The Millennium Science Complex

The Pennsylvania State University

IPD / BIM Thesis 2010-11

BIMception

Schematic Design and Construction Planning
Technical Report 2
October 22, 2010

Stephen Pfund
Christopher Russell
Alexander Stough
Thomas Villacampa

Advisors:
Dr. Andres Lepage
Dr. Richard Mistrick
Dr. Jelena Srebric
Dr. John Messner

Table of Contents

Executive Summary

BIM*ception* is an interdisciplinary team brought together to reevaluate the building systems of the Millennium Science Complex. Through integrated project delivery, BIM*ception* will use building information modeling as a tool to create unique and effective solutions to improve the Complex's performance. This report will investigate the integration of façade and plenum designs to highlight the benefits the IPD/BIM process can have on designing a better whole building project.

Redesigning the exterior façade will require the integration of all disciplines as each system is reevaluated to optimize performance. The aesthetics and integrity of the architecture will be kept consistent as the engineering systems evolve to better reflect the advantages of integrated design. An in-depth daylighting analysis will take advantage of solar orientation, providing natural light, while helping to manage and reduce building loads. The façade composition will be reconstructed to improve energy usage, while reducing its weight to alleviate stresses on the structural system and construction logistics. An integrated façade redesign will realize savings in design, construction, energy, and life cycle costs.

The performance of each building system is directly related to the level of coordination achieved in the ceiling plenum. Every system is involved in the space creating the life support of the occupants and the building itself. In the plenum the defining factor is available space. Alternative structural systems will be evaluated for efficiency and applicability to most effectively reduce the spatial usage in the plenum. The possibility of removing light fixtures from the ceiling entirely will be. Additional plenum space reduces conflict potential and increases the applicability of a higher performance mechanical system, realizing energy savings. BIM*ception* will utilize an integrated design approach to reduce and eliminate these conflicts, producing construction and operation cost savings.

Every design decision has an implication – a measurable cost. It is the job of BIM*ception*'s integrated team to analyze and balance each of these decisions to create the most effective whole building solution. The interdependencies of building systems will be analyzed to understand the implications each discipline has on another. BIM will be used as a design tool to help the Integrated Project Delivery team analyze these decisions and project the best solution for a whole building's life cycle design.

Façade Redesign

Problem Statement

While the exterior façade is largely designed as an architectural aesthetic element, it, in reality, is a unique building element that demands the engineering of all disciplines to provide optimum performance. Oftentimes, as is the case with the Millennium Science Complex, the architecture demands an engineering solution. BIM*ception* will focus on retaining the architectural features, while revealing the benefits integrated design can have on building performance when developed in conjunction with the architecture.

Most noticeably, the façade is uniform in composition around the entire building. This form of design does not properly address the effects of solar orientation, as it generates varying daylighting and solar load gains on the different building faces. Ignoring the influences of solar orientation can have significant effects on the engineering systems as they are forced to accommodate the unmanaged loads. By incorporating engineering design earlier in the design phase the façade could be designed to utilize solar orientation to provide better daylighting and to better manage mechanical loads.

The Millennium Science Complex's façade was designed to be a prefabricated panel system - a system that helps streamline construction and reduce costs. Each panel, however, weighs over 25,000 pounds creating structural and logistic issues. Reducing the weight of each panel, could reduce the load on the structural system and ease limitations on construction logistics. Reducing weight will require a redesign of the façade system and materials, while retaining and improving thermal performance.

An interdisciplinary design will be required to achieve all possible performance enhancements. BIM*ception* will strive to retain the architectural integrity of the façade while it redesigns the engineering systems to improve the building operation and reduce the life cycle cost of the Millennium Complex's exterior.

Construction Management

A change in the façade of the building can create a ripple effect throughout all aspects of construction. In general, any change made will have an effect on how the building is constructed. The façade for the Millennium Science Complex consists of precast concrete panels ranging from 9 to 12 feet in height and 22 feet in length. These panels weigh upwards of 25,000 pounds, and were brought into the site one at a time during the construction of the building enclosure. The enclosure of the building, excluding the areaway entrances, soffit and light well, took approximately 10 months to complete.

One way to reduce cost and the time required to construct the enclosure is to use a lighter weight façade design. By redesigning the façade, it is possible to find cost savings in the materials used when fabricating the façade at the manufacturing plants. Whether the redesign uses a similar precast concrete panel with a lighter, more efficient design, or an entirely new material, such as metal paneling, it is possible to find savings in the material used for façade.

In addition, changing the design of the façade will have an effect on the schedule and time required to place the façade on the building. While using a similar precast concrete panel design may not impact the schedule greatly, changing to a different type of façade panel, such as a metal paneling, will create a different time frame required for placing the panels on the building. Selecting a façade design that can be placed on the building in a more efficient manner will help speed up the schedule for the enclosure, which will directly correlate to starting the interior of the building sooner.

The current façade panels have very stringent quality requirements, requiring high amounts of quality control and time put into maintaining the look of the enclosure. Choosing a design that would require less quality control can result in cost savings, as well as allowing time for other activities. Additionally, it can cut down on the costs put into façade fabrication at the manufacturing plant. Large amounts of time and money were put into producing the bricks for the current façade in a specific way so the appearance of the building fits the architect’s vision. Using a design that could cut down on the process required to produce panels with such stringent requirements would create a more cost efficient enclosure.

From a structural standpoint, a redesigned façade would create different loads on the framing at the exterior of the building, which is responsible for holding the enclosure. If the façade redesign results in a lighter façade panel, then it may be possible to reduce the size of the members connecting the panels to the framing. This, in turn, would result in a small cost savings for the structural system of the building.

The façade plays an important role in the heating and cooling of a building. Different façade designs will have different thermal resistance values associated with the assemblies. This would change heating and cooling loads on the building, and have a direct effect on the requirements of the mechanical systems for the building. If the design of the mechanical systems changes as a result of a façade change, this would have a large impact on both the cost and schedule of the building. The mechanical system constitutes the largest percentage of the construction cost of the building; so accordingly, any change to this system will have a greater impact on the cost than similar changes to other systems. In addition, the mechanical system is the second largest system within the building, which provides challenges in coordinating and constructing it. If additional coordination is required, or the system requires additional work in the field in order to construct, this can have a negative effect on both the overall cost and the schedule of the system.

Daylighting systems can have an effect on how the building enclosure is constructed. Implementing a new daylighting system, such as a light shelf, for the offices on the exterior of the building would provide an increase in upfront cost for the building, but can result in a lower life cycle cost due to lower energy usage over the life of the building from the lighting system. In addition, this could add to the scheduled time for the interior of the building, depending on how complicated the system design is. However, the benefits of a system like this can outweigh the increased time required to install it. Additionally, changing the shading system on the façade of the building will have similar impacts on the cost and schedule for the building. If mechanical louvers were to be installed on the exterior of the building rather than the current exterior shade, this would similarly have a greater upfront cost for the overall lighting system, but due to reduced loads in the building, could repay this increase in cost over the lifetime of the building. Because the louvers are of a relatively large size, this also presents logistical issues in placing these on the building. While a crane may not necessarily be needed to place this on the building, a JLG, at a minimum, would be required to hoist the components up to the respective locations for installation. Careful planning and consideration would need to be done when installation occurs to reduce the risks involved with this activity. Risks can come from the fact that the louvers are placed on the exterior of the building in potential high traffic locations, as well as preventing damage to both the exterior façade and the louver system itself during installation. Weather can also play a large factor in the risks involved with the installation of this type of system because it is installed on the exterior of the building.

Lighting Design

Existing

The façade of a building has a large impact on daylighting performance. This section will take a look at different daylighting designs, and the impact it will have on the façade. It's important to provide the best possible solution that still follows the architect's vision of horizontality.

The façade of the Millennium Science Complex as designed is comprised of precast panels that provide two overhangs for the daylight system. One overhang is built into the overall geometry by stepping the glazing into the space over two feet. The other overhang is a continuous louvered overhang the goes around the entire perimeter of the building. The Millennium Science Complex has larger overhangs, on the wings along Bigler and Pollock Roads. This report contains a daylight study of the large overhangs, some preliminary design concepts to improve the existing daylighting system, along with other design decisions and the implications they present to the rest of the building system.

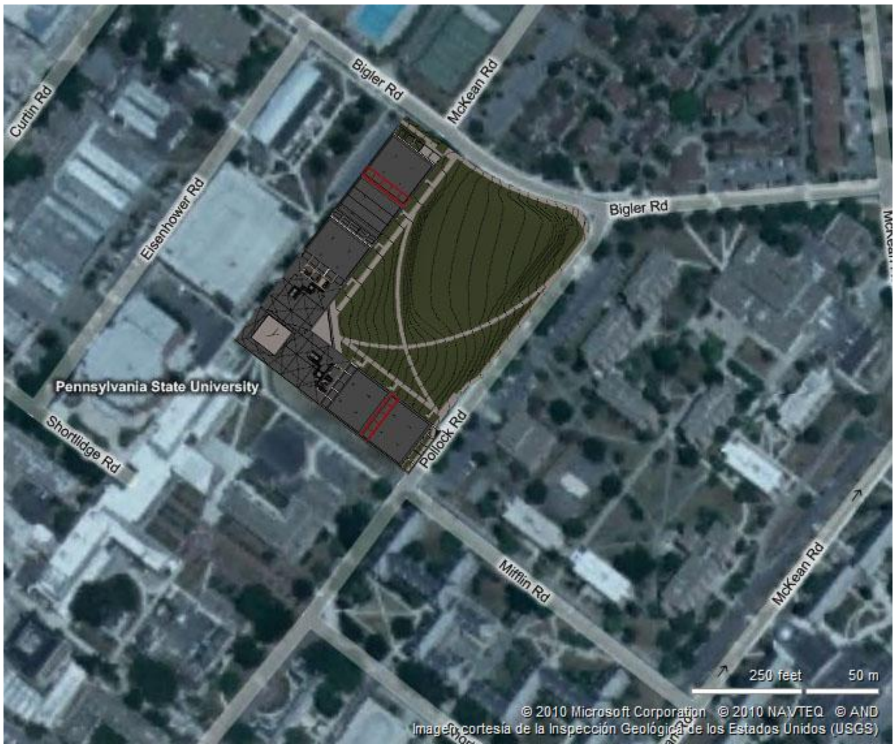

Figure 1: Site plan with analyzed overhangs in red.

