Acoustics and Lighting in Architectural Engineering Education: the experience of WPI

Umberto Berardi

Abstract – This paper describes the challenge of project oriented courses to teach acoustics and lighting to architectural engineers. In particular, the new courses of Building & Architectural Acoustics and Building Electrical & Lighting Systems offered at the Worcester Polytechnic Institute (WPI) within the new program of Architectural Engineering are taken into account. In both courses, measurements and software simulations are used to solve real life problems. This approach allows students to develop a professional attitude in which theoretical principles are applied to real problems while modern professional tools are used in an inspiring, but strongly theoretically based, way. The experience of solving the problems of the illumination in the Worcester Art Museum and the acoustic problems in a few classrooms at WPI is described.

Keywords: Architectural Engineering, Acoustics, Lighting, Software Simulation, Case study education.

INTRODUCTION

A new Architectural Engineering (AE) program has recently started within the Worcester Polytechnic Institute (WPI). This new program has been promoted to fill the gap in this kind of programs in New England. The program has been developed and promoted within the Civil and Environmental Engineering Department. As many other programs through the country, the possibility to offer courses of structures and construction management has facilitated the organization of the curriculum of this new AE program [1-3]. However, the development of this new AE program has offered the opportunity of several discussions about possible peculiarities of AE. Programs in AE are facing several challenges mainly due to the evolution of the building sector [4-5]. New requirements of the building sector underline the importance to increase people’s knowledge, and a certain difficulty in identifying the precise expectations of the market generated several doubts during the development of this new AE program.

Consequently, it was important to clarify the peculiarities of an AE program. Twenty years ago, the executive board of the National Society of Architectural Engineers stated that “Architectural Engineering is the profession in which a knowledge of mathematics and natural sciences, gained by study, experience, and practice, is applied with judgment to the development of ways to use economically and safely, the materials and forces of nature in the engineering design and construction of buildings and their environmental systems” [6]. Later, it also affirmed “Architectural Engineering is a multidisciplinary application of building design, construction and management to the architectures”. These broad definitions leave a certain flexibility in defining the competencies and knowledge that have to be offered in an AE program.

A possible help to solve this problem is offered by the Accreditation Board on Engineering and technology (ABET) requirements which state “The program must demonstrate that graduates can apply mathematics through differential equations, calculus-based physics, and chemistry. The four basic architectural engineering curriculum areas are building structures, building mechanical systems, building electrical systems, and construction/construction management. Graduates are expected to reach the synthesis (design) level in one of these areas, the application level in a second area, and the comprehension level in the remaining two areas. The engineering topics required by the general criteria shall support the engineering fundamentals of each of these four areas at the specified level. Graduates are expected to discuss the basic concepts of architecture in a context of architectural design and history”. [7]

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The goal to reach the design level requires the following abilities for the AE program:

✓ Working within the overall architectural design;
✓ Including communication and collaboration with other design or construction team members;
✓ Including computer-based technology and considers applicable codes and standards;
✓ Considering fundamental attributes of building performance and sustainability.

The above requirements leave enough freedom to select the courses to offer and their contents within the four areas indicated by the ABET [7]. Consequently, designing the new AE program at WPI, other accredited programs were primarily considered. Table 1 reports the list of the accredited programs [7]. The idea that emerges from their curricula is that many AE programs still have a root in Civil Engineering departments which support these with courses of structures and construction management [1,8]. However, several other courses to cover the requests of ABET are offered. Moreover, extensive literature has shown that AE programs need to integrate different approaches and the addition of a few courses is not sufficient to guarantee a holistic building performance attitude in AE students [1,9]. In particular, the ABET requirements in the electrical and mechanical curricula allowed WPI to offer new courses. Among these, two new courses were lectured this year by a new faculty with a PhD in AE. These courses are Building & Architectural Acoustics (AREN 300x) and Building Electrical & Lighting Systems (AREN 3004). This paper focuses on the specificities of these courses in the context of an AE education and describes the challenge of teaching these courses with a project oriented methodology.

