Photo courtesy of Steven Holl Architects

The Performing Arts Center

New Jersey, U.S.A.

Turner

Final Thesis Proposal

Eric Luttmann | Construction Management | http://ewl5165.weebly.com

Advisor: Dr. John Messner

Photo courtesy of Turner Construction Co.

Table of Contents

Executive Summary

This proposal analyzes various issues that have presented themselves throughout construction of the Performing Arts Center. It illustrates alternative solutions to meet the owner goals and project goals related to value engineering, constructability and schedule adherence.

Analysis 1 | Cast-in-Place Concrete Wall Pour Productivity Analysis

This analysis addresses the schedule delay concerns caused by constructability issues of the cast-in-place concrete walls on the building façade. For millwork to be fully installed by May 2017, the critical path stipulates the enclosure is completed by April 2016. Schedule re-design will incorporate alternative pouring techniques, formwork strategies, manpower, equipment and pouring phasing based on case study investigation. Breaking down production into productivity rates of concrete poured in concrete per cubic yard, an alternative schedule can be proposed to meet project goals.

Analysis 2 | Alternative Façade Analysis

An alternative façade veneer is proposed to drive the project schedule during the installation phase with the utilization of a semi-automated mason (SAM). This analysis will focus on the milestone of completing the veneer by January 2017 using anchored clay brick masonry veneer vertically supported by steel angles and laterally supported by metal ties at 16". Due to a decision to alter Lecce Limestone finish providers, there is a need for schedule acceleration for the stone façade. To ensure that this installation exceeds project schedule goals, a potential solution includes the usage of Construction Robotics' Semi-Automated Mason. Through case study investigation into productivity comparisons, a more detailed schedule can be devised to see if this solution meets project schedule goals with a delayed logistics and supply chain management (LSCM) process. This analysis also strives to illustrate the architectural consequences of utilizing clay brick veneer rather than custom Lecce Limestone panels.

Analysis 3 | Focused Acoustical & Energy Analysis of Alternative Terminal Unit

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). The University places high priority on energy expectations for this project and this potential solution will be analyzed by focusing on the alternative design in the instrument rehearsal room. By comparing actual performance of the FPIU through an energy model to the VAV system performance projected by ARUP in the construction documents, the energy performance of FPIU can be validated for the Performing Arts Building. Furthermore, the alternative system designed will be tested for acoustical performance against the required STC for this space. Finally, the constructability will be tested based on the resulting coordination issues related to space occupancy of equipment and piping.

Analysis 4 | Digital Fabrication in Construction

Construction needs to shift from a human-centric industry to one in which digital fabrication ushers in a new generation for the architecture, engineering and construction industry. This portion proposes solutions to digitally fabricate and 3D print buildings at the appropriate scale, durability, and material strength to meet the original design intent of the Performing Arts Center and for construction scalable structures in general. By analyzing workflows of data throughout the fabrication information modelling (FIM) process, material and fabrication design & assembly and applying it to the opportunities on this project, a process map is to be proposed to leverage digital fabrication on the Performing Arts Center.

Proposal Analyses

Analysis 1 | Cast-in-Place Concrete Wall Pour Productivity Analysis

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 and sequencing goals. One of the major contributors to this difficulty includes the implication of board forms to create architectural concrete finish. When the board forms are on both sides, pours become exceptionally difficult. As a result of these unforeseen constructability challenges, enclosure of the building glazing system and the curtain wall installation has been delayed. Without enclosure, interior completion cannot be started, which impacts the critical path schedule. To resolve this opportunity, alternative pouring process techniques and sequencing are to be proposed so that façade construction can finish on time. Note that this opportunity goes beyond increasing manpower through crew size or total man-hours.