A study was done on the large overhangs at the end of each wing, the one on Bigler and the one on Pollock Road. The study was conducted by modeling the wings with and without the overhang to see the performance of the overhang; this shows the performance of the overhang itself. The analysis was done using AGi32 for the Summer and Winter Solstice. The study shows that the large overhangs are somewhat effective, but adjustments could be made in order to maximize their performance. The times where the overhang, or the removal of, has an effect on the building can be found in Figures: 2-7.

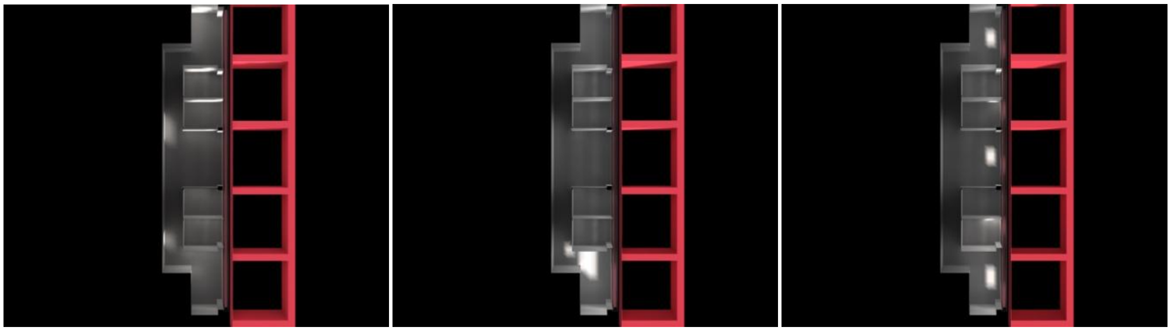

Figure 2: Bigler Road wing study for early summer mornings with overhang.

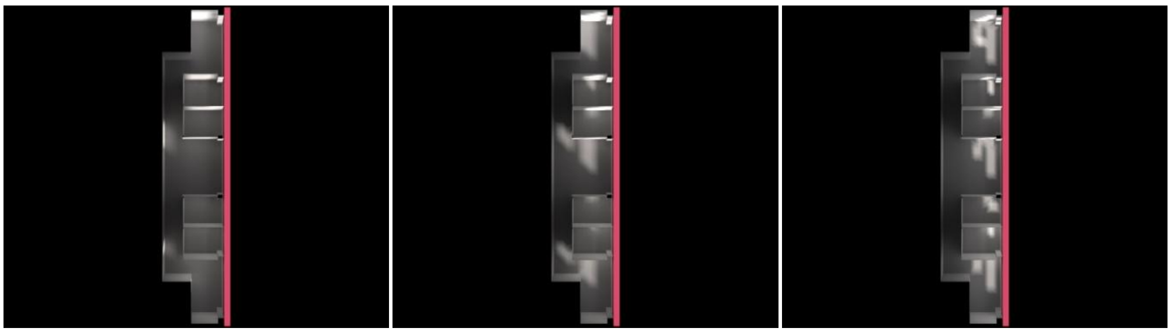

Figure 3: Bigler Road wing study for late summer mornings without overhang.

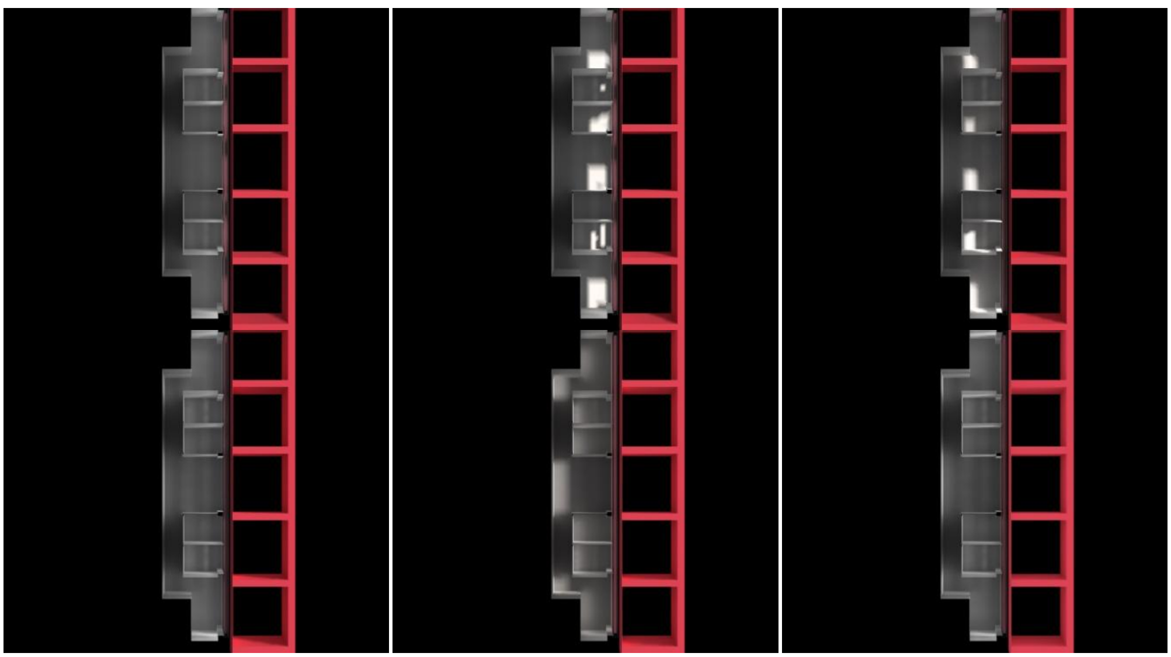

Figure 4: Pollock Road wing study for late summer afternoons with overhang.

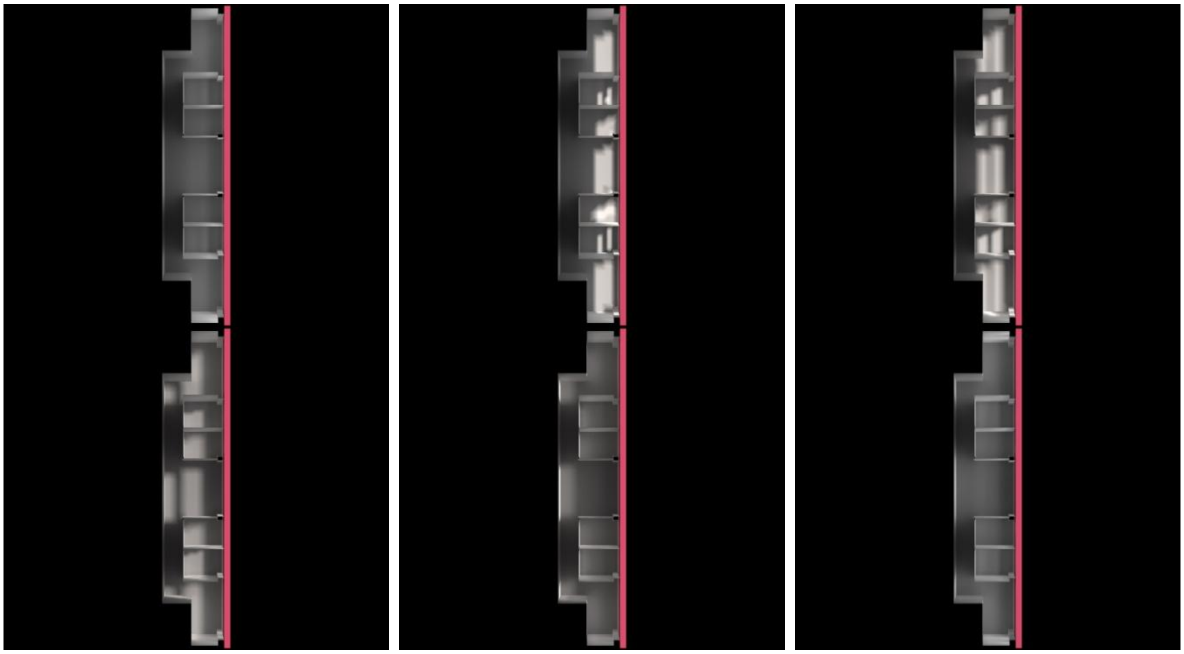

Figure 5: Pollock Road wing study for late summer afternoons without overhang.

