Architectural Design as a way for Civil Engineers to Learn Building Systems and BIM

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Abstract

This paper profiles an innovative design course in an undergraduate civil engineering program. The course teaches architecture as a senior design option, while integrating multi-disciplinary building systems design and Building Information Modeling (BIM) into the course. Each student designs a complete fire station while satisfying the requirements of an architectural program for a real fire station. The course includes blocks on architectural programming and preliminary design, design development (including building systems design) and design integration and presentation. The students learn how architects and engineers work together in multi-disciplinary teams to complete a building design project. The course is assessed each year through course assessment plans, course assessment reports, student course critiques and program graduation surveys. Quantitative and qualitative assessment data are presented. It supports multiple ABET student outcomes and criteria. Students rate it among their favorite undergraduate courses. More importantly, it prepares them for their future roles in designing and managing real building projects.

Keywords: *ABET, architecture, civil engineering, engineering design, interdisciplinary, BIM*

Introduction

Undergraduate civil engineering programs across the United States and much of the world are accredited by ABET, formerly the Accreditation Board for Engineering and Technology. ABET general criteria for these programs include Student Outcomes. The seven Student Outcomes for civil engineering programs, are:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies [1].

In addition to the student outcomes, ABET's program criteria for civil engineering require curricula to prepare graduates to "design a system, component or process, and to include principles of sustainability in design". The curriculum program criteria on engineering design emphasizes that design is a decision-making process that is often iterative [1]. The American Society of Civil Engineers (ASCE), in their commentary on the ABET civil engineering criteria, explicitly emphasizes including principles of sustainability in design [2].

Although not explicitly required by ABET, Building Information Modelling (BIM) has become a more common subject in civil engineering curricula. It may be more familiar in architecture and architectural engineering but is not yet universal in civil engineering. Abdirad and Dossick conclude that, "BIM education in university curricula is an important requirement for satisfying educational demands of the (architecture, engineering and construction) industry [3]. Barak and Sacks say more specifically that:

> Unless BIM is introduced into undergraduate civil engineering curricula in a fundamental way, graduate civil engineers will lack the skills needed to serve a construction industry in which three-dimensional models are the main medium for expression and communication of design intent and the basis for engineering analysis [4].

Some of the requirements mentioned above would not be easily met in traditional design-oriented technical civil engineering courses. For example, consideration of global, cultural, and social factors has not been part of a traditional civil engineering curriculum until recent years. The ability to communicate effectively with a wide range of audiences might depend on other courses outside of the civil engineering department. The ability to function effectively on a team may come from working with other civil engineering students on group projects. Principles of sustainability might be taught in a stand-alone course rather than included in design courses. Many schools may find it difficult to fit BIM into already full curricula [5].

ABET-accredited civil engineering programs are finding a variety of ways to satisfy some of the newer aspects of these criteria. This paper profiles an architectural design course in an undergraduate civil engineering curriculum as an example of how one course can contribute to these wide-ranging outcomes and criteria.

Background

In addition to roads, bridges, airfields and water systems, civil engineers, especially structural engineers, work with architects and other engineers to design and construct buildings. Students in architectural engineering or construction programs often have an opportunity to take a course in architecture as part of their curriculum. But it seems to be less common for civil engineering programs. At some institutions, especially those with architecture or architectural engineering programs, civil engineering students do have an opportunity to take some type of architecture course, at least as an elective. For example, at Northwestern University's McCormick School of Engineering, civil engineering students can take "Civil Environmental Engineering 385: Architectural Engineering & Design" [6]. How much better might collaboration between architects and engineers be if this were more common?

The first author teaches in an ABET-accredited civil engineering program at the United States Air Force Academy, an undergraduate-only institution with about 4,000 students. The Air Force Academy does not have an architecture program. The civil engineering program includes courses in the sub disciplines of construction, environmental, geotechnical and structural engineering. Every senior chooses two "design option" courses for more depth in one or two of these disciplines. The architectural design course is one of two design options offered by the construction division, and has been taught since 1990. Moreover, the construction engineering discipline is the integrating element of this program curriculum (see [7] for more background). Over the years, both architects and civil engineers have taught the course. The Architectural Design course replaced an older architectural drafting course and focused on residential design from 1990-2014. Students designed a house for a client or their future selves as a vehicle to learn computer-aided drafting (CAD). As CAD programs evolved and became more powerful, the students were able to create more elaborate and often unrealistic "dream houses" in a single semester.