Background Research Performed

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. With the entire schedule riding on this, it is necessary for the concrete façade to be accelerated so that the curtain wall and glazing systems can be installed. Turner has experience accelerating the schedule through crew size re-design and sequencing of these shifts. Another alternative may be resource loading. The pre-fabricated wooden board forms used for the architectural concrete finish became an issue when the board forms got wet, and had to be thrown away while new forms were ordered. To meet the current plan for concrete façade pours, concrete is planned to be poured 3-4 times per week with at least 13 trucks each day, reaching an average of 130 cubic yards of concrete poured a day.

Potential Solutions

The main solution will be a schedule reduction to align the critical path so that interiors can begin on time. This will be delivered through manipulation of resource loading & sequencing including additional shift implementation, and overlapping of events. Furthermore, alternative case study analysis of pouring, sequencing and staging techniques used to accelerate construction will be leveraged. When increasing resource loading, the resources and equipment onsite will determine the capacity to leverage increased manpower. Due to the immense space onsite for this job, leveraging another crane would allow a larger area of façade to be poured since forms could be moved into place at an increased rate. Based on the board form weather and staging issues presented above, a potential solution could include just in time delivery of board form elements and development of temporary weather protection facilities for these components. On this project, steel concrete forms are moved in place by crane and then wooden forms are placed inside the form when necessary. Therefore, a potential solution will be to design a custom steel wall form with wooden board form as part of the assembly, rather than an additional part of the logistics and supply chain management (LSCM). This data will be retrieved and applied through standards and case study investigation.

Analysis Methodology

The methodology will include analysis of current operations, owner and zoning construction requirements, analysis of the current pouring techniques including the formwork types and applications, the sequencing and staging of concrete, and the prefabricated board forms will be analyzed in depth.

The analysis steps are as follows:

1. Gain comprehensive understanding of the current operation & schedule:
   - Investigate Turner's detailed resource allocated control system to see patterns of forecast manpower (man-months) & WIP ($K) vs. the actual production.
   - Interview structural and façade superintendent to find exact pouring sequence and technique
   - Analyze current schedule to find areas where schedule acceleration will need to occur in portions of concrete façade construction and where high priority areas are for curtain wall and glazing enclosure to occur. The goal of this analysis is to find how structural façade and enclosure is phased so that it can lead to redesign of phasing.
2. Investigate case studies to find alternative strategies for concrete pouring methods. This will include analysis:
   a. Quantity of concrete trucks delivered: Measured in cubic yards of concrete / day
   b. Formwork Implemented: this will include the strategies for how formwork is staged onsite and moved using cranes.
   c. Rate of pouring: concrete cubic yardage poured per day
   d. Investigation of pre-fabricated board form & formwork integrated design: This will replace the original application mentioned above
3. Interview & discuss alternative concrete pouring methods with Ray Sowers, manager of renovation services at Penn State University. This discussion will serve to check viability of alternative methods and improve upon them. Furthermore, it will serve as a way to benchmark against Penn State's methods.
4. Create new productivity rates for concrete (cubic yard) poured per day based on crew sizes, resource loading, adjusted practice with detailed assumptions for man-hours per day, time saved with new formwork techniques.
5. Create revised milestones for pouring completion of walls integrated with layout staging of pouring by building & specific façade walls.
6. Create revised comprehensive schedule for Cast in Place walls & compare with original durations Turner composed. Compare all staging, pouring and LSCM practices with local and owner requirements.
7. Create revised cost estimate based on changes to schedule, resources loaded, manpower leveraged.
8. Recommend opportunities for schedule acceleration based on comprehensive schedule result

Expected Outcomes

The expected outcome will be a new schedule that will meet the goals of the critical path to complete enclosure by April 2016. This schedule will be based off case-study presented solutions for manpower allocation, equipment utilization, concrete pouring strategies and formwork strategies. The presented solutions will serve to maximize efficiency of concrete pouring (concrete/cubic yard) to achieve an accelerated schedule, and thus, project schedule goals. Otherwise, improvements for focused parts of the pouring process will be illustrated (i.e. concrete formwork time saver) and can be utilized for future pours on this project. In addition to a schedule and recommendations, a cost estimate analysis will be presented to illustrate the monetary impacts to the University by choosing the proposed, alternative concrete pouring methods.