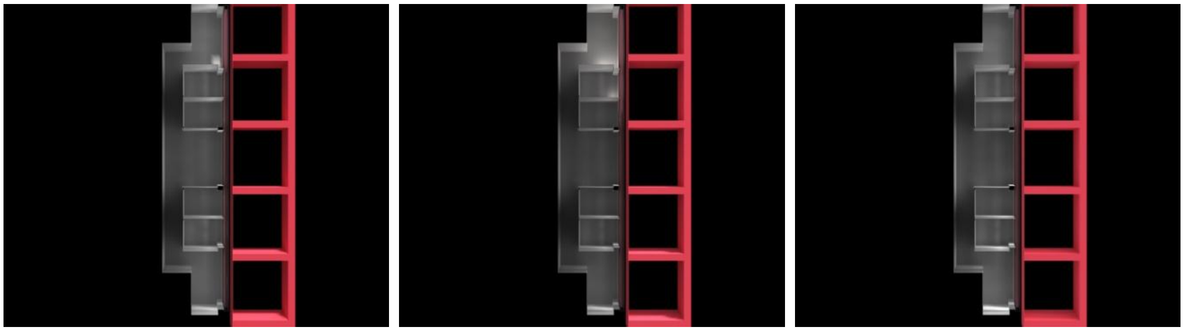

Figure 6: Pollock Road wing study for late winter afternoons with overhang.

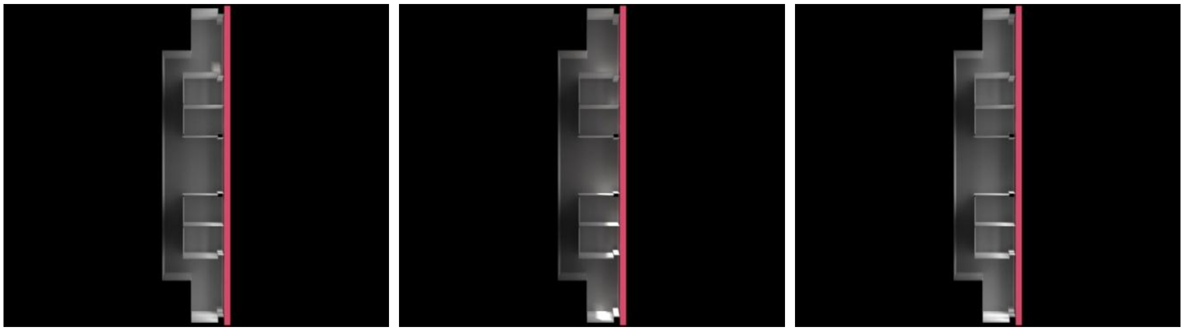

Figure 7: Pollock Road wing study for late winter afternoons without overhang

The study shows the large overhang performance is better than if there wasn't an overhang, but there is room for improvement. Some areas to study involve filling in the voids of the overhang, or modifying the overhang all together. If the voids where to be filled in coordination would be required with the structural engineer to make sure the added weight could be supported. This also takes away from the architects theme of horizontality with floating floors. If the overhang were to be redesigned proper coordination with mechanical and structural team members would be required. A redesign would affect supported weight for the structure and internal building loads for the mechanical system. These options will be further analyzed as the design process progresses.

Redesign Options

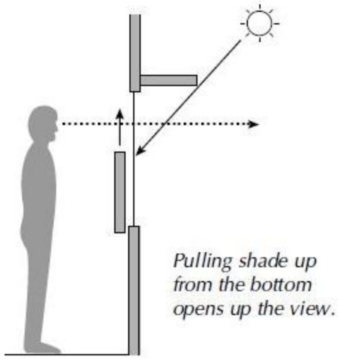

Figure 8: Bottom-up shade Diagram[1].

The first area of study to improve the daylighting design maintains the existing architecture without any modification. The only change to the existing design would be to use bottom-up shades instead of the original top-down ones. The original top down shade needs to be pulled all the way down in order to block low angle sun, essentially blocking the occupants view to the exterior (Figure 8: Bottom-Up Shade Diagram). This minor change will allows the system to block lower sun angles, while maintaining the occupants view to the exterior. The current Millennium Science Complex design earns LEED points for view to the exterior. This relatively simple solution will be further analyzed as the redesign process moves forward.

Another area of study will be to alter the existing shelf. There are many areas that could be studied here: the shelf could be moved up or down, broken into more than one protrusion, and an interior portion could be added. Moving the shelf up or down would alter the sun profile angles that would enter the space. This can affect the occupant comfort by reducing direct glare. Blocking direct sun also helps reduce the solar heat gain into the space. Another way to reduce the direct sunlight penetration is to break the shelf into more, shorter protrusions. This will block direct gain without the need for excessive protrusions. The final study of altering the existing shelf includes adding an interior component to the light shelf. The adding of an interior component can provide an orientation specific façade without compromising the architect's original concept. The addition would provide brighter ceilings and an overall more pleasant space if implemented correctly. All three of these options will be further analyzed as façade redesign is considered.

Figure 9: CS Group Solarmotion Shade[2].

The final area of study would be the removal of the continuous overhang. By removing the overhang an exterior solar tracking shade could be utilized. This system would fit within the existing setback of the glazing. The horizontal louvers would maintain the architects theme. The Solarmotion tracking system is incorporated into a computer system that automatically adjusts the shades as the sun moves in the sky (Figure 9: CS Group Solarmotion Shade). The areas of concern with this system deal with views to the exterior. If a non-perforated blade is selected there will be times without a view of the exterior. This option will be further analyzed with façade redesign, but will be more difficult to fully analyze with the solar tracking aspect.

Façade Specific

In order to fully optimize the daylighting system, each façade would be specific to its orientation. The addition of vertical fins on the East and West façade would maximize performance, but break up the architects theme. This is something that will need to be discussed and evaluated within the design team. In order to fully maintain the architects theme, some sort of continuous horizontal daylighting system needs to be incorporated. Based on the direction of the design team, a combination can be obtained utilizing orientation specific components on the interior. Vertical fins could be utilized on the interior by moving the glazing to the same plane as the face brick. This would have an effect on the solar gain on the window along with the volume of the space that needed to be conditioned by the mechanical system. These types of decisions need to be evaluated within the team to determine the best overall system for not only building performance, but maintaining the horizontal nature of the building.

Shades

The selection of different components, and their materials, of a daylight system has a large impact on the building system as a whole. The selection of shades needs to be evaluated and chosen with input from the Mechanical Engineer. People psychologically feel better when they have control over their environment. Therefore occupant controlled shades may provide the occupant with a better experience within the space. This system is also cheaper, but may affect the overall performance of the system. The decision to fully integrate the shades and their controls into the system will help optimize the system in place. This concept is more expensive and needs to be evaluated on a life cycle cost to find out if it’s feasible to use through the whole building, or location specific.

The shade material also has a large impact on the building system as a whole. Using a dark colored shade is less noticeable from the exterior and is easier to see through providing the occupant with a view, but absorbs heat which adds additional load on the mechanical system. A light colored shade will reflect heat away from the building, but at the cost of occupant comfort. The light shade hinders the ability to see outside, and creates a bright glowing spot on the interior wall of the space. Increasing the transmittance of either type of shade will allow more light into the space, but once again increase the mechanical load on the space. The decision on what type of shade needs to be addressed with the mechanical engineer within the design team in order to select the best one for the building as a whole.

Individual Discipline Compromises for Owner Benefit

When designing a system there are aspects that will lead to cost reduction or other owner benefits in the long run. A furniture integrated lighting design may add increased cost that outweighs the benefits in energy or space saving. Selecting material properties for the daylighting system is another area where a compromise may outweigh the benefits. The increased load on the mechanical system from choosing dark colored shades, or a higher transmittance glazing could potentially trump the added natural light in the building. These are all areas that need to be thoroughly studied and discussed within the design team to find the best possible solution for the building owner.

Mechanical Design

The building envelope consists of a multifaceted system that requires the input of all disciplines to function most efficiently. A natural compromise of each discipline will lead to a whole building solution that best fits the Millennium Science Complex.

The external environment is coupled to the building load through the building's envelope. By utilizing the façade design, heating and cooling loads can be managed. A poor design can result in elevated heating and cooling costs, while a good design helps to minimize the extremes of each. The size of mechanical equipment and the amount of energy consumed by the mechanical systems are directly related to the peak loads that enter the building through the exterior façade.

Reducing and flattening peak loads on a building envelope can have dramatic effects on the upfront selection of equipment. Designers could begin to "right-size" and downsize equipment to help save upfront construction costs. Equipment could be staged to best match the building loads, operating at higher efficiencies creating energy savings.

Adjusting the façade to have an optimal glazing to wall ratio, along with a daylighting analysis will enable a redesigned façade to better react to the environment and generated loads. Design of this system will require integration with the lighting designer to analyze the best façade design to take advantage of both daylighting opportunities and load reduction.

The current exterior facing of brick and concrete while very dense, has poor heat capacity. More effective insulation could be provided while reducing weight if a radiant system or phase change material were added. The heat capacity of a phase change material can be a hundred times greater than that of concrete and has its best operating temperatures between 50 and 85 degrees F – a feasible range for State College. Changing the composition of the façade could have beneficial energy cost savings, while retaining the architectural integrity. A reduction in weight from a composition redesign could also have beneficial reductions in the structural system and construction logistics.

