Experiential Learning for Teaching Heating, Ventilation, and Air-conditioning Engineering

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***Abstract*—In this Work in Progress Innovative Practice paper, we describe a teaching and learning facility that is being developed to test the effectiveness of using full-scale heating, ventilation, and air-conditioning (HVAC) systems, and hands-on activity with these systems and their components, to improve learning outcomes. This facility is being developed to support the mission of an architectural engineering program, whose graduates normally practice engineering as building designers after their formal education. One hypothesis in this work is that interacting with these systems will increase the pace of learning, facilitating a rapidly expanding set of knowledge that is required for effective building design, compared with the status quo lecture and textbook delivery methods. Another hypothesis in this work is that the hands-on activity, and reflection on this activity, will lead to increased recruitment to, and retention within, programs that teach HVAC. This paper provides a background on this engineering specialization and the importance of effective education within it, then describes a novel educational facility that is being developed, the program in which it will be deployed, and describes results of a survey that revealed the need for this type of activity. The educational facility includes a full-scale functional HVAC system, of the type used in medium and large commercial buildings, that is housed within the learning facility, but not used by the facility for actual space conditioning, so that students can experiment freely, and have complete access to the system. Additional purpose-built equipment modules address specific learning objectives. These teaching innovations are being used to augment several existing courses in HVAC, as well as providing the basis for a new course that has been developed. The effectiveness of the innovations will be assessed, so that the methods and tools can be improved and generalized for wider scale. adoption.**

Keywords—architectural engineering, experiential learning, learning technology, recruitment, retention.

I. Introduction

Heating, ventilation, and air-conditioning (HVAC) engineers design commercial building systems to maintain occupant health and comfort, minimize energy expense and environmental impact, and function in a wide variety of operating conditions. To do this effectively, they must understand how the myriad components that make up these systems work and interact with one another. Existing buildings vary dramatically in their performance; the complexity of buildings and the requirement for a custom design in each one means that a designer lacking in appropriate expertise could spend their entire career designing poorly performing buildings. Considering that buildings use over 70% of electricity in the US [1] and we spend about 90% of our time indoors [2] it is critically important to educate HVAC engineers effectively before they enter the workforce.

A related problem is that the demand for effective HVAC design engineers significantly outpaces supply, so that engineers often enter these careers after graduating from more general engineering programs that offer little or no curriculum that is specific to building science and HVAC.

HVAC equipment application, function, and system interaction are typically taught to mechanical and architectural engineering students via textbook and lecture delivery. As new engineering approaches (e.g., so-called *Smart Buildings* that interact with the electrical grid), new types of equipment, and rapid changes to codes and standards appear, textbooks can lag behind technology, and the required quantity of knowledge and understanding to be covered within a finite curriculum grows.

The intent of the work described in this paper is to explore the question: to what extent can hands-on learning and experiential learning approaches be used to improve the learning outcomes of students studying HVAC design? A key premise is that learning about HVAC equipment can be faster or deeper when students interact with real, full sized HVAC systems. The authors are developing a facility – named the Experiential Learning Laboratory – to test and demonstrate ways in which hands-on approaches can augment and replace traditional teaching methods. The goal of presenting this work in progress is to dialog with engineering education researchers and practitioners, to improve our plan.

II. Background

A. Current State of Program

The University of Nebraska Architectural Engineering program is a five-year combined bachelor's and master's degree. Students in this program all take an array of introductory coursework in structural, electrical, and mechanical engineering topics related to buildings. Students choose one of these technical options as an emphasis area and continue studies in that option for 400 level and higher courses. The introductory mechanical courses include textbook and lecture courses in fundamentals, such as thermodynamics and fluid mechanics, and an introduction to HVAC. The upper-level courses include a building controls course, advanced HVAC course, indoor air quality, noise control, building science elective courses, a refrigeration cycle simulation course, and capstone HVAC design courses in the fourth and fifth year.

Nearly all mechanical graduates of the program take positions as design or consulting engineers. Typically, these designers and consultants do not work hands-on with HVAC equipment. The bulk of their practice consists of load calculations and schematic system design. After graduation, these professionals' physical interaction with the equipment they specify occurs primarily at technical conferences, equipment sales technical sessions, and site assessment visits. These interactions are typically brief and involve little or no observation of the equipment as it is working. Designers rarely receive feedback on whether their designs performed well (i.e., provided healthy and comfortable indoor environments while minimizing energy usage and operating expense).