Analysis 2 | Alternative Façade Analysis

Opportunity

The initial façade design included a Lecce limestone exterior cladding system that would be supplied by Becker and Becker Stone Company out of Iowa. Due to a decision late in the process, the supplier for this vital component of the façade was changed to a company, PiMar in Italy. For PiMar to resubmit approval for shop drawings for 3,000 stones, fabricate them and then ship them from Italy would delay installation until summer 2017, which is the end of the project. As a result, Turner would have to reschedule the project so that panels could be installed while late tasks occur including closeout items, courtyard construction and landscaping. Therefore, this presents a significant site logistics and schedule reorganization challenge. This analysis proposes to accelerate the veneer installation to finish ahead of schedule. In order to do so, a Semi-Automated Mason (SAM) can be leveraged to more efficiently install local, traditional masonry that is substituted for the lecce limestone finish.

Background Research & Potential Solutions:

The challenges posed by utilizing Lecce Limestone on this project can be resolved by installation of traditional masonry using a semi-automated mason. This will enable a similar finish with a more efficient installation process that will fit the tight constraints of the project schedule. To ensure that this installation exceeds project schedule goals, an integral solution includes the usage of Construction Robotics' Semi-Automated Mason (SAM). Since SAM can only be used with traditional masonry brick, this study will focus on the viability of using this façade alternative. This machine is used to support masonry worker jobs by "picking up bricks, applying mortar, and placing them in their designated location" (MIT Technology Review). It is three times as efficient as a construction worker. Clark Construction Group is utilizing SAM on construction of a high school project in Palisades, Washington D.C. The machine also worked with masons on the AIT Barracks Complex Phase II Construction site in Fort. Lee, Virginia.

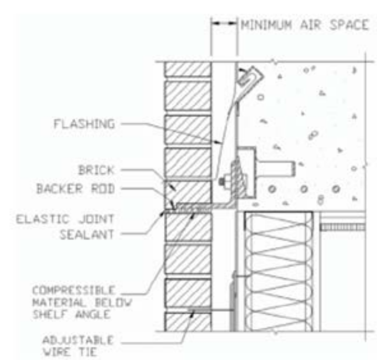

Figure 1: Elevation of an anchored masonry veneer wall system.

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 (McGinley 2013). For lateral support of the veneer, metal ties at 16" can be leveraged (Wiss, Janney, Elstner Associates, Inc.). Please see figure 1 for a visual representation of the possible support solution. The brick potentially needs to be refractory clay material so that it burns into pale yellow or fine white sand that resembles a limestone finish. Based on review of suppliers, likely solutions for the stone include Alaska White Smooth face brick, or "Cape Fear" selection offered by Triangle Brick Company. The ultimate solution of this analysis will result in a proposed schedule to construct the entire program's veneer utilizing the final product system and process with the semi-automated mason. The methodology below will detail the process necessary to analyze the brick.

Analysis Methodology

To test whether the clay brick masonry veneer will serve as a viable alternative, the analysis will focus on the installation efficiency and schedule acceleration opportunities presented by the SAM installation process of local, masonry material. If the alternative brick façade proves to be a solution that can save Turner Construction time in the schedule to meet overall schedule goals, then it will be determined viable. Furthermore, the recommendation will be based on whether the veneer is suitable from an architectural standpoint and whether it will meet The University's expectations of constructing a world class performing arts center inside and out. Therefore, the final comparison will be whether the brick façade meets or exceeds schedule goals to be finished by January 2017, the original date of completion when utilizing Lecce Limestone from Becker and Becker.