While the course was very popular, and course assessment showed that the students performed well in all its aspects, the instructors concluded that designing extravagant dream houses was not the best way to meet the stated course objectives such as "Integrate structural, mechanical and electrical building systems into an architectural design."

The instructors considered how a more complex building type could include more comprehensive building systems and still be simple enough to design in one semester, which opened the door to designing a fire station which is a facility with many types of industrial, commercial, and residential features in one building.

The Revised Course and its Content

The architectural design course was redesigned and reintroduced in 2014 in a new format to provide civil engineering students a more comprehensive understanding of building design. The most significant change was to reconfigure the course around the design of a fire station rather than a house. The revised course objectives are:

1. Integrate planning concepts and design skills learned in this and other courses to solve a complex, open-ended problem -- the design of a fire station
2. Demonstrate proficiency in using architecture and engineering software as analysis and design tools
3. Apply written and oral communication skills through history presentations, designer/instructor interaction, design narratives and a final briefing.
4. Apply design and construction skills, including reading, interpreting, and creating design and working drawings and 3D Building Information Models (BIM)
5. Practice the professional roles of architects and engineers
6. Integrate site, foundation, structural, mechanical and electrical building systems into an architectural design
7. Evaluate a building's cost, energy use, and sustainability in its design

The revised course continues to teach architecture as a senior design option. Even though a fire station may be relatively small (approximately 15,000 square feet in the course) it still requires a variety of public, industrial and residential spaces. The fire station's site, foundation, structure, heating/cooling and electrical systems better represent the types of projects civil engineers are likely to design than a house. Other small to medium project types might work just as well, such as a child care center, doctor/dentist office or police station. But when the course was revised, the author had recently spent a sabbatical with an architecture firm that had designed several fire stations and was willing to share programming documents. To take on larger or more complex projects would take a two-semester course sequence and be more difficult for engineers to teach versus architects.

Regarding the first course objective above about solving complex, open-ended problems, Saliklis, Ahrens and Hanus describe architecture design courses as requiring students to reach the highest level of Bloom's taxonomy such as analysis, evaluation and synthesis [8]. They describe engineering curricula as often starting at the lowest taxonomy level and gradually progressing to higher levels. The content of this course could help strengthen student progression to higher taxonomy levels.

In the revised course, each student designs a unique fire station of their own. The course includes blocks on architectural programming and preliminary design, design development (including building systems design), design integration and a final design presentation.

