

Building Sustainability into Control Systems: Preliminary Assessment of a New Facilities- Based and Hands-On Teaching Approach

Melody Baglione, *Member, ASEE*, and Gerardo del Cerro, *Member, ASEE*

Abstract—This paper presents an overview and preliminary assessment of an NSF TUES funded project, “Building Sustainability into Control Systems Courses.” The new inductive teaching strategy utilizes an energy efficient academic building to provide students with direct, practical exposure to modern heating, ventilation, and air conditioning (HVAC) and building automation systems. Students are taken on tours of the building’s HVAC mechanical rooms and partake in process control laboratory experiments. New curriculum materials introduce basic operational principles of central HVAC systems and provide an overview of the control systems theory involved. A value-added, mixed-method assessment strategy uses both qualitative and quantitative techniques to closely track student performance and outcomes. Preliminary direct and indirect assessment results reveal this new facilities-based and hands-on teaching approach helps students appreciate the real-world applicability of control systems theory.

Index Terms—control systems education, inductive learning and teaching, mixed-methods evaluation, building automation

I. MOTIVATION

MANY studies have found that traditional, lecture-based undergraduate engineering courses leave many students with an abstract or incomplete understanding of the concepts being taught [1]. Several methods of inductive learning, in which students are actively engaged with practical applications or experimental procedures, have been generally shown to provide engineering undergraduates with a broader understanding of course material [2]. The case study approach can be an effective inductive learning method since students are shown how the theory they are learning has been applied to existing engineering projects [3]. Students at Purdue University reported that case studies added realism to their coursework and increased their level of engagement [4]. The University of Minnesota expanded on the case study concept

by developing facilities-based undergraduate thermodynamics course materials and also reported positive results [5].

The motivation for this NSF sponsored Transforming Undergraduate Education in STEM (TUES) project is to reveal the real-world relevance of control systems theory by exposing students to actual mechanical systems housed in *their* environment. Since all academic buildings have heating, ventilation and air conditioning (HVAC) systems and their design encompasses many engineering concepts, why not leverage these systems to enhance student learning and motivation? Given that students are often familiar with typical home heating and refrigeration systems, introducing feedback control theory using HVAC systems may further improve learning by helping students build on their existing knowledge structures [6]. Exposing students to green building technologies also increases awareness of the importance of sustainability and has the potential to further elicit student interest and motivation. This paper presents preliminary assessment results of a facilities-based and hands-on inductive teaching approach. This new approach utilizes modern HVAC facilities to tangibly illustrate feedback control applications and introduce the importance of sustainable building technologies.

II. BACKGROUND

This project implements and evaluates several new inductive facilities-based and hands-on teaching methods in a junior-level mechanical engineering Feedback Control Systems (ME151) course. ME151 is a continuation of the Systems Engineering course (ESC161), which introduces students to the mathematical modeling and time response analysis of mechanical, electromechanical, fluid, and thermal systems. ME151 builds upon this knowledge, teaching students various methods of analyzing and controlling linear time-invariant (LTI) dynamic systems. Course topics include root locus and frequency response analysis methods, computer simulations using MATLAB, and PID control applications.

The project aims to improve student learning and motivation by leveraging a new Leadership in Energy and Environmental Design (LEED) Platinum certified academic building, shown in Fig. 1, as a context to explore applications of the theory they learn. Another goal is to provide students with opportunities to experiment with systems that mirror those they would encounter in professional practice. To achieve these goals, the ME151 course was redesigned to incorporate a

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M. Baglione is with the Mechanical Engineering Department, The Cooper Union for the Advancement of Science and Art, New York, NY 10003 USA (email: melody@cooper.edu).

G. del Cerro is the Director of Institutional Assessment at The Cooper Union for the Advancement of Science and Art and serves as the external evaluator for this project, New York, NY 10003 USA (e-mail: cerro@cooper.edu).

significant laboratory component [7]. In eight new laboratory sessions, students are exposed to practical applications of process control using two experimental rigs from Feedback, Inc. The first rig allows students to control the level and flow of water through a circuit and tank, while the second rig is a thermal system, as shown in Fig. 2, in which temperature is regulated by controlling the primary and secondary flow rates through a heat exchanger. Using both these rigs, small student groups identify process variables in the physical systems and utilize industrial control equipment to implement the tuning methods learned in class.