Therefore, to address a critical need for effective HVAC engineers, the goal of this program is to provide systematic, unbiased, hands-on learning, to introduce future engineers to HVAC systems and give them the opportunity to see how the components interact in a functioning system. This project will develop the Experiential Learning Lab (ELL), where students will work hands-on with systems and equipment to gain a deeper understanding of the complex behaviors and interactions they exhibit. In addition to assessing the learning outcomes, this project also aims to evaluate the impact of this intervention on the retention and recruitment outcomes for the program, and effectiveness of our graduates in their profession.

B. *Theoretical Background/Literature Review*

Programs devoted exclusively to architectural engineering (AE) make up a very small portion of the total engineering programs in the U.S. Of the 136,266 engineering bachelor's degrees awarded during the 2017-2018 academic year, only 642 were architectural engineering degrees [3]. Often, AE programs are a sub-specialty of civil, construction, or other engineering discipline. Many HVAC engineers are actually graduates of mechanical engineering programs that have taken a course in HVAC

Some HVAC programs have developed learning laboratories or have published plans to do so [4][5]. Similar facilities have been constructed for construction engineering or construction management programs [6]. These facilities vary greatly in complexity, cost and use, but each is designed to teach one or more aspects of HVAC systems. For construction programs, it is common that graduates will work with physical systems in their careers, in contrast to the architectural engineers who will design these systems, but not physically interface with them.

Several schools have explored alternatives to building in-house teaching facilities. In some cases, schools have relied on students doing design or analysis of real-world systems either within their own universities' facilities [7][8], or on the facilities of local businesses. Utilizing existing facilities for student learning means that the system has already been designed and built, severely restricting opportunities for testing alternate approaches or system arrangements. Further, since these systems are operational and serving occupied spaces, they cannot be shut down to explore components or take invasive measurements. As a result, these types of interactions commonly include monitoring existing performance and (in some cases) testing variations to the system via a virtual model [9] Other schools have been working on developing remote hands-on learning or simulation to teach HVAC concepts [10][11][12]. Utilizing a remote learning environment does benefit schools by allowing them to pool resources and potentially split cost of facility upgrades, but this type of interaction may limit student learning opportunities. These types of facilities give students the option to control a system and measure output remotely, but students do not have the opportunity to investigate systems and components up close.

Looking beyond teaching HVAC to undergraduate students, there are examples of hands-on learning being shown to improve understanding and retention of other engineering systems. For example, hands-on work (for group projects) was found to produce better student outcomes for a beam stress-test lab [13]. The potential for hands-on or active project to provide deeper cognitive and psychomotor learning, along with some affective learning improvements, was demonstrated in three different subject areas as part of another study [14].

III. Description of Research

The goal of this research is to test the effectiveness of hands-on learning experiences, using functioning HVAC systems and equipment. Educational modules will be integrated into existing HVAC courses and also compiled into a single upper-level experiential learning course. The learning modules may address a single concept or single device, or they may focus on the integration and behavior of multiple devices under varying conditions. As student knowledge grows, they will move from small, single-device modules to more and more complex setups until they are able to manage, measure, and control a full building system. As noted earlier, the students that learn with these systems likely will have careers that do not involve direct interaction with such systems. Thus, the goal is not hands-on training; rather, it is intended as a method to promote deeper understanding and more efficient learning.

Fig. 1: Hydronic and air systems in the ELL

A. *Learning Facility Description*

The facility includes a complete HVAC system suitable for a large commercial building, housed within a classroom (Fig. 1). The components are: a chiller; a boiler; an air-handling unit with cooling and heating coils, fans and filters; a hydronic distribution system with variable speed pumps; an air distribution system with several variable air volume air terminals; and a control system. The control system connects to each component to relay status, measurements, and control commands. These systems (often called a Building Automation System, or BAS) normally reside in a desktop computer, where a facilities manager can reconfigure behaviors of components, diagnose problems, and modify setpoints. One innovation of the ELL is that we will connect nine duplicate BASs in parallel, using a switch so that only one BAS is in control. This will allow students or small teams to develop and program control sequences and settings simultaneously, then switch to an individual BAS to observe the outcome.

