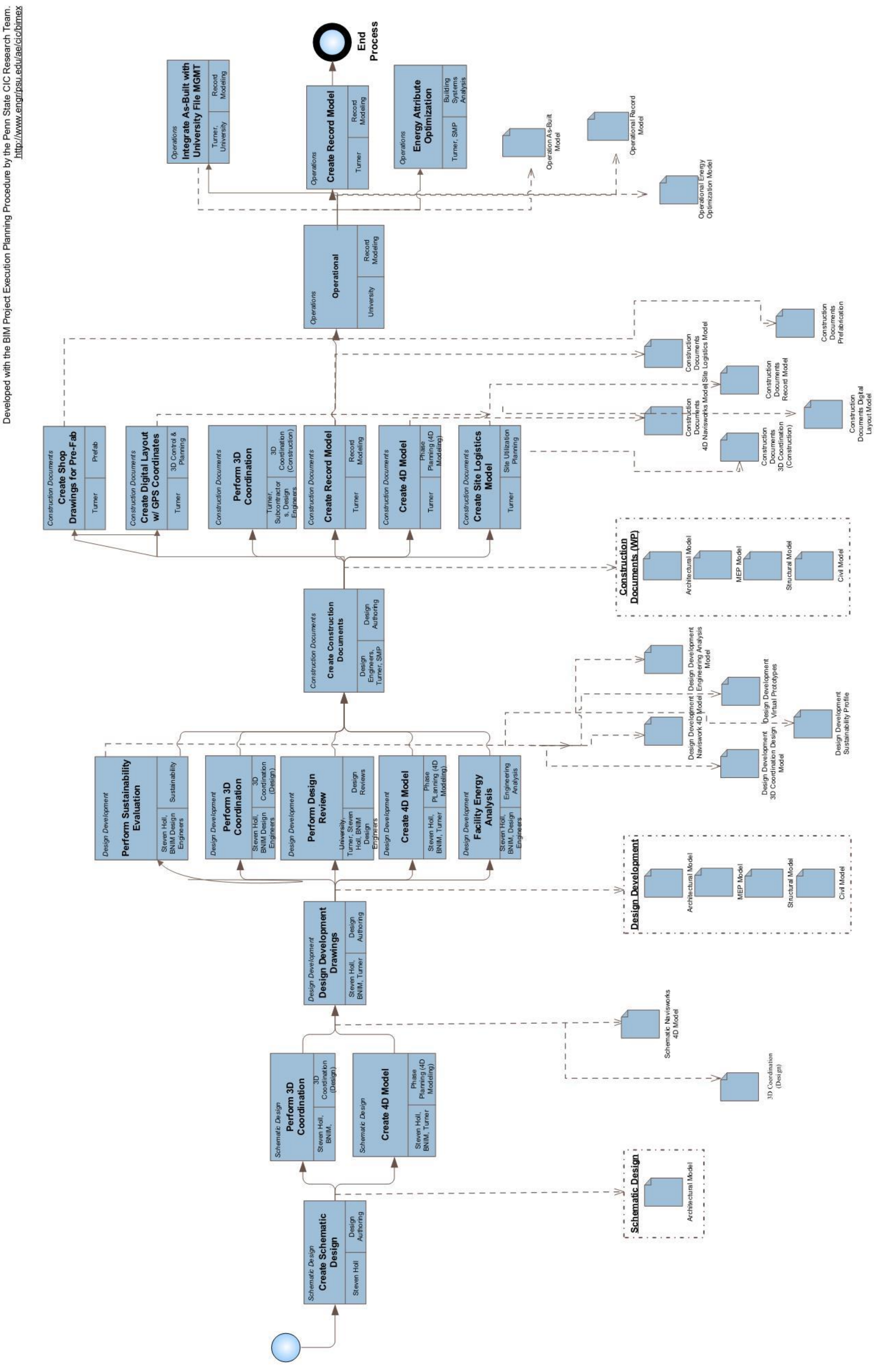
🟪 Curtain Wall System

🟨 Stone

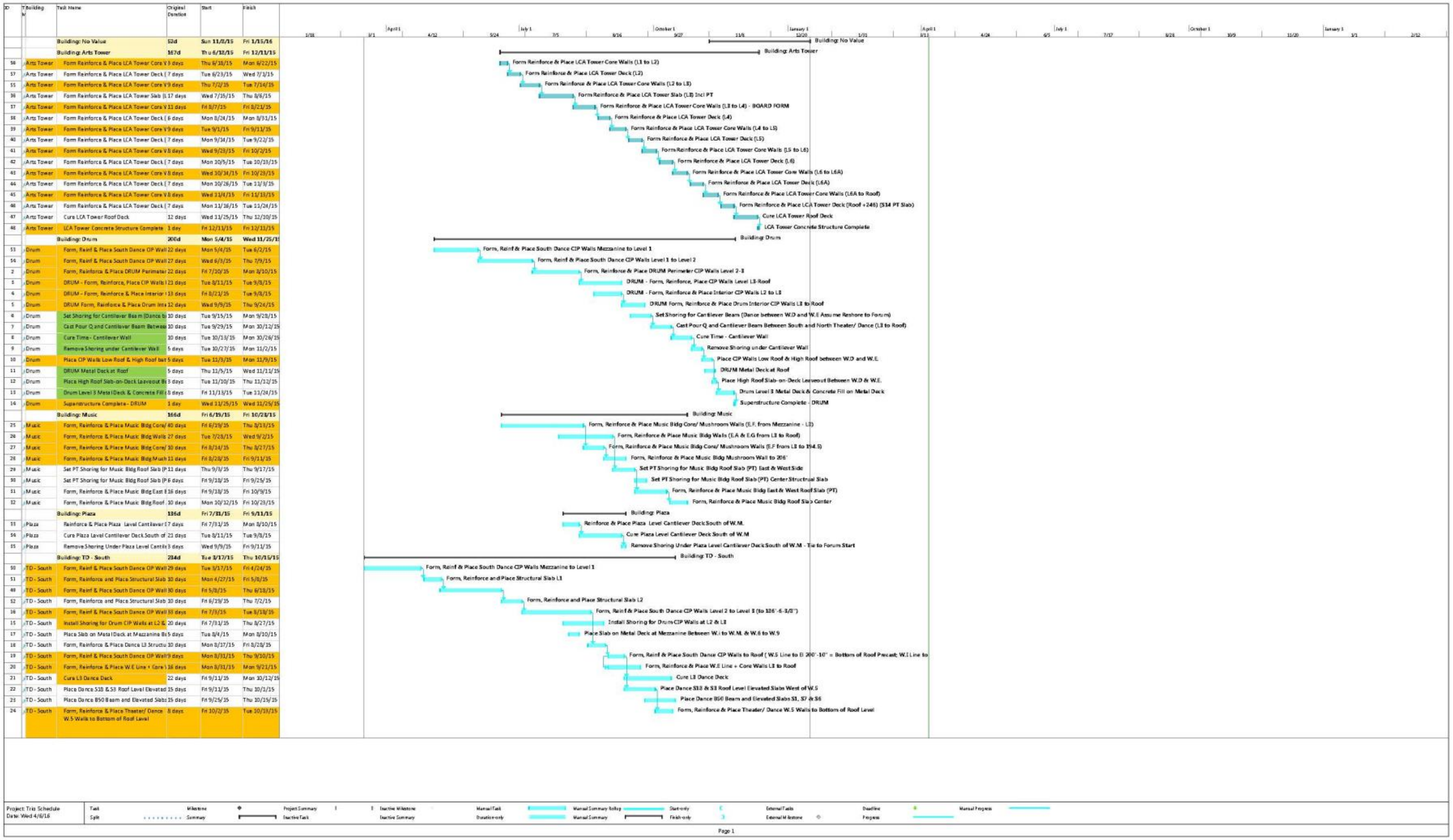
i. = Permanent elevator for construction
ii. = Start of main walkway to campus

Key:
3:Paved road with faculty/public access
4: Temp. Pedestrian Sidewalk
5: Construction Temp. Road
6: Trailers
7: Lecce Stone Staging area
8: Temporary Power
9. Geothermal wells
10. Restaurant/Cafe Renovation (Enabling)
11. Construction Gate & Exit(s)
12. Curtain wall Staging Area