Fig. 1. 41 Cooper Square. A new LEED Platinum certified academic building is used as a context to explore control system concepts.



Fig. 2. Temperature Process Control Rig. Students apply feedback control principles to control the primary and secondary flow rates through a heat exchanger.

Midway through the course, students are taken on a tour of the HVAC mechanical rooms (refer to Fig. 3) and are shown the Building Management System, a state-of-the-art automation system that monitors and manages every aspect of the building's operation (refer to Fig. 4). As part of this project, the faculty and student researchers created a content management website (engfac.cooper.edu/melody/10) that includes system descriptions, photos, and schematics [8]. An excerpt of the content management website is shown in Fig. 5. Before the tours, students are assigned background reading from the content management website to supplement their learning from the tours. An energy dashboard is also under development to give students access to real-time building energy consumption.



Fig. 3. Centrifugal Chiller. Students visit the chiller mechanical room during building tours.

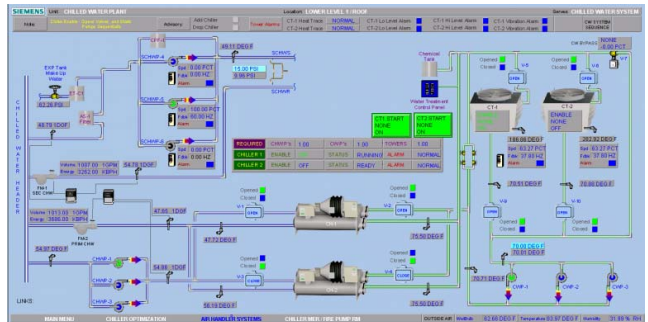


Fig. 4. Building Management Site (BMS). Students are shown the BMS, a central control system that monitors and manages the building's operation.

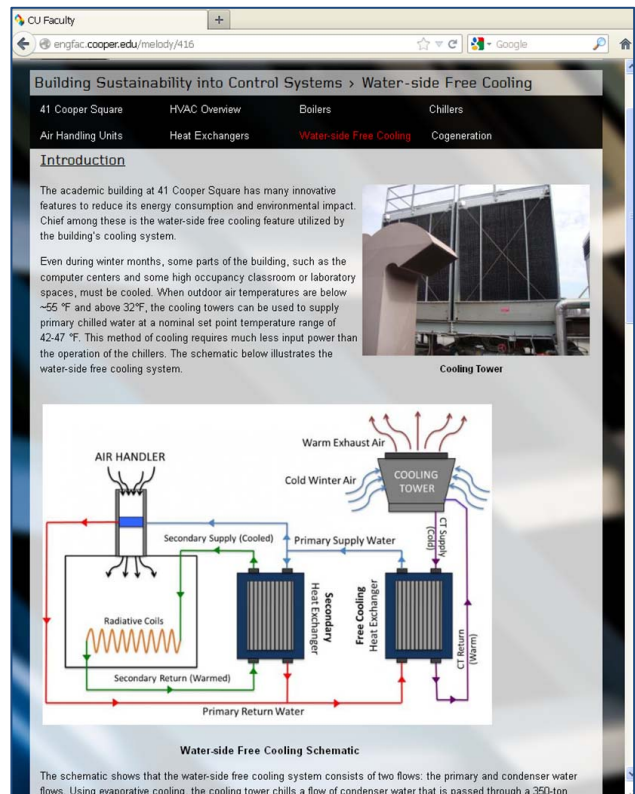


Fig. 5. Content Management Website. Students are assigned background reading material before going on mechanical room tours.

The project has two main objectives: (1) to create new learning experiences and curriculum materials that introduce

students to building systems and their related control systems terminology, and (2) to provide opportunities for hands-on process control experimentation within the context of real-world applications. The student learning outcomes for the ME151 course are listed in Table I. The new teaching strategies are intended to fulfill three new student learning outcomes as indicated by the asterisks in Table I.