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**ACOUSTICS AND LIGHTING IN ARCHITECTURAL ENGINEERING PROGRAMS**

The development of the new courses of acoustics and lighting firstly looked at other accredited programs. Table 1 lists the U.S. institutions and includes their offer of acoustics or lighting courses. The information to fill the table were taken from their public websites and does not account to recent changes not documented on the website. A review of the syllabus of acoustics and lighting courses was done before developing the courses at WPI. However, this is not reported in this paper because is outside the scope of this study which looks more at the challenge of these education than to the contents of the courses.

Table 1 reveals that the inclusion of a lighting course is often offered in several programs, probably as a consequence of the electrical curriculum within the accreditation requirements of ABET [7]. Reversely, only a few universities offer a course focused on acoustics. Investigating the lecture contests of these courses, they seemed
related mainly to the presence of a faculty with a research interest for acoustics. Similarly, the course of Building & Architectural Acoustics was offered at the WPI as an experimental course after the hiring of a faculty with a research focus on this subject.

The courses of acoustics and lighting aim to apply physics principles to buildings. According to the AE curriculum at WPI, students should take these courses in their junior year. All students majoring in engineering at WPI take math and basic science courses in the first two years. In particular, the basic physical concepts of lighting and acoustics are covered in two fundamental physics courses (PH 1110 and PH 1120): Newton’s law, mechanic calculations, electromagnetic wave and circuit operation are among the topics of these courses. Moreover, at the end of their first year, students attend a course about differential equations which includes concepts such as harmonic motion, exponential decay and resoration. Consequently, students have a general idea of light and sound fundamentals before enrolling in the acoustics and lighting courses. The prerequisite course of Introduction to Electricity and Circuit (ECE 210), offered by the Electrical and Computer Engineering Department, guarantees that students have a background on insight to basic circuit operations before attending the lighting course.

The introduction of basic knowledge allowed the courses of lighting and acoustic to directly look at architectural engineering applications. In fact, both lighting and acoustical courses have been based on the analysis of real cases [9]. This must be considered within the short and intensive term of the WPI education which concentrates each undergraduate course in seven weeks with classes every day. A project-base course with lectures dedicated to real architectures was considered the best way to show students acoustical and lighting solutions. In fact, although both disciplines are engineering based, they strongly involve the architectural sense that need to be developed in students by increasing their knowledge about past experiences. This is because for both disciplines it is often impossible to offer a unique solution, and therefore a critical approach has to be developed.

In the report at the end of the course, a student declared “this course helped me extensively to understand people’s experience of the building and to know many famous architecture. Unlike heat and ventilation system, which can be based on quantitative measurements such as temperature that I am more familiar with, this course was based on intuitive and qualitative aspects to which I usually did not pay attention to before this course”. This judgment synthesizes the importance of these courses which cannot be considered exclusively to be within engineering disciplines. In fact, these courses aimed to develop a critical sense in the students towards analysis of real buildings, and by doing this, to stimulate students’ creativity and the creation of a personal thought in them.

The case based attitude was also supported by studying case studies of many buildings in the Boston area. In fact, the possibility to know the buildings (with visits organized during the course directly) allowed students to re-discover buildings that they know and live. In this spirit, students were incentivized to take measurements of acoustical and lighting characteristics in these spaces, analyze the results, recreate those enclosures with dedicated software, explain existing problems and propose solutions. The sections below describe in more details the organization and the experience of students through the two courses.

**ACOUSTICS AT WPI**

There probably is not a better place to teach a course in acoustics than in new England, where the modern acoustics was created thanks to the pioneer work of the physician and MIT professor Wallace Clement Sabine. In fact, the number of acoustical consultants is particularly high in Massachusetts and many of the most famous companies in the world have started their activity in this state. However, the course of Building & Architectural Acoustics was a novelty for WPI.

Acoustics is a huge discipline, strongly based on physics, but whose applications nowadays cover several areas from biomedical, to aerospace, telecommunication and noise insulation. However, a certain interpretation of the acoustics as the science of propagation of the sound in buildings remains. It was hence thought to offer a course of building and architectural acoustics to junior students in the AE program. Although it was an experimental course for AE students, the course attracted students from other majors including mechanical engineering, electrical engineering and design and game engineering.