Appendix I: BIM Process Map



Appendix J: Peri Trio CIP Wall Schedule Export

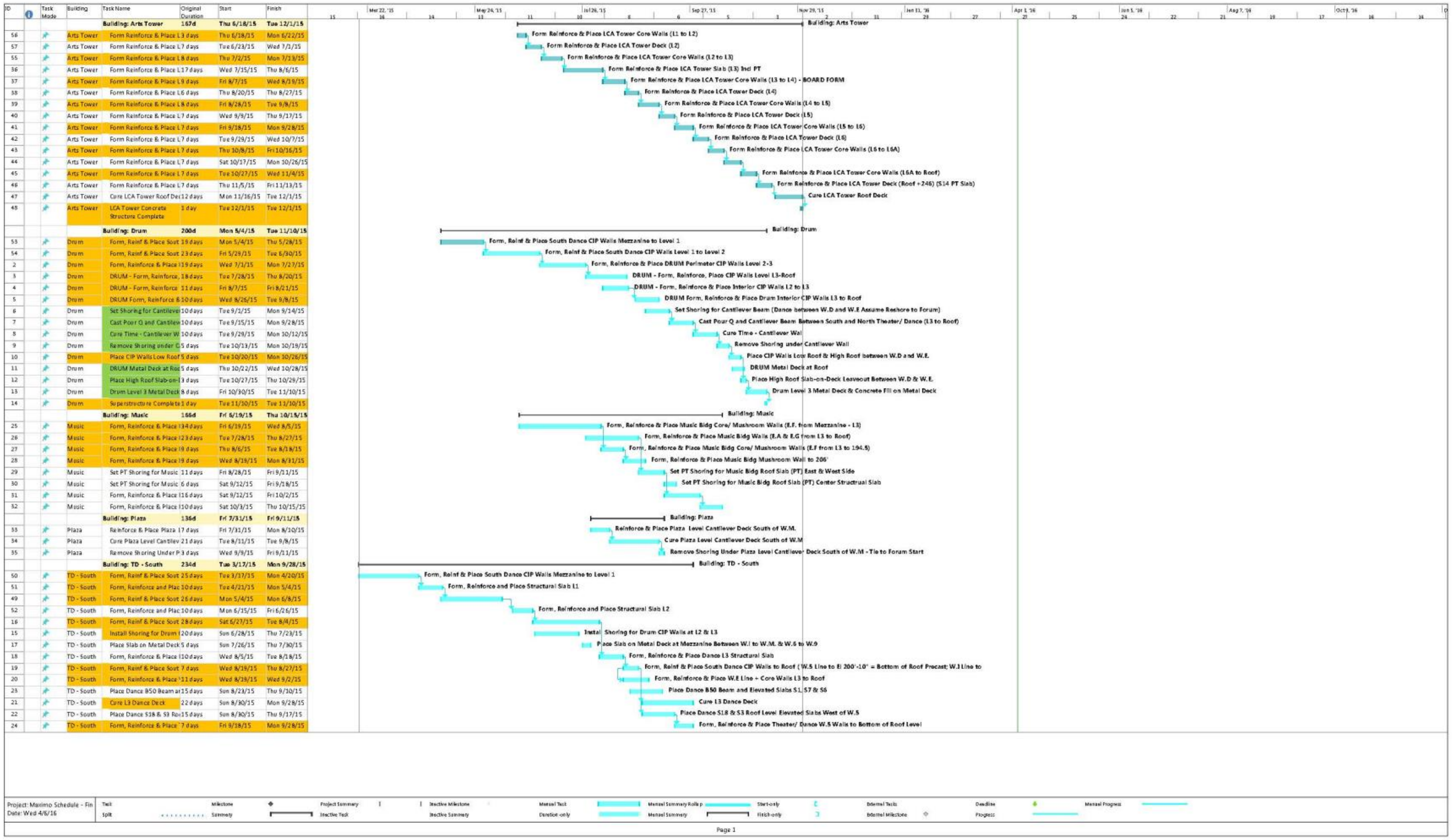


ID	T M	Building	Task Name	Original Duration	Start	Finish
			Building: No Value	**52d**	**Sun 11/8/15**	**Fri 1/15/16**
			Building: Arts Tower	**167d**	**Thu 6/18/15**	**Fri 12/11/15**
58		Arts Tower	Form Reinforce & Place LCA Tower Core V	3 days	Thu 6/18/15	Mon 6/22/15
57		Arts Tower	Form Reinforce & Place LCA Tower Deck (	7 days	Tue 6/23/15	Wed 7/1/15
55		Arts Tower	Form Reinforce & Place LCA Tower Core V	9 days	Thu 7/2/15	Tue 7/14/15
36		Arts Tower	Form Reinforce & Place LCA Tower Slab (L	17 days	Wed 7/15/15	Thu 8/6/15
37		Arts Tower	Form Reinforce & Place LCA Tower Core V	11 days	Fri 8/7/15	Fri 8/21/15
38		Arts Tower	Form Reinforce & Place LCA Tower Deck (	6 days	Mon 8/24/15	Mon 8/31/15
39		Arts Tower	Form Reinforce & Place LCA Tower Core V	9 days	Tue 9/1/15	Fri 9/11/15
40		Arts Tower	Form Reinforce & Place LCA Tower Deck (	7 days	Mon 9/14/15	Tue 9/22/15
41		Arts Tower	Form Reinforce & Place LCA Tower Core V	8 days	Wed 9/23/15	Fri 10/2/15
42		Arts Tower	Form Reinforce & Place LCA Tower Deck (	7 days	Mon 10/5/15	Tue 10/13/15
43		Arts Tower	Form Reinforce & Place LCA Tower Core V	8 days	Wed 10/14/15	Fri 10/23/15
44		Arts Tower	Form Reinforce & Place LCA Tower Deck (	7 days	Mon 10/26/15	Tue 11/3/15
45		Arts Tower	Form Reinforce & Place LCA Tower Core V	8 days	Wed 11/4/15	Fri 11/13/15
46		Arts Tower	Form Reinforce & Place LCA Tower Deck (	7 days	Mon 11/16/15	Tue 11/24/15
47		Arts Tower	Cure LCA Tower Roof Deck	12 days	Wed 11/25/15	Thu 12/10/15
48		Arts Tower	LCA Tower Concrete Structure Complete	1 day	Fri 12/11/15	Fri 12/11/15
			Building: Drum	**200d**	**Mon 5/4/15**	**Wed 11/25/15**
53		Drum	Form, Reinf & Place South Dance CIP Wall	22 days	Mon 5/4/15	Tue 6/2/15
54		Drum	Form, Reinf & Place South Dance CIP Wall	27 days	Wed 6/3/15	Thu 7/9/15
2		Drum	Form, Reinforce & Place DRUM Perimeter	22 days	Fri 7/10/15	Mon 8/10/15
3		Drum	DRUM - Form, Reinforce, Place CIP Walls I	21 days	Tue 8/11/15	Tue 9/8/15
4		Drum	DRUM - Form, Reinforce & Place Interior	13 days	Fri 8/21/15	Tue 9/8/15
5		Drum	DRUM Form, Reinforce & Place Drum Inte	12 days	Wed 9/9/15	Thu 9/24/15
6		Drum	Set Shoring for Cantilever Beam (Dance b	10 days	Tue 9/15/15	Mon 9/28/15
7		Drum	Cast Pour Q and Cantilever Beam Betwee	10 days	Tue 9/29/15	Mon 10/12/15
8		Drum	Cure Time - Cantilever Wall	10 days	Tue 10/13/15	Mon 10/26/15
9		Drum	Remove Shoring under Cantilever Wall	5 days	Tue 10/27/15	Mon 11/2/15
10		Drum	Place CIP Walls Low Roof & High Roof bet	5 days	Tue 11/3/15	Mon 11/9/15
11		Drum	DRUM Metal Deck at Roof	5 days	Thu 11/5/15	Wed 11/11/15
12		Drum	Place High Roof Slab-on-Deck Leaveout B	3 days	Tue 11/10/15	Thu 11/12/15
13		Drum	Drum Level 3 Metal Deck & Concrete Fill	8 days	Fri 11/13/15	Tue 11/24/15
14		Drum	Superstructure Complete - DRUM	1 day	Wed 11/25/15	Wed 11/25/15
			Building: Music	**166d**	**Fri 6/19/15**	**Fri 10/23/15**
25		Music	Form, Reinforce & Place Music Bldg Core/	40 days	Fri 6/19/15	Thu 8/13/15
26		Music	Form, Reinforce & Place Music Bldg Walls	27 days	Tue 7/28/15	Wed 9/2/15
27		Music	Form, Reinforce & Place Music Bldg Core/	10 days	Fri 8/14/15	Thu 8/27/15
28		Music	Form, Reinforce & Place Music Bldg Mush	11 days	Fri 8/28/15	Fri 9/11/15
29		Music	Set PT Shoring for Music Bldg Roof Slab (P	11 days	Thu 9/3/15	Thu 9/17/15
30		Music	Set PT Shoring for Music Bldg Roof Slab (P	6 days	Fri 9/18/15	Fri 9/25/15
31		Music	Form, Reinforce & Place Music Bldg East 8	16 days	Fri 9/18/15	Fri 10/9/15
32		Music	Form, Reinforce & Place Music Bldg Roof	10 days	Mon 10/12/15	Fri 10/23/15
			Building: Plaza	**136d**	**Fri 7/31/15**	**Fri 9/11/15**
33		Plaza	Reinforce & Place Plaza Level Cantilever	7 days	Fri 7/31/15	Mon 8/10/15
34		Plaza	Cure Plaza Level Cantilever Deck South of	21 days	Tue 8/11/15	Tue 9/8/15
35		Plaza	Remove Shoring Under Plaza Level Cantile	3 days	Wed 9/9/15	Fri 9/11/15
			Building: TD - South	**214d**	**Tue 3/17/15**	**Thu 10/15/15**
50		TD - South	Form, Reinf & Place South Dance CIP Wall	29 days	Tue 3/17/15	Fri 4/24/15
51		TD - South	Form, Reinforce and Place Structural Slab	10 days	Mon 4/27/15	Fri 5/8/15
49		TD - South	Form, Reinf & Place South Dance CIP Wall	30 days	Fri 5/8/15	Thu 6/18/15
52		TD - South	Form, Reinforce and Place Structural Slab	10 days	Fri 6/19/15	Thu 7/2/15
16		TD - South	Form, Reinf & Place South Dance CIP Wall	33 days	Fri 7/3/15	Tue 8/18/15
15		TD - South	Install Shoring for Drum CIP Walls at L2 &	20 days	Fri 7/31/15	Thu 8/27/15
17		TD - South	Place Slab on Metal Deck at Mezzanine B	5 days	Tue 8/4/15	Mon 8/10/15
18		TD - South	Form, Reinforce & Place Dance L3 Structu	10 days	Mon 8/17/15	Fri 8/28/15
19		TD - South	Form, Reinf & Place South Dance CIP Wall	9 days	Mon 8/31/15	Thu 9/10/15
20		TD - South	Form, Reinforce & Place W.E Line + Core	16 days	Mon 8/31/15	Mon 9/21/15
21		TD - South	Cure L3 Dance Deck	22 days	Fri 9/11/15	Mon 10/12/15
22		TD - South	Place Dance S18 & S3 Roof Level Elevated	15 days	Fri 9/11/15	Thu 10/1/15
23		TD - South	Place Dance B50 Beam and Elevated Slabs	15 days	Fri 9/25/15	Thu 10/15/15
24		TD - South	Form, Reinforce & Place Theater/ Dance W.5 Walls to Bottom of Roof Level	8 days	Fri 10/2/15	Tue 10/13/15

Project: Trio Schedule
Date: Wed 4/6/16

Page 1

Appendix K: Peri Maximo (Alternative) CIP Wall Schedule Export



ID	ⓘ	Task Mode	Building	Task Name	Original Duration	Start	Finish
				Building: Arts Tower	**167d**	**Thu 6/18/15**	**Tue 12/1/15**
56		📌	Arts Tower	Form Reinforce & Place L	3 days	Thu 6/18/15	Mon 6/22/15
57		📌	Arts Tower	Form Reinforce & Place L	7 days	Tue 6/23/15	Wed 7/1/15
55		📌	Arts Tower	Form Reinforce & Place L	8 days	Thu 7/2/15	Mon 7/13/15
36		📌	Arts Tower	Form Reinforce & Place L	17 days	Wed 7/15/15	Thu 8/6/15
37		📌	Arts Tower	Form Reinforce & Place L	9 days	Fri 8/7/15	Wed 8/19/15
38		📌	Arts Tower	Form Reinforce & Place L	6 days	Thu 8/20/15	Thu 8/27/15
39		📌	Arts Tower	Form Reinforce & Place L	8 days	Fri 8/28/15	Tue 9/8/15
40		📌	Arts Tower	Form Reinforce & Place L	7 days	Wed 9/9/15	Thu 9/17/15
41		📌	Arts Tower	Form Reinforce & Place L	7 days	Fri 9/18/15	Mon 9/28/15
42		📌	Arts Tower	Form Reinforce & Place L	7 days	Tue 9/29/15	Wed 10/7/15
43		📌	Arts Tower	Form Reinforce & Place L	7 days	Thu 10/8/15	Fri 10/16/15
44		📌	Arts Tower	Form Reinforce & Place L	7 days	Sat 10/17/15	Mon 10/26/15
45		📌	Arts Tower	Form Reinforce & Place L	7 days	Tue 10/27/15	Wed 11/4/15
46		📌	Arts Tower	Form Reinforce & Place L	7 days	Thu 11/5/15	Fri 11/13/15
47		📌	Arts Tower	Cure LCA Tower Roof Dec	12 days	Mon 11/16/15	Tue 12/1/15
48		📌	Arts Tower	LCA Tower Concrete Structure Complete	1 day	Tue 12/1/15	Tue 12/1/15
				Building: Drum	**200d**	**Mon 5/4/15**	**Tue 11/10/15**
53		📌	Drum	Form, Reinf & Place Sout	19 days	Mon 5/4/15	Thu 5/28/15
54		📌	Drum	Form, Reinf & Place Sout	23 days	Fri 5/29/15	Tue 6/30/15
2		📌	Drum	Form, Reinforce & Place I	19 days	Wed 7/1/15	Mon 7/27/15
3		📌	Drum	DRUM - Form, Reinforce,	18 days	Tue 7/28/15	Thu 8/20/15
4		📌	Drum	DRUM - Form, Reinforce	11 days	Fri 8/7/15	Fri 8/21/15
5		📌	Drum	DRUM Form, Reinforce &	10 days	Wed 8/26/15	Tue 9/8/15
6		📌	Drum	Set Shoring for Cantilever	10 days	Tue 9/1/15	Mon 9/14/15
7		📌	Drum	Cast Pour Q and Cantilev	10 days	Tue 9/15/15	Mon 9/28/15
8		📌	Drum	Cure Time - Cantilever W	10 days	Tue 9/29/15	Mon 10/12/15
9		📌	Drum	Remove Shoring under C	5 days	Tue 10/13/15	Mon 10/19/15
10		📌	Drum	Place CIP Walls Low Roof	5 days	Tue 10/20/15	Mon 10/26/15
11		📌	Drum	DRUM Metal Deck at Roo	5 days	Thu 10/22/15	Wed 10/28/15
12		📌	Drum	Place High Roof Slab-on-I	3 days	Tue 10/27/15	Thu 10/29/15
13		📌	Drum	Drum Level 3 Metal Deck	8 days	Fri 10/30/15	Tue 11/10/15
14		📌	Drum	Superstructure Complete	1 day	Tue 11/10/15	Tue 11/10/15
				Building: Music	**166d**	**Fri 6/19/15**	**Thu 10/15/15**
25		📌	Music	Form, Reinforce & Place I	34 days	Fri 6/19/15	Wed 8/5/15
26		📌	Music	Form, Reinforce & Place I	23 days	Tue 7/28/15	Thu 8/27/15
27		📌	Music	Form, Reinforce & Place I	9 days	Thu 8/6/15	Tue 8/18/15
28		📌	Music	Form, Reinforce & Place I	9 days	Wed 8/19/15	Mon 8/31/15
29		📌	Music	Set PT Shoring for Music	11 days	Fri 8/28/15	Fri 9/11/15
30		📌	Music	Set PT Shoring for Music	6 days	Sat 9/12/15	Fri 9/18/15
31		📌	Music	Form, Reinforce & Place I	16 days	Sat 9/12/15	Fri 10/2/15
32		📌	Music	Form, Reinforce & Place I	10 days	Sat 10/3/15	Thu 10/15/15
				Building: Plaza	**136d**	**Fri 7/31/15**	**Fri 9/11/15**
33		📌	Plaza	Reinforce & Place Plaza I	7 days	Fri 7/31/15	Mon 8/10/15
34		📌	Plaza	Cure Plaza Level Cantilev	21 days	Tue 8/11/15	Tue 9/8/15
35		📌	Plaza	Remove Shoring Under P	3 days	Wed 9/9/15	Fri 9/11/15
				Building: TD - South	**234d**	**Tue 3/17/15**	**Mon 9/28/15**
50		📌	TD - South	Form, Reinf & Place Sout	25 days	Tue 3/17/15	Mon 4/20/15
51		📌	TD - South	Form, Reinforce and Plac	10 days	Tue 4/21/15	Mon 5/4/15
49		📌	TD - South	Form, Reinf & Place Sout	26 days	Mon 5/4/15	Mon 6/8/15
52		📌	TD - South	Form, Reinforce and Plac	10 days	Mon 6/15/15	Fri 6/26/15
16		📌	TD - South	Form, Reinf & Place Sout	28 days	Sat 6/27/15	Tue 8/4/15
15		📌	TD - South	Install Shoring for Drum	20 days	Sun 6/28/15	Thu 7/23/15
17		📌	TD - South	Place Slab on Metal Deck	5 days	Sun 7/26/15	Thu 7/30/15
18		📌	TD - South	Form, Reinforce & Place I	10 days	Wed 8/5/15	Tue 8/18/15
19		📌	TD - South	Form, Reinf & Place Sout	7 days	Wed 8/19/15	Thu 8/27/15
20		📌	TD - South	Form, Reinforce & Place	11 days	Wed 8/19/15	Wed 9/2/15
23		📌	TD - South	Place Dance B50 Beam ar	15 days	Sun 8/23/15	Thu 9/10/15
21		📌	TD - South	Cure L3 Dance Deck	22 days	Sun 8/30/15	Mon 9/28/15
22		📌	TD - South	Place Dance S18 & S3 Ro	15 days	Sun 8/30/15	Thu 9/17/15
24		📌	TD - South	Form, Reinforce & Place	7 days	Fri 9/18/15	Mon 9/28/15