The new teaching methods also aim to foster active student learning and thereby increase student motivation and engagement. The following is a discussion of the plan to

TABLE I

FEEDBACK CONTROL SYSTEMS STUDENT LEARNING OUTCOMES

1	Students will be able to characterize the proportional, integral, and derivative terms in a controller and tune controller parameters to improve the performance or stability of systems.
2	Students will be able to explain qualitatively and quantitatively how behavior can be improved according to performance specifications, such as rise time, overshoot and settling time, using a combination of parameter tuning and feedback control.
3	Students will be able to predict and show in the complex plane how pole and zero location affect system response.
4	Given a linear, time-invariant differential equation and a sinusoidal input, students will be able to sketch the frequency response and use the gain and phase to predict stability, steady-state output, and transient performance.
5	* Given a system, students will be able to identify the control goals, the process variables, the controller inputs and outputs, and the corresponding sensors and actuators.
6	* Students will be able to describe the basic operational principles of fundamental central HVAC systems.
7	* When designing a system, component, or process, students will consider the impact of their design on the environment and energy consumption.

assess these new learning outcomes and the project's impact on student learning and engagement.

III. ASSESSMENT PLAN

A. Nature and Purpose of the Assessment Plan

The benefits of inductive learning and case-based approaches include broader student participation in the learning process, enhanced communication skills, and promotion of critical and proactive thinking. Case-based, active learning approaches also facilitate the development of "soft skills" necessary for engineering graduates as embodied in the ABET Engineering Criteria (EC) 2000 outcomes.

Instructional activities that use concrete manipulatives in engineering education, including hands-on experimentation or case-based learning experiences, help instructors address a broad range of conceptual and engineering knowledge and personal attitudes. Assessing learning goals across this broad spectrum requires "a repertoire of assessment strategies that promote the fit between learning styles and desired educational outcomes [9]." As such, the project assessment plan follows three paradigms:

1. It is *value-added*, utilizing a pre- and post- evaluation method of student learning gains via concept inventories and a standardized Student Assessment of Learning Gains (SALG) survey instrument.
2. It is *mixed-method*, using quantitative (pre- and post-concept inventories and scoring rubric of teacher/assessor observations of student behavior)

and qualitative (semi-structured interviews and rapid ethnography) evaluation techniques.

3. It is *performance assessment*, with a scoring rubric based on Bloom's taxonomy to code and register student cognitive understanding, and closely follows the design of the project from inception.

B. Value-Added Evaluation

Direct value-added assessment is an effective way to measure student learning by measuring and comparing what students know and can do at a minimum of two points in time. For this project, baseline surveys are implemented at the beginning of the ESC161 course, an interim survey at the end of the ESC161 course, and a final survey at the end of ME151. The student learning outcomes were formulated into questions using the SALG survey instrument. The SALG is an online survey that measures student perceptions of their learning gains due to any components within a course [10]. In addition, specific SALG questions on student attitudes measure the course's influence on student engagement and motivation. A pre- and post- concept inventory also measures student learning before and after the mechanical room tours and writing assignment.

C. Mixed-Method Evaluation

In addition to surveys, the project incorporated a mix of quantitative and qualitative evaluation approaches where students were assessed by instructors or assessors rather than themselves. The evaluation plan followed a mixed-method approach and included:

- i. *quantitative* techniques: a writing assignment graded using a cognitive skills rubric and pre- and post-concept inventories whereby the instructor is able to assess and quantify student understanding as it relates to the project at hand, and
- ii. *qualitative* techniques: the use of semi-structured interviews and observations by an external assessor to probe results from student surveys and to clarify the nature and extent of student learning gains as well as the characteristics of student behavior during the project.

D. Performance Assessment

Performance assessment suits the nature of this project as it highlights the behavioral components of student learning. Student behavior and understanding is observed and then rated in a scoring rubric. The progression of the proposed new teaching approach is loosely based on Bloom's taxonomy and the levels of intellectual behavior important in learning [11] and Kolb's experiential learning sequence [12]. The project follows a sequence that involves:

1. Introducing a problem and providing motivation by relating it to students' interests and experiences: the focal question is why?
2. Presenting pertinent facts, experimental observations, theories and principles, and problem-solving methods: the focal question is what?

3. Providing guided hands-on practice in the methods and types of thinking the lessons are intended to teach: the focal question is how?
4. Encouraging exploration on consequences and applications of the newly learned material: the focal question is what if? [2].