The analysis of the schedule will be focused on the milestone of completing the veneer by January 2017. This is the originally planned completion date for the stone finish of the entire program, ending with the North face of the Music building. To track this completion date, the entire LSCM model will need to be assumed using standard time frames for shop drawing and submittal submission and approval and delivery times for a specified supplier. Then, the productivity of installation will be how the two façade installation tasks are compared. To compare, productivity rates will be broken down into square feet of masonry installed per day based off of case studies published by Construction Robotics for projects that leveraged SAM. These include the project examples mentioned in background research above. Then, this productivity will be projected into an overall schedule for the entire building and compared to the original schedule time frame. To test the architectural viability of the alternative, three interviews will be competed: One interview with Steven Holl Architects, one with BNIM architects, and one with the architect of The University. Based on go/no go decision by two out of the three stakeholders, the alternative recommendation will be validated.

Steps Defined:

1. Determine best alternative option for brick masonry veneer based off of potential solutions including Alaska White Smooth face brick, or "Cape Fear" selection offered by Triangle Brick Company.
    a. The alternative will be chosen based on proximity to the jobsite and the closest fit to the original Lecce limestone façade appearance to achieve original façade, aesthetic goals.
2. Determine logistics and supply chain management (LSCM) for retrieving masonry material from a supplier. To track this completion date, the entire LSCM model will need to be assumed using standard time frames for shop drawing and submittal submission and approval and delivery times for a specified supplier
3. Consult Construction Robotics to learn limitations of SAM, productivity rates per square foot of masonry, optimal manpower usage with SAM or additional needs to use SAM to install brick masonry.
    a. Other consultation and investigation may be through contractors for the projects including Clark Construction
4. Determine productivity rate for masonry veneer installation per square foot of masonry based off of research from Construction Robotics case study history. Case study investigation will look into the project examples mentioned in the background research above. Overall schedules will be broken down into a productivity rate that can be applied to this job.

5. Create schedule that illustrates the overall steps to constructing the brick, masonry veneer using SAM. The goal of this schedule is to finish before January 2017. This schedule will be based off of the productivity rates, schedule breakdown and associated research with Construction Robotics history
6. Compare new schedule completion date using alternative material and SAM to the original completion date posed by the Lecce Limestone material change
7. Test the architectural viability through an interview process illustrating the proposed change.
    a. Interview with The University Architects
    b. Interview with Steven Holl Architects
    c. Interview with BNIM architects
8. Recommend whether the alternative façade and SAM installation process will meet schedule acceleration goals. If the alternative brick façade proves to be a solution that can save Turner Construction time in the schedule to meet overall schedule goals, then it will be determined viable.
9. Recommend whether the alternative façade is viable from an architectural and overall aesthetic standpoint

Expected Outcomes

The overall expected outcome is to determine whether the utilization of SAM with a clay brick veneer façade construction will lead to a faster schedule for overall façade completion. The purpose of this outcome is to present a viable solution for accelerating or at a minimum, meeting original project goals of façade completion by Jan 2017. This will illustrate the scale that SAM can enhance the schedule length of a project with a majority, masonry façade. From an architectural outlook, it can show the consequences of utilizing clay brick veneer rather than custom Lecce Limestone panels.

Analysis 3 | Focused Acoustical & Energy Analysis of Alternative Terminal Unit

Opportunity

The Performing Arts Center is designed at a caliber to exceed energy expectations and design codes by utilizing 50% less energy. However, the LEED Project Checklist illustrates a rating of Silver level of certification. Based on the "Energy & Atmosphere" category, the Optimization of Energy Performance could be enhanced to meet improved cost savings. The 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 in performance and occupied zones. Therefore, 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 one, specific space of the building based on constructability, acoustical analysis and the energy optimization over the existing system.