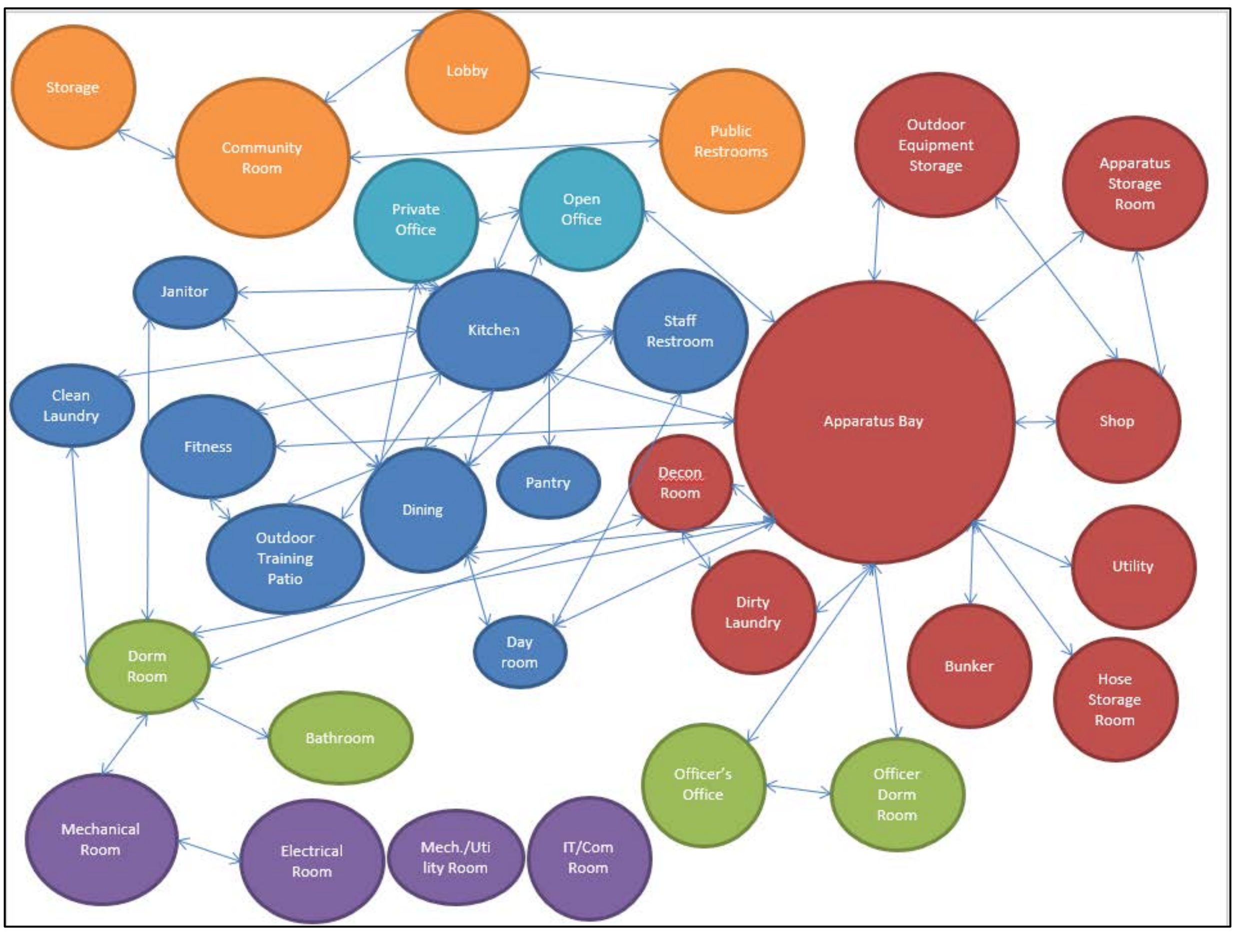

Figure 1. Example Student Bubble Diagram of a Fire Station

The students' designs must meet the requirements of a real and recent fire station architectural program that includes public health, safety and welfare. The course includes a lesson on the National Fire Protection Association 101 Life Safety Code including topics such as assembly occupancy, building egress and fire safety. Early in the course the students visit a new fire station in the local area to better understand the program requirements and to identify design needs from the fire fighters' perspective. They discover that fire fighters have their own culture that must be considered in the design. The students gain some appreciation for other cultures through studying different periods in architectural history and making a presentation to their classmates on what they can apply from other eras in today's designs. They are also constrained by a realistic construction budget and use parametric cost estimating software to check the cost of their preliminary design against the budget.

