Session 1793

INTRODUCING DESIGN-BUILD CONCEPTS INTO SENIOR CAPSTONE DESIGN PROJECTS

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Abstract

Traditionally, there has been a widespread sense on the part of the construction industry of a lack of connection between design engineers and contractors. There have been numerous cases where it has been discovered during the construction phase of a project that a proposed design is very difficult and sometimes even impossible to build. These types of problems can cause significant delays in construction time and increase in cost. For example, in a recent case of a school building construction, a number of large prefabricated steel trusses had to be returned to the fabrication shop for modifications because of incompatible sizing. Part of the problem can be attributed to the fact that some design engineers, particularly recent graduates, may not have had adequate exposure to construction experience. This follows the classic argument that learning out of a textbook is much different than the "real-world."

Civil engineering curricula traditionally focus heavily on design and analysis often neglecting issues of constructability. While this track of education may serve the constituency who are involved in the design phase of the traditional design-bid-build project delivery system, it may not adequately address the needs of firms engaged in the design-build project delivery system. Since the latter system is becoming increasingly popular, it may be prudent for civil engineering schools to place increased emphasis on constructability issues in order to produce industry-ready engineers prepared for work in the design-build system. It is suggested that a construction focus be incorporated into the senior capstone design project. In certain cases, it may even be feasible to make the students perform a limited hands-on construction activity.

An example of such a project is described in this paper. The first author supervised a group of four students at Ohio Northern University during their senior design project in the 2002-03 academic year. The project involved rehabilitation of a second floor observation deck at Schoonover Observatory in Lima, Ohio. The project consisted of design, analysis and a small construction phase. The work was completed with consultation and assistance from the City Engineer, City of Lima, Ohio.

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Introduction

In the United States' higher education system it is common practice to educate architects, engineers and construction professionals in separate programs. In a typical civil engineering program, often there is no significant portion of the curriculum devoted specifically to the introduction of concepts from architecture and construction. In the real word, of course, a significant amount of interaction and cooperation between architects, engineers and construction personnel is required for the successful completion of any project. Chan et al.[1] reported that the traditionally segregated roles that professionals such as engineers, architects and surveyors occupied in the construction industry were changing and that transprofessional practice was becoming more commonplace. They suggested that aspiring construction industry professionals should be educated with a curriculum that embraces a multidisciplinary and integrative-professional approach.

The primary focus of this paper is on the introduction of construction concepts into civil engineering programs. The failure to integrate the curriculum associated with the design phase together with that pertaining to the construction phase appears to be particularly problematic for civil engineering programs compared to other engineering disciplines. At Ohio Northern University (ONU), the capstone project for students in Mechanical Engineering and Electrical & Computer Engineering usually incorporates aspects of both design as well as manufacturability. Students are usually expected to perform a technical design and then build an actual prototype model. Some of the examples of senior design projects from the past include fire-fighting robots, cameras capable of taking seamless panoramic pictures, can-crushers and remote controlled airplanes.

Any experienced construction professional will most likely have an arsenal of stories about foul-ups caused by design engineers. To cite just a few examples – students in the Structures 1 class taught by author FR were on a field trip to view the construction of a new academic building on the ONU campus when they noticed trucks carrying large steel trusses apparently on their way out rather than incoming. The tour guide informed us that the prefabricated trusses had to be sent back because the depth of the trusses did not allow sufficient clearance for HVAC without making the ceiling elevation too low. Another story related by a recent ONU graduate, now working for a construction company, told of a set of plans that specified pipes which had to cross each other at the same elevation! These types of errors translate into economic losses because of construction delays and additional costs.

The authors believe that some of these problems stem from the fact that engineers may not have fully considered constructability issues. One step in the right direction towards resolving this unhappy situation may to be to encourage undergraduate student engineers to "try walking in the contractor's shoes". In other words, they need to think in the same way that the contractor does and consider realistic issues and constructability problems.

Traditionally, the most common system of project delivery has been the design-bid-build approach. In this system the owner commissions an engineer to prepare drawings and specifications under a design services contract. The owner then separately contracts for at risk

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construction by engaging a contractor through competitive bidding or negotiation. The owner warrants to the contractor that the drawings and specifications are complete and free from error. This system is further illustrated by the following flowchart (Fig. 1).