Project: Maximo Schedule - Fin
Date: Wed 4/6/16

Page 1

Appendix L: Trio vs. Maximo formwork Calculations

Performing Arts Center CIP Concrete Schedule Comparison using Trio vs. Maximo Formwork

						Trio			Maximo			
Building	Face	SF of Formwork		Trio Rate (sq ft / mh)	Maximo rate (sq ft/mh)	Total Trio Time (MH)	Trio in days	Total days by building	Accelerated Rate	Total Maximo Time (MH)	Maximo in Days	Total days by building
Arts	North Tower Wall	3153.32		15.00	17.40	210.2213333	26.2776667	56	0.862068966	181.2252874	22.65316092	48
	South Tower Wall	3515.67		15.00	17.40	234.378	29.29725		0.862068966	202.05	25.25625	
Dance / Theatre	South Wall	3546		15.00	17.40	236.4	29.55	121	0.862068966	203.7931034	25.47413793	105
	East Wall	2351.83		15.00	17.40	156.7886667	19.5985833		0.862068966	135.1626437	16.89533046	
	West Wall	5073		15.00	17.40	338.2	42.275		0.862068966	291.5517241	36.44396552	
	North Wall	3590		15.00	17.40	239.3333333	29.9166667		0.862068966	206.3218391	25.79022989	
Music Building	South Wall	3877		15.00	17.40	258.4666667	32.3083333	53	0.862068966	222.816092	27.85201149	46
	North Wall	2522		15.00	17.40	168.1333333	21.0166667		0.862068966	144.9425287	18.11781609	
DRUM	East Wall	8069		15.00	17.40	537.9333333	67.2416667	117	0.862068966	463.7356322	57.96695402	101
	West Wall	5939		15.00	17.40	395.9333333	49.4916667		0.862068966	341.3218391	42.66522989	
Totals		41636.82			Total	2775.788	346.9735			2392.92069	299.1150862	

Total savings	47.85841

Actual Schedule Interpolation Configuration

	Trio start date	Trio finish date	Total Days	Maximo Start Date	Maximo Finish Date	Total Days
TD- South	3/17/2015	10/13/2015	151	3/17/2015	9/28/2015	140
Music	6/19/2015	10/23/2015	91	6/19/2015	10/15/2015	85
Arts	6/18/2015	12/11/2015	127	6/18/2015	12/1/2015	119
Drum	5/4/2015	11/25/2015	148	5/4/2015	11/10/2015	137
Final	**3/17/2015**	**12/11/2015**	**517**	**3/17/2015**	**12/1/2015**	**481**

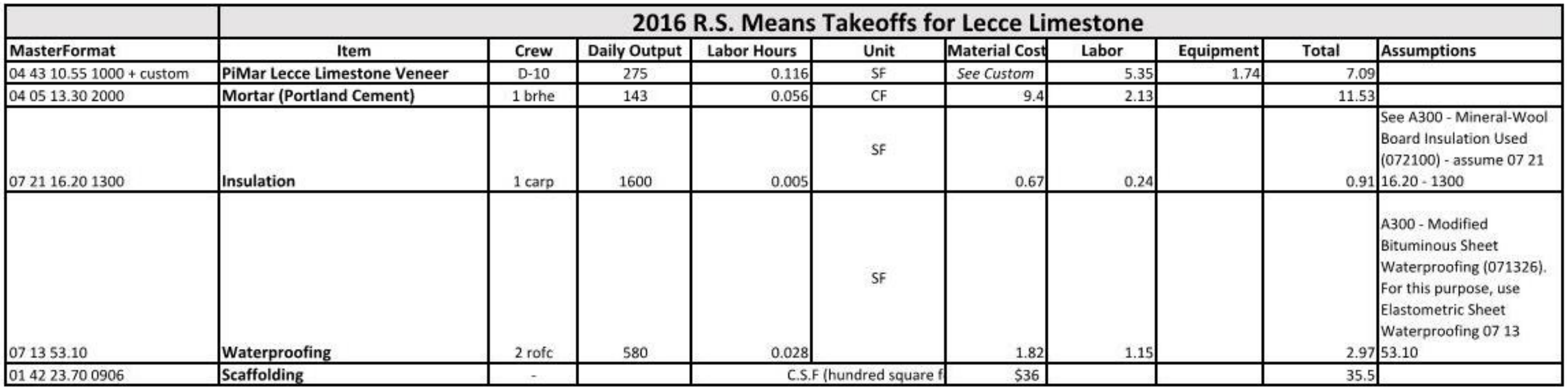
TD - South						
Mezzanine - 1			29			25
*** L 1-2**			30			26
L 2 -3			33			28
L3 to roof			8			7
Core L3 to Roof			13			11
W.5 Walls to bottom roof			8			7
		Total	**121**			**104**

Music						0
Mezzanine - Level 3			40			34
L3 to Roof			27			23
Core L3 to 194.5			10			9
Mushroom wall to 206			11			9
		Total	**88**			**76**

DRUM						0
Mezzanine - 1			22			19
*** L 1-2**			27			23
L 2 -3			22			19
L3 to roof			21			18
Interior L2 - L3			13			11
Interior L3 to Roof			12			10
		Total	**117**			**101**

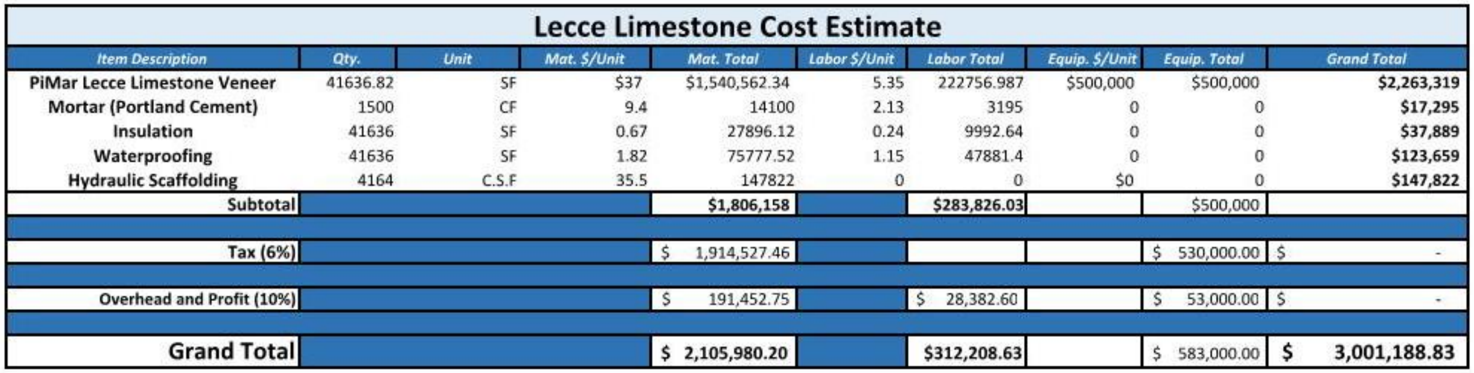
Arts Tower						0
*** L 1-2**			3			3
*** L 2 -3**			9			8
L3 to L4			11			9
L4 to L5			9			8
L5 to L6			8			7
L6 - L6A			8			7
L6A to Roof			8			7
		Total	**56**			**48**

Appendix M: R.S. Means Data for Lecce Limestone Cost Estimate



2016 R.S. Means Takeoffs for Lecce Limestone

MasterFormat	Item	Crew	Daily Output	Labor Hours	Unit	Material Cost	Labor	Equipment	Total	Assumptions
04 43 10.55 1000 + custom	PiMar Lecce Limestone Veneer	D-10	275	0.116	SF	*See Custom*	5.35	1.74	7.09	
04 05 13.30 2000	Mortar (Portland Cement)	1 brhe	143	0.056	CF	9.4	2.13		11.53	
07 21 16.20 1300	Insulation	1 carp	1600	0.005	SF	0.67	0.24		0.91	See A300 - Mineral-Wool Board Insulation Used (072100) - assume 07 21 16.20 - 1300
07 13 53.10	Waterproofing	2 rofc	580	0.028	SF	1.82	1.15		2.97	A300 - Modified Bituminous Sheet Waterproofing (071326). For this purpose, use Elastometric Sheet Waterproofing 07 13 53.10
01 42 23.70 0906	Scaffolding	-			C.S.F (hundred square f	$36			35.5	

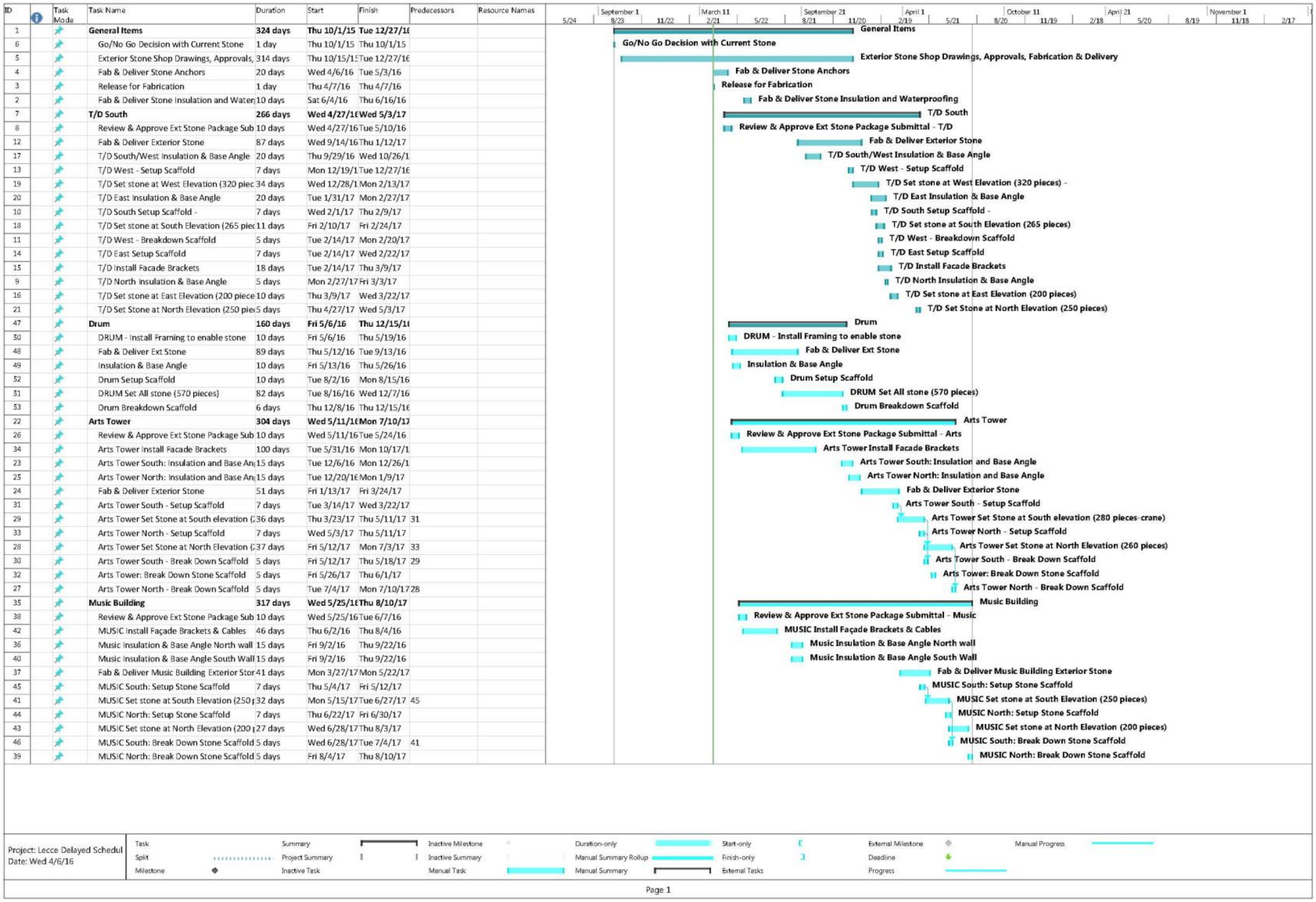


Lecce Limestone Cost Estimate

Item Description	*Qty.*	*Unit*	*Mat. $/Unit*	*Mat. Total*	*Labor $/Unit*	*Labor Total*	*Equip. $/Unit*	*Equip. Total*	*Grand Total*
PiMar Lecce Limestone Veneer	41636.82	SF	$37	$1,540,562.34	5.35	222756.987	$500,000	$500,000	**$2,263,319**
Mortar (Portland Cement)	1500	CF	9.4	14100	2.13	3195	0	0	**$17,295**
Insulation	41636	SF	0.67	27896.12	0.24	9992.64	0	0	**$37,889**
Waterproofing	41636	SF	1.82	75777.52	1.15	47881.4	0	0	**$123,659**
Hydraulic Scaffolding	4164	C.S.F	35.5	147822	0	0	$0	0	**$147,822**
Subtotal				**$1,806,158**		**$283,826.03**		$500,000	
Tax (6%)				$ 1,914,527.46				$ 530,000.00	$ -
Overhead and Profit (10%)				$ 191,452.75		$ 28,382.60		$ 53,000.00	$ -
Grand Total				**$ 2,105,980.20**		**$312,208.63**		$ 583,000.00	**$ 3,001,188.83**