Background Research & Potential Solutions:

Fan Powered Induction Units serve as a viable energy savings solution to VAV boxes. An FPIU uses a cooling coil, heating coil and fan to condition air and diffuse it into an individual space. Since VAV boxes rely on the central air handling unit for dehumidication, air distraction and cooling capacity, thick ductwork lines the ceiling. With the FPIU, the air handler is only responsible for flow of filtered, dry ventilation of air. FPIU can rely on sensible chilled water piping rather than ductwork to reduce ductwork by 25% (Southland Industries). One of the main ways FPIU optimize energy is by metering outdoor air delivery directly to each zone for measurement and control which leads to substantial energy savings. From the Owner's perspective, utilizing a higher end product will potentially prove to be more expensive on the front end, however, this system will help meet the energy performance goals. Furthermore, the constructability is simplified since chilled water piping reduces space occupied in the above ceiling plenum compared to ducts that VAV boxes require.

Analysis Methodology

The analysis of this alternative mechanical system will focus on one space in the Performing Arts Center, the instrument rehearsal room. The instrument rehearsal room utilizes overhead VAV, but has the lowest STC requirement of the entire program at 15. The mechanical system of the space can be visualized in figure 2 below. Therefore, this space will be analyzed to primarily see the total zones loads for the space. Then a custom fan powered induction unit system for this space will be designed using ASHRAE standards for facility type and square footage. After that, the system coefficients of performance for both heating and cooling will be tested through an energy model simulation in which the actual power utilized in comparison to heat supplied (Q_H) or removed (Q_C) will be referenced to the anticipated performance*. Please see the Mechanical Breadth in Appendix A to see the full methodology for FPIU design and comparison to the existing system.

* Note that the design and simulation of the FPIU & energy model will serve as a mechanical breadth of this report.

By comparing actual performance through an energy model to the performance projected by ARUP in the construction documents, the energy performance of FPIU can be validated for the Performing Arts Building. Furthermore, the alternative system designed will be tested for acoustical performance against the required STC for this space. Finally, the constructability will be tested based on the resulting coordination issues based on space occupancy of equipment and piping. If the overall space occupied is less than that of the VAV box system, and if there are no drastic coordination issues with other systems, then the alternative solution will pass the constructability tests. If the energy performance is better for the FPIU system and the FPIU system meets this STC requirement, it can be argued that the system is a better alternative for owner.

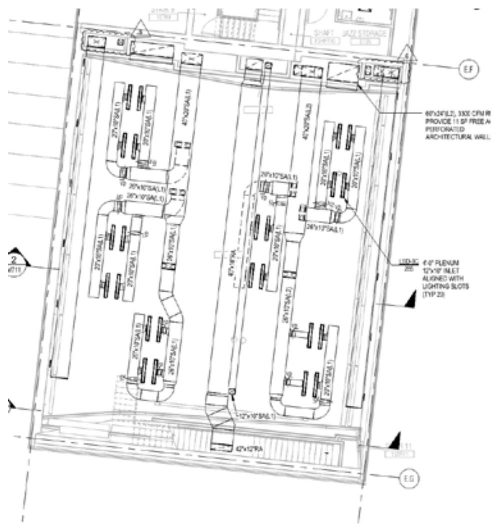

Figure 2: Mechanical ductwork plan instrument rehearsal

Expected Outcomes:

The expected outcomes of this analysis include a mechanical system with greater overall energy optimization. Thus it will lead to a higher performing building and meet the goals of the owner at a higher degree. This analysis should validate whether an FPIU terminal unit proves to be more efficient that a Variable Air Volume terminal unit for a select space in the building. Due to the acoustic precedent of this system, the instrument rehearsal space will validate whether the FPIU can be used throughout the building to meet acoustical STC requirements as it is the lowest STC rated space in the entire program. Finally, the constructability of the alternative system will be validated. In addition to these expected outcomes, this analysis will serve as a foundation for the mechanical breadth and acoustical breadth noted in Appendix A. The mechanical breadth will focus on the FPIU design, energy model simulation and testing of the actual power to be utilized by the FPIU system. The acoustical breadth will focus on solutions to enable an acoustical performing space at the required STC 15 class when the FPIU meet a dB rating that exceeds this.

