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Building Sustainability into Control Systems: A New Facilities-Based and Hands-On Teaching Approach

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Building Sustainability into Control Systems: A New Facilities-Based and Hands-On Teaching Approach

Abstract

This paper presents an overview of and the latest outcomes from an NSF Transforming Undergraduate Education in STEM (TUES) funded project, "Building Sustainability into Control Systems Courses." The new teaching strategy leverages an energy efficient academic building to expose students to modern heating, ventilation, and air conditioning (HVAC) and sustainable building concepts. Students perform new process control laboratory experiments, are taken on tours of the building's HVAC mechanical rooms, and are shown the Building Management System. A formative assessment plan is guiding the development of new curriculum materials and assignments. Direct and indirect assessment results suggest this new facilities-based and hands-on teaching approach helps students appreciate the real-world applicability of classroom theory.

Motivation

Traditional, lecture-based undergraduate engineering approaches can leave many students with an abstract or incomplete understanding of the concepts being taught.[1] Actively engaging students with practical applications or experimental procedures has been generally shown to provide engineering undergraduates with a broader understanding of course theory.[2] Inductive learning approaches, such as case study methods, show students how the theory they are learning is applicable to real-world 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 outcomes.[5] This project combines a facilities-based and hands-on approach, leveraging a state-of-the-art academic building, as a context to explore control systems applications and sustainability.

Background

Preliminary outcomes for this new facilities-based and hands-on teaching approach are presented in the 2014 ASEE Zone 1 Conference proceedings.[6] This paper will describe how a formative assessment plan is shaping the development of new learning materials and experimental procedures and present the most recent findings.

The project involves students from a junior-level mechanical engineering Feedback Control Systems (ME151) course. ME151 is a continuation of a Systems Engineering (ESC161) course, which introduces students to the mathematical modeling and time response analysis of mechanical, electromechanical, fluid, and thermal systems. ME151 expands on ESC161 teaching students various methods of analyzing and controlling linear time-invariant dynamic systems. Course topics include root locus and frequency response analysis methods, computer simulations using MATLAB, and PID control applications.

The project utilizes a new Leadership in Energy and Environmental Design (LEED) Platinum certified academic building, shown in Fig. (1)a, as a context to explore applications of the theory students' learn. Another goal is to provide opportunities for hands-on experimentation with systems that reflect professional practice. To achieve these goals, the ME151 course was redesigned to incorporate a significant laboratory component.[7] These laboratory sessions expose students to practical applications of process control using two educational rigs from Feedback Instruments. A level-flow rig allows students to control the flow of water or the level of a tank, while a temperature rig, shown in Fig. 1(b), allows students to control temperature by actuating servo valves that regulate primary and secondary flows through a heat exchanger. Using both rigs, small student groups identify process variables in the physical systems and utilize industrial control equipment to implement the tuning methods learned in class.

Figure 1. (a) 41 Cooper Square. A new LEED Platinum certified academic building is used as a context to explore control system concepts. (b) Temperature Process Control Rig. Students apply feedback control principles to control the primary and secondary flow rates through a heat exchanger.

The development of the laboratory sessions has been guided by instructor observations and student feedback. Initially, nine lab modules were created each lasting one hour. Students often felt rushed during the one-hour lab sessions; therefore, the number of sessions was reduced to seven and the duration of some of the sessions was increased to two hours. The design of the laboratory modules, topics, and duration are shown in Table 1. A lab manual and background questions were designed to better prepare students before coming to the lab sessions.