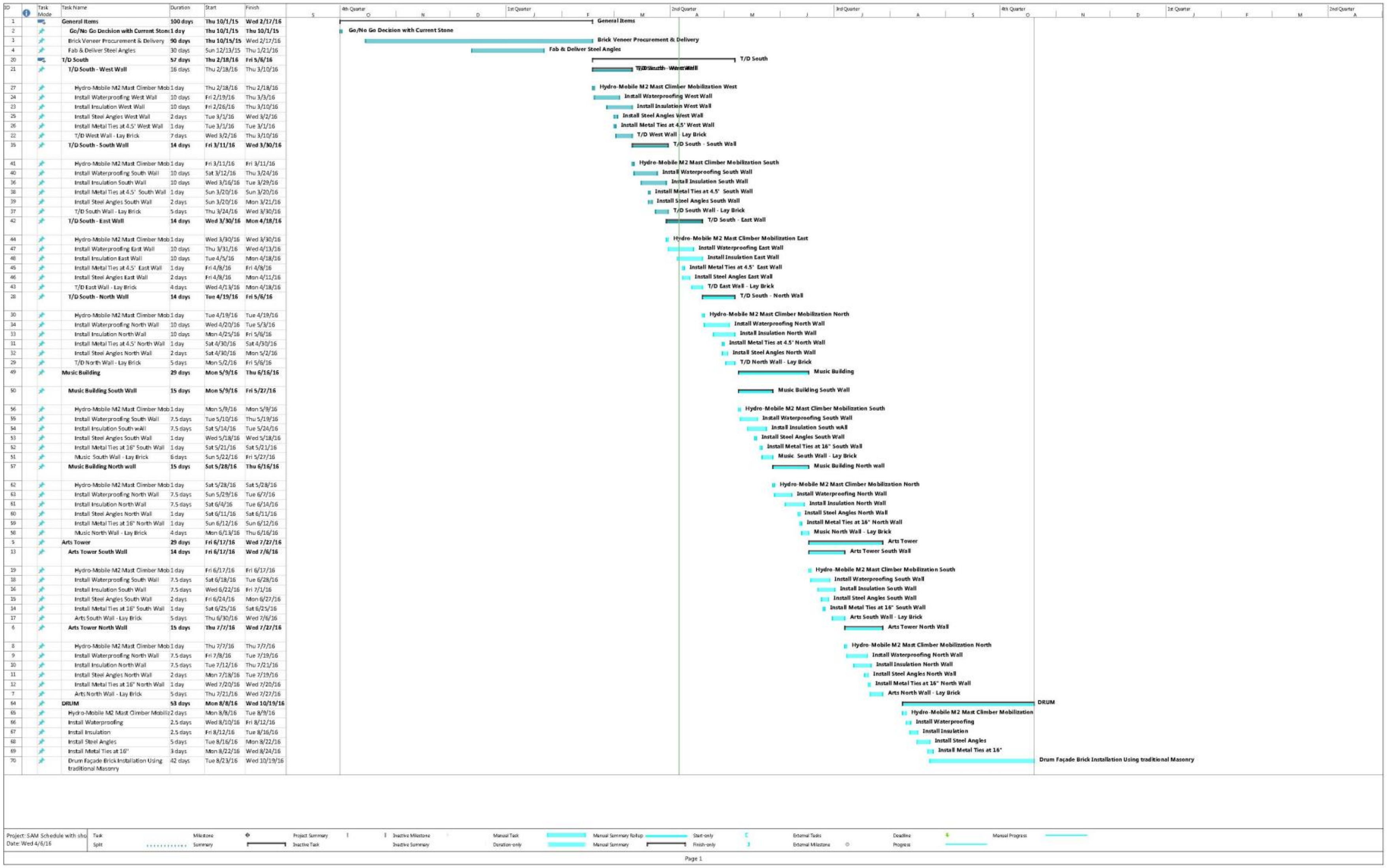
Appendix N: SAM Analysis Schedule Comparisons

Delayed Lecce Schedule



ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1		**General Items**	**324 days**	**Thu 10/1/15**	**Tue 12/27/1**		
6		Go/No Go Decision with Current Stone	1 day	Thu 10/1/15	Thu 10/1/15		
5		Exterior Stone Shop Drawings, Approvals,	314 days	Thu 10/15/1	Tue 12/27/1		
4		Fab & Deliver Stone Anchors	20 days	Wed 4/6/16	Tue 5/3/16		
3		Release for Fabrication	1 day	Thu 4/7/16	Thu 4/7/16		
2		Fab & Deliver Stone Insulation and Water	10 days	Sat 6/4/16	Thu 6/16/16		
7		**T/D South**	**266 days**	**Wed 4/27/1**	**Wed 5/3/17**		
8		Review & Approve Ext Stone Package Sub	10 days	Wed 4/27/16	Tue 5/10/16		
12		Fab & Deliver Exterior Stone	87 days	Wed 9/14/16	Thu 1/12/17		
17		T/D South/West Insulation & Base Angle	20 days	Thu 9/29/16	Wed 10/26/1		
13		T/D West - Setup Scaffold	7 days	Mon 12/19/1	Tue 12/27/1		
19		T/D Set stone at West Elevation (320 piec	34 days	Wed 12/28/1	Mon 2/13/17		
20		T/D East Insulation & Base Angle	20 days	Tue 1/31/17	Mon 2/27/17		
10		T/D South Setup Scaffold -	7 days	Wed 2/1/17	Thu 2/9/17		
18		T/D Set stone at South Elevation (265 piec	11 days	Fri 2/10/17	Fri 2/24/17		
11		T/D West - Breakdown Scaffold	5 days	Tue 2/14/17	Mon 2/20/17		
14		T/D East Setup Scaffold	7 days	Tue 2/14/17	Wed 2/22/17		
15		T/D Install Facade Brackets	18 days	Tue 2/14/17	Thu 3/9/17		
9		T/D North Insulation & Base Angle	5 days	Mon 2/27/17	Fri 3/3/17		
16		T/D Set stone at East Elevation (200 piece	10 days	Thu 3/9/17	Wed 3/22/17		
21		T/D Set Stone at North Elevation (250 pie	5 days	Thu 4/27/17	Wed 5/3/17		
47		**Drum**	**160 days**	**Fri 5/6/16**	**Thu 12/15/1**		
50		DRUM - Install Framing to enable stone	10 days	Fri 5/6/16	Thu 5/19/16		
48		Fab & Deliver Ext Stone	89 days	Thu 5/12/16	Tue 9/13/16		
49		Insulation & Base Angle	10 days	Fri 5/13/16	Thu 5/26/16		
52		Drum Setup Scaffold	10 days	Tue 8/2/16	Mon 8/15/16		
51		DRUM Set All stone (570 pieces)	82 days	Tue 8/16/16	Wed 12/7/16		
53		Drum Breakdown Scaffold	6 days	Thu 12/8/16	Thu 12/15/1		
22		**Arts Tower**	**304 days**	**Wed 5/11/1**	**Mon 7/10/17**		
26		Review & Approve Ext Stone Package Sub	10 days	Wed 5/11/16	Tue 5/24/16		
34		Arts Tower Install Facade Brackets	100 days	Tue 5/31/16	Mon 10/17/1		
23		Arts Tower South: Insulation and Base An	15 days	Tue 12/6/16	Mon 12/26/1		
25		Arts Tower North: Insulation and Base An	15 days	Tue 12/20/1	Mon 1/9/17		
24		Fab & Deliver Exterior Stone	51 days	Fri 1/13/17	Fri 3/24/17		
31		Arts Tower South - Setup Scaffold	7 days	Tue 3/14/17	Wed 3/22/17		
29		Arts Tower Set Stone at South elevation (	36 days	Thu 3/23/17	Thu 5/11/17	31	
33		Arts Tower North - Setup Scaffold	7 days	Wed 5/3/17	Thu 5/11/17		
28		Arts Tower Set Stone at North Elevation (	37 days	Fri 5/12/17	Mon 7/3/17	33	
30		Arts Tower South - Break Down Scaffold	5 days	Fri 5/12/17	Thu 5/18/17	29	
32		Arts Tower: Break Down Stone Scaffold	5 days	Fri 5/26/17	Thu 6/1/17		
27		Arts Tower North - Break Down Scaffold	5 days	Tue 7/4/17	Mon 7/10/17	28	
35		**Music Building**	**317 days**	**Wed 5/25/1**	**Thu 8/10/17**		
38		Review & Approve Ext Stone Package Sub	10 days	Wed 5/25/16	Tue 6/7/16		
42		MUSIC Install Façade Brackets & Cables	46 days	Thu 6/2/16	Thu 8/4/16		
36		Music Insulation & Base Angle North wall	15 days	Fri 9/2/16	Thu 9/22/16		
40		Music Insulation & Base Angle South Wall	15 days	Fri 9/2/16	Thu 9/22/16		
37		Fab & Deliver Music Building Exterior Stor	41 days	Mon 3/27/17	Mon 5/22/17		
45		MUSIC South: Setup Stone Scaffold	7 days	Thu 5/4/17	Fri 5/12/17		
41		MUSIC Set stone at South Elevation (250 p	32 days	Mon 5/15/17	Tue 6/27/17	45	
44		MUSIC North: Setup Stone Scaffold	7 days	Thu 6/22/17	Fri 6/30/17		
43		MUSIC Set stone at North Elevation (200 p	27 days	Wed 6/28/17	Thu 8/3/17		
46		MUSIC South: Break Down Stone Scaffold	5 days	Wed 6/28/17	Tue 7/4/17	41	
39		MUSIC North: Break Down Stone Scaffold	5 days	Fri 8/4/17	Thu 8/10/17		