Analysis 4 | Digital Fabrication in Construction

Opportunity

Building construction has traditionally been a human-centric industry where management labor personnel collaborate. However, advancements in technology including computer science, robotic additive fabrication and software abilities pose a shift from human-centric production to an automated process. With the evolution of technology, "the reigning paradigm dictates that the construction industry should follow industrial trends of increased efficiency, control, quality, productivity and overall decrease in cost per unit as seen in the automobile, shipping, and aerospace industries" (Ranta). This analysis will examine how automated construction, specifically digital fabrication, can usher in the next era of the architecture, engineering, and construction industry. With multiple prefabricated elements on "The Performing Arts Center", this analysis will extend to examining how these pre-fabricated elements were fabricated and how this specific structure could be constructed digitally.

Background Research & Potential Solutions

The foundation of this research is built upon the need for the construction industry to shift its production processes from a labor intensive process to a streamlined, automated approach similar to the manufacturing industry. Through scaling of 3D printing technology, companies such as "Contour Crafting", and MX3D have developed means to 3D print or fabricate building and structural components at large scale and with reasonably durable material. Large-scale robotic construction systems have been the vision of Dr. Behrokh Khoshnevis who envisions a world where housing and shelter will be rapidly printed in only a few days. MIT Media labs has devised a process called Fabrication Information Modeling (FIM) in which the end product informs the design with data focused on form generation, digital fabrication and material computation. Furthermore, Emerging Objects is printing scalable, organically curved structural components made from concrete that reaches 4537 PSI.

The comprehensive solution will illustrate the process to translate a file into a scalable physical product. Therefore, it will exemplify the workflow necessary with the types of data necessary at each stage of the building lifecycle so that a fabricator can process a model. Furthermore, a specified concrete material and fabricator infrastructure will need to be conveyed that is appropriate for this project. For the "Performing Arts Center", the greatest solution would prove viable to print concrete elements such as walls, ceilings and slabs. Another solution would be to digitally fabricate wooden board forms onsite to utilize in the pouring of architectural concrete finish. Rather than wooden board forms, these could potentially be made from a synthetic material printed with the wooden finish.

Investigation Methodology

To investigate how to make digital fabrication feasible in construction, current technologies and capabilities will be expressed in literature review format. The research will be performed in accordance with the AE481W Schreyer

Syllabus to conduct and prepare a literature review consisting of relevant publications, white papers, TED Talks or related, legitimate sources for this topic.

The investigation will take the following steps:

1) Find sources related to these objectives:
    a. **Workflow Design**: Creating a workflow that enables Fabrication Information Modeling including the relevant data scheme, the software utilized throughout and the algorithms necessary for the relevant geometric, material and mechanical data to speak to each other at each stage.
        i. Sources investigated will be case studies and research publications for processes. These sources may also take the shape of white papers and interviews with companies digitally fabricating structures.
        ii. The culminating workflow will be based upon previously generated processes that have proved viable to digitally fabricate architectural structures. By benchmarking various workflows and determining their focus areas, successes and failures, a new workflow can be devised based on specific constraints and focuses for this study.
    b. **Material & Fabricator Design & Assembly:** Analyze the material solutions that offer substantial durability and strength for the longevity of a building structure. Analyze and determine the best design and assembly of a printer or fabricator for a large structure.
2) Investigate the process that The Performing Arts Center utilized to prefabricate major elements including concrete beams in the Theater and Dance building as well as prefabricated wooden board forms. This investigation will take place through communication with the project manager and general superintendent. Furthermore, referral from Turner's project team will potentially lead to discussion with the structural prefabrication plants for specific procedures.
3) Explore alternative solutions for how these specific components could be fabricated based on digital fabrication.
4) Determine the areas of the Performing Arts Center that could be digitally fabricated at the appropriate scale, material, and functionality to meet original goals of the project design. This should focus on substructure, superstructure and interior elements, rather than the entire building.
5) Based on the literature review material, create process map(s) directed to The Performing Arts Center to digitally fabricate the elements mentioned in steps 3 & 4 detailing the software, file types, data exchanged, intrinsic algorithms, hardware, etc. necessary.
6) Illustrate alternative process map(s) and solutions for digital fabrication in the architecture, engineering and construction industry.