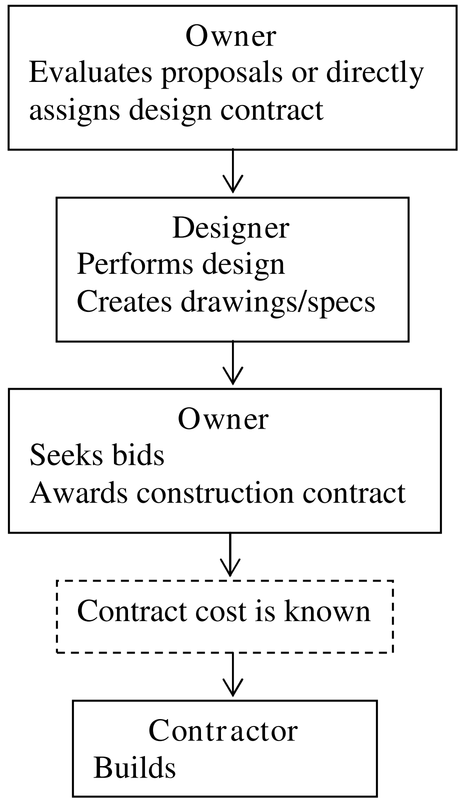

Fig. 1. Design-bid-build approach to project delivery

The design-build delivery system is now rapidly increasing in popularity. In this system, the owner contracts with one entity to perform both engineering and construction under a single contract. The design-builder warrants to the owner that it will produce design documents that are complete and free from error. Under the design-build system it is even possible to begin construction while the full design has not yet been completed. This is known as fast-track construction. The design-build system is further illustrated in Fig. 2.

Molenaar and Saller[2] argue that professionals engaged in the design-build industry have unique educational needs. They state that practicing professionals are now being forced to educate themselves in how their design or construction counterparts think and act; without this understanding and common language, partnerships are not likely to be successful.

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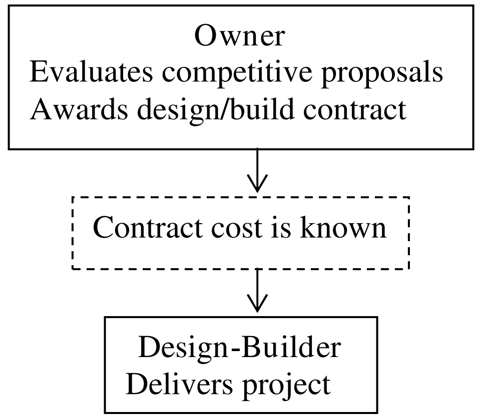

Fig. 2. Design-build approach to project delivery

ABET Criterion 4 (Professional Component) includes manufacturability on the list of topics most of which must be included in the major design experience. It may be argued that the term manufacturability encompasses constructability in the realm of civil engineering. The civil engineering program criteria require that graduates have an understanding of professional practice issues such as "how the design professionals and construction professionals interact to construct a project." The general trend in civil engineering programs across the nation seems to be a reduction in the number of credit hours required for graduation; therefore, it does not seem feasible for civil engineering programs to devote a significant portion of the curriculum to construction issues. The authors do believe however, that construction concepts can be incorporated into senior capstone design courses. An example of such a project is outlined in this paper. The following paragraphs provide a brief synopsis of the efforts of various schools in addressing construction issues as published in the literature.

The Department of Civil and Environmental Engineering at Worcester Polytechnic Institute has implemented a graduate-level course entitled "Integration of Design and Construction."[3] The course involves a mix of class discussion, laboratory and lecture activities. The students are given turns at playing the roles of owner, designer and contractor in studying the same project. The Department of Civil Engineering and Construction at North Dakota State University utilizes real-life projects for senior design drawn from the nearby community[4]. This type of project is known as service-learning. Service-learning can assist students in seeing the relevance of the academic subject to the real world. Students are able to fill unmet needs in the community through direct service which is meaningful and necessary.

The Department of Civil and Environmental Engineering at the United States Air Force Academy has adopted an integrated engineering curriculum approach[5]. Students participate in hands-on construction activities in a Field Engineering course. This is followed by discipline-specific technical design courses in environmental, geotechnical and structural areas. The capstone course is a Construction Management and Administration course. Students build upon a project covered in the previous courses and must incorporate construction engineering and realistic issues. The Department of Civil Engineering at Technion-Israel Institute of Technology has created a construction engineering laboratory that houses many construction-related

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resources such as up-to-date catalogs, videotapes, scale models, drawings etc[6]. Students utilize the room both as part of course requirements through organized activity as well as for individual learning.