The control hardware will also have a flexible interface, to allow additional components, such as IoT devices, to be added or tested with the system, providing scalability for an expanding set of applications that are becoming available, and a safe environment for future designers to test their implementation.

In addition to the main HVAC system, there are several standalone learning stations that are being developed. For example, a module with a hot-box that demonstrates heat transfer through alternate wall assemblies. Other mobile learning stations are described below. These standalone modules will be utilized as part of the curriculum and will also be used as demonstrations during "open house" events and during recruitment visits from potential future students.

Finally, a thermal environment chamber is being designed, which will facilitate students experiencing the comfort tradeoffs between (1) air velocity, (2) temperature, (3) humidity, and (4) radiant temperature.

B. Program Assessment Surveys

The plan for the teaching and learning facility was guided by the outcome of a focused survey that we administered in 2019 to all 26 of our Mechanical Option AE graduates from the previous 6 years, to better understand students' thoughts about the ways in which their degrees effectively prepared them for their careers. Hiring managers and mentors at firms that had previously hired graduates from the program were also surveyed. A link to an anonymous, online survey was sent directly to each of the alumni, and a separate link was created and distributed to mentors and managers of program graduates.

The alumni survey included demographic characterization: length of time in the field, type of professional experience, and current day-to-day job functions. The response rate was 100% (i.e., sample is full population). Of the 26 respondents, 25 indicated design or consulting as their primary role. Nine mentor surveys were received. The surveys asked respondents how well each of nine HVAC-related topics, as taught by the AE program, prepared them for real-world practice (Fig. 2). Respondents were also asked to rate the importance of each of these technical topics. Finally, they were asked to write comments on what the AE program did or did not do well.

The topics were chosen by the authors based on their professional experience as design engineers. To limit the bias in the survey from this topic selection: (1) respondents ranked the importance of each topic; (2) an open-ended question asked about other topics that are important, but under-taught. These responses were coded and integrated into the results from the numeric survey. The following topics were identified by students as important and needing instructional improvement:

- Plumbing
- Controls and controls sequencing
- Load calculations and energy modeling
- Hands-on systems, equipment exposure, and real-world applications
- Building codes
- Construction documentation

Using a similar questionnaire framework, hiring managers and mentors reported a need for improvement in preparedness in the following categories:

- Plumbing

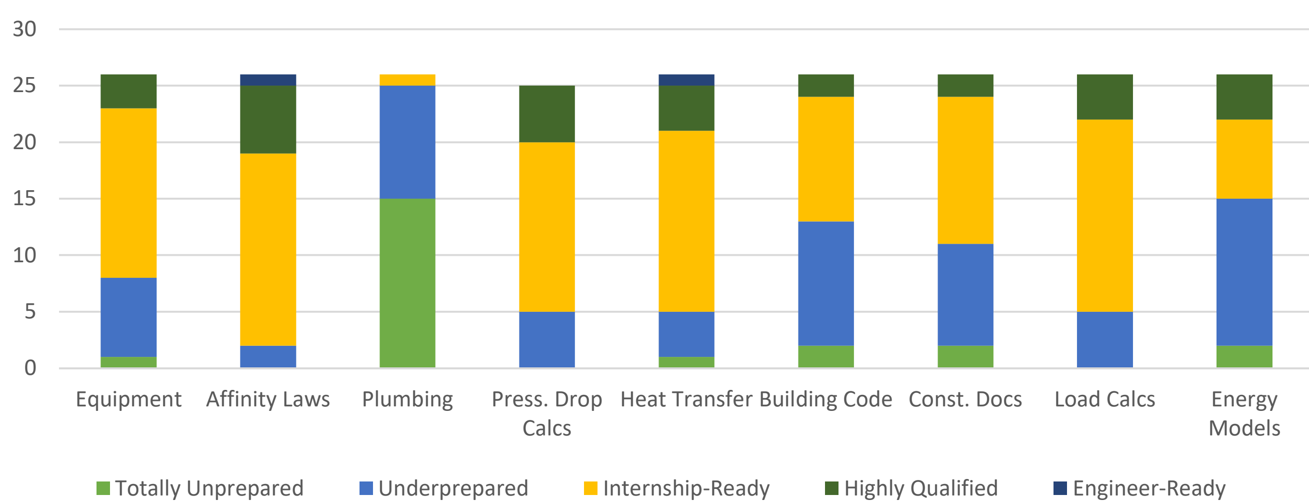

Fig. 2: Alumni Survey Responses - Perceived Effectiveness of HVAC Curriculum by Program Graduates

- Building codes
- 3D modeling
- Controls

These, and other detailed technical results, have shaped the hands-on curricular plan. Based on these responses, the authors identified controls, building codes, and plumbing as the subjects to be taught using hands-on approaches within the ELL.