Table 1: Feedback Control Laboratory Session Design

Session	Initial Laboratory Modules	Re-designed Laboratory Modules
1	Introduction to Process Control: Level-Flow or Temperature Rig (1 hour)	Introduction to Process Control: Level-Flow and Temperature Rig (2 hours)
2	Level-Flow On-off and P-Control (1 hour)	Level-Flow On-off and PID-Control (2 hours)
3	Level-Flow PID-Control (1 hour)	Temperature On-off and PID-Control (2 hours)
4	Temperature On-off and Process Control (1 hour)	HVAC and BMS Tours (1 hour)
5	Temperature PID-Control (1 hour)	DC Motor Speed Control (1 hour)
6	HVAC and BMS Tours (1 hour)	DC Motor Position Control (1 hour)
7	DC Motor Speed Control (1 hour)	Ziegler-Nichols Tuning Method on Level-Flow Rig (1 hour)
8	DC Motor Position Control (1 hour)	

9	Ziegler-Nichols Tuning Method on Level-Flow Rig (1 hour)	

Midway through the course, students are taken on a tour of the HVAC mechanical rooms (refer to Fig. 2(a)) and are shown the Building Management System (BMS), a state-of-the-art automation system that monitors and manages every aspect of the building's operation (refer to Fig. 2(b)). As part of this project, the faculty and student researchers created a content management website (http://engfac.cooper.edu/melody/10) that includes system descriptions, photos, and schematics.[8] Before the tours, students are assigned background reading from the content management website to supplement their learning from the tours. An online dashboard was also created to give students access to real-time building energy consumption. A touchscreen kiosk was placed in the lobby of the building to share real-time data and information about the building's green features to the entire student body and general public.

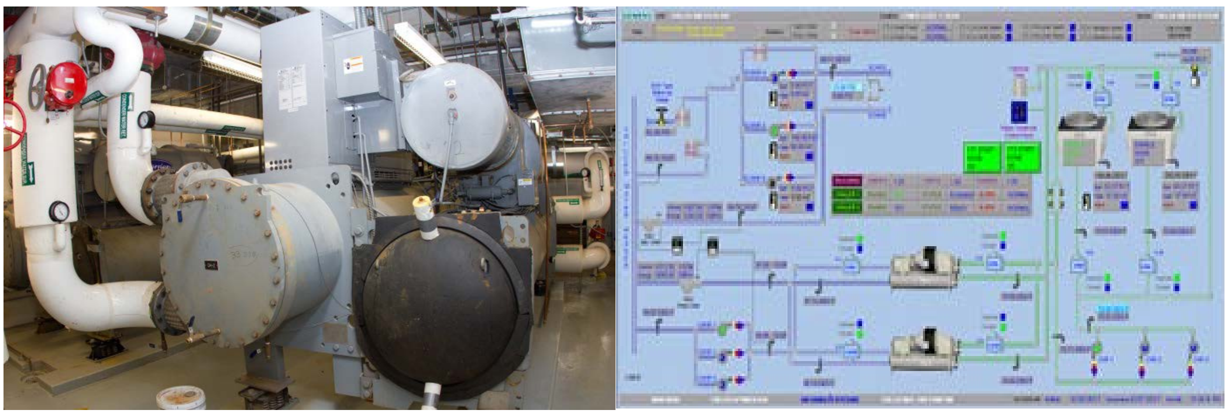

Figure 2. (a) Centrifugal Chiller. Students visit the chiller mechanical room during building tours. (b) Building Management Site (BMS). Students are shown the BMS, a central control system that monitors and manages the building's operation.

Assessment Plan and Results

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 2. The new teaching strategies are intended to fulfill three new student learning outcomes as indicated by asterisk in Table 2. The new teaching methods also aim to foster active student learning and thereby increase student motivation and engagement.

Table 2: 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, such as motor position, level-flow and temperature control 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	Student will be able to design controllers using classical and modern methods, and be able to describe the advantages and disadvantages associated with both methods.
6	* 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.
7	* Students will be able to describe the basic operational principles of basic central HVAC systems including centrifugal chillers, heat exchangers, and air handling units.
8	* When designing a system, component, or process, students will consider the impact of their design on the environment and energy consumption.