Civil Engineering capstone sequence at ONU

The Department of Civil Engineering at Ohio Northern University employs the following sequence of courses culminating in the major design experience in the senior year. Design courses begin in the freshman year as students receive exposure to the fields of mechanical, electrical and civil engineering. During the junior and senior years, students take classes in discipline-specific technical design courses such as Reinforced Concrete Design and Steel Design. In the fall quarter of the senior year, students take a course entitled "Project Management." This course introduces many construction-related topics such as bidding process, scheduling, blueprint reading, quantity takeoffs and cost estimating. Also during the fall quarter, the senior design process begins. Each faculty member is responsible for and spends a considerable amount of time finding suitable projects in his field so that there are at least two projects each in the areas of structural, geotechnical, environmental, water resources and transportation engineering. The majority of these projects are real-life projects with external clients. Furthermore, whenever possible, the faculty give preference to a community type project which can provide for service-learning opportunities. The faculty then draft the problem statements and submit them as Requests for Proposal to the students.

Students are divided into teams of 3 or 4 based on similar interest and such that the average GPA from group to group is similar. Students work in the newly constructed Civil Engineering Design Studio which is designed to simulate a professional workplace environment. The design studio provides ample office space, hanging file folders for full size drawings, computing and plotting facilities, reference library and a boardroom where groups can meet with faculty or external clients. Students prepare statements of qualifications and submit proposals for their top 3 project choices. Students spend a considerable amount of time obtaining background information by talking to faculty members, meeting the outside clients, visiting the sites and even occasionally surveying or obtaining soil samples. Projects are then awarded competitively to the team with the best proposal for that particular project. At the end of the fall quarter, each team makes an oral presentation outlining the scope of work and their proposed plan of attack.

In the winter quarter, students perform the technical design and prepare cost estimates. The teams meet with their faculty adviser on a weekly basis. The final deliverables usually include a final design report, ready-for-bid drawings and an oral presentation. Each team must also prepare a poster for presentation to the College of Engineering Advisory Board. In addition, one team is chosen to make an oral presentation to the board. This team is recognized by inscribing the members' names on a plaque outside the Dean's office. In addition, the Engineering Advisory Board selects the best project and presentation among the three groups from Civil, Mechanical, and Electrical and Computer Engineering.

Rehabilitation of Schoonover Observatory

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Schoonover Observatory (see Fig. 3) was built in 1964 and is located in Schoonover Park in Lima, Ohio. It is owned by the City of Lima and operated by the Lima Astronomical Society. The Observatory is an important venue for community activities because of public visitation, and educational programs that are hosted for adults and children. The main attraction is the 14-inch Celestron telescope, housed within a revolving dome, which is capable of a 360º panoramic view. There is also a second-story observation deck which affords a scenic view of the park and Schoonover Lake. The ground floor of the Observatory hosts a small lecture room.

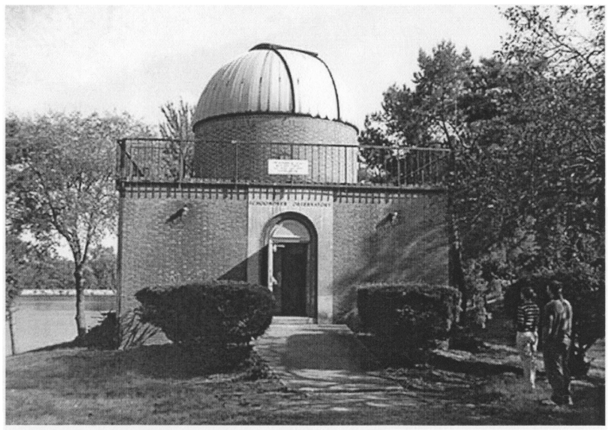

Fig. 3. Schoonover Observatory

In October 2002, Dr. Earl Lhamon, Vice President of the Lima Astronomical Society contacted the Civil Engineering Department of ONU for advice on the deteriorated concrete observation deck. Two faculty members visually inspected the deck and found severe deterioration particularly around the edges. Fig. 4 shows an example where the extent of section loss can clearly be seen. In many places the wire mesh reinforcement was exposed and rusting. There was also extensive cracking of the deck. Members of the Lima Astronomical Society had made several attempts to patch the missing sections and fill in the cracks. The repair patches did not work but the cracks seemed to be satisfactorily sealed. The Civil Engineering Department felt that the project would be interesting to use as a senior design project.