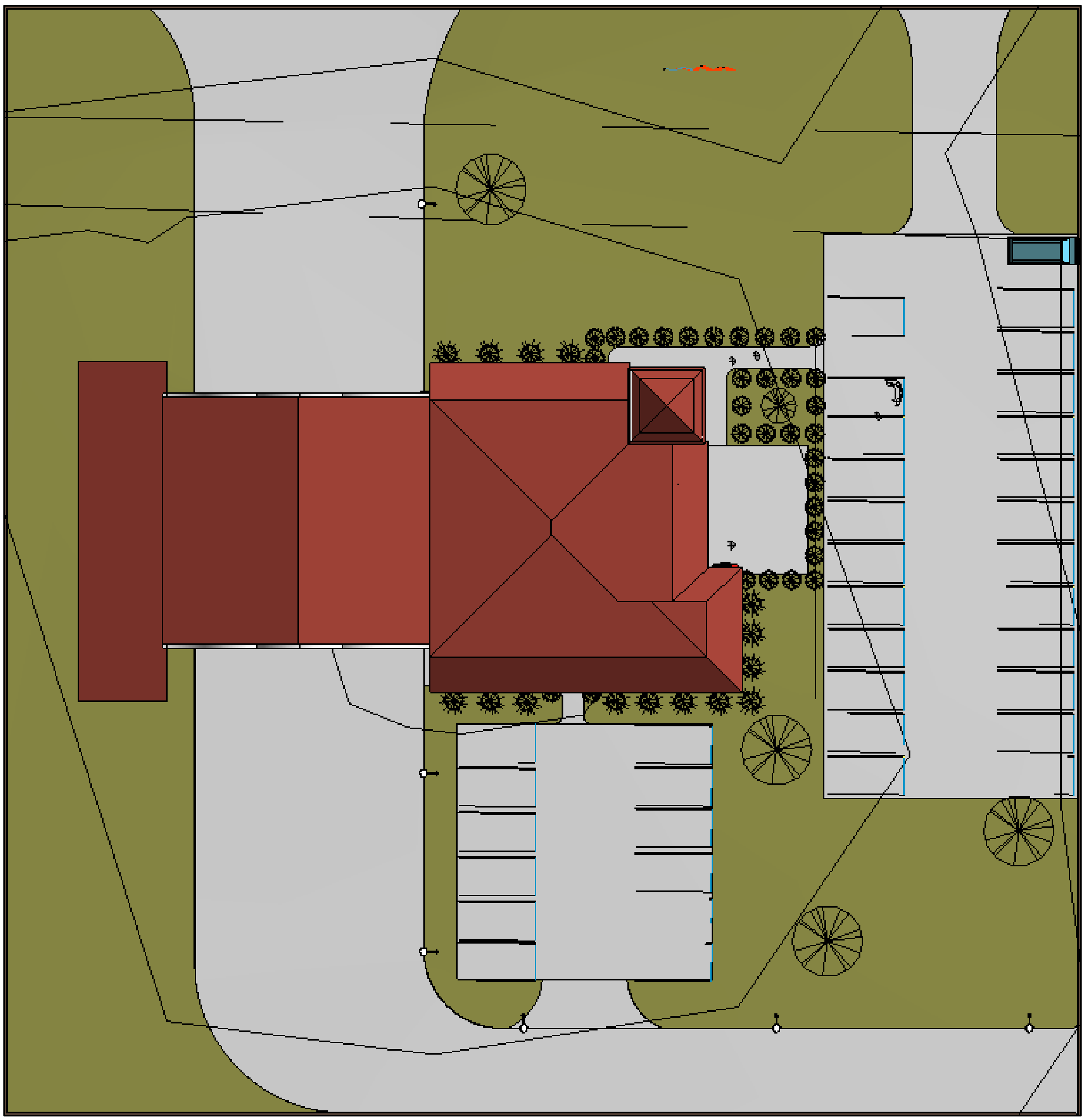

Figure 2. Example Student Site Plan of a Fire Station

Each student has to decide where to place their fire station on a real site. The site design must consider where to locate the building, how to orient it on the site, how to access adjacent roads, provide parking and how to regrade the site for the building and drainage.

Students experience the iterative nature of the design process by translating the architectural program into bubble diagrams. Then, based on instructor feedback, the unscaled bubble diagrams become schematic plans drawn to scale by hand or in Autodesk AutoCAD™. Again, with instructor feedback, the schematic plans are converted into floor plans drawn in Autodesk Revit™ software. In later design submittals, the floor plans will go through more iterations before the final design.