To better manage the exterior loads on the Millennium Complex and realize the potential savings described above, the façade must be redesigned with these goals in mind. BIM will provide the tools to analyze multiple façade designs to select a façade that produces the best whole building life cycle cost.

Future reports will analyze the effects that these changes could have on the whole building life cycle costs and how each application affects other disciplines.

Structural Design

A direct relation is made between the façade and its impact on the structural system. The main goal of a structural system, with respect to the façade, is to adequately support its weight while maintaining its integrity and performance. The existing system clearly addresses these issues, yet a redesign of the building enclosure requires a proportional reaction of the structural system. The new proposed design for the façade will incorporate more effective daylighting as well as attempting to limit the peak thermal loads on the building. This requires the incorporation of alternative and in some cases more materials. Therefore weight is an issue an issue, along with how that weight is supported.

The current precast concrete panels, as mentioned before, weigh up to 25,000 lb. Overall this accounts for approximately one tenth the entire building weight. This is mostly due to the 6-8in of concrete thickness of each panel. Adequate thickness need be given for the inlaid brick veneer and to support the applied materials on the inside of the panel, however the existing thickness is excessive for this purpose. It is plausible that this thickness could be reduced by half. The panels are not structural load bearing, except supporting itself and the applied materials, and should not show as a significant load on the building structure. Other materials as mentioned in the mechanical discussion can be used to obtain the required thermal ratings.

The existing weight also impacts the design of structural elements. Building weight is the defining factor on seismic demand loads. For this structure seismic loads result in the controlling base shear over wind. Reducing the overall weight of the building directly results in a reduction of the design seismic loads. The most effective way to reduce weight is in a system that is currently oversized for its application like the façade. The total load of the façade as a gravity load also affects the sizing of members on exterior frames that must support these loads. A weight reduction may help to reduce the load demand on these exterior members as well as the connections of the structure to the façade panels and lower the cost of the structural system.

Any changes in façade design will author the redesign of the connections applied to the structure to support the façade panels. Every innovative façade system needs an appropriate connection to the structure for support. This will not have a bearing on the overall façade or structural design concepts, but will need to be considered as it is the direct physical contact between the systems.

Façade Redesign Conclusion

The façade redesign for the Millennium Science Complex will utilize design integration. It's important to evaluate all design decisions and how they will impact the building as a whole. Upfront costs for system optimizing materials, such as phase changing material, solar tracking overhangs, specialized glazing, and daylighting control, need to be compared with life cycle and energy costs in order to justify their use. The team also needs to determine whether system performance or architectural theme is more important to the building. These decisions will have a large impact on the overall direction the team pursues for façade redesign, and these decisions cannot be made until further analysis can be done on the proposed design methods.

Plenum Coordination

Problem Statement

The ceiling plenum is the most critical location in the building with regards to system integration. Every engineered system uses this plenum to service and support the multitude of spaces throughout the building. High levels of congestion result in the constant interaction of each individual system with the others. Without a proportional level of integration between disciplines this space becomes littered with component collisions. If these conflicts are not realized or addressed before construction on these systems begin they will be realized in the field causing schedule issues, change orders, and even system redesigns. Therefore it is not the efficiency of each system, but the integration of all systems working as one unit that defines the integrity of a building design. The existing designs, although efficient do not always respond to this goal.

In the existing systems' design highly efficient coordination has been accomplished to accommodate the advanced systems that are in place in this state of the art building. A defining factor in plenum coordination and efficiency is the availability of space, which is directly proportional to the vertical dimension of the plenum and the flexibility of the building systems involved. The main systems involved currently are the structural floor, HVAC duct and pipe, electrical conduit, and lighting systems. A large plenum space measuring approximately 6 feet in height from ceiling to bottom of structure is highly congested throughout the building. Floor to floor heights, although a leading factor in building cost for multi-story medium to high rise structures, does not play as much of a role in the Millennium Complex with only four stories. Floor to floor height can, however, have an impact on façade cost and weight given the large perimeter and massiveness of the existing building enclosure. Instead, system conflicts, spatial limitations, and system compromises are and will continue to be the defining factors in the most effective plenum design.

To produce the most effective plenum design, the compromises, efficiencies and life cycle costs of each discipline must be understood and analyzed. In this following section, each discipline will begin to analyze the implications a plenum redesign could have on their specific design and the interdependencies of the systems involved.

Construction Management

Coordination will be of the utmost importance when constructing an efficient and cost-effective design for the Millennium Science Complex, given its large scale and intricacies. Because the Millennium Science Complex contains a multitude of different lab spaces that have strict requirements on the mechanical, electrical and lighting systems that support these spaces, coordination within the plenum spaces of the building is pushed to the forefront of the issues that must be resolved. Through increasing size of the plenum space, as well as more efficient design and coordination of this space, collisions in the field can be reduced drastically. This, in turn, will keep the construction cost of the building from inflating due to change orders. And, although the number and cost of change orders has not been reported, it is believed to be approaching a very high number. Any reduction in additional work required in the field will be extremely beneficial to both the construction and the owner.

When looking at making the plenum space more efficient and easier to coordinate, one of the first places to look is at the structure. The size and depth of the structure will greatly affect the size of the plenum space available for use. The current design for the Millennium Science Complex uses a steel frame with concrete on metal decking. It is a relatively typical design for the building, with the only significant changes coming inside the framing of the cantilever. While this is a highly economical design for the structure, what it sacrifices is the flexibility of coordination within the plenum space. Deep steel members protrude into the space, reducing much needed space within the plenum, above such areas as the laboratories. This creates coordination issues, which can lead to additional work in the field and additional cost through change orders. Unfortunately for this project, the additional cost believed to be accumulated through change orders is very high. Because of change orders, coordination can be a huge contributing factor towards the cost of building.

In order to improve the space available for the plenums, several concrete designs were created to shrink the depth of the structure. Shrinking these depths, which could be anywhere from one to two feet, will greatly increase the ability to coordinate within these plenum spaces. A concrete building is drastically different from a steel building, and the design of these new structural systems would entail that the building be built, in essence, as three separate structures. The cantilever and all framing required for lateral bracing and anchoring the frame will be untouched and remain intact. The two building wings that begin just outside this frame will be changed to concrete. Changing from steel to concrete will have implications on the cost of the structure, and could very well lower the cost of the structure, depending on the type of concrete system used. However, further investigations would need to be conducted in order to determine the effect this change would have on the structural cost of the building. While the cost of this change may not necessarily have a profound effect on solely the structural cost, it is highly possible that the ramifications of this change can be seen in the reduction in field collisions and change orders. Additionally, the change from steel to concrete can reduce the required time for the large mobile cranes on site, which would reduce both labor and equipment costs for the construction of the structure.

The schedule implications of changing this steel structure to concrete will be of great importance and must be managed carefully. A steel structure can be erected at a rapid pace, but fabrication of the steel members and their lead times must be considered and can slow the process down. A concrete structure, assuming cast-in-place, will have no need for lead times, but the time required for pouring and curing will have an effect on the scheduling and sequencing of the building. Steel erection is also sequenced in a different method than concrete as well. Steel is typically sequenced vertically first, then horizontally, whereas concrete is horizontal, then vertical. This would typically pose a challenge to the construction of a building designed around the sequencing of a steel structure, but if managed correctly, the redesigned structure of concrete and steel could be sequenced in a more efficient manner. Although an investigation of the schedule will be needed to confirm this, because of lead times, it may be possible to start concrete pours sooner than the erection of the steel began. Moving the pouring of the concrete up sooner in the schedule has the potential to outweigh the losses due to increased time required for formwork, rebar placement, pouring and curing.

It is also possible to find ways to speed up the schedule with proper sequencing of the redesigned structure. With the construction of the building essentially broken into three pieces, it is possible to start the construction of the cantilever at the same time as the concrete framing of the wings. The sequencing used for the current structure consisted of completing the foundation, starting steel erection at the ends of the two wings, completing up to the cantilever, and then erecting the cantilever. While efficient for this steel structure, the sequencing that could be used for the redesigned structure would be far different. The concrete would similarly begin pours at the ends of the two wings and move horizontally level by level, but where the difference would lie is in the construction of the cantilever. If the erection of the steel framing of the cantilever could begin at the same time the first level of the building would begin to be poured, the entire structure of the building would be constructed at the same time. The advantage of having the wings built at the same time as the cantilever is that it could be possible to reduce the overall duration of the construction of the superstructure with this type of sequencing.

The logistics of producing a concrete structure during this time frame, as well as having two major trades operating at the same time, presents risks that need to be managed properly. Safety should always be at the forefront of everyone's minds, so efforts would need to be made to maintain a safe and efficient environment. Crane locations would not need to be reconsidered as the locations of the two main cranes used for erection are already in an optimal location for the cantilever. Because pours will be going on around the erection of the cantilever, proper management will need to be done to avoid any safety issues that could arise from these trades working in such close proximity. Assuming pump trucks are used to pump concrete into the different levels of the building, the locations of these trucks would need to be planned to avoid logistical issues. However, the path of these trucks that was used to pump the concretes for the slabs for the current structure could be reused without issue. The trucks were located along the outside of the building on the northwest end adjacent to the Eisenhower Parking Deck, as well as along the south end adjacent to the Thomas Building. These trucks travelled along the edge of the building pumping concrete into each level, which would be equally effective for the redesigned concrete structure. Keeping these trucks on these paths would avoid any new logistical issues within the site.