Designing a sequence of activities around this learning cycle is complimentary to different learning styles [13].

The project assessment is ethnographic in nature as it involves field evaluation work done in natural settings which can yield a broad picture and a more complete context of the hands-on activities. In a rapid ethnography model, researchers perform short focused studies to rapidly gain understanding of the research problems and the actions surrounding them. For this project, an external evaluator observed lectures and laboratory sessions. The external evaluator also interviewed current and former students and other key informants, including senior faculty personnel and student researchers.

IV. PRELIMINARY RESULTS

A. Student Assessment of Learning Gains (SALG)

The SALG survey consists of two question types. Most questions in the survey are in a multiple-choice format, allowing students to qualify their learning experience using a five-point Likert scale. The SALG includes a standard template of questions and also allows users to create custom questions. The student learning outcomes from Table I were formulated into pre- and post- survey questions. At the end of ESC161 (prior to ME151 hence “pre”) students were asked to comment on their ability to perform the student learning outcomes. At the end of ME151 (hence “post”) students were asked how the course experience helped their ability to perform these student learning outcomes. The pre- and post-results for the new student learning outcomes are shown in Figs. 6-8. For all three new learning outcomes, students on average felt the course experience provide some help in improving their abilities and in most cases, the course experience provided much help.

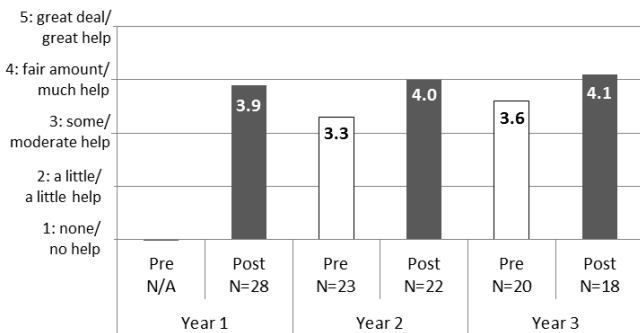


Fig. 6. Pre- and post-SALG survey results. The results reveal students’ perceived ability before taking ME151 and how the ME151 course helped improve their ability to “identify the control goals, process variables, controller inputs/outputs, and the corresponding sensors and actuators.”

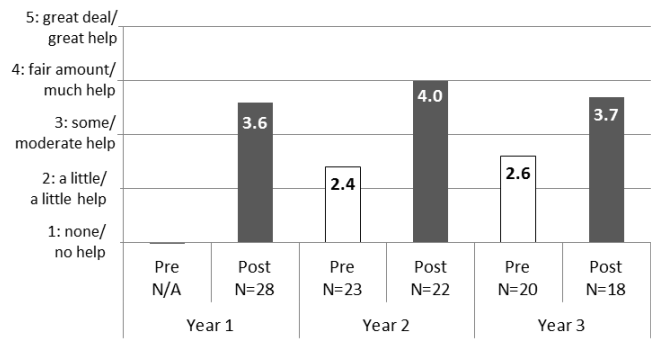


Fig. 7. Pre- and post-SALG survey results. The results reveal students’ perceived ability before taking ME151 and how the ME151 course helped improve their ability to “describe the basic operational principles of central HVAC systems.”

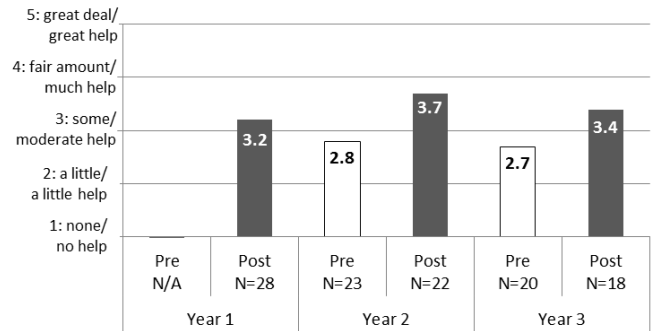


Fig. 8. Pre- and post-SALG survey results. The results reveal students’ perceived ability before taking ME151 and how the ME151 course helped improve their ability to “consider the impact on energy consumption and the environment when designing a system, component, or process.”