SAM 90 day procurement

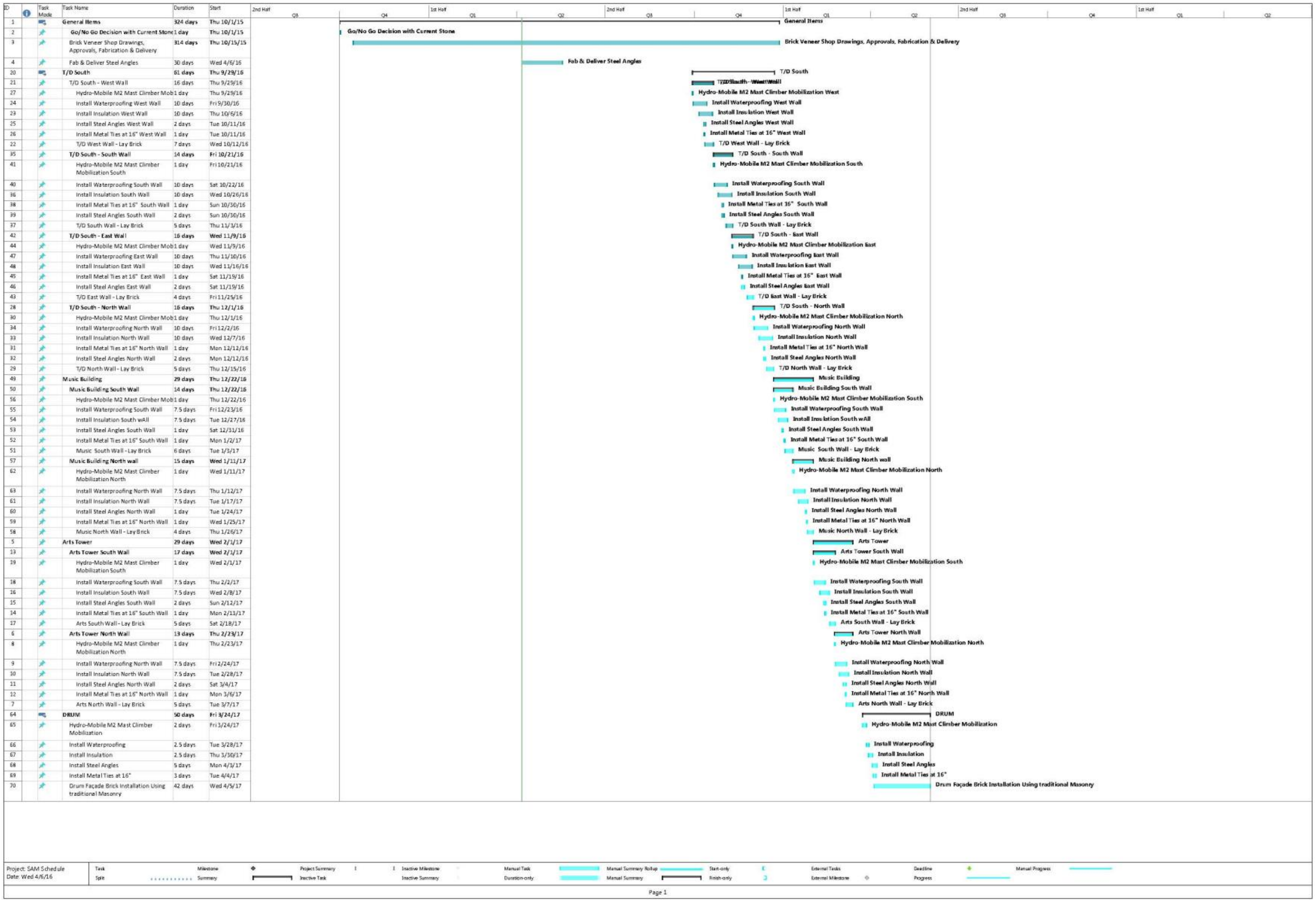


ID	Task Mode	Task Name	Duration	Start	Finish
1		**General Items**	**100 days**	**Thu 10/1/15**	**Wed 2/17/16**
2		**Go/No Go Decision with Current Stone**	**1 day**	**Thu 10/1/15**	**Thu 10/1/15**
3		Brick Veneer Procurement & Delivery	**90 days**	**Thu 10/15/15**	Wed 2/17/16
4		Fab & Deliver Steel Angles	30 days	Sun 12/13/15	Thu 1/21/16
20		**T/D South**	**57 days**	**Thu 2/18/16**	**Fri 5/6/16**
21		**T/D South - West Wall**	16 days	Thu 2/18/16	Thu 3/10/16
27		Hydro-Mobile M2 Mast Climber Mob	1 day	Thu 2/18/16	Thu 2/18/16
24		Install Waterproofing West Wall	10 days	Fri 2/19/16	Thu 3/3/16
23		Install Insulation West Wall	10 days	Fri 2/26/16	Thu 3/10/16
25		Install Steel Angles West Wall	2 days	Tue 3/1/16	Wed 3/2/16
26		Install Metal Ties at 4.5' West Wall	1 day	Tue 3/1/16	Tue 3/1/16
22		T/D West Wall - Lay Brick	7 days	Wed 3/2/16	Thu 3/10/16
35		**T/D South - South Wall**	**14 days**	**Fri 3/11/16**	**Wed 3/30/16**
41		Hydro-Mobile M2 Mast Climber Mob	1 day	Fri 3/11/16	Fri 3/11/16
40		Install Waterproofing South Wall	10 days	Sat 3/12/16	Thu 3/24/16
36		Install Insulation South Wall	10 days	Wed 3/16/16	Tue 3/29/16
38		Install Metal Ties at 4.5' South Wall	1 day	Sun 3/20/16	Sun 3/20/16
39		Install Steel Angles South Wall	2 days	Sun 3/20/16	Mon 3/21/16
37		T/D South Wall - Lay Brick	5 days	Thu 3/24/16	Wed 3/30/16
42		**T/D South - East Wall**	**14 days**	**Wed 3/30/16**	**Mon 4/18/16**
44		Hydro-Mobile M2 Mast Climber Mob	1 day	Wed 3/30/16	Wed 3/30/16
47		Install Waterproofing East Wall	10 days	Thu 3/31/16	Wed 4/13/16
48		Install Insulation East Wall	10 days	Tue 4/5/16	Mon 4/18/16
45		Install Metal Ties at 4.5' East Wall	1 day	Fri 4/8/16	Fri 4/8/16
46		Install Steel Angles East Wall	2 days	Fri 4/8/16	Mon 4/11/16
43		T/D East Wall - Lay Brick	4 days	Wed 4/13/16	Mon 4/18/16
28		**T/D South - North Wall**	**14 days**	**Tue 4/19/16**	**Fri 5/6/16**
30		Hydro-Mobile M2 Mast Climber Mob	1 day	Tue 4/19/16	Tue 4/19/16
34		Install Waterproofing North Wall	10 days	Wed 4/20/16	Tue 5/3/16
33		Install Insulation North Wall	10 days	Mon 4/25/16	Fri 5/6/16
31		Install Metal Ties at 4.5' North Wall	1 day	Sat 4/30/16	Sat 4/30/16
32		Install Steel Angles North Wall	2 days	Sat 4/30/16	Mon 5/2/16
29		T/D North Wall - Lay Brick	5 days	Mon 5/2/16	Fri 5/6/16
49		**Music Building**	**29 days**	**Mon 5/9/16**	**Thu 6/16/16**
50		**Music Building South Wall**	**15 days**	**Mon 5/9/16**	**Fri 5/27/16**
56		Hydro-Mobile M2 Mast Climber Mob	1 day	Mon 5/9/16	Mon 5/9/16
55		Install Waterproofing South Wall	7.5 days	Tue 5/10/16	Thu 5/19/16
54		Install Insulation South wAll	7.5 days	Sat 5/14/16	Tue 5/24/16
53		Install Steel Angles South Wall	1 day	Wed 5/18/16	Wed 5/18/16
52		Install Metal Ties at 16" South Wall	1 day	Sat 5/21/16	Sat 5/21/16
51		Music South Wall - Lay Brick	6 days	Sun 5/22/16	Fri 5/27/16
57		**Music Building North wall**	**15 days**	**Sat 5/28/16**	**Thu 6/16/16**
62		Hydro-Mobile M2 Mast Climber Mob	1 day	Sat 5/28/16	Sat 5/28/16
63		Install Waterproofing North Wall	7.5 days	Sun 5/29/16	Tue 6/7/16
61		Install Insulation North Wall	7.5 days	Sat 6/4/16	Tue 6/14/16
60		Install Steel Angles North Wall	1 day	Sat 6/11/16	Sat 6/11/16
59		Install Metal Ties at 16" North Wall	1 day	Sun 6/12/16	Sun 6/12/16
58		Music North Wall - Lay Brick	4 days	Mon 6/13/16	Thu 6/16/16
5		**Arts Tower**	**29 days**	**Fri 6/17/16**	**Wed 7/27/16**
13		**Arts Tower South Wall**	**14 days**	**Fri 6/17/16**	**Wed 7/6/16**
19		Hydro-Mobile M2 Mast Climber Mob	1 day	Fri 6/17/16	Fri 6/17/16
18		Install Waterproofing South Wall	7.5 days	Sat 6/18/16	Tue 6/28/16
16		Install Insulation South Wall	7.5 days	Wed 6/22/16	Fri 7/1/16
15		Install Steel Angles South Wall	2 days	Fri 6/24/16	Mon 6/27/16
14		Install Metal Ties at 16" South Wall	1 day	Sat 6/25/16	Sat 6/25/16
17		Arts South Wall - Lay Brick	5 days	Thu 6/30/16	Wed 7/6/16
6		**Arts Tower North Wall**	**15 days**	**Thu 7/7/16**	**Wed 7/27/16**
8		Hydro-Mobile M2 Mast Climber Mob	1 day	Thu 7/7/16	Thu 7/7/16
9		Install Waterproofing North Wall	7.5 days	Fri 7/8/16	Tue 7/19/16
10		Install Insulation North Wall	7.5 days	Tue 7/12/16	Thu 7/21/16
11		Install Steel Angles North Wall	2 days	Mon 7/18/16	Tue 7/19/16
12		Install Metal Ties at 16" North Wall	1 day	Wed 7/20/16	Wed 7/20/16
7		Arts North Wall - Lay Brick	5 days	Thu 7/21/16	Wed 7/27/16
64		**DRUM**	**53 days**	**Mon 8/8/16**	**Wed 10/19/16**
65		Hydro-Mobile M2 Mast Climber Mobiliz	2 days	Mon 8/8/16	Tue 8/9/16
66		Install Waterproofing	2.5 days	Wed 8/10/16	Fri 8/12/16
67		Install Insulation	2.5 days	Fri 8/12/16	Tue 8/16/16
68		Install Steel Angles	5 days	Tue 8/16/16	Mon 8/22/16
69		Install Metal Ties at 16"	3 days	Mon 8/22/16	Wed 8/24/16
70		Drum Façade Brick Installation Using traditional Masonry	42 days	Tue 8/23/16	Wed 10/19/16