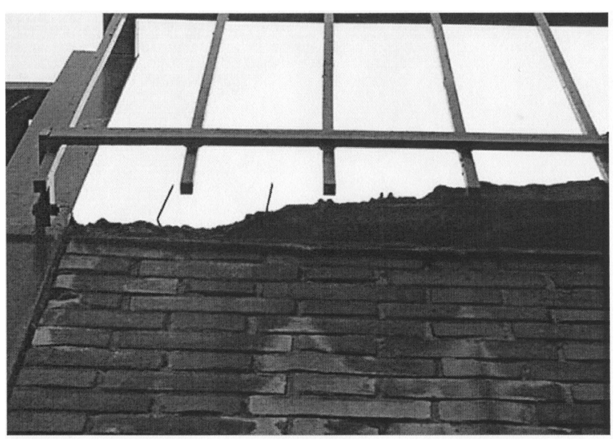

Fig. 4. Side view of deteriorated concrete deck. The concrete slab is intact on the right hand side, but on the left the concrete has eroded to almost full–depth.

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An understanding was reached that ONU students would devise a high quality short-term rehabilitation solution and also offer suggestions for proper maintenance of the deck after repairs had been made. Author FR suggested that the project provided a perfect learning opportunity where the students could perform hands-on construction activity which was within their abilities. An agreement was reached that all work had to be performed with the approval of and in cooperation with the office of the City Engineer. In fact, the Civil Engineering Department welcomed the opportunity for students to work with a practicing engineer. In order to introduce more technically challenging design aspects, author FR also imposed the following requirements: students needed to investigate the causes of deterioration, devise a long-term solution which might include design of a brand new deck, and also propose solutions to minimize or eliminate nuisance vibrations which were affecting the telescope performance.

The unique construction aspect of the project seemed to interest the students as two teams chose the project as their number one choice and another team had it as the second choice. There were a total of six design teams. The project was awarded to a team who adopted the name of Livic Engineering Incorporated or LEI. One of the first things that LEI had to accomplish was to examine the feasibility of pouring concrete during the cold winter months of Northwest Ohio. Based on their recommendation, the City Engineer concurred that it would be best to wait till spring; thus the LEI team voluntarily agreed to complete the construction phase of the project in the spring quarter.

Because the project required the students to construct an actual deliverable that would be open to the public, it was felt that they should have some proper training. Thus, the LEI team was sent to an American Concrete Institute Workshop on Concrete Repair under the sponsorship of author FR and the Civil Engineering Department. The students gained a wealth of information at the workshop. Based on a condition survey and design calculations it was determined that the most likely cause of deterioration of the deck was a combination of low quality concrete, improper maintenance and weathering.

The LEI team conducted a condition survey of the deck using nondestructive methods including hammer testing and chain testing. Based on this testing they were able to determine the extent of damaged concrete that would have to be removed. Fig. 5 shows the areas requiring removal of concrete. Some areas required full depth removal of 5 inches and some required half-depth (2.5 inches) removal. The students also delineated the lines along which saw cuts were to be made. This figure was drawn in AutoCAD and the program was able to calculate the volume of new concrete required.

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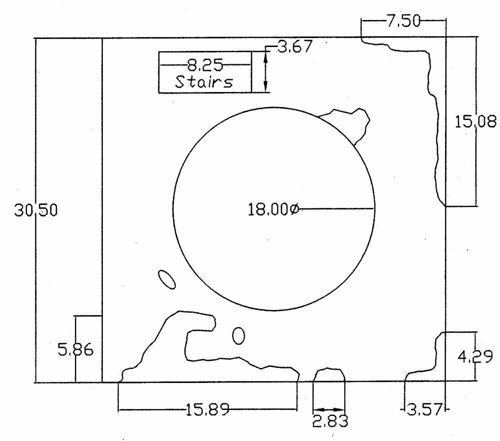

Fig. 5. Areas of deck requiring removal of concrete and subsequent patching. Apart from the big circle representing the dome and the rectangular stairwell, the remaining area represents the surface area of the concrete deck. The damaged sections of the deck are outlined by the freeform curves.