The SALG survey also includes a section on attitudes to assess whether the new teaching methods increased student motivation and engagement. Table II reveals that as a result of their ME151 coursework their enthusiasm, interest and confidence in systems and control greatly improved.

TABLE II
SALG SURVEY RESULTS: CLASS IMPACT ON ATTITUDES

As a result of your work in this class, what gains did you make in the following? (1: no gain, 2: some gain, 3: moderate gain, 4: good gain, 5: great gain)	Fall 2011 N=28	Fall 2012 N=22	Fall 2013 N=18
Enthusiasm for systems and control	3.7	4.3	4.3
Interest in asking questions about the material or discussing the subject	3.4	3.9	4.3
Interest in taking additional classes or working on projects related to control systems	3.5	4.1	4.2
Confidence that you understand the material and can work in this area	3.9	4.3	4.2
Your comfort level in working with complex systems	3.6	4.3	4.2

Students were also asked how different class activities helped their learning as shown in Table III. Students found the lectures to be the most helpful to their learning which is expected as the new laboratories were intended to supplement the lecture theory by providing real-world context and hands-on learning opportunities. The majority of students found the process control laboratories to be of much help with an average rating of 3.6, where 1 indicates “no help” and 5

indicates “great help”. When asked how much the HVAC mechanical room and BMS tours helped their learning, the mean score was 3.4 (N=68).

TABLE III
SALG SURVEY RESULTS: CLASS ACTIVITIES

How much did each of the following aspects of the class help your learning? (1: no help, 2: a little help, 3: moderate help, 4: much help, 5: great help)	Fall 2011 N=28	Fall 2012 N=22	Fall 2013 N=18
Attending lectures	4.0	4.5	4.3
Process control laboratories (level/flow and temperature rigs)	3.3	3.8	3.6
HVAC mechanical rooms and Building Management System tours	3.3	3.8	3.1

Additional SALG survey questions are given in an open response format providing students with the opportunity to openly share their individual experiences and ideas for improvements. Example student comments include:

“The HVAC mechanical rooms/BMS tour brought some of the concepts taught in class to reality and solidified the purpose of learning the material. By making the material concrete and seeing it in action in a building the course information was reinforced.”

“The tour was a great example of control systems engineering in action, and I wish we had more tours of how the NAB [New Academic Building] works.”

B. Writing Assignment Grading Rubric

Students are assigned writing assignments to assess learning outcomes from the new learning materials and mechanical rooms and Building Management System tours. In the writing assignment, students are asked to consider three subsystems from the tours: (1) the chiller plant, (2) the radiant panel plate and frame heat exchangers, and (3) the air handling units. They are asked to write three short paragraphs describing from a high-level the plants, the process variables, the controller inputs and outputs, and the actuators. The writing assignments are graded on a scale of 1-4 using a cognitive skills rubric based on Bloom's Taxonomy as shown in Table IV.

TABLE IV
WRITING ASSIGNMENT GRADING RUBRIC

Sophisticated 4	Student able to describe basic principles of systems and identify control goals; Students able to further apply concepts from control systems to analyze process in terms of inputs and outputs and how system level components, e.g., actuators, achieve these goals.
Good 3	Student able to describe basic principles of systems and identify control goals; Students identify the components yet fail to fully analyze the interaction of the components and process inputs/outputs.
Developing 2	Student able to describe basic principles of systems and high-level control goals; Students attempt to identify components but may incorrectly describe their function/interaction.
Unsatisfactory 1	Students inaccurately describe principles of operation and control goals

The writing assignment scores for the past three years of the project are shown in Fig. 9. The scores track the project from inception. In the first year, students only went on tours and

were not given background reading material. In year 2, student learning improved considerably as the content management website was created to supplement what they learned on the tours with background material. In year 3, the pre- and post-concept inventories were added to the project and served as a further supplemental learning tool.