Sources breakdown:

- The goal is to expand the literature review beyond research publications in order to capture industry related breakthroughs and current business practices related to digital fabrication of large-scale structures. The collection of sources investigated will resemble the following structure:

- Research Publications & Journals: 50%
- Whitepapers & company reports: 12.5%
- Interviews with companies & researchers (especially those with lack of documentation of processes and results): 12.5%
- Associated media, patents, books, news, broadcast: 25%

Expected Outcomes

After examining digital fabrication applications for the building lifecycle, the expected outcome is a detailed process map & description that illustrates how to digitally fabricate The Performing Arts Center in the form that will most directly correlates to the original design intent and form of the project. Furthermore, this analysis will illustrate how the Performing Arts Center project team was able to prefabricate elements including the logistics and supply chain management (LSCM) that enabled the usage of these elements. In addition, this analysis will illustrate alternative ways to prefabricate these elements through digital fabrication. Finally, this study should exemplify where the industry currently has evolved to and where it can go from a digital fabrication perspective.

Bibliography

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

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

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

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

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.

Appendix A | Breadth Analysis

Mechanical Breadth

In the "Focused Acoustical & Energy Analysis of Alternative Terminal Units", the comparison of a proposed fan power induction unit (FPIU) to the original variable air volume (VAV) terminal unit based on energy performance, constructability and acoustics will require design of a FPIU for the instrument rehearsal room and an energy model simulation in which the system coefficients of performance for both heating and cooling will be tested. As a component of the overall analysis, this breadth will focus on determining whether the FPIU can be recommended instead of the original VAV unit. After FPIU design, an energy model simulation will determine the energy performance of the FPIU so that it can be used for the comparison against the original mechanical system. To design the FPIU for the instrument rehearsal space, ASHRAE standards for facility type and square footage will be leveraged against the total zone loads for the space. After that, system coefficients of performance for both heating and cooling will be tested through an energy model simulation in which the actual power utilized in comparison to heat supplied (Q_H) or removed (Q_C) will be referenced to the anticipated performance. This energy model will be run using Trane's Trace 700 energy modeling service. By comparing actual performance through an energy model to the performance projected by ARUP in the construction documents, the energy performance of FPIU can be validated for the Performing Arts Building. Based on the energy performance ($\frac{\text{BTU/ft2}}{\text{year}}$) of the FPIU vs. VAV box, the appropriate system can be recommended in the "Focused Acoustical & Energy Analysis of Alternative Terminal Units".

Acoustical Breadth

This breadth study reveals how the Instrument Rehearsal Space infrastructure will need to be redesigned from an acoustic standpoint when using fan power induction units (FPIU) rather than VAV boxes. Assuming that the FPIU units exceed the standard transmission class (STC) of 15 for the space, acoustical provisions will need to be taken in order to maintain the required acoustical performance for the space. Based on the resulting design of the systems in Analysis 3, the acoustical properties FPIU systems will be verified. For the purposes of this study, the FPIU will, at a minimum, generate a sound level that meets STC 25, which is the STC value for the rest of the occupied and performance spaces of the Performing Arts Center. To restore the space to STC 15 requirement, a system will be designed to absorb additional sound through ceiling, wall or floor layering or material selection. In addition, silencers and acoustical means of reducing the FPIU will be inspected so that the overall space meets the STC 15 requirement. The proposed solutions will be determined based on constructability standards within that space and staging of the project.