The LEI team evaluated several different cement-based repair mixtures including conventional concrete, conventional mortar, fly-ash concrete, silica fume concrete and commercial bag mix products. Compressive strength tests were performed on test cylinders. The students evaluated the mixes using a decision matrix with several parameters including strength, shrinkage, permeability, ease of placement, availability, cost and color. In the end, a conventional concrete mixture was recommended and the City Engineer also approved this choice. LEI also evaluated several bonding agents and sealers and recommended one of each. LEI then provided cost estimates to the City Engineer. As standard operating procedure, the City Engineer also obtained quotations from two other professional contractors and the LEI bid proved to be the lowest cost bid.

The long-term rehabilitation solution proposed by the students was the complete removal of the existing 40 year-old deck and replacement with a new deck. As such, LEI performed the structural design of a new reinforced concrete deck. The structural design posed some technically challenging aspects which were slightly more difficult than the usual types of problems that students are exposed to in their courses. Fig. 6 shows the floor plan of the existing beams which provide support to the slab. The slab is also supported all around its perimeter by brick walls. The presence of the circular cutout in the center of the slab and the support from the curved beams increased the complexity of the structural analysis. LEI also needed to consider a different live load inside the dome than that outside the dome as well as unbalanced snow loads. They also had to deduce critical locations for live load placement to produce maximum effects. The students performed a finite element analysis of the slab to validate their hand calculations.

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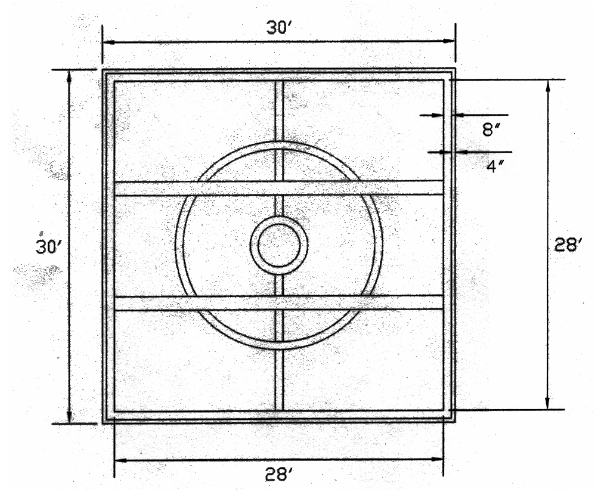

Fig. 6. Floor plan showing beam supports for concrete slab. The small inside circle is a cutout in the slab – this is where the column supporting the telescope comes through. The larger circular beam supports the brick wall atop which the dome rests. There are two additional steel beams that run in the horizontal direction and one in the vertical direction.

The LEI team was forced to consider the construction aspects of demolishing the old deck and building a new one. Since the brick wall which supported the dome was attached to the existing deck, it would have to be removed. The LEI team considered several alternatives including jacking and the use of a crane. The final recommended solution was to demolish the existing brick wall and then later rebuild it with an attempt to match the original as closely as possible.

Dr. Lhamon had indicated that vibrations caused by trains passing on the nearby tracks would cause slight problems with the ability of the telescope to track moving objects such as meteors. The LEI team studied possible solutions to minimize or eliminate this problem. They needed to obtain an estimate of the magnitude of displacement of the telescope caused by vibration. Without having access to accelerometers, the team back-calculated the displacement based on deviations observed through the telescope. This required the students to use their knowledge of optics and geometry. A professor in the Physics Department assisted them with the process. The telescope is placed on a column with its own foundation as seen in Fig. 7. The column is structurally isolated from the rest of the building so that live-load vibration does not affect the telescope. The LEI team considered alternatives such as geotechnical trench digging and base isolation of the telescope.

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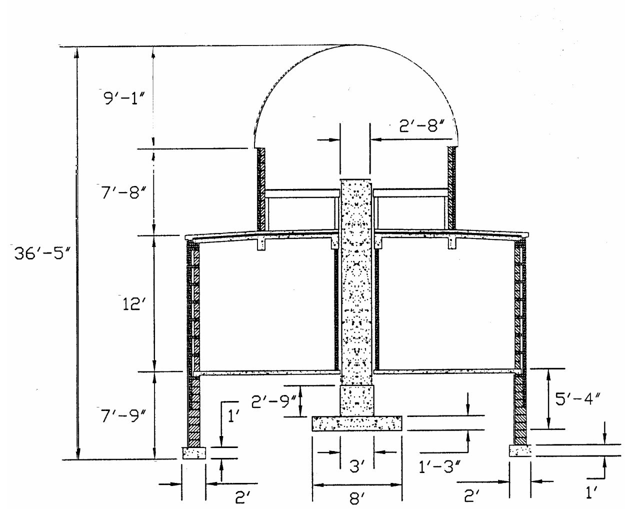

Fig. 7. Cross-section view of Schoonover Observatory. The telescope sits on a concrete column with its own foundation in the center of the figure. Loads from the rest of the building cannot be transmitted to the column and instead go through the perimeter load-bearing walls to separate foundations.