A major goal of the assessment plan is to ascertain whether this hands-on and facilities-based approach results in broader student participation in the learning process, enhanced communication skills, and promotion of critical and proactive thinking. A value-added, mixed-method assessment strategy uses both direct and indirect techniques to closely track student performance and outcomes. The assessment plan was designed to measure student learning outcomes, the project's impact on student motivation, as well as the efficacy of the project beyond its initial implementation. The project assessment plan follows three paradigms:

1. It is ***value-added***, as it uses a pre-/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***, because it uses quantitative (pre-/post- concept inventories and scoring rubric of teacher/assessor observations of student performance/behavior) and qualitative (semi-structured interviews and rapid ethnography) evaluation techniques.
3. It is ***performance assessment***, since it uses a scoring rubric based on Bloom's taxonomy to classify student cognitive understanding based on writing assignments and closely follows the design of the project from inception.[6]

An external evaluator assessed the impact of the project by observing lectures, labs, and tours and by interviewing key informants. Initially, the course interventions were implemented by the primary investigator (PI). In year 4, after the three-year implementation phase, the new course interventions were tested by a new lecturer and laboratory teaching assistant to evaluate the efficacy of the project. The new lecture instructor had no involvement in the design and implementation of the project and thus served as an external assessor. Instead of the PI giving the building tours in year 4, a former Master's student, who worked on this project and is now working in the construction industry, came back to lead the tours. The former Master's student also led an informational session about his Master's project, in which he analyzed the energy and cost savings of building's cogeneration plant, and shared other potential building-related student research projects. Consequently, current students learned how this project helped a former student in his academic and professional career. The following includes a discussion of the most recent assessment results.

Student Assessment of Learning Gains (SALG)

Customized pre- and post- SALG surveys assess perceived learning gains and affective outcomes. The SALG is an online survey that measures student perceptions of their learning gains due to various components within a course.[9] 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 in Table 1 were formulated into pre- and post- survey questions. Prior to the Feedback Controls course, students were asked to comment on their ability to perform the student learning outcomes. At the end of the course, 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. 3-5. For all three new learning outcomes, students felt the course experience provided moderate to much help in improving their abilities. Note that students are introduced to control systems in ESC161, the pre-requisite course for ME151, and as such, Fig. 3 shows the students perceive their abilities in Outcome 6, related to identifying control goals and variables, higher on the pre-SALG survey.

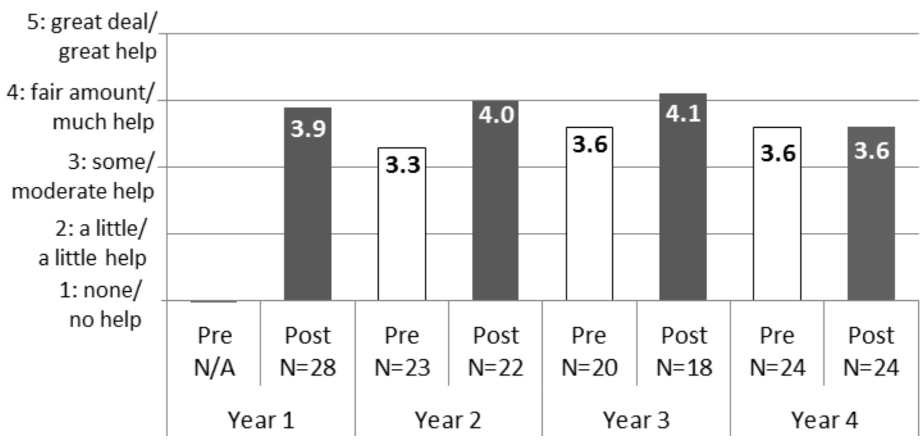

Figure 3. Pre- and post-SALG survey results. The results reveal students' perceived ability before taking ME151 and how the ME151 course helped improve their ability to "identify the control goals, process variables, controller inputs/outputs, and the corresponding sensors and actuators."