Another issue that would need to be managed is the time of the year the concrete would be poured on site. Construction of the superstructure began in July 2009 and ran into the winter months. With this in mind, weather becomes a risk for construction. Assuming similar conditions to this past winter, snow becomes a major factor and inhibitor to pouring concrete. Proper management and planning would need to be done in order to avoid delays due to weather. Additives to prevent freezing and to help speed the curing process, as well as use of hot water in the concrete mix will all be necessary steps to prevent issues that can arise from the winter weather. If additives are not used, and a proper temperature is not maintained during the curing process, the concrete may not reach its maximum strength. This presents a serious problem for the construction manager, and must be managed to avoid the need to deal with this.

One of the prominent issues that will need to be faced is the interface between the concrete frame of the two wings and the steel frame of cantilever. These two connections are crucial and can carry much risk. At this point in time, the exact design of this connection has not been determined, but further investigation will continue on how to effectively connect the wings and the cantilever. However, through preliminary analysis, some sort of building expansion joint will be used to join the concrete and steel. This connection presents a risk in that it is possible that more than one structural engineer will be designing the structure. In the event that there is a structural engineer designing the steel frame and a different engineer designing the concrete frame, coordination at this point will be of the utmost importance. During the design phase of this building, these engineers must be required to work together to design a connection that will properly connect the structure without concern or issue. As with all other aspects of this structure, proper planning and management must be done to limit the risks apparent with this type of design.

Coordinating mechanical ductwork within the plenum space can often be a challenge, and on a project with the intricacies of the Millennium Science Complex, coordination can be a great challenge. Mechanical equipment within these spaces will take priority due to the sheer size of the ductwork. A redesign of the mechanical system would clearly follow a change to the structural system, especially if additional space within the plenum space was attained through a structural redesign. One of the overriding issues the design and constructions teams on the Millennium Science Complex faced was the routing of ductwork around and through the structural framing of the building. There are many locations where steel members were cut in order to pass ductwork through, much of which was done through change orders and field work. This presents a concern because change orders create higher costs and can lengthen a schedule if not managed properly. With the institution of a new structural system, especially one designed entirely of concrete, coordination would once again be at the forefront of discussion. However, with a system that would create a larger plenum space, it is possible to avoid the need to run ductwork through the structural framing of the building and avoid the collisions which were evident throughout the building. This would cut down on the number of change orders and the corresponding costs associated with them.

In addition to having more space to improve coordination within the plenum space, this also opens the possibility to redesign the mechanical systems to take advantage of this newly acquired space. The space available to run ductwork is an inhibiting factor when designing ductwork for a system because you cannot design a duct that is larger than the space allotted for the system. With additional plenum space, the mechanical engineer can use this space to expand the sizes of the ductwork, which can lead to a more efficient system. For a specific load on a mechanical system, there is an ideal duct size and layout that corresponds with that system. If a more efficient system is attained through increasing duct size, then this will correspondingly increase the cost of the overall system. However, a more efficient system can reduce the energy required to perform at a satisfactory level. What would result from this is a higher upfront cost with a lower lifecycle cost, which can be a cost savings over the life of the building and a benefit to the owner. A change in the mechanical system would also have an effect on the schedule for the construction of the system. However, it is difficult to predict what type of effect increasing duct sizes would have on the time frame of the installation of the system. Using ductwork that is larger could increase the time required for prefabrication, which would increase lead times. Keeping in mind the goal of making coordination easier and more efficient within the plenum space, it is entirely possible that the change in system would have no effect if the installation of the ductwork was easier due to more space being available and a reduction in collisions.

While electrical systems take up a much smaller percentage of the plenum space in a building, they still must be coordinated within the space to reduce the occurrence of conflicts within the space. If the lighting system were to be changed to a system which incorporates the lighting into the casework of the specific rooms, this would change how electrical wiring is run through the plenum space. Conduit would no longer need to be run to lighting in the ceiling, but rather to outlets in the floor. Coordination would need to be done to account for where these outlets come up through the slab of the floor, and would affect the cost of the formwork as additional formwork would be required for these locations. If this process was done after the slabs were poured, then further cost would be accumulated due to the need for additional field work, which is undesirable. In addition, the cost of the system would also be higher because of the need for more fixtures than a typical lighting system. However, this can be offset by the possibility of a more efficient system, which would reduce the lifecycle cost of the electrical system. The schedule implications of such a change are difficult to predict in that additional time would be required for the formwork for the slabs, as well as running wiring to additional locations. However, a system that does not require light fixtures to be installed in the ceiling, and instead has fixtures built into the casework, can offset the time required for this additional work. Ultimately, the cost versus benefit of such a change would need to be weighed to determine whether the benefits of this change will outweigh the potential negatives.

Structural Design

It is very apparent when examining the existing BIM models the compromises that have been made. The structural system, consisting of typical steel framing topped with a concrete slab on metal deck extends over two feet downward into the ceiling plenum from the finished floor. For the majority, MEP systems routing across the building must stay under the plane of the structural system. These systems may break this plane with branch systems for local serviceability. The structural framing has been laid out effectively with beams spaced at 11 feet, or half the bay width, in most areas. This allows much flexibility for systems needing usable space within the dedicated structural space. However, due to high levels of congestion this space was not sufficient. As noted on all structural plans, including the third floor, penetrations through the webs of the structural framing were needed to effectively route large pipes and mechanical ducts. In some cases this requires the removal of nearly the entire web of a wide flange and varying lengths. This requires extra engineering efforts to retain the strength of these members and extra field fabrication not foreseen in the initial schedule. These techniques were applied in the field and not part of the initial steel fabrication, noted as field changes with revision clouds on the plan drawings. Other structural compromises stem from slab penetrations for electrical conduit at the electrical rooms that required the reinforcing of those areas with added steel framing surrounding those penetrations. Spatial requirements can also imply limits on the size of mechanical ducts, as expressed in the mechanical discussion.

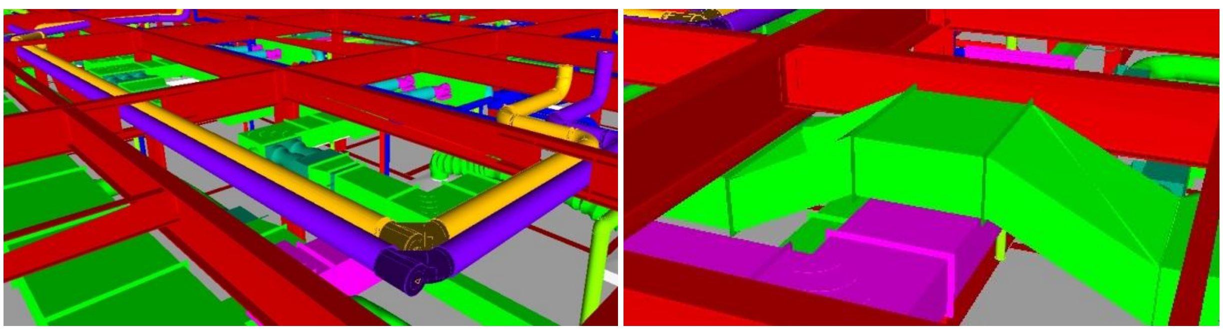

Figure 10: Navisworks views of typical plenum coordination issues.

Structural Optimization

Solutions to these field issues can be solved by reevaluating the effectiveness of each system and its individual impact on other systems involved. When analyzing the structure as an individual system to resist dead, live, and applied lateral forces, the existing system is extremely efficient in some respects, yet could perform better in others. The gravity resisting system is the most efficient component of the structural system. Slabs span the width of the wings in the outside two spans on both sides. Beams spaced at 11ft then span to the beam-girders also running the short-dimensions of the wings transfer loads to the columns. The square bays allow for maximum flexibility of span directions allowing the most interior bay to span all members the opposite direction to account for the higher loads due to the

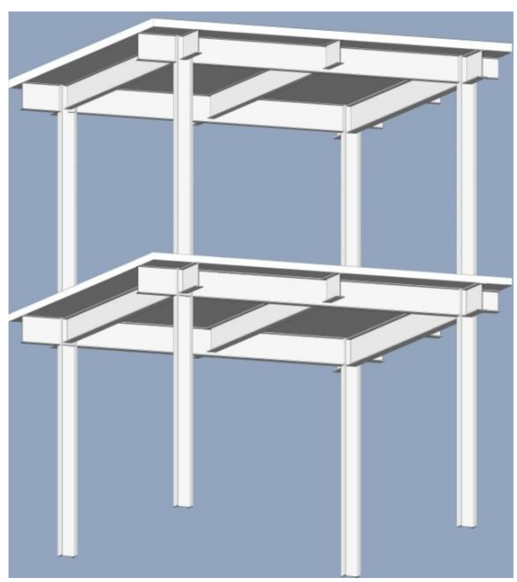

Figure 11: Typical Bay-Existing Steel

equipment corridors on the second and third floors. These square bays at only 22ft allow for the optimized slab spans approaching the allowable limits. Beams and girders have been sized for strength and the most efficient sections have been selected based on weight. One of the issues of this system are these section sizes. The least weight sections will have a greater depth than a lower profile section with a greater weight. In most cases the least weight section will control the design because of reduced cost due to less material costs; however, the deeper sections are causing the coordination problems as discussed above. The added weight of a reduced depth for the framing members would most likely outweigh the extra plenum space attained due to the material costs. This extra height would only be in the order of inches. With ducts over one foot in height running through framing members, a structural profile reduction on the order of the same size would be needed for the most optimized plenum coordination. The presence of these coordination issues reinforces the fact that the most efficient structure is not always the most effective structure for overall building integration. Therefore the existing system needs a reevaluation. The current steel framing may be very efficient as a structural solution for resisting gravity loads, but in some ways, does not address critical coordination issues specific to a building of this magnitude. Therefore alternative systems must be considered for structural as well as interdisciplinary optimization. The optimum system will effectively balance material and construction costs, structural performance, and interdisciplinary coordination, primarily in the ceiling plenum.