Project: SAM Schedule with sho
Date: Wed 4/6/16

Page 1

SAM 314 day procurement

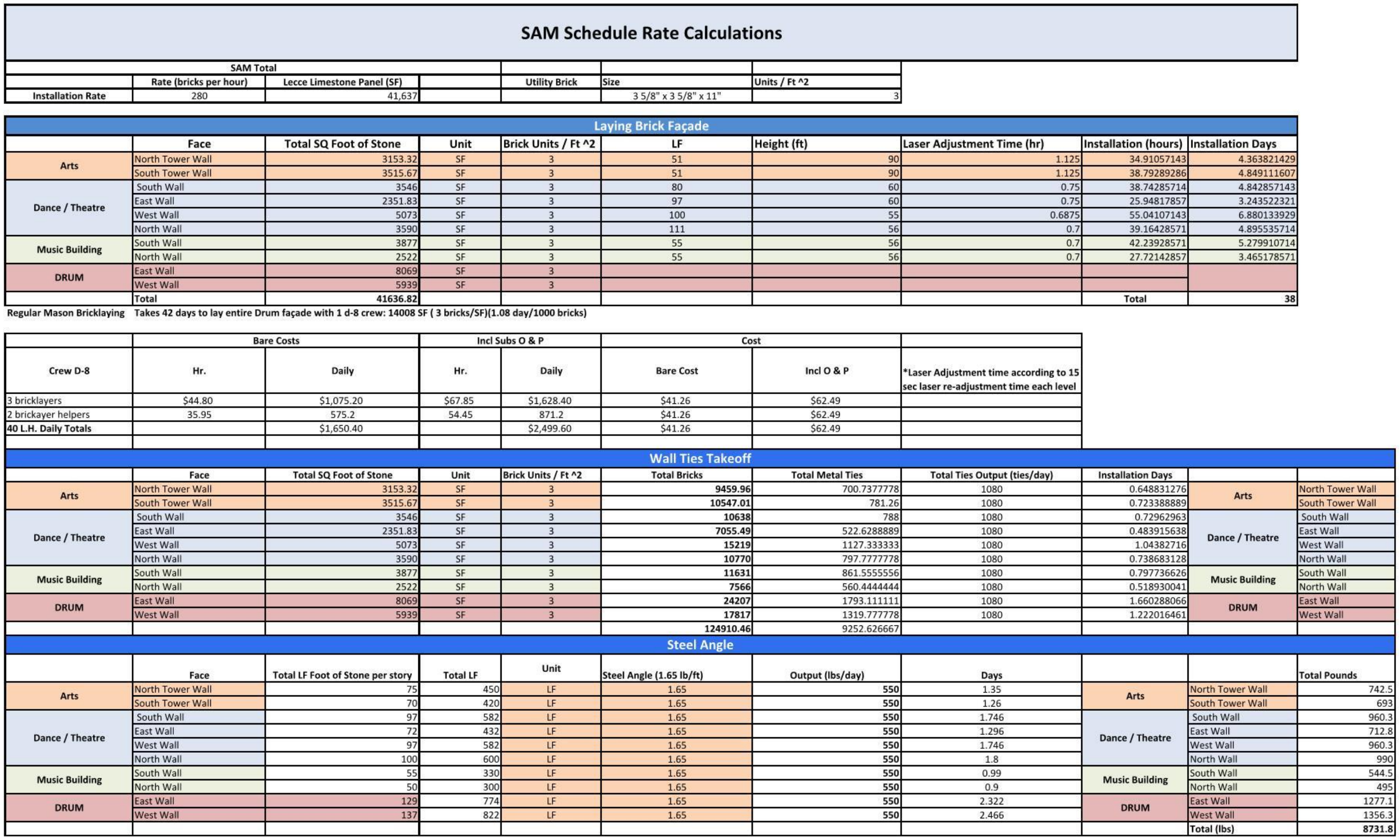


ID		Task Mode	Task Name	Duration	Start
1			**General Items**	**324 days**	**Thu 10/1/15**
2			**Go/No Go Decision with Current Stone**	**1 day**	**Thu 10/1/15**
3			Brick Veneer Shop Drawings, Approvals, Fabrication & Delivery	**314 days**	**Thu 10/15/15**
4			Fab & Deliver Steel Angles	30 days	Wed 4/6/16
20			**T/D South**	**61 days**	**Thu 9/29/16**
21			T/D South - West Wall	16 days	Thu 9/29/16
27			Hydro-Mobile M2 Mast Climber Mob	1 day	Thu 9/29/16
24			Install Waterproofing West Wall	10 days	Fri 9/30/16
23			Install Insulation West Wall	10 days	Thu 10/6/16
25			Install Steel Angles West Wall	2 days	Tue 10/11/16
26			Install Metal Ties at 16" West Wall	1 day	Tue 10/11/16
22			T/D West Wall - Lay Brick	7 days	Wed 10/12/16
35			**T/D South - South Wall**	**14 days**	**Fri 10/21/16**
41			Hydro-Mobile M2 Mast Climber Mobilization South	1 day	Fri 10/21/16
40			Install Waterproofing South Wall	10 days	Sat 10/22/16
36			Install Insulation South Wall	10 days	Wed 10/26/16
38			Install Metal Ties at 16" South Wall	1 day	Sun 10/30/16
39			Install Steel Angles South Wall	2 days	Sun 10/30/16
37			T/D South Wall - Lay Brick	5 days	Thu 11/3/16
42			**T/D South - East Wall**	**16 days**	**Wed 11/9/16**
44			Hydro-Mobile M2 Mast Climber Mob	1 day	Wed 11/9/16
47			Install Waterproofing East Wall	10 days	Thu 11/10/16
48			Install Insulation East Wall	10 days	Wed 11/16/16
45			Install Metal Ties at 16" East Wall	1 day	Sat 11/19/16
46			Install Steel Angles East Wall	2 days	Sat 11/19/16
43			T/D East Wall - Lay Brick	4 days	Fri 11/25/16
28			**T/D South - North Wall**	**16 days**	**Thu 12/1/16**
30			Hydro-Mobile M2 Mast Climber Mob	1 day	Thu 12/1/16
34			Install Waterproofing North Wall	10 days	Fri 12/2/16
33			Install Insulation North Wall	10 days	Wed 12/7/16
31			Install Metal Ties at 16" North Wall	1 day	Mon 12/12/16
32			Install Steel Angles North Wall	2 days	Mon 12/12/16
29			T/D North Wall - Lay Brick	5 days	Thu 12/15/16
49			**Music Building**	**29 days**	**Thu 12/22/16**
50			**Music Building South Wall**	**14 days**	**Thu 12/22/16**
56			Hydro-Mobile M2 Mast Climber Mob	1 day	Thu 12/22/16
55			Install Waterproofing South Wall	7.5 days	Fri 12/23/16
54			Install Insulation South wAll	7.5 days	Tue 12/27/16
53			Install Steel Angles South Wall	1 day	Sat 12/31/16
52			Install Metal Ties at 16" South Wall	1 day	Mon 1/2/17
51			Music South Wall - Lay Brick	6 days	Tue 1/3/17
57			**Music Building North wall**	**15 days**	**Wed 1/11/17**
62			Hydro-Mobile M2 Mast Climber Mobilization North	1 day	Wed 1/11/17
63			Install Waterproofing North Wall	7.5 days	Thu 1/12/17
61			Install Insulation North Wall	7.5 days	Tue 1/17/17
60			Install Steel Angles North Wall	1 day	Tue 1/24/17
59			Install Metal Ties at 16" North Wall	1 day	Wed 1/25/17
58			Music North Wall - Lay Brick	4 days	Thu 1/26/17
5			**Arts Tower**	**29 days**	**Wed 2/1/17**
13			**Arts Tower South Wall**	**17 days**	**Wed 2/1/17**
19			Hydro-Mobile M2 Mast Climber Mobilization South	1 day	Wed 2/1/17
18			Install Waterproofing South Wall	7.5 days	Thu 2/2/17
16			Install Insulation South Wall	7.5 days	Wed 2/8/17
15			Install Steel Angles South Wall	2 days	Sun 2/12/17
14			Install Metal Ties at 16" South Wall	1 day	Mon 2/13/17
17			Arts South Wall - Lay Brick	5 days	Sat 2/18/17
6			**Arts Tower North Wall**	**13 days**	**Thu 2/23/17**
8			Hydro-Mobile M2 Mast Climber Mobilization North	1 day	Thu 2/23/17
9			Install Waterproofing North Wall	7.5 days	Fri 2/24/17
10			Install Insulation North Wall	7.5 days	Tue 2/28/17
11			Install Steel Angles North Wall	2 days	Sat 3/4/17
12			Install Metal Ties at 16" North Wall	1 day	Mon 3/6/17
7			Arts North Wall - Lay Brick	5 days	Tue 3/7/17
64			**DRUM**	**50 days**	**Fri 3/24/17**
65			Hydro-Mobile M2 Mast Climber Mobilization	2 days	Fri 3/24/17
66			Install Waterproofing	2.5 days	Tue 3/28/17
67			Install Insulation	2.5 days	Thu 3/30/17
68			Install Steel Angles	5 days	Mon 4/3/17
69			Install Metal Ties at 16"	3 days	Tue 4/4/17
70			Drum Façade Brick Installation Using traditional Masonry	42 days	Wed 4/5/17

Project: SAM Schedule
Date: Wed 4/6/16

Page 1

Appendix O: SAM Schedule Rates & Calculations



SAM Schedule Rate Calculations

	SAM Total					
	Rate (bricks per hour)	Lecce Limestone Panel (SF)		Utility Brick	Size	Units / Ft ^2
Installation Rate	280	41,637			3 5/8" x 3 5/8" x 11"	3

Laying Brick Façade

	Face	Total SQ Foot of Stone	Unit	Brick Units / Ft ^2	LF	Height (ft)	Laser Adjustment Time (hr)	Installation (hours)	Installation Days
Arts	North Tower Wall	3153.32	SF	3	51	90	1.125	34.91057143	4.363821429
	South Tower Wall	3515.67	SF	3	51	90	1.125	38.79289286	4.849111607
Dance / Theatre	South Wall	3546	SF	3	80	60	0.75	38.74285714	4.842857143
	East Wall	2351.83	SF	3	97	60	0.75	25.94817857	3.243522321
	West Wall	5073	SF	3	100	55	0.6875	55.04107143	6.880133929
	North Wall	3590	SF	3	111	56	0.7	39.16428571	4.895535714
Music Building	South Wall	3877	SF	3	55	56	0.7	42.23928571	5.279910714
	North Wall	2522	SF	3	55	56	0.7	27.72142857	3.465178571
DRUM	East Wall	8069	SF	3					
	West Wall	5939	SF	3					
	Total	41636.82						Total	38

Regular Mason Bricklaying **Takes 42 days to lay entire Drum façade with 1 d-8 crew: 14008 SF (3 bricks/SF)(1.08 day/1000 bricks)**

	Bare Costs		Incl Subs O & P		Cost		
Crew D-8	Hr.	Daily	Hr.	Daily	Bare Cost	Incl O & P	*Laser Adjustment time according to 15 sec laser re-adjustment time each level
3 bricklayers	$44.80	$1,075.20	$67.85	$1,628.40	$41.26	$62.49	
2 brickayer helpers	35.95	575.2	54.45	871.2	$41.26	$62.49	
40 L.H. Daily Totals		$1,650.40		$2,499.60	$41.26	$62.49	

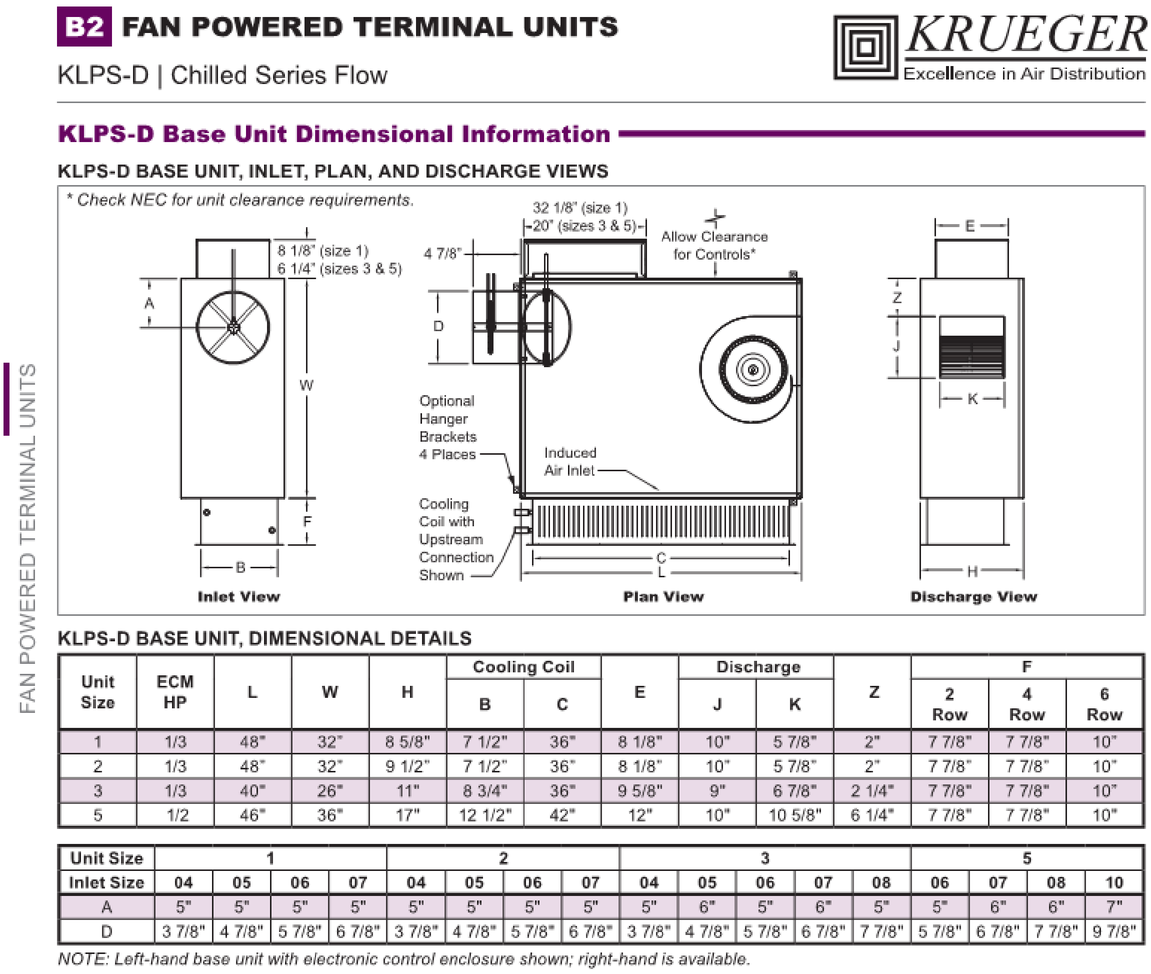
Wall Ties Takeoff

	Face	Total SQ Foot of Stone	Unit	Brick Units / Ft ^2	Total Bricks	Total Metal Ties	Total Ties Output (ties/day)	Installation Days		
Arts	North Tower Wall	3153.32	SF	3	**9459.96**	700.7377778	1080	0.648831276	Arts	North Tower Wall
	South Tower Wall	3515.67	SF	3	**10547.01**	781.26	1080	0.723388889		South Tower Wall
Dance / Theatre	South Wall	3546	SF	3	**10638**	788	1080	0.72962963	Dance / Theatre	South Wall
	East Wall	2351.83	SF	3	**7055.49**	522.6288889	1080	0.483915638		East Wall
	West Wall	5073	SF	3	**15219**	1127.333333	1080	1.04382716		West Wall
	North Wall	3590	SF	3	**10770**	797.7777778	1080	0.738683128		North Wall
Music Building	South Wall	3877	SF	3	**11631**	861.5555556	1080	0.797736626	Music Building	South Wall
	North Wall	2522	SF	3	**7566**	560.4444444	1080	0.518930041		North Wall
DRUM	East Wall	8069	SF	3	**24207**	1793.111111	1080	1.660288066	DRUM	East Wall
	West Wall	5939	SF	3	**17817**	1319.777778	1080	1.222016461		West Wall
					124910.46	9252.626667				

Steel Angle

	Face	Total LF Foot of Stone per story	Total LF	Unit	Steel Angle (1.65 lb/ft)	Output (lbs/day)	Days			Total Pounds
Arts	North Tower Wall	75	450	LF	1.65	**550**	1.35	Arts	North Tower Wall	742.5
	South Tower Wall	70	420	LF	1.65	**550**	1.26		South Tower Wall	693
Dance / Theatre	South Wall	97	582	LF	1.65	**550**	1.746	Dance / Theatre	South Wall	960.3
	East Wall	72	432	LF	1.65	**550**	1.296		East Wall	712.8
	West Wall	97	582	LF	1.65	**550**	1.746		West Wall	960.3
	North Wall	100	600	LF	1.65	**550**	1.8		North Wall	990
Music Building	South Wall	55	330	LF	1.65	**550**	0.99	Music Building	South Wall	544.5
	North Wall	50	300	LF	1.65	**550**	0.9		North Wall	495
DRUM	East Wall	129	774	LF	1.65	**550**	2.322	DRUM	East Wall	1277.1
	West Wall	137	822	LF	1.65	**550**	2.466		West Wall	1356.3
									Total (lbs)	**8731.8**

Appendix P: Krueger KLPS-D Fan Powered Induction Unit: Product Specifications & Discharge Sound Data