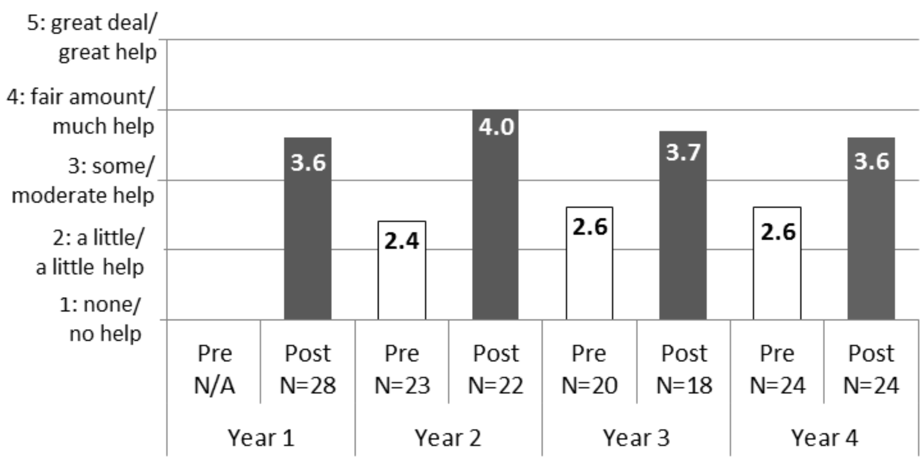

Figure 4. Pre- and post-SALG survey results. The results reveal students' perceived ability before taking ME151 and how the ME151 course helped improve their ability to "describe the basic operational principles of central HVAC systems."

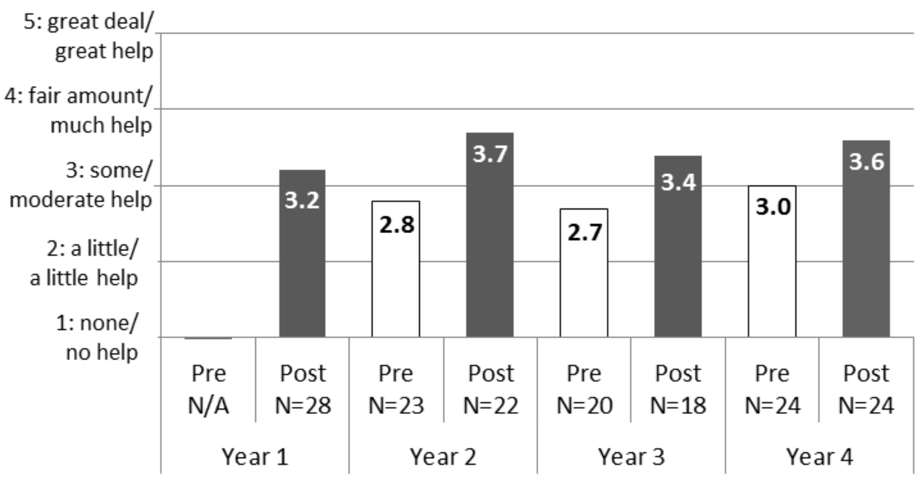

Figure 5. Pre- and post-SALG survey results. The results reveal students' perceived ability before taking ME151 and how the ME151 course helped improve their ability to "consider the impact on energy consumption and the environment when designing a system, component, or process."

The SALG survey also includes a section on attitudes to assess whether the new teaching methods increase student motivation and engagement. Table 3 reveals that as a result of the ME151 course their enthusiasm, interest and confidence in control systems improved.

Table 3: 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	Fall 2014 N=24
Enthusiasm for systems and control	3.7	4.3	4.3	3.5
Interest in asking questions about the material or discussing the subject	3.4	3.9	4.3	3.2
Interest in taking additional classes or working on projects related to control systems	3.5	4.1	4.2	3.1
Confidence that you understand the material and can work in this area	3.9	4.3	4.2	3.5
Your comfort level in working with complex systems	3.6	4.3	4.2	3.7

Students were also asked how different class activities helped their learning as shown in Table 4. Students found the lectures to be the most helpful to their learning which is expected as the new laboratories and tours 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 3.5, where 1 indicates "no help" and 5 indicates "great help". When asked how much the HVAC mechanical rooms and BMS tours helped their learning, the mean score was 3.4 (N=92).