Alternative Structural Systems

An attempt has been made to compare the existing steel framing system with other modern typical floor systems. Three concrete floor systems, including a one-way joist and girder, flat plate, and flat slab system, have been designed for a typical bay by bay layout using the maximum existing dead and live loads on the third floor. Alternative steel options have been considered including a girder-slab system and a composite beam system with hollow core precast concrete planks instead of slab on metal deck. Initial calculations for these floor systems have been performed but are not included in this report; however, the results from these designs and advantages of each are discussed in the following paragraphs.

Steel Systems

The girder-slab although highly efficient was eliminated as an option immediately due to the application. This system incorporates a composite design between precast hollow core planks and the steel girders coupled with an extreme ease of construction. Normally used for low floor-to-floor height residential buildings and hotels, the girder-slab puts the concrete planks and the steel girders at the same level that essentially forms a steel and precast alternative to a concrete flat slab. The girder is flame cut in a saw tooth pattern through the web to create WT-sections. A new flange, not as wide yet thicker, is then welded to the saw tooth side of the web as a new flange. Orienting this side upwards allows the steel to be erected first and the concrete planks to be lowered in from above, fit in-between the top flanges and sit on the bottom flanges. Knock outs at each hollow core on each side of the beam are broken and

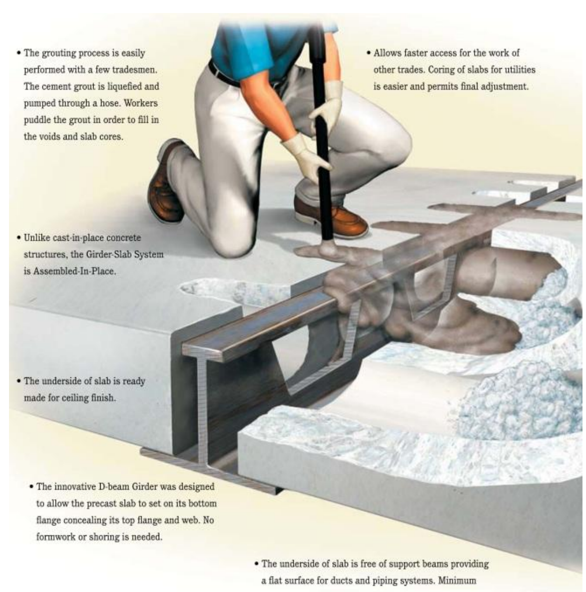

Figure 12: Girder-Slab system[3]

pushed back into the cores. To achieve the composite action grout is then poured over this entire section which penetrates into the cores, through the holes in the beam made by the saw tooth and above the beam flange. In some cases a concrete topping could be applied. This issue with this system is its application to the existing beams and girders, which are composite beams. Girder-slab systems tend to work in applications of low service loads for the fact that the girders are the same or smaller in depth than the precast panels so a low profile structure. This would mean W8 or W10 sections for our building which is not applicable. For our service loads, even with composite beams, W18 to W24 sections are being used. Girder-slab construction could not be done with the large beams without suspending the floor panels higher off the bottom flange. Also even larger sections would be needed due to smaller moment of inertias due to the smaller top flange. This would be uneconomical for our building system.

On the other hand, a comparable system to the existing floor is a composite beam system that uses the precast hollow core planks in a different fashion. Steel studs are welded to the top flange and the planks span from beam to beam and sit either side of the top flange. The planks taper at the ends and channels like the punch outs in the girder slab are also positioned around the beams. Composite action is obtained by grouting the area above the beam, covering the studs and extending back to the ends of the slot channels. This system is a direct comparison to the existing composite beam design, but may be more efficient in some ways. Using load-span table from Bison precast products, for the existing 11ft beam to beam span a 6in hollow core precast panel would be needed. This compares the existing 6 ¼ in light weight concrete slab typical for most of the floors. Similar composite action would be observed for the beams; however, due to a larger topping thickness over the beam to transfer it is possible that smaller beam section could be chosen. Other savings could come from the reduced labor and staff costs for pouring slabs by greatly reducing the concrete poured for the floors on site. The drawback to this system as well as any similar steel system is the impact on the ceiling plenum. No extra space for expansion or enhanced coordination is obtained and existing conflicts are not eliminated.

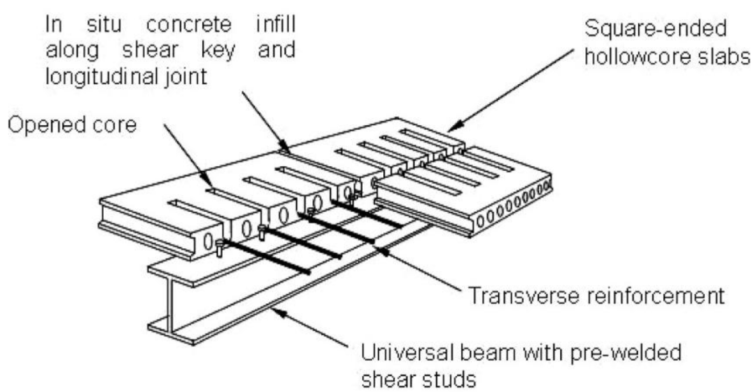

Figure 13: Composite beam with precast hollow core floor slab[4]

Concrete Systems

A traditional concrete system, flexible for many bay dimensions and proportions, the one-way slab-joist-girder system is a multi-purpose system adequate for a multitude of uses. This system includes a generic floor slab collecting floor loads and spanning between pan-joist or beams at a regular spacing that span between large girders, which transfers the load to the columns. The construction of this simple system consists of a consistent shored level of bottom formwork to support the entire floor cast. To then achieve the joist and girder depths, inverted metal pans of a certain depth are setup with spaces in between pans designating the joist and girder widths. Reinforcing bars are suspended within these spaces. The square bay layout allows these components to span in either direction. For this building, girders were run in the long direction of the wings with joists spanning the short directions. A 30/6 pan joist system has been specified, 30in wide pans with 6” wide joists sustaining a 3ft module. The pans are 8” deep. The same depth would then apply to the girders, which with carrying the additive loads from the joists and needing a larger moment resistance, would then have to be wider. The pans have then been specified to extend only 19ft centered in between the column lines to create 3ft wide girders. A general 4.5in slab poured monolithically across the entire system links all joist and girder elements into one rigid floor system. Overall this would result in a raw concrete demand of 9.0 cubic yards (CY) per bay of floor area.

Figure 14: One-way joist system

Two other concrete floor systems were designed as versions of a two way slab design. These are the flat-plate and flat-slab systems. The flat plate is a simple as it sounds. The main system is one solid concrete slab spanning in two orthogonal directions supported only by the columns. No other supporting elements are involved. The formwork is simply one plane of formwork like the one-way system however the slab can be poured directly on this plane at the desired thickness. Reinforcing is suspended above this plane within the slab. This design resulted in an 8in slab thickness; however stud rails would be needed around the columns to resist punching shear, thus resulting in 11.95CY per bay. Also a 10in slab could be used without stud rails resulting in 14.94CY per bay. In some cases if slab thickness is unreasonable due to higher loads or larger spans, a flat slab system could be used, incorporating a thinner slab while adding drop panels - areas of increased slab thicknesses- around the columns. The drop panels help resist punching shear and negative moments at the columns. In this case with the small bay sizes the flat slab design resulted in the same 8in slab with 2.25in drop panels around the columns. This system is adequate however poses no benefit over the flat plat system, no thinner slab, and results in more formwork and concrete material due to the drop panels, at 13.65CY per bay.

Figure 15: Flat plate system

Floor System conclusions

Among the three concrete systems and three steel systems, including the existing system, both the one-way and flat plate systems have the most advantages associated with the goal of optimizing ceiling coordination. The one-way system offers lower concrete material costs, however higher costs are apparent due to extra formwork and pans. Also the one way system is more flexible to slab penetrations as any section of slab in between the supporting joists can be removed without disrupting the integrity of the structure. The flat plate system has some penetration flexibility for core drilling for pipes and conduit; however, if large portions are removed the slab may not be able to support the loads without extra reinforcing for it was designed to span in both directions and not to cantilever in one direction toward a slab opening. The one aspect of these systems that may help decide between the two systems is the vertical profile thickness. The overall thickness of the one-way system is 12.5in while the flat plate can save a few inches of space at only 8in of thickness. In the case of our building where floor-to-floor heights are not a critical issue and the current structural depth extends past 30in in some cases, only 2.5in may not be a deciding factor. Both of these systems add 1-2ft of plenum space depending on the area of the building. If it is determined a steel system should be used, the composite beam with precast hollow core floor panels is a plausible alternative as well. With the assistance of BIM modeling it will be possible to further analyze the effectiveness of these structural floor alternatives to achieve the best integrative solution for the ceiling plenum.