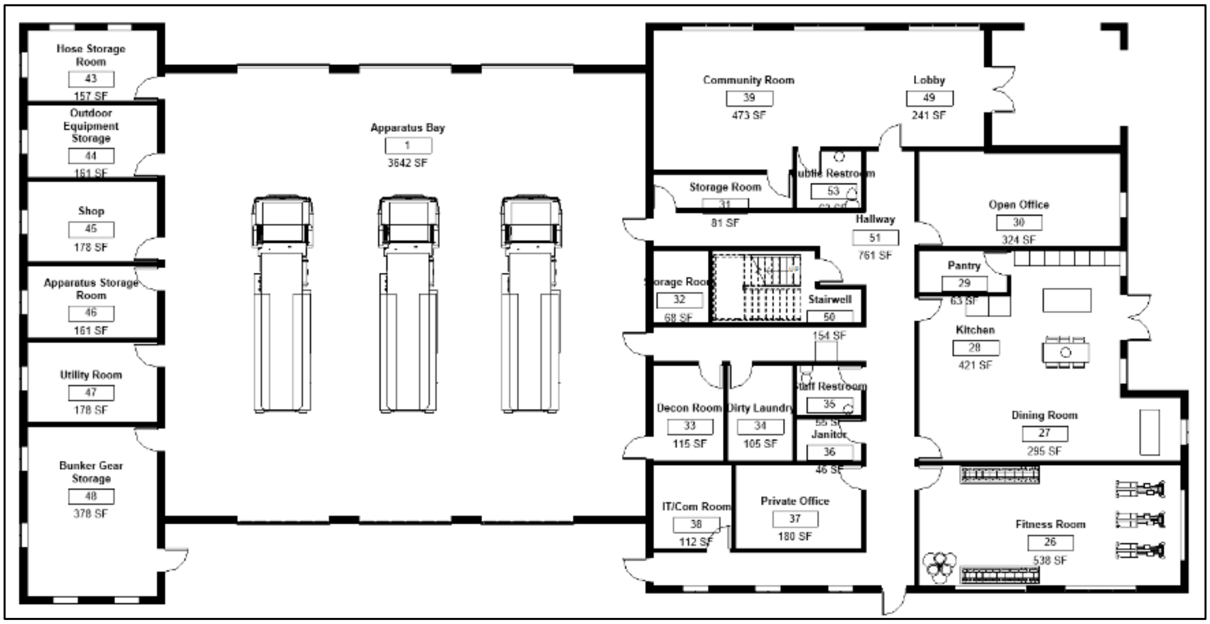

Figure 3. Example Student Floor Plan of a Fire Station

Sustainable design is also a course topic and each student's design must include a strategy for Leadership in Energy and Environmental Design (LEED) Gold certification and complete a LEED scorecard showing specifically which credits they would pursue. This contributes to ABET program criteria for sustainable design and student outcome number 2.

The current version of the course integrates architectural design with multi-disciplinary building systems design. The students learn how architects and engineers work together in multi-disciplinary teams to complete a building design project. The students must integrate their building's site, foundation, structural, heating/cooling, sustainable and electrical designs into the overall architectural design. They learn how far architects go in the initial design of each system before collaborating with engineers or consultants from these and other disciplines in a project team.

In terms of effective communication, many of the assignments include a narrative in which the students must communicate the intent and rationale of their design decisions. The Heating, Ventilation and Air Conditioning (HVAC) assignment is unique in that they don't design the

HVAC system for their fire station. Rather they research multiple possible options for heating and cooling systems, differentiating between the apparatus bay and the rest of the building. After analyzing the choices and considering such factors as life-cycle cost and energy efficiency, the student's product is a recommendation to the client (i.e. the fire department) on which systems would be best for their building design. The site analysis, bubble diagrams and schematic plans assignments encourage students to do some hand sketching and drawing, something Alias. Gray, and Black say engineering students could use more of [9]. In the final presentation they brief their fellow students and multiple faculty on how their unique design satisfies all the project requirements.

The course progressed from teaching various versions of a CAD-based approach to a Building Information Modeling (BIM) workflow in the revised course. The students become fairly proficient with Autodesk Revit software by the end of the semester. Dr. Ali Nejat conducted a study that showed Revit was among the most widely used BIM platforms in the construction industry [10]. The students produce a 3D site and building model that is comparable to the 60% design phase for a real project. Using Revit as a BIM tool enables students to better communicate their building's three dimensional design, building materials, building systems, sustainable design, energy use, and to estimate its cost. This is consistent with the National Institute of Building Sciences definition of a building information model as, “a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward [11]." These sorts of BIM skills not only support ABET student outcomes and our course goals, but industry increasingly expects them of our graduates [3]. Dr. Alcinia Sampaio even goes so far as to say, “Universities must focus on the strategy of using BIM as an innovative technology to allow the acquisition of the new skills by students and prepare them for their future activity in a more competitive world” [12].

Since some of the course topics are not mentioned above, here is a more complete list:

- Architectural History
- Professional Roles of Architects and Engineers
- Architectural Program and Building Scope
- Planning Principles
- Site Analysis and Planning
- Site Design
- Site Grading and Topography
- Solving Ill-defined Problems
- Written and Oral Communication
- Functional Relationships/Bubble Diagrams
- Life Safety and Welfare
- Revit Architecture software use
- Building Layout & Floor Plans
- Parametric Cost Estimating
- Sustainable Design
- Foundations & Floor Slabs
- Building Envelope/Materials

- Roofs & Curtain Walls
- Architectural Drawings
- Structural Systems
- Electrical & Lighting Plans
- Heating & Cooling Systems
- LEED v. 4 Scorecard and Strategy
- Working Drawings
- Architectural Rendering

Figure 4. Example Student Exterior Rendering of a Fire Station

Curriculum Integration

Students who wish to take the architectural design course must first take a 200-level prerequisite course to learn basic competency in AutoCAD and Revit. With this basic proficiency, the students acquire additional depth of Revit skill in the architectural design course. Lesson by lesson, they apply their Revit skills to create their individual fire station designs.