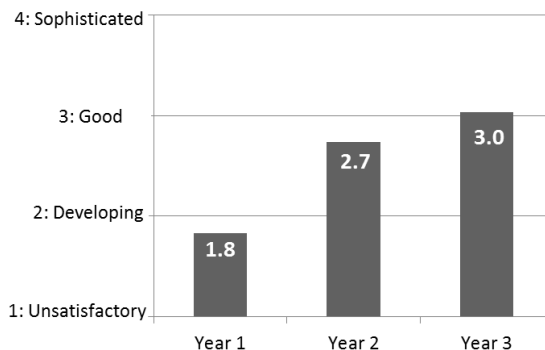


Fig. 9. Average Writing Assignment Rubric Score. In Year 1, students only experienced the building tour; in Year 2, the tour was supplemented with background material, and in Year 3, pre- and post-concept inventories were added.

C. Pre-/Post- Concept Inventories

The pre- and post- concept inventories implemented in Fall 2013 (Year 3) assessed student understanding before and after the mechanical room and BMS tours and writing assignment. Students were told that neither the pre- nor post-concept inventory scores would be factored into their final course grades. The pre- and post- concept inventory scores are shown in Fig. 10 and an excerpt of the concept inventory is shown in the Appendix.

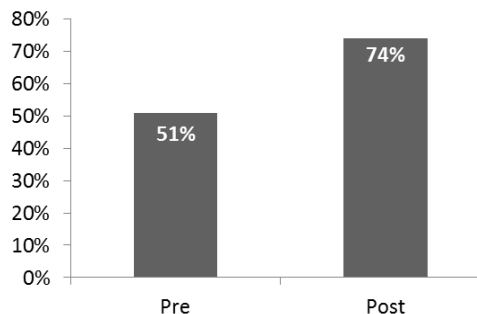


Fig. 10. Pre- and Post-Concept Inventory Scores. The concept inventories served as both assessment instruments and learning tools

Although the concept inventory scores demonstrate an increase in student learning, there is room for improvement. Students better understood HVAC systems but further work is necessary to help students relate their learning of these complex HVAC systems to the feedback control system theory learned in ME151. Also the concept inventory needs further refinement to improve its effectiveness. A challenge exists to create a concept inventory that is objective and quantitative yet flexible to account for different learning styles. For example, the PI designed the concept inventory with predominantly fill-in-the-blank questions and a list of possible correct answers. However, in some instances more than one “correct” answer could be selected, which may have led to confusion. The concept inventory could be designed to

be of multiple choice format; however, the possible answers would need to be carefully chosen so as to include common misconceptions or distractors [14].

Nevertheless, the pre- and post-concept inventories unexpectedly serve not only as assessment instruments, but as learning tools for the students. By giving a pre-test, the students better understand in advance what they are supposed to take away from the experience. For instance, the concept inventory includes a schematic of how hot water from the boilers and chilled water from the chiller plant is delivered to the radiant ceiling panels in the classrooms. While students could be shown such schematics in background reading before the tour, seeing such a schematic on the concept inventory better indicates the importance of these concepts. Furthermore, by giving students the same post-concept inventory after the tours, students are able to reflect on their learning gains.

D. Interviews

Through interviews with students, lab observations, and interviews with key informants the external evaluator helped to gain further insight into the effectiveness of the new inductive teaching approach. Key informants included undergraduate student researchers, former students, and senior faculty personnel.

What follows are interview questions posed to former ME151 students and excerpts of their responses:

Question: Sometimes evaluators talk about the “value-added” of an educational or research experience. By value-added we mean the gains in learning that occurred by being exposed to such educational or research experience. Please explain what are the most important things you learned by participating in this project.

Answer: The most important things I learned from this project are the practical applications of the classroom material. It was great that this relevant example of our own academic building could be used in our learning.

Answer: In this project I learned a lot about how control systems are used in a state-of-the-art building to maintain comfort and reduce energy usage. I also learned the drawbacks of these systems in the laboratory experiments.

Answer: The most important value was that I actually got to experience the building control system. I could understand that the control system is more practical and complicated than I imagined. Before that, I perceived the control system only theoretically.

Answer: The most important things I learned pertained to the building management system tour and website. I was in my second semester of learning control theory, but I had no clue that this theory was being applied right under my feet. I assumed that it was reserved for utility and chemical plants.

Answer: The ability to see the equipment and the read-only system screen were the two added values from this grant.