Effect of Floor System on Entire Structure

Analysis of the structural floor system is a general testament to the effectiveness and cost of the overall structural system. However, typical bay to bay structure is only present on the ends of both wings. The majority of this structure is structure is special conditions. These include the quiet isolations labs in the basement and the large cantilevered section above that area. Therefore the main floor system must be integrated with these special systems. The current design of the cantilever does this in an efficient way by extending two steel truss frames in each direction that meet at the ends of the cantilever to anchor it from the two orthogonal directions. This system uses the framing elements, beams and columns, along with diagonal braces, that align with the truss to help transfer the loads back to the c-shaped shear walls and into the foundation. The issue with using a different floor system, especially one with concrete members, is how to support this cantilever structure. There are a few options.

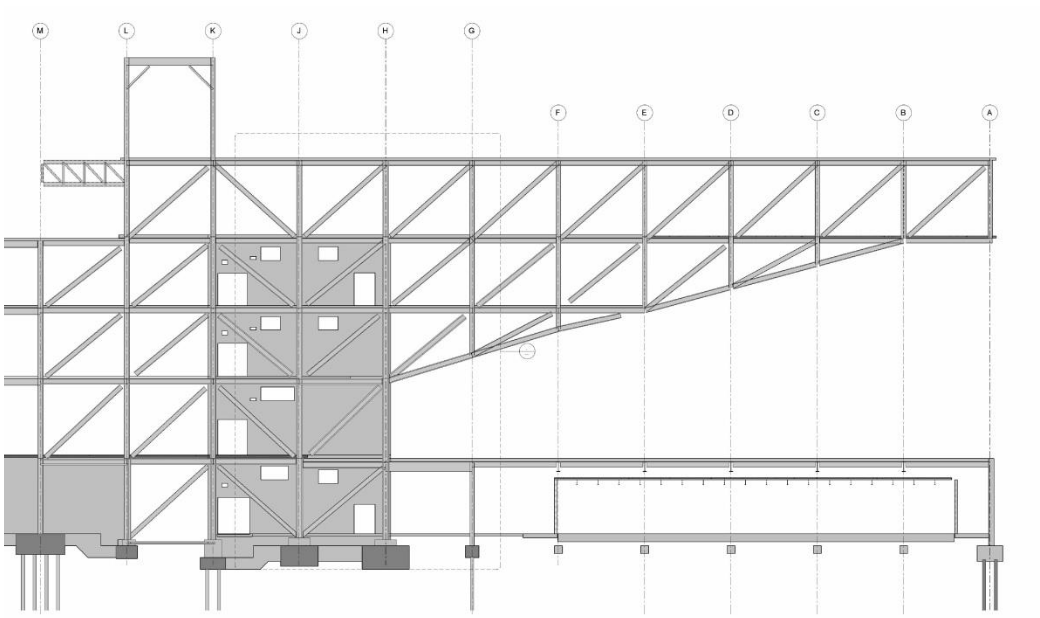

Figure 16: Existing Cantilever- Steel Truss

One option is to continue the use of concrete as the main support system of the cantilever. Instead of a steel truss, a cantilever wall could be used in the same plane, consisting of a thin shear wall coupled with large top and bottom chords of concrete resisting large axial loads creating a counter to the overturning moment. The loads would be transferred to the same shear walls that anchor the current system. The rest of the truss would be a concrete moment frame. This would eliminate the use of steel in the superstructure all together. The basement can also be framed in concrete. Unless it is proven uneconomical the large 81'-7" spans over the isolation labs could potentially e spanned with large concrete double-T beams as in a long span parking structure. Otherwise this area could potentially remain steel as it does not support a superstructure above.

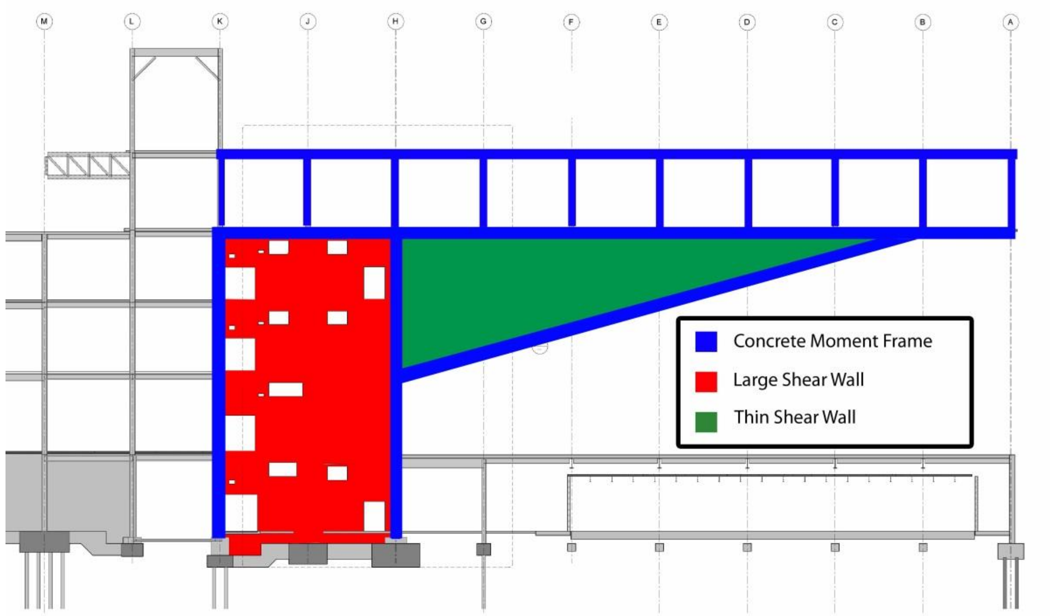

Figure 17: Concrete cantilever alternative

Alternatives to a structure with one primary system are to incorporate a hybrid system of concrete and steel. There are multiple levels to how this would be done. A few are discussed herein. If it is uneconomical due to material cost or inefficient due to constructability, the cantilever support system could remain as the four steel trusses anchored by the concrete shear walls. If then a concrete floor system were to be used, the floor system could be formed and poured around the members of the truss incorporating some of the horizontals into the floor system. Although simple in concept other issues arise. Multiple frames hang from and transfer loads to these trusses including the exterior frame in the cantilever and the two frames in between. In some cases steel trusses spanning perpendicular to the main trusses help transfer these loads. These are needed because a good portion of the usable floor space in this area is also cantilevered, not only the inaccessible space, so long spans occur without column supports. In the cantilever where the exterior bay is hung entirely from the trusses using diagonal braces in tension these members would need to remain steel to adequately connect to the steel in members in the main trusses. Therefore there is no reason to be using any concrete in the cantilever area except for floors. However if all of the framing remains steel there is no reason to continue the all concrete floor system into this area as well for a concrete slab. For constructability this technique would not be suggested.

Instead another hybrid solution is considered. An alternative structural system based on a balance of constructability and systems coordination. The main theme of this design is the division of the entire structure into three completely separately constructed entities. These three independent structures would include the cantilever portion of the building to the back of the truss systems as one building and the rest of each wing as the other two buildings. The wings would be constructed in typical bay construction and the cantilever section would remain the same steel framing and truss design. The structures would be separated by a building expansion joint. Using this technique the three sections of building would be designed separately. This may have benefits with the design of the lateral system of each building. The lateral resistance of the cantilever section would be the same c-shaped shear walls that are there now. In the wings constructed of concrete moment frames, the lateral resistance would be attained with no extra resisting elements; although some walls may be added at stair wells and other slab openings. Also the irregularities of the initial building will be eliminated for the most part.

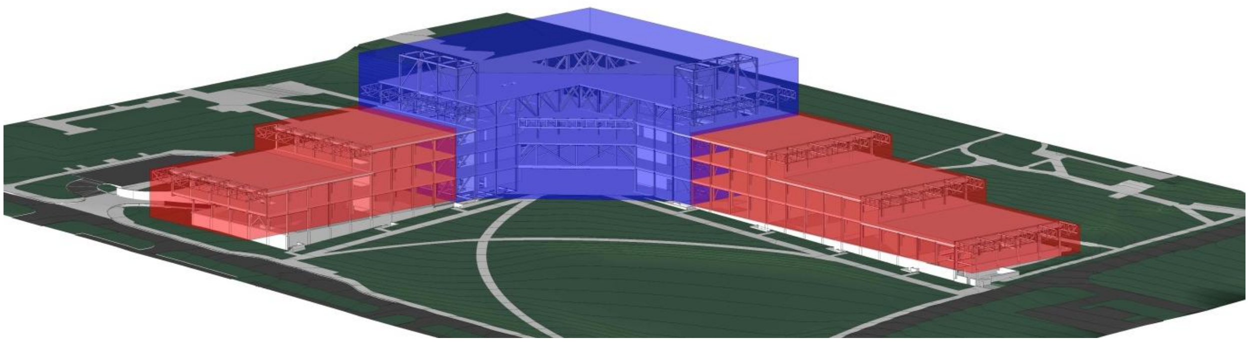

Figure 18: Three building steel and concrete hybrid

In all, considering the entire structure it benefits ceiling plenum coordination to use a concrete floor system to reduce the effective structural profile. Examining the construction documents, most of the coordination conflicts exist in the wings, which warrants using a concrete system in these areas. When looking at the cantilever structure the existing design has been optimized with a steel structure. A further design and analysis of this system in all concrete will be carried through this process, however due to constructability, cost, and schedule an all concrete option does not see plausible. Therefore this area of the structure is proposed to remain as a steel framed system. Therefore from a structural engineering perception as well as considering the goals of BIM*ception* it is recommended that the three building option be used.