In the final semester of their civil engineering curriculum, all students take a common capstone course together that integrates their design option experiences as collaborative project team members. Clevenger et al [13] recommend this approach of students learning BIM skills and concepts in a standalone course and then applying their more advanced skills in engineering courses such as a capstone. In our capstone course, students who have had the architectural design course take the lead in their team's building design while collaborating with other team members on the foundation, structure and environmental design requirements. While they worked individually in the architectural design course, they experience an integrated design team in the capstone course.

Course Assessment

The course is assessed each semester through a course assessment plan, a course assessment report, student course critiques and program graduation surveys. Course assessment plans include recommendations from the previous offering and describe assessment methods such as instructor/student interaction, design submittals and final presentations. The plans also show which graded events assess each course objective. They also map the course objectives to which student outcomes they support (see Table 2 below).

Course assessment reports assess how well implementation of previous recommendations succeeded. They also include specific assignment results to assess course objectives, provide lessons learned and recommendations for the next course offering. Examples of recent lessons learned include:

- Providing note-taking outlines encourages students to take more thorough notes and to remain engaged during the lecture portion of lessons
- It is important for student success with Revit software to enforce completion of the prerequisite course
- Because of the software-based nature of the course and the computer lab, the instructor can only manage a limited number of students per section

Table 1. Linkage of Course Objectives to ABET Student Outcomes

Architectural Design Course Objectives	ABET Student Outcomes						
	1. Solve Engineering Problems	2. Engineering Design	3. Communicate	4. Ethical & Professional	5. Function on a Team	6. Experiment, Analyze & Interpret	7. Acquire & apply Knowledge
1. Integrate planning concepts	x	x					
2. AE Software	x	x					
3. Communication			x				
4. Drawings/3D BIM		x	x				
5. Professional Roles		x	x	x		x	x
6. Building systems integration	x	x					x
7. Evaluate cost, energy & sustainability		x		x		x	x

Examples of recommendations for the next offering tend to include additional design or BIM capabilities that new versions of the software allow, such as energy modelling, and how to incorporate them in the course content. After ten semesters, the execution of the course is well established and indicators of success are routinely exceeded. The greatest value of the course assessment report is in identifying trends and measuring results of course adjustments.

The house design version of the course was popular and received positive feedback from students in course critiques. For example, in spring 2011, 27 of 66 seniors (41%) in the civil engineering program took Architectural Design as one of their two design options. They rated the value of the course overall at 5.6 on a 6 point Likert scale. That compared to an average of 4.67 for the department's 14 other courses.

The new fire station version of the course continues to be a popular choice. Although Architectural Design is just one of eight (12.5%) design option courses, in the last two years 42% of civil engineering majors have chosen it as one of their two design options. The course continues to receive high ratings on recent course critiques, averaging 5.8 out of 6 for overall value over the last three semesters. Focus groups of our graduating seniors rate it as among the best design options and some students rate it among their favorite undergraduate courses.

Conclusions

This paper describes a course that is unique and innovative in multiple ways. First, it gives civil engineering students an appreciation for architecture and the role of architects, their future colleagues. The students in this course come away with a better understanding of how their role as civil engineers integrates with the rest of a building design team.

The reader may respond that this sounds nice but would not work at a school without an architecture program. But this institution does not have one either. The course doesn't have to be taught by an architect. A civil engineer with BIM expertise and experience in building design can also teach a course like this. In fact, since 1990, eight of the twelve instructors have been civil engineers with a construction engineering background. They often supplemented their own expertise by bringing in architects as guest speakers and to give students feedback on their designs.

The authors intend this as an example of how one course can support multiple ABET outcomes and criteria. The course objectives link to six of the seven ABET student outcomes. Besides the obvious problem solving and design, the course requires students to consider public health, safety, and welfare, cultural, environmental, and economic factors. The students must communicate effectively with their classmates, their clients (fire fighters) and instructors. Among the ethical and professional responsibilities they learn are satisfying economic and environmental requirements through cost estimating, site and sustainable design. The students research, analyze and recommend the best option for their building's HVAC system. And the course prepares them to work collaboratively with other civil engineering disciplines in their capstone course.

This architectural design course provides a unique way of including BIM and building systems in a civil engineering curriculum. While it may not be necessary for every civil engineering graduate to be able to design with AutoCAD or Revit, some level of BIM literacy is required for success in the current technologically advanced the AEC industry.

We consider it an improvement over our old house-design course. Anecdotally, one of our 2007 graduates who took the earlier version of the course said during a recent campus visit that he has not designed a house in his career as a structural engineer, but he has designed a fire station. Most importantly the architectural design course prepares civil engineering students for their future roles in designing and managing real building projects.

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