Table 4: 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	Fall 2014 N=24
Attending lectures	4.0	4.5	4.3	4.5
Process control laboratories (level/flow and temperature rigs)	3.3	3.8	3.6	3.5
HVAC mechanical rooms and Building Management System tours	3.3	3.8	3.1	3.2

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 on how the HVAC mechanical rooms/BMS tours helped the students' learning include:

> "Seeing the relation [of the HVAC and BMS] in real life helped me understand a bit more about how plant, controllers, sensors, etc. are all linked together." *– Fall 2014 Student*

> "[The HVAC mechanical rooms/BMS tour] allowed me to see how controls is being used in the real world. Plus, the HVAC system in the building is something that directly affects me, which made it more interesting." *- Fall 2013 Student*

> "The HVAC mechanical rooms/BMS tours helped by providing a common 'real world' application of the course materials. It also strengthened my interest in controls, maybe even leading to interest in a controls engineering profession in the future." *- Fall 2012 Student*

> "Personally, I've worked with HVAC and building management systems before, so the tour was interesting to me to compare it to other systems I have seen. If it had been my first exposure to such a system, it would have been extremely beneficial to understanding how control systems are applicable in the real world. " *- Fall 2012 Student*

> "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." *Fall 2011 Student*

The students' comments related to the process control laboratories suggested their effectiveness may be dependent on the students' learning styles:

> "[The process control] labs were a great first introduction to actually using controls and seeing how they impact a system." *– Fall 2014 Student*

> "Being able to fiddle with the numbers and seeing how the response changes is a lot easier to understand than the theoretical concepts discussed in class." *– Fall 2014 Student*

> "Strong introduction to actual control systems and helped solidify class knowledge and make it applicable." *– Fall 2014 Student*

The next two comments suggest that some students felt the course components were not always well connected:

> "[The process control labs] felt very separate from the lectures, so while I learned a few conceptual things about control systems, I couldn't apply these to the classwork or homework." *– Fall 2014 Student*

> "The process control labs felt a little disconnected from what we were doing in class." *– Fall 2014 Student*

Throughout the progression of the project, efforts were made to better integrate student learning. As the SALG survey results in Table 5 suggest, the project clearly helps students see how control systems help engineers address real world problems. Table 5 also shows how students feel the ME151 course components fit together and how control system concepts relate to other mechanical engineering concepts.

Table 5: SALG Survey Results: Integration of Learning

As a result of your work in this class, what gains did you make in integrating the following? (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	Fall 2014 N=24
How studying control systems helps engineers address real world issues	4.0	4.2	4.5	4.2
How the class topics, assignments, reading, BMS/HVAC mechanical room tours, process control labs, and DC motor labs fit together	3.8	4.0	3.6	3.3
How concepts from control systems relates to other mechanical engineering concepts	3.9	4.3	4.4	3.8

Based on formative feedback, attempts were made to better link course concepts to the experimental procedures. Furthermore, since the experimental procedures include concepts from beyond control systems, such as thermodynamics, heat transfer, and fluid mechanics, the PI worked with other faculty to integrate examples and data from the building and process control rigs into their teaching. One example of integrating student learning includes having students complete a homework problem that models the liquid-level experimental rig in ESC161, then students experimentally determine the time constant in a ME151 laboratory session, and later in the semester students analyze the same system again using Bernoulli's equation in their Fluid Mechanics course, which is taken concurrently with ME151. Hence, lecture and homework problems were designed around a physical system that students interacted with in a laboratory setting. A student researcher presented how these analytical and experimental techniques were designed to help students connect concepts from their core courses in a 2014 ASEE Conference Student Paper.[10]

Writing Assignment Grading Rubric

Students are assigned writing assignments to assess learning outcomes from the new learning materials, laboratory sessions, 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[11] as shown in Table 5.