Mechanical Design

The design of the ceiling plenum involves the coordination of all disciplines to effectively and efficiently locate the necessary components to provide for the Millennium Science Complex's operation. The design and layout of the mechanical systems uniquely has life cycle cost implications that dictate energy consumption. While the current design successfully employs energy saving strategies, an integrated design approach could better evaluate the relationship between design, construction, and cost.

In the existing design, energy is managed on a demand basis per laboratory space. Each lab employs a combination of occupancy sensors, static pressure sensors, and venturi valves designed to minimize wasted energy. The occupancy sensors are used to provide setbacks for exhaust equipment, reducing the rooms' required air changes to those comparable of an office space (about 4 Air Changes per Hour). In tandem, the static pressure sensors and venturi valves provide the air handlers with information to unload the supply fans. By adjusting to a lower static pressure, there can be great fan energy savings. While the existing design attempts to adjust for static pressure changes, it is possible for integrated design to permanently reduce static pressure.

Based on fan laws, a 10 percent reduction in static pressure creates a 15 percent reduction in fan energy. In the Millennium Science Complex, this 15 percent savings will have a significant effect on energy as supply air fans make up a quarter of the electricity demands. With a nationwide demand to reach 30 percent energy savings over ASHRAE 90.1, each incremental saving has a noticeable impact on reaching this goal.

Static pressure increases in the Millennium Science Complex can be traced back to two basic duct design principles – fitting losses and friction losses. In each case, it is possible for coordinated design to analyze the effect each has on the operational costs of the ventilation system.

Fitting losses in the duct system develop from the energy required to change the direction of airflow. By coordinating the plenum space early in a design, these fitting losses due to unnecessary bends can be greatly reduced. The coordination of space in the plenum now has a tangible reward as fewer fitting losses increase energy savings. To reduce fitting losses, the duct, plenum, and structural systems must integrate to allow for the most direct routing of air.

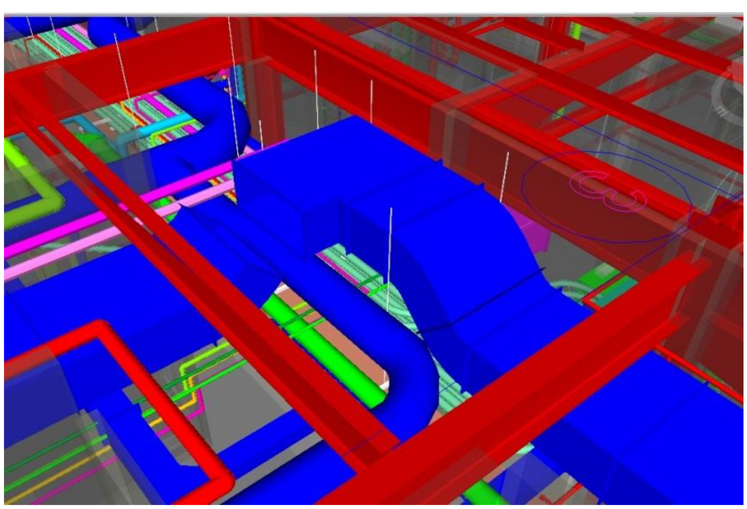

Figure 19: Duct Fitting Loss Inefficiencies in Service Corridor Ceiling Plenum

Friction losses in duct systems are a function of the cross sectional area and the quantity of airflow. By increasing the cross sectional area, the airflow can be kept constant, while reducing static pressure losses and increasing energy savings. An increase in duct size would, however, have adverse effects on the spatial constraints of the plenum, potentially increasing the fitting losses described above. Again, this will require an integrated redesign of the duct, plenum, and structural systems.

Figure 20: Spatial Constraints in Service Corridor Ceiling Plenum

When analyzed in combination – fitting and friction losses – there will be an ideal layout and size of the duct that will reduce the static pressure enough to have significant effects on the energy required to move air. This analysis cannot be done in sole isolation of other disciplines as building design requires the understanding of the interdependencies of building systems. In order to weigh the operational cost savings with the potential savings from other disciplines an integrated design solution must be analyzed. Through coordination, there will be a whole building solution for the Millennium Complex that addresses and balances the life cycle costs of all disciplines. An integrated design approach could then begin to analyze the costs of coordination vs. the costs of operation as a function of duct and plenum size. As energy becomes increasingly expensive, there will be a greater demand to conserve operational costs by requiring more efficient coordination utilizing the plenum space. Design teams will have to work in unison using BIM as a tool to provide the most efficient use of plenum space.

Lighting Design

The plenum space in the Millennium Science Complex is highly congested. This space houses structural, mechanical, and electrical systems. With all these systems needing to fit coordination is a huge focus to successful system design. Plenum space coupled with the selected structural system dictates the height at which the ceiling is located. The ceiling height has an effect on daylighting design along with electric lighting design.

In analyzing the overcrowded plenum space there are a couple areas of lighting that need to be addressed. While looking into a way to provide indirect lighting in conference and seminar rooms, the ceiling height may need to be adjusted. To incorporate a cove system one of two things needs to be worked out, either space needs to be created to raise that portion of the ceiling, or the overall ceiling height of the space needs to be lowered. This decision needs to be coordinated with the structural and mechanical team to determine which solution is better. In an attempt to clear up space in the plenum, a furniture integrated system will be analyzed for the student areas and laboratories. These systems also present the opportunity for added energy savings with reduction in wasted light. The ceiling height also affects the depth of daylight penetration in a space. The higher the ceiling the deeper daylight can go into the space. So in analyzing the daylighting design, any additional height from the structural or mechanical team member could add to system optimization.

Plenum Redesign Conclusions

In a building as complicated as the Millennium Science Complex, plenum coordination is of the utmost importance. Because this space is created through the design of the structure, and houses equipment from the mechanical, electrical and lighting trades, it is highly important to adopt an integrated project design in order to efficiently coordinate and construct these high-traffic locations hidden within the ceilings of the building. Using building information modeling tools can greatly increase the efficiency of this coordination, and should be a requirement in design.

While the current design of the building is efficient, and coordination was done to a satisfactory level, it is possible that through additional analysis and greater integration of all trades, a more efficient, constructible design can be found and developed. This more efficient design begins with the structure, which must be balanced around creating a structurally sound design, as well as allowing ease of accessibility when installing equipment. By finding a design that could reduce the structural depth of the frame, whether it is through a newly designed concrete system or a redesigned steel system, it will provide benefits throughout all disciplines. The system which will be focused on is a three structure design with a combination of steel and concrete. This design will ensure that the logistics of constructing the building do not become complicated beyond need, and will accomplish the goal of reducing structural depth within the plenum space. With more space available for the plenum, the number of collisions can be reduced, which directly lowers both the cost and time required to address these conflicts. In addition, this additional space can lead to an analysis of the mechanical systems, where it can be possible increase efficiencies through adjusted duct sizes and reductions in bends due to collisions. While this could lead to an increased upfront cost, the benefit of a reduced lifecycle and energy costs of the building must be weighed and considered. While both electrical and lighting equipment take up a small portion of the plenum space, this must still be considered. In conjunction with a more efficient, coordinated plenum design, the lighting designs are being analyzed which could decrease the amount of conduit, reducing the potential for collisions to occur. In addition, changes to ceiling heights are being analyzed in conjunction with lighting designs to take advantage of additional space that can be created within the plenum through a redesigned structural system. Similar to the mechanical systems, these system redesigns could push the upfront cost higher, but will provide great returns over the life of the building.

The goal of BIM*ception*'s plenum redesign is to create a more efficient design, leading to stronger coordination within the plenum space. Better coordination will produce upfront and lifecycle cost savings. An integrated design approach and the use of building information modeling will allow BIM*ception* to produce a building product that enhances the potential for the owner's cost savings.

APPENDIX A: Index of Figures and Tables

APPENDIX B: Citations

[1] "Home | Construction Specialties, Inc.." *Home | Construction Specialties, Inc.*. N.p., n.d. Web. 23 Oct. 2010. <http://www.c-sgroup.com/>.

[2] Connor, J.O. (1997). *Tips for Daylighting with Windows*. Berkeley, CA: The Regents of the University of California.

[3] Fig. 1 Composite beam with precast hollow core slabs.Developments in steel composite construction with precast hollowcore slabs. The Structural Engineer, 5 July, 2005. Page 13. www.istructe.org/technical/files/research/28.pdf

[4] The Combined Advantages of Structural Steel & Flat Plate Concrete. Girder Slab Composite Steel and Precast System. Design Guide v1.4, 2008. Page 6. http://www.girder-slab.com/downloads/GSDGv1.4.pdf