Answer: The most important thing that I gained from participating in this project is a better understanding of what goes into creating a building control system as well as physical manifestations of the things that we design in our various classes.

Answer: Feedback Control Systems and Systems Engineering were my favorite ME classes at Cooper. The building tour, engfac [content management] website was useful for reference outside of class, and the writing assignment was very useful and interesting.

Question: Did the project enhance your learning experience? If so, in what ways?

Answer: Yes, I had never been on a building tour with respect to its HVAC components, so this was an innovative and exciting way of learning. Seeing the scale of these components and the way they interact and synthesize on a physical level and on a control systems level was quite intriguing.

Answer: This project did enhance my learning experience. I tend to be a more “big picture” type of person. If I know exactly why I’m learning something, it is often easier for me to learn the subject. After seeing the building’s systems and taking a look at the sensors, I was able to make the connection between theory and reality, so learning in class became easier.

Answer: Yes, anytime you can see what you’re learning in a real world application, it always helps. You understand why you’re learning the material, how it could be used, and even numbers start making sense such as the capacity of a chiller for a building of this size. When the labs were straightforward and clear, they were also very helpful. We could see the feedback control process in action, such as PID control.

Answer: Yes. It is not an ordinary opportunity to see the operation of a brand new, high tech building. Especially, looking at the control panel through the remote desktop was helpful to broaden my understanding of control systems.

Answer: The project enhanced my learning experience by relating theoretical concepts with physical devices and also allowed me to visually see the impact of control systems on how a system operates.

Answer: I thought it was a nice compliment to the theoretical Feedback Control Systems course, where we got to see an application of the concepts that we were learning in the classroom. It also related to other classes, such as Thermodynamics and Heat Transfer, by providing physical insight to systems that we had/would only see in our heads or on paper. This gave a better sense of what the calculations “meant” creating a deeper understanding overall.

Question: How does the project fit in your larger learning aims as a Mechanical Engineering major at Cooper Union?

Answer: This project was part of the inspiration for my senior design project. I am working with another student on designing an energy dashboard which will educate both technical and non-technical audiences on the energy efficiency and green features of 41 Cooper [our New Academic Building]. I am researching more in depth about the BMS and HVAC systems. I was also an MEP intern last summer which taught me a great deal about the mechanical engineering process when designing and constructing buildings. I am possibly looking into working for an engineering consulting firm in the future.

Answer: After learning so much about the building, I decided to shape my senior design project around the operation of the building, focusing on reducing energy usage. Learning control systems and how they work is a crucial component of my thesis.

Answer: As an engineer, I am interested in optimizing a system, and that usually involves the control system. It was the first learning experience on a large scale of a real control model.

Answer: As mentioned previously, this project is not simply relevant to control systems, but encompasses a larger scope pertinent to various areas of the Mechanical Engineering curriculum. We studied heat transfer through the heat exchangers, chiller, and boilers. Aspects of fluid mechanics and thermodynamics were relevant as well with the components and pumps in the system.

Answer: I thought it was a nice overview of things that one might see if they were to go into the field of Mechanical Engineering related to HVAC, as is prevalent among engineering firms in NYC. Beyond that, I don't think that it was particularly enlightening for a specific career-based besides a broadly improved understanding of how things that we look at in a classroom end up being created in real life.

Answer: As a Mechanical Engineering major at Cooper, I wanted to gain a very broad skill set that could apply to many engineering fields later on. Systems and Control Systems (the two theory classes associated with this project) fit that larger learning aim very well. This project in particular, as I said previously, enhanced my learning experience of this broad field. By observing how this theory is applied even in the building I spend hours in, I could easily make the connection with other systems which would use control theory.

The external assessor also observed laboratory sessions and interviewed students immediately following the laboratory experience during Fall 2013. Excerpts of the interviews are included here:

Question: In your own words, what did you learn in the lab today? Please elaborate.

Answer: Generally, in today's lab we learned about Ziegler-Nichols tuning, which involves methods for finding the minimum values for control that make a system stable (instead of just guessing and checking). We specifically implemented two different methods (Continuous Cycling and Reaction Curve). We learned how to read the graphs, develop the gain values to control the system and compared how good/bad the two methods were at stabilizing a system. Basically we learned that each method had its ups and downs but both were much more efficient and accurate than guessing based on generic trends in the theory.