C. Developing Learning Activities

a) HVAC System in the ELL

For each component within the system, such as a sensor, heat exchanger, or fan, learning objectives focus on (a) understanding the component itself; and (b) understanding how the component interacts with other components and with the full system.

As an example, by simply seeing a fan within an air-handling unit, students in the introductory course gain a mental image to work with as they learn about air-handling units. In the advanced course, they return to run it at different speeds and pressure differentials, while measuring power and flow rate, to expand their understanding of fan operational characteristics. In the controls course, they program the fan speed controller to respond to a pressure setpoint within the air distribution system (ductwork and variable-air-volume terminals) as the system dynamically responds to varying loads. The outcome of the sequence of learning is that the student can select appropriate fans, which operate efficiently and stably for the given conditions, when they are designing full HVAC systems.

b) Individual modules

Modules are being constructed on wheeled carts, so that they can be brought to classrooms, or used within the ELL.

One module in development has a duct pressure drop test that allows students to measure static pressure and airflow for a specific duct fitting arrangement. Students investigate various duct construction standards and test the impact of potential fittings (e.g., compare 90° elbow to radius bend), damper types, or filter types on overall fan capacity, noise, and efficiency.

Another module is the coil control cart, where students investigate hydronic heating or cooling coil control valves, to better understand tradeoffs between fine control, fast control, and pressure drop (hence energy use) for typical valve types. A pump provides flow, and flow rate and pressure measurements are shown, while each valve type is deployed.

These modules address learning outcomes identified in the survey that cannot easily be achieved with the full system.

D. Assessments

There are four avenues that we currently plan to follow to assess the effectiveness of the experiential learning intervention. However, we recognize that assessment is important and challenging, so we will continue to seek improved assessments. The first avenue is to use pre- and post-tests when the learning modules are used to augment an existing course. This will demonstrate the extent to which students' understanding increased for a topic that they had already studied on a theoretical basis. The second avenue is to repeat the survey (discussed above) for the new cohorts who use the ELL. The third avenue is to conduct a statistical analysis of the retention and recruitment data from before and after the intervention. Finally, one of the authors has taught a capstone HVAC design course for several years, in which students apply their knowledge of HVAC systems theoretically to develop a design for a real building. The designs, developed by teams of 2-4 students, are evaluated by the instructor, and by industry professionals using an established rubric. This course provides an authentic assessment of student learning in HVAC. We anticipate that comparison of the designs of the pre- and post-intervention will give the most meaningful of the assessments currently planned.

IV. Conclusion

Due to the specialized nature of HVAC education, there is limited research in this specific field. A novel facility and teaching approach for students studying the engineering of HVAC systems is proposed and described in this paper. A project is underway to develop the required facilities and implement the approach. The effectiveness of this intervention will be assessed, and if found to be successful, could be applied in other engineering fields. A survey of graduates and supervisors identified specific focus areas, and a conclusion from this survey is that hands-on experience with HVAC equipment, and deeper understanding of control systems are prime targets for improved learning outcomes that can be brought about using the facility and hands-on methods. Recruitment and retention are also of interest for the AE program and the associated industry, and will be studied to determine whether there is a positive impact from the new teaching method.

V. Future Work and Challenges

This paper describes work that is in the early stages of development. It comes from a research team with significant experience in practice and research of HVAC topics, but is new to formal study of engineering education. Part of the future work in this project, therefore, is to gain knowledge in pedagogy and educational research methods.

As the learning modules are developed and refined, the equipment in the ELL will be constructed or modified to support these learning modules. The design focuses on expanded controls and sensing capabilities, and considerations to enable the facility to meet the needs of new technology.

A vital future element of this project is assessment of the success of the educational methods that are proposed. This includes characterization of the extent to which the hypotheses – that hands-on learning with HVAC equipment can improve learning outcomes and also improve recruitment and retention within the subfield – can be demonstrated to be true. The key challenge of assessment is that the sample sizes are so small that meaningful quantitative assessments will be limited.

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