B2 FAN POWERED TERMINAL UNITS

KLPS-D | Chilled Series Flow

KRUEGER
Excellence in Air Distribution

FAN POWERED TERMINAL UNITS

KLPS-D Base Unit Dimensional Information

KLPS-D BASE UNIT, INLET, PLAN, AND DISCHARGE VIEWS

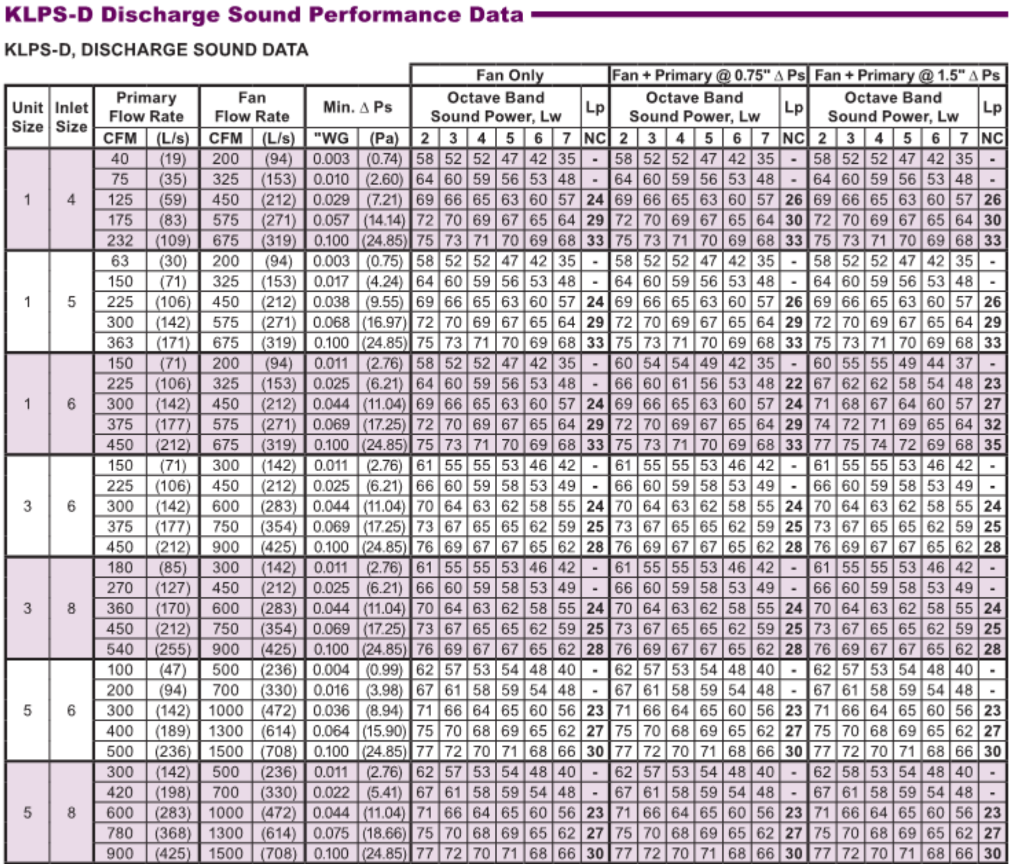
** Check NEC for unit clearance requirements.*

KLPS-D BASE UNIT, DIMENSIONAL DETAILS

Unit Size	ECM HP	L	W	H	Cooling Coil		E	Discharge		Z	F		
					B	C		J	K		2 Row	4 Row	6 Row
1	1/3	48"	32"	8 5/8"	7 1/2"	36"	8 1/8"	10"	5 7/8"	2"	7 7/8"	7 7/8"	10"
2	1/3	48"	32"	9 1/2"	7 1/2"	36"	8 1/8"	10"	5 7/8"	2"	7 7/8"	7 7/8"	10"
3	1/3	40"	26"	11"	8 3/4"	36"	9 5/8"	9"	6 7/8"	2 1/4"	7 7/8"	7 7/8"	10"
5	1/2	46"	36"	17"	12 1/2"	42"	12"	10"	10 5/8"	6 1/4"	7 7/8"	7 7/8"	10"

Unit Size	1				2				3					5			
Inlet Size	04	05	06	07	04	05	06	07	04	05	06	07	08	06	07	08	10
A	5"	5"	5"	5"	5"	5"	5"	5"	5"	6"	5"	6"	5"	5"	6"	6"	7"
D	3 7/8"	4 7/8"	5 7/8"	6 7/8"	3 7/8"	4 7/8"	5 7/8"	6 7/8"	3 7/8"	4 7/8"	5 7/8"	6 7/8"	7 7/8"	5 7/8"	6 7/8"	7 7/8"	9 7/8"

NOTE: Left-hand base unit with electronic control enclosure shown; right-hand is available.



KLPS-D Discharge Sound Performance Data

KLPS-D, DISCHARGE SOUND DATA

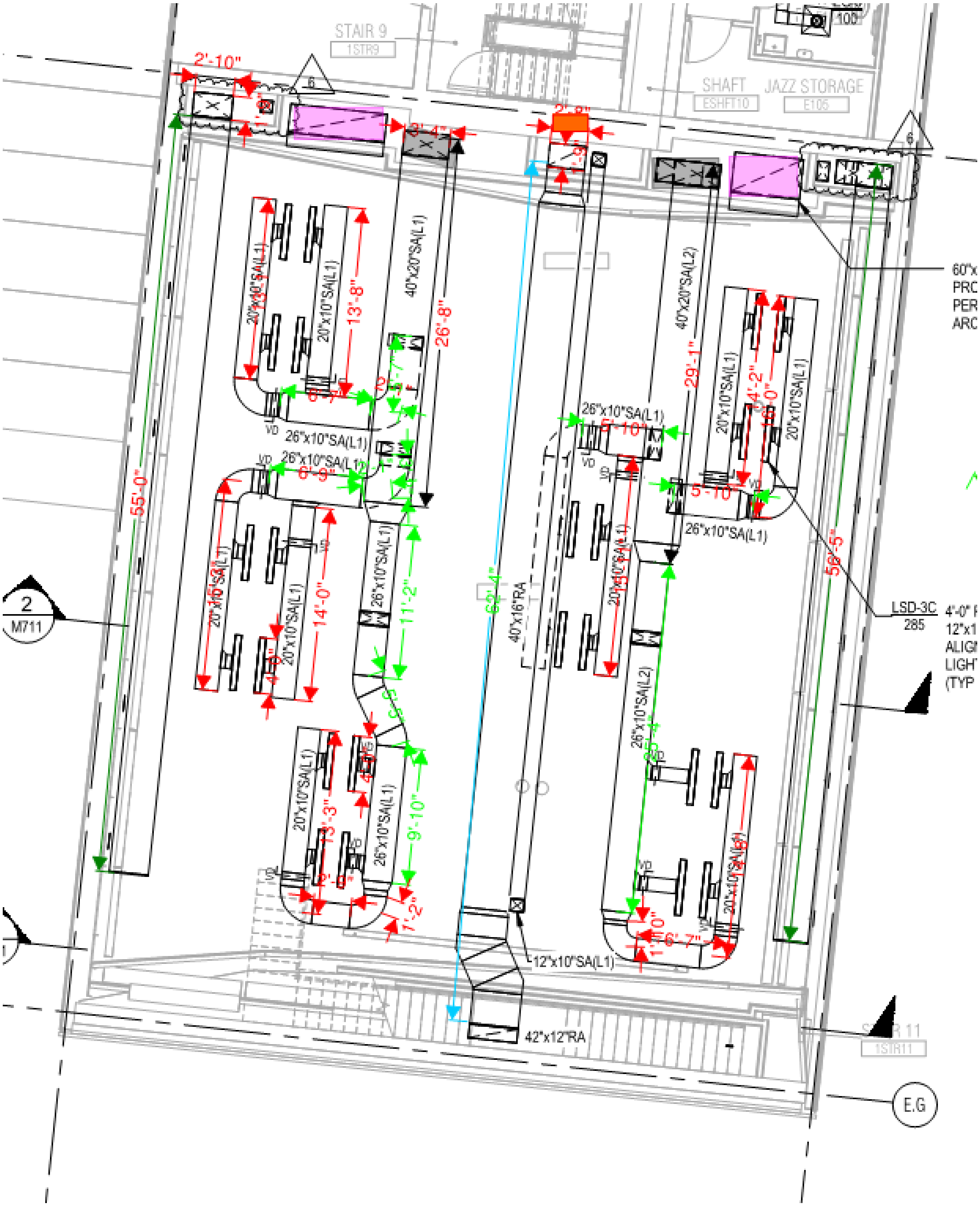
								Fan Only							Fan + Primary @ 0.75" Δ Ps							Fan + Primary @ 1.5" Δ Ps						
Unit Size	Inlet Size	Primary Flow Rate		Fan Flow Rate		Min. Δ Ps		Octave Band Sound Power, Lw						Lp	Octave Band Sound Power, Lw						Lp	Octave Band Sound Power, Lw						Lp
		CFM	(L/s)	CFM	(L/s)	"WG	(Pa)	2	3	4	5	6	7	NC	2	3	4	5	6	7	NC	2	3	4	5	6	7	NC
1	4	40	(19)	200	(94)	0.003	(0.74)	58	52	52	47	42	35	**-**	58	52	52	47	42	35	**-**	58	52	52	47	42	35	**-**
		75	(35)	325	(153)	0.010	(2.60)	64	60	59	56	53	48	**-**	64	60	59	56	53	48	**-**	64	60	59	56	53	48	**-**
		125	(59)	450	(212)	0.029	(7.21)	69	66	65	63	60	57	**24**	69	66	65	63	60	57	**26**	69	66	65	63	60	57	**26**
		175	(83)	575	(271)	0.057	(14.14)	72	70	69	67	65	64	**29**	72	70	69	67	65	64	**30**	72	70	69	67	65	64	**30**
		232	(109)	675	(319)	0.100	(24.85)	75	73	71	70	69	68	**33**	75	73	71	70	69	68	**33**	75	73	71	70	69	68	**33**
1	5	63	(30)	200	(94)	0.003	(0.75)	58	52	52	47	42	35	**-**	58	52	52	47	42	35	**-**	58	52	52	47	42	35	**-**
		150	(71)	325	(153)	0.017	(4.24)	64	60	59	56	53	48	**-**	64	60	59	56	53	48	**-**	64	60	59	56	53	48	**-**
		225	(106)	450	(212)	0.038	(9.55)	69	66	65	63	60	57	**24**	69	66	65	63	60	57	**26**	69	66	65	63	60	57	**26**
		300	(142)	575	(271)	0.068	(16.97)	72	70	69	67	65	64	**29**	72	70	69	67	65	64	**29**	72	70	69	67	65	64	**29**
		363	(171)	675	(319)	0.100	(24.85)	75	73	71	70	69	68	**33**	75	73	71	70	69	68	**33**	75	73	71	70	69	68	**33**
1	6	150	(71)	200	(94)	0.011	(2.76)	58	52	52	47	42	35	**-**	60	54	54	49	42	35	**-**	60	55	55	49	44	37	**-**
		225	(106)	325	(153)	0.025	(6.21)	64	60	59	56	53	48	**-**	66	60	61	56	53	48	**22**	67	62	62	58	54	48	**23**
		300	(142)	450	(212)	0.044	(11.04)	69	66	65	63	60	57	**24**	69	66	65	63	60	57	**24**	71	68	67	64	60	57	**27**
		375	(177)	575	(271)	0.069	(17.25)	72	70	69	67	65	64	**29**	72	70	69	67	65	64	**29**	74	72	71	69	65	64	**32**
		450	(212)	675	(319)	0.100	(24.85)	75	73	71	70	69	68	**33**	75	73	71	70	69	68	**33**	77	75	74	72	69	68	**35**
3	6	150	(71)	300	(142)	0.011	(2.76)	61	55	55	53	46	42	**-**	61	55	55	53	46	42	**-**	61	55	55	53	46	42	**-**
		225	(106)	450	(212)	0.025	(6.21)	66	60	59	58	53	49	**-**	66	60	59	58	53	49	**-**	66	60	59	58	53	49	**-**
		300	(142)	600	(283)	0.044	(11.04)	70	64	63	62	58	55	**24**	70	64	63	62	58	55	**24**	70	64	63	62	58	55	**24**
		375	(177)	750	(354)	0.069	(17.25)	73	67	65	65	62	59	**25**	73	67	65	65	62	59	**25**	73	67	65	65	62	59	**25**
		450	(212)	900	(425)	0.100	(24.85)	76	69	67	67	65	62	**28**	76	69	67	67	65	62	**28**	76	69	67	67	65	62	**28**
3	8	180	(85)	300	(142)	0.011	(2.76)	61	55	55	53	46	42	**-**	61	55	55	53	46	42	**-**	61	55	55	53	46	42	**-**
		270	(127)	450	(212)	0.025	(6.21)	66	60	59	58	53	49	**-**	66	60	59	58	53	49	**-**	66	60	59	58	53	49	**-**
		360	(170)	600	(283)	0.044	(11.04)	70	64	63	62	58	55	**24**	70	64	63	62	58	55	**24**	70	64	63	62	58	55	**24**
		450	(212)	750	(354)	0.069	(17.25)	73	67	65	65	62	59	**25**	73	67	65	65	62	59	**25**	73	67	65	65	62	59	**25**
		540	(255)	900	(425)	0.100	(24.85)	76	69	67	67	65	62	**28**	76	69	67	67	65	62	**28**	76	69	67	67	65	62	**28**
5	6	100	(47)	500	(236)	0.004	(0.99)	62	57	53	54	48	40	**-**	62	57	53	54	48	40	**-**	62	57	53	54	48	40	**-**
		200	(94)	700	(330)	0.016	(3.98)	67	61	58	59	54	48	**-**	67	61	58	59	54	48	**-**	67	61	58	59	54	48	**-**
		300	(142)	1000	(472)	0.036	(8.94)	71	66	64	65	60	56	**23**	71	66	64	65	60	56	**23**	71	66	64	65	60	56	**23**
		400	(189)	1300	(614)	0.064	(15.90)	75	70	68	69	65	62	**27**	75	70	68	69	65	62	**27**	75	70	68	69	65	62	**27**
		500	(236)	1500	(708)	0.100	(24.85)	77	72	70	71	68	66	**30**	77	72	70	71	68	66	**30**	77	72	70	71	68	66	**30**
5	8	300	(142)	500	(236)	0.011	(2.76)	62	57	53	54	48	40	**-**	62	57	53	54	48	40	**-**	62	58	53	54	48	40	**-**
		420	(198)	700	(330)	0.022	(5.41)	67	61	58	59	54	48	**-**	67	61	58	59	54	48	**-**	67	61	58	59	54	48	**-**
		600	(283)	1000	(472)	0.044	(11.04)	71	66	64	65	60	56	**23**	71	66	64	65	60	56	**23**	71	66	64	65	60	56	**23**
		780	(368)	1300	(614)	0.075	(18.66)	75	70	68	69	65	62	**27**	75	70	68	69	65	62	**27**	75	70	68	69	65	62	**27**
		900	(425)	1500	(708)	0.100	(24.85)	77	72	70	71	68	66	**30**	77	72	70	71	68	66	**30**	77	72	70	71	68	66	**30**