Table 5: Writing Assignment Grading Rubric

4: Sophisticated	Student able to **describe** basic principles of systems and **identify** control goals; Student 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.
3: Good	Student able to **describe** basic principles of systems and **identify** control goals; Student identifies the components yet fail to fully analyze the interaction of the components and process inputs/outputs.
2: Developing	Student able to **describe** basic principles of systems and high-level control goals; Student attempts to identify components but may incorrectly describe their function/interaction.
1: Unsatisfactory	Student inaccurately describes principles of operation and control goals.

The writing assignment scores for the past four years of the project are shown in Fig. 6. The scores track the project from inception. In the first year, students only went on tours and were not assigned background reading material. In year 2, student learning improved considerably as the content management website was created to supplement what students learn on the tours with background material. In year 3, the pre- and post-concept inventories were added to the project and served as supplemental learning tools. In year 4, the course interventions were implemented in a course taught by a different instructor, laboratory teaching assistant, and tour guide.

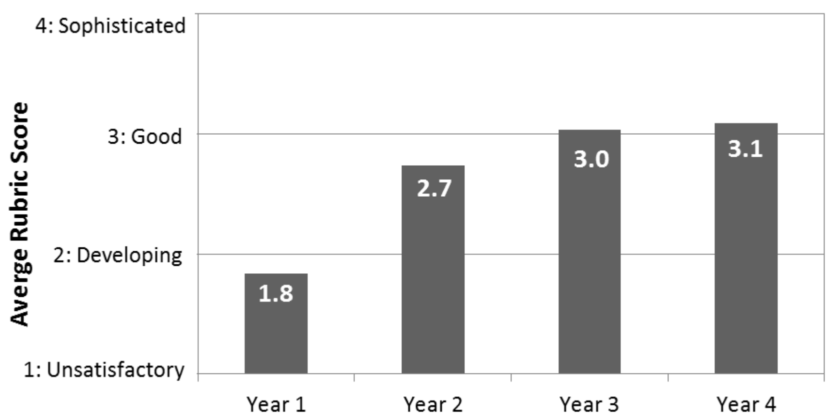

Figure 6. Average Writing Assignment Rubric Score. In year 1, students only experienced the building tour; in year 2, the tour was supplemented with background material, in year 3, pre- and post-concept inventories were added, and in year 4, the course was taught by new instructors.

The average writing assignment score has increased over the project duration. These results demonstrate how the content management site and tours successfully introduce students to HVAC systems; yet there is room for improvement. Students still have difficulties in synthesizing the components and analyzing the inputs and outputs of building subsystems.

Pre-/Post- Concept Inventories

Pre- and post- concept inventories were implemented in year 3 and assessed student understanding before and after the tour and writing assignment. Students were told that neither the pre- nor post-concept inventory scores would be factored into their final course grades. A challenge exists to create an objective and quantitative concept inventory that accurately reflects student understanding and misconceptions. The concept inventory design includes predominantly fill-in-the-blank questions and a list of possible correct answers. However, in the initial concept inventory, more than one "correct" answer could be selected, which may have led to confusion. The concept inventory language was modified in year 4 to reduce confusion and improve its effectiveness. Multiple choice questions were added and possible answers for all the questions were carefully designed to include common misconceptions or distractors and to avoid multiple possible answers.[12] Table 6 includes the question types and topics included on the initial and re-designed concept inventories. The concept inventory results are shown in Fig. 7.