Answer: I was able to have a hands-on experience with a level/flow system and experimentally control the system by applying Ziegler-Nichols methods without having to derive a transfer function for the system.

Answer: In the lab, I learned how to experimentally determine control parameters such as control gains, integral control, and derivative control. We used two different methods: Reaction Curve and Continuous Cycling.

The new course components are primarily intended to help students appreciate the real-world applicability of control systems theory. Preliminary interviews suggest that this objective was attained. Some students also expressed how the building tours and their exposure to HVAC control systems fit into their larger learning goals, gave them a broader context for the theory they learn, and helped guide their future projects and career goals.

E. Discussion of Preliminary Results and Future Work

Preliminary results demonstrate the new hands-on and facilities-based teaching approach added realism to the course and improved the overall course experience. The assessment of this new teaching approach and its impact on student learning and motivation is ongoing. Further interviews, observations, surveys and refinement of the concept inventories are planned. Systematic evaluation will steer future plans to improve the instructional methods and curricular materials. Faculty observations and student feedback are guiding the redesign of the process control laboratory procedures as well as their structure and integration into the curriculum. For instance, students often feel rushed during the one-hour laboratory sessions; therefore, reducing the number of laboratory sessions but increasing the duration to two hours is being considered. New problem assignments that mirror the systems under consideration in the laboratories and mechanical rooms will also further help students connect lecture theory to real-world applications. The goal is to cohesively align the facilities-based instruction and hands-on experimentation with the systems and control lecture theory and mechanical curriculum as a whole to improve student learning outcomes.

V. CONCLUSION

Preliminary assessment of a new facilities-based and hands-on teaching approach suggests that exposing students to real-world applications of classroom theory positively impacts the learning experience and engages students in the learning process. Pre- and post- results indicate the course provided much help in increasing the students' abilities in three new learning outcomes involving identifying control systems, describing basic HVAC operational principles, and considering the environment and energy consumption during design. SALG survey results generally reveal students view building systems tours as an opportunity to appreciate the real-world applicability of control systems theory. Writing assignments graded based on a cognitive rubric indicate that the new learning materials and a content management website further increase conceptual understanding. Pre- and post-concept inventories serve not only to evaluate the project but also help students gauge important concepts before the tours and reflect on their learning after the tours.

Initial student interviews conducted by an external assessor show the new teaching approach has a positive impact on affective outcomes, such as increased appreciation for the course material and interest in working on projects related to building systems. These results are confirmed by the number of students that have initiated research projects related to building systems after being exposed to the new teaching strategies and materials. A total of 17 undergraduate and graduate students have been involved to varying degrees in building systems research projects advised by the PI and senior faculty personnel since the inception of the project. The faculty also observed that more students are pursuing advanced degrees or going to work in fields related to building systems and sustainability. In conclusion, exposing students to control systems theory and sustainable design principles in a real-world and hands-on context enhances student learning and elicits student interest and motivation.

APPENDIX – CONCEPT INVENTORY EXCERPT

Chiller Plant Concepts

Possible Fill-in-the-Blank words (not all words will be used)

Atkinson	Carnot	vapor-compression	Rankine	ice
refrigerant	cooling tower	water vapor	liquid water	steam
primary	secondary	radiant	compressor	pump
servo	variable voltage	variable frequency	variable current	

- The two centrifugal chillers operate on the _____ cycle; a thermodynamic cycle used for refrigeration.
- Chillers are usually the single largest consumption of energy in a building. A 500 ton chiller will consume about 225 kW of power. A ton of refrigeration is equivalent the power required to turn a ton of _____ at 0°C into a ton of _____ at 0°C in 24 hours.
- A centrifugal chiller uses a _____ to increase the pressure of a refrigerant.
- The purpose of the chiller is to supply cold water where needed in the building for cooling. Inside the chiller evaporator, heat is absorbed from the _____ chilled water by the refrigerant.
- When the cooling demand increases due to changes in outside air temperature or building occupancy, the chiller's cooling capacity can be increased by running the chiller compressor and motor at a higher speed. A _____ drive is used to modulate the speed of the alternating current (AC) motor and compressor.

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