Appendix Q: HVAC Duct Takeoff & Estimate Calculations

Instrument Rehearsal Room

	Duct Dimensions	Metal Gage	Sum 2-Sides	Weight per LF	Length (ft)	Weight (lbs)	Wt.-Lb/SF	SF
🟥	20"x10"	24	30	6.5	142.5	926.25	1.156	801.2543
🟩	26" x 10"	22	36	9	96.1	864.9	1.156	748.1834
🟦	40" x 16"	20	56	16.2	62	1004.4	1.156	868.8581
⬛	40" x 20"	20	60	17.4	140	2436	1.156	2107.266
🟪	42" x 12"	22	54	13.5	17	229.5	1.156	198.5294
⬜	12" x 10"	24	22	4.7	5.166	24.2802	1.156	21.00363
🟨	32 " x 21"	22	53	13.3	42	558.6	1.156	483.218
🟩	34" x 21"	20	55	16	200	3200	1.156	2768.166
🟪	38" x 24"	20	62	18	57	1026	1.156	887.5433
Total					**761.766**	**10269.9302**	**Total SF**	**8884.02**

	Total lbs:	**10269.9302**
	Total LF:	**761.766**
	Total SF:	**8884.02266**
	Supply SF:	**5922.68178**
FPIU Sheetmetal	**Total lbs:**	3423.310067
	Total LF:	253.922
	Total SF:	2961.340888
	Supply SF:	1974.227259


STAIR 9
1STR9
SHAFT
ESHFT10
JAZZ STORAGE
E105
100
6
6
2'-10"
1'-3"
2'-8"
3'-4"
1'-9"
55'-0"
56'-5"
62'-4"
26'-8"
29'-1"
13'-8"
13'-3"
14'-0"
4'-6"
11'-2"
9'-10"
6'-7"
6'-9"
5'-10"
14'-2"
15'-0"
25'-4"
1'-2"
1'-10"
6'-7"
2'-0"
40"x20"SA(L1)
40"x20"SA(L2)
20"x10"SA(L1)
26"x10"SA(L1)
26"x10"SA(L2)
40"x16"RA
42"x12"RA
12"x10"SA(L1)
VD
2
M711
60"x
PRC
PER
ARC
LSD-3C
285
4'-0" F
12"x1
ALIGI
LIGHT
(TYP
E.G
1STR11

BIBLIOGRAPHY

"3D Printer Linear Motion Systems." Dabbletron. N.p., n.d. Web. 01 Apr. 2016. <http://dabbletron.com/3d-printer-linear-motion-systems/>.

Beck, Henry C., 111. "What The AEC Industry Can Learn from Steve Jobs, Master of the Interface." Construction, Building & Engineering News: ENR. Engineering News-Record, 15 May 2013. Web. 23 Oct. 2014.

Behrokh Khoshnevis, Automated construction by contour crafting—related robotics and information technologies, Automation in Construction, Volume 13, Issue 1, January 2004, Pages 5-19, ISSN 0926-5805, http://dx.doi.org/10.1016/j.autcon.2003.08.012. (http://www.sciencedirect.com/science/article/pii/S0926580503000736) Keywords: Contour crafting; Housing construction; Construction information technology; Construction on other planets

"BNIM." BNIM. N.p., n.d. Web. 11 Nov. 2015. Collaboration.Http://www.collaborativemodeling.com/. Collaborative Modeling Ltd., n.d. Web. 11 Nov. 2015.

"Commonly Used Statistics." Occupational Safety and Health Administration. United States Department of Labor, n.d. Web. 18 Dec. 2015.

"Construction Robotics - Advancing Construction | Home of the Semi-Automated Mason." Construction Robotics. Construction Robotics, n.d. Web. 31 Mar. 2016.

Curtis, Paul. "Masonry Anchors and Ties by the Code - Masonry Magazine." Masonry Magazine. N.p., 14 Sept. 2012. Web. 31 Mar. 2016.

Duro Royo J, and Oxman N (2015) Towards Fabrication Information Modeling (FIM): Four Case Models to Derive Designs informed by Multi-Scale Trans-Disciplinary Data, Symposium NN: Adaptive Architecture and Programmable Matter: Next Generation Building Skins and Systems from Nano to Macro, 2015 MRS Spring Meeting, MRS Online Proceedings Library, Cambridge University Press.

"Fan-Powered Induction Unit Part I." YouTube. Southland Industries, 15 July 2015. Web. 18 Jan. 2016. <https://www.youtube.com/watch?v=WAxbVnpqXas>.

Farwest Steel Corporation. Standard Weights & Gauges of Steel. N.p.: Farwest Steel Corporation, n.d. Farwest Steel. Web. <http://www.farweststeel.com/content/misc_uploads/FWS_Standard_Weights_and_Gauges1.pdf>.

Jing Zhang, Behrokh Khoshnevis, Optimal machine operation planning for construction by Contour Crafting, Automation in Construction, Volume 29, January 2013, Pages 50-67, ISSN 0926-5805, http://dx.doi.org/10.1016/j.autcon.2012.08.006. (http://www.sciencedirect.com/science/article/pii/S0926580512001471) Keywords: Contour Crafting; Operation planning; Process planning; Tool path planning; Optimization

Gramazio, Fabio, Matthias Kohler, Antoine Picon, François Roche, and Tom Verebes. Made by Robots: Challenging Architecture at a Larger Scale. N.p.: Wiley, 2014. Wiley. Web. 11 Apr. 2016.

"Lewis Center for the Arts | BNIM." *Lewis Center for the Arts | BNIM*. N.p., n.d. Web. 03 Sept.

McGinley, Mark. "Design of Shelf Angles for Masonry Veneers." STRUCTURE Magazine. N.p., n.d. Web. 10 Dec. 2015.

"National BIM Standard." National Institute of Building Sciences, n.d. Web. 11 Nov. 2015.

Niu, Y., Lu, W., Chen, K., Huang, G., and Anumba, C. (2015). "Smart Construction Objects." J. Comput. Civ. Eng. ,10.1061/(ASCE)CP.1943-5487.0000550 , 04015070.

Oxman N. Material-Based Design Computation. Massachusetts Institute of Technology 2010. PERI Gmbh. Maximo: Panel Formwork with One-sided MX Tie Technology.

PERI Gmbh. TRIO. Weissenhorn, Germany: PERI Gmbh, 2010. Print.

Persson S, Malmgren L, Johnsson H (2009) Information management in industrial housing design and manufacture, ITcon Vol. 14, pg. 110-122, http://www.itcon.org/2009/11

Pniewski, Voytek. Building Information Modeling (BIM) Interoperability Issues in Light of

Interdisciplinary

Rael, Ronald, and Virginia San Fratello. Material Design and Analysis for 3D-Printed Fiber-Reinforced Cement Polymer Building Components. Tech. Emerging Objects, n.d. Web. 2 Dec. 2015

Ranta, J., 1993, *On the Dynamics and Evolution of Production Paradigms*, SITRA 130, Helsinki.

"Roller Screws." SKF. SKF, n.d. Web. 01 Apr. 2016. <http://www.skf.com/group/products/linear-motion/ball-and-roller-screws/roller-screws/index.html>.

San Fratello, Rael. "EMERGING OBJECTS." EMERGING OBJECTS. N.p., n.d. Web. 18 Dec. 2015.

"Smart Nation Singapore - Forbes." Smart Nation Singapore - Forbes. N.p., n.d. Web. 11 Nov. 2015.

Sklar, Julia. "Robots Lay Three Times as Many Bricks as Construction Workers." MIT Technology Review. N.p., 02 Sept. 2015. Web. 10 Dec. 2015.

TRANE. "Understanding Single-Zone VAV Systems." Engineer's Newsletter 42-2 (n.d.): 1. Print.

Williams, Adam. "Berkeley Researchers Pioneer New Powder-based Concrete 3D Printing Technique." GizMag. N.p., n.d. Web. 01 Apr. 2016. <http://www.gizmag.com/berkeley-researchers-pioneer-powder-based-concrete-3d-printing/36515/).>.

Wiss, Janney, Elstner Associates, Inc. "Building Envelope Design Guide - Masonry Wall Systems." Building Envelope Design Guide. National Building Sciences, n.d. Web. 10 Dec. 2015.

Zeiss, Geoff. "Singapore's National 3D Model Wins Be Inspired Award at YII2015." 'Between the Poles' Geospatial Blogs, n.d. Web. 11 Nov. 2015.

Academic Vita

Eric Wildey Luttmann
Elutt3@gmail.com

PASSION

To create a great product & end-user experience through the integration of the built environment & technology

EDUCATION

The Pennsylvania State University – Schreyer Honors College **May 2016**
Bachelor of Architectural Engineering - Construction Management Architectural Studies Minor
International Experience – The Pantheon Institute - Rome, Italy Summer 2014

WORK EXPERIENCE

Computer Integrated Construction Research Group **July 2014-Present**
Research Assistant - University Park, PA

- Investigate & implement virtual reality and immersive display capabilities for AEC industry teams
- Developed Planning section of Interactive Workspaces Guide to assist integrated project teams
- Consortium for Building Energy Innovation (CBEI) - Member of Collaborative Workspaces & Information Technology team for $10 Million annual Department of Energy funded initiative

Turner Construction Company **June 2015 – August 2015**
Assistant Project Engineer Intern – Philadelphia, PA

- Responsible for on-site engineering and construction management of $10 Million hospital renovation
- Cost estimation and bid scope development for hospital interior projects
- Coordination of virtual walkthrough / design review meeting for FMC Tower ($490 Million project)

Krause Innovation Studio **August 2013-Dec 2014**
Innovation Consultant - University Park, PA

- Documented studio space usage for interior design research & assisted users with digital interfaces
- Facilitated optimal data sharing experience for a premier, collaborative workspace on campus

SmallBatch Speakeasy **August 2015-Present**
Experience Designer & Event Planner – State College, PA

- Startup creating an inspiring food, drink and nightlife experience (*SmallBatchSpeakEasy.com*)

MASTERS LEVEL BIM PROGRAM

Virtual Facility Prototyping - *Penn State Architectural Engineering* **Fall 2015**

- Design & Development of Unity interactive prototypes for immersive visualization of buildings
- Develop integrated Unity-Grasshopper Daylighting Model with C# to control overhang and textures

BIM Execution Planning - *Penn State Architectural Engineering* **Spring 2015**

- Developed BIM Execution Plan for Turner Construction project to leverage BIM successfully
- Created strategic implementation plan for Jacobs Engineering to improve BIM management & tech

SKILLS

Revit software: 3D BIM architectural design, site layouts, massing components
Unity Rendering Engine - develop real-time, 3D immersive architectural models by workflow from 3DS Max
Web Design – develop responsive web projects using Bootstrap framework (HTML, CSS & JS)
C^{++} Programming – development and implementation of algorithms in procedure-oriented language
Swift Programming – fundamental understanding of Apple iOS app development in Xcode
Adobe Illustrator & Photoshop – marketing design for CBEI Department of Energy project, professional poster presentations; material edits for Revit; creation & editing brand logos for small businesses
Microsoft Excel – engineering calculation programming, graphic visual development, function application

INVOLVEMENT

Alpha Tau Omega Fraternity

- *Social Chairman* **–** Position integrated into every aspect of fraternity; **Jan 2013-May 2014** Primary role in the organization, networking, and risk management of social and philanthropic events

Innoblue – entrepreneurship community, coding skill development, innovation to change the world for better

- Developed iOS mobile app at HackPSU (PSU Hackathon); placed top 10 in national competition **Mar 2015**

S: PACE – Placement Officer for Student Chapter of The Partnership for Achieving Construction Excellence

- Coordinate with companies to bring AEC industry professionals and AE students together

Leblon Cachaça - Sales & Marketing Rep - Target accounts & ignite product experience **Jan 2015-Present**
Schreyer Honors Orientation Mentor **Aug 2013- May 2014**