Table 6: Feedback Control Laboratory Session Design

Question Type	Question Topic	# Initial Concept Inventory	# Re-designed Concept Inventory
Complete the Acronym	HVAC, LEED, and Air Handling Units (AHUs)	3	3
Fill-in-the-Blank	Chillers, Heat Exchangers, and AHUs	17	15
Multiple Choice	Air Handling Units	0	2
Matching	System Components and Descriptions	1	1
Short Answer	Identify and Describe Energy Saving Features	2	2
Sketches	Heat Exchangers	2	2
	Total Points	25	25

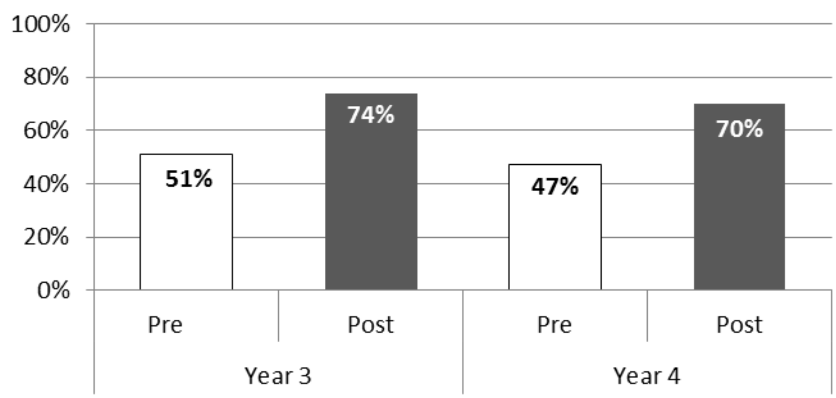

Figure 7. Pre- and Post-Concept Inventory Scores. The concept inventories served as both assessment instruments and learning tools.

In year 4, over 42% of the students could not identify one energy-saving building feature on the pre-concept inventory. After reading the background materials and taking the tours, all students correctly identified and described the principle of operation of at least one energy-saving building feature (and most identified two).

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

Interviews

The external evaluator helped gain further insight into the effectiveness of the new inductive teaching approach by observing the tours and laboratory sessions and by interviewing students and other key informants. Key informants included undergraduate and Master's student researchers, current and former students, senior faculty personnel, as well as the external instructor and teaching assistant that tested the new course interventions.

Interviews were conducted after the conclusion of the ME151 course so students had time to reflect on their learning gains. Interview questions posed to former ME151 students and excerpts of their responses are detailed in the 2014 ASEE Zone 1 Conference Proceedings.[6] When asked to describe the most important things learned by participating in this project and how the project enhanced their learning, example student responses included:

> "The biggest gain I got from the HVAC systems project was the knowledge that control theory can be used to control a very important but very complicated system, with various subsystems embedded within it. Another important thing that I learned, which I would not have learned otherwise in the class, was that one should keep in mind concerns related to sustainability when designing something like an HVAC system. Learning about things like the rain water collection system and the air recirculation system at 41 Cooper Square contributed to this second learning gain." – *Fall 2014 Student*

> "I learned how control systems are applied in practice and the different type of ways control can be applied. I also saw how important it is in governing many day to day systems. I learned how to approach problems from a control mindset." – *Fall 2013 Student*

> "[The project] exposed us to control outside of the classroom. While lectures are good for learning, they can never provide the complete picture. Lab experience and the tours gave us hands-on experience and let us see real life applications (something that is hard or impossible to implement and cover in a purely lecture course)." – *Fall 2013 Student*

> "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." – *Fall 2012 Student*

> "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." – *Fall 2012 Student*

> "…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." – *Fall 2012 Student*

Some students' comments help illuminate which new course components were most helpful:

> "…the building tour, website, and writing assignment were useful in understanding machinery which was new to me and seeing things laid out and having their relations explained to me was very helpful. The website then served to reinforce things which were missed, or not fully understood, and the writing assignment guided this process. These elements worked together nicely." – *Fall 2014 Student*

> "The valuable thing learned from the project, I believe, is vocabulary. You can learn about all sorts of systems and models in the classroom, but to get an idea of industry standards and terminology, I believe, is very valuable. The tour and the fill-in-the-blank surveys pushed a lot of terms…now I can better hold a conversation with an actual engineer about building systems and these types of common systems in general. If you can't hold a conversation about these things then you can't really do anything with your knowledge." – *Fall 2014 Student*

Some of the interview questions and students' comments revolved around their interaction with the lab equipment:

> "A hands-on approach proved valuable in emphasizing non-obvious characteristics of systems. For example, it is easier to control the level of the tank than the flow rate in a pipe because the capacitance of the tank causes slow response times. In addition, I learned different kinds of control such as on-off control, PID control, weighted PID control, and an introduction to noise filtering." – *Fall 2014 Student*

> The most important thing that I learned was the appropriate time to apply different feedback elements. For example, I learned that derivative control is not suitable for flow control as the signal is too noisy. This pitfall of derivative control was mentioned in passing in lecture, but it did not become clear to me until I actually implemented derivative control on the noisy flow signal and saw the undesirable response." – *Fall 2013 Student*

The external evaluator also interviewed students immediately after laboratory sessions. When asked what they learned following a Fall 2014 lab session student interviewees responded:

> "I learned the advantages and disadvantages of Ziegler-Nichols tuning. I observed how reactive curve tuning was better suited to controlling a slow-acting control variable, such as level in a tank, especially when the autotune function calculated similar control gains, confirming the earlier statement."

> “In this lab I learned about different methods of tuning a control system. I used continuous cycling tuning and reaction curve tuning to hand calculate parameters, and then compared those results to automated tuning. I learned that different methods of tuning are appropriate for different systems.”

When asked whether the lab experience was an important learning aid in the course, students responded:

> “The lab adds an essential hands-on component to the Feedback Control class. It demonstrates the limits and merits of theoretical plant models and control models. For example, the BPR [level-flow rig] had an orifice whose flow resistance significantly decreases at low heads…”

> “I think having labs really helps in learning the material. The things we do in class are theoretical and sometimes it’s hard to see what actually happens in reality. Labs help visualize what really occurs as we change the different values.”

> “I found the lab experience to be an extremely important part of the course. Doing the labs made the material relatable and clear. The labs felt like they related to the course material well and strongly supplemented my learning.”

While some students thought the process control interface was intuitive and the instructions were clear, one student thought the interface could be “more user-friendly”. The external instructor thought a Matlab-based interface might be useful to allow students to build and test their own controller designs.

The new instructor served as an external evaluator and provided formative feedback related to the new course components and how to better integrate them into the lecture and homework. For example, many students had problems identifying all of the components and the corresponding inputs and outputs for the building systems; therefore, the instructor suggested adding more block diagrams and flow charts to the background material. The external instructor also identified areas where the labs could reinforce concepts from lecture.

Discussion of Results and Future Work

Pre- and post- assessment results indicate the course provides measurable gains in increasing the students’ abilities in three new learning outcomes: identifying control systems, describing basic HVAC operational principles, and considering the environment and energy consumption during design. The concept inventories and writing assignment demonstrate that the content management website and tours effectively familiarize students with modern HVAC systems and sustainability.

Student feedback suggests the new course components help students appreciate the real-world applicability of control systems. 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 plans.

Ongoing assessment will steer future efforts to improve the instructional methods and curricular materials. The learning materials are being peer-reviewed at the PI's institution and by external institutions and are being edited based on their feedback. Future work includes better integrating the facility and experimental rigs as learning resources throughout the curriculum. Additional problems that mirror tangible systems, with which students can interact, in the building or in a laboratory setting, will further help students connect theory to real-world applications. A goal is to cohesively align these new facilities-based and hands-on teaching methods with the mechanical engineering curriculum as a whole to improve student learning and motivation.

Conclusion

This project developed new building tours, online learning materials, and hands-on process control laboratory experiments that introduce students to HVAC and sustainable building concepts. A content management website, a kiosk, real-time energy dashboard, experimental process control interface, related assignments, and laboratory manual were created and integrated into the learning environment. The efficacy of the course interventions is being assessed using a value-added, mixed-methods approach that includes different instructors and external reviewers.

Assessment results reveal this facilities-based and hands-on teaching approach positively impacts student learning and motivation. Student feedback reveals an 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 22 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 this project. 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 engages students in the learning process.

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