In the spring quarter, the short-term rehabilitation solution was implemented. Because of safety concerns, the City Engineer's Office decided to perform the saw cutting and the formwork construction themselves. On April 26, 2003, the student members of the LEI team performed the repair of the concrete deck (see Fig. 8). They were assisted by their adviser (author FR), the Lima City Engineer and an experienced construction worker from his crew. A final cleaning of loose material was performed, bonding agent was applied by paintbrush, and the concrete was poured and finished. The City of Lima provided a truck carrying the aggregates and cement with a mixer in the back. The concrete was carried in buckets up to the second floor. The experience of the City Engineer and his worker proved very valuable, particularly in the skillful finishing of the floor.

Fig. 8. Repairs being made to concrete deck.

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Conclusions

There is a need for undergraduate civil engineering students to be exposed to construction aspects in addition to the technical design aspects of engineering. This need is expected to become even more critical as the popularity of design-build project delivery increases. An example of a senior capstone design project that incorporated construction aspects along with technical design was discussed in the paper. The project also provided students with an opportunity for service-learning. In other engineering disciplines, it may also be desirable to expose the students to manufacturability concepts rather than just purely technical design; however, many of the typical senior capstone projects already involve the production of a prototype model as a deliverable.

The Schoonover Observatory project was felt to be a positive experience by all parties involved. The students provided positive feedback on course evaluations. The student design team received recognition by being selected to make a presentation to the Engineering Advisory Board of Ohio Northern University. In addition, articles about the project were published in the Lima News, Stargazer Magazine, ONU Alumni Magazine and the ONU website.

Since the project extended into a second quarter, the assignment of grades posed a dilemma. It was decided not to issue a grade of Incomplete since this would appear on the permanent transcript of the students. Rather, a grade was assigned based on the quality of the work performed up till the end of the first quarter with the understanding that it could be changed later if the work was not completed as originally agreed upon.

At the end of the capstone course students are given an evaluation sheet where they have the chance to reflect upon the learning outcomes of the project as well as to comment on team dynamics. Most of the time, all of the members in a team will receive the same grade. If it is evident that one member of the team has not performed satisfactorily, there is the possibility of him/her receiving a lower grade. These problems can usually be detected early on in the project, thus giving the faculty member the opportunity to intervene. This is because students are expected to meet weekly with their adviser, turn in a weekly progress report and document the hours that each individual has spent on each task.

This was the first time that a project of this nature was attempted by the Civil Engineering Department at ONU. For the most part, the experience was viewed as positive. The advantages included an increased sense of professionalism on the students' part which stemmed from the knowledge that they had to shoulder some responsibility, having the opportunity to work on a real-life project with tangible results, having to satisfy an external client and working on a schedule to meet their expectations, and operating within a real budget. These collective experiences can be a powerful teacher. Among the disadvantages of adding a construction aspect is the fact that the project will most likely require additional time to complete. There may also be problems due to some students feeling disenfranchised because they were not involved in a similar experience and conversely the students involved in the project may feel that they are being tasked with extra work.

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It is most likely that the opportunity to implement this type of project may change from year to year. In the branches other than structural engineering, namely transportation, hydraulics, environmental and geotechnical engineering, construction projects may be harder to find. The total number of students interested in a particular area will dictate whether or not a sizable project that involves multiple groups can be used. The fact that students have the choice and only compete for the projects that they wish to work on will ensure that they have the motivation and interest to perform the additional construction aspects. Due to the fact that students may have limited construction experience, and also for safety concerns, the construction tasks should be kept to simple skill levels. Furthermore, because of liability considerations there should be active involvement from experienced practitioners or supervision from professional contractors. Another reason why this type of project was successful at ONU was the fact that students had taken a course in project management so that extra class time during senior design was not necessary. While admitting that these design-build types of projects may be difficult to administer on a regular basis, the authors feel that they provide a rich learning experience and recommend that they should be utilized whenever feasible.

Acknowledgements

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