The course was organized with an intensive approach to the theoretical aspects of the discipline in the first five weeks, while the last two weeks were dedicated to the case study project. A continuous reference and analysis of real case studies was done, since the first lecture where the early experiments of the modern architectural acoustics led by Sabine in the Harvard University’s Fogg Art Museum Lecture Hall were described.
The program included a general introduction to the fundamentals of sound, sound sources, and sound propagation; subjective and objective scales of measurement and laws of psychoacoustics; relationships between sound and listener in different scenarios: source and listener outdoor, source and listener in a room, and source and listener in separate rooms. These scenarios provided comprehensive coverage of the principles relevant to architects and engineers related to the architectural and building acoustics. The course also described the design of acoustical specialized spaces such as conference rooms, classrooms, lecture halls, music halls, theaters, and churches. It covered the selection and determination of appropriate spatial and temporal acoustical measurements such as background noise levels, reverberation time and speech transmission index. The second part of the course was dedicated to noise control at high and low frequency; effects of noise and vibration on man and buildings; design of noise control systems; calculation of airborne and impact sound insulation; and noise and vibration control implementations in various indoor spaces, such as residential units, offices, schools and mechanical rooms.

Many studies about the assessment of acoustical perception were presented to students during the first part of the course. This allowed the introduction of several parameters currently used in architectural acoustics. The complexity of subjective sensation of the acoustics of a space was strongly emphasized to students in order to develop the awareness in them of the complex relationship between room acoustics and people perception.

The possibility to comment and visit several buildings in Worcester such as the Mechanics Hall and the Hannover Theater allowed students to discover the peculiarities of different performance halls. A report from another musical hall was required to students (who generally selected one of the halls in Boston).

The assessment of this course was based on three assignments: the first one was dedicated to the analysis of the acoustical characteristics (absorption and insulation) in a room, the second to the sound insulation of a classroom and the third to the virtual simulation and re-design of the acoustical behaviour of classrooms of the WPI campus.

A specific software for acoustical simulation (CATT Acoustics) was used by students to simulate the room after having created a virtual model of the room in AutoCAD. The software modeling was particularly demanding for students who have characterized the acoustical proprieties of all the surfaces of the room. Literature research and online database have represented the main source to answer this request and have showed to the students the typical difficulties of real profession. The simulations were performed by the students in a dedicated studio equipped with computer to each single student. The availability of this studio allowed students to work for many hours a day, in a typical architectural firm environment where the communication and collaboration among students were incentivized. To this regard, different degrees and majors of the students represented a key element for the cross-comparisons.

In the last assignment, students investigated the acoustical characteristics of classrooms under different circumstances. They were hence required to write a report in which different scenarios were critically analyzed. For example, figure 1 shows the Speech Transmission Index (STI), a parameter dedicated to evaluate the listening perception, in a WPI classroom with two external background noises.

![Figure 1 – Simulated result of the Speech Transmission Index in a WPI classroom with background noise of 35 dB (left) and 58 dB (right).](image)

A particularly challenge activity within this course was the presentation of the final simulation results to the department community. A poster presentation was organized to allow students to describe their work and to compare each other. This event helped evaluating the interest of students for a subject like this, which is often neglected in AE programs.
LIGHTING AT WPI

The course of Building Electrical & Lighting Systems aims to make students familiar with basic lighting equipment, as well as the design criteria and analysis procedures that are applied in the design of lighting and electrical systems. Topics of this course are: energy efficiency analysis and design of electrical and illumination systems in buildings; basic concepts of light; the visual environment, including subjective and objective scales of measurement, visual perception, photometry, brightness, luminance, illumination, and daylight; different types of lamps, their applications and interactions with buildings, such as museums, residential and commercial buildings. Before focusing on design problems, the course has dedicated two weeks to electrical concepts such as circuits, transients, electrical loads, panel-boards, switching system, grounding, fault calculations, over current protection, and design and specification of emergency power backup; finally, lighting field measurements and computers simulations are treated.

The evaluation was based on three assignments, that were all related to real-world problems developed and solved according to a professional setting. For the last two assignments, students visited the Worcester Art Museum and performed a study about the existing lighting system in different halls. The analysis started with geometrical and lighting measurements of the halls and their paintings. Photometers were used to take real measurement of lighting conditions in the room; these measurements were then used for software simulation calibrations. For this course, students used DIALux to simulate the rooms previously modeled with AutoCAD. Room and paintings were recreated at the level of details, using photos of the paintings as real texture and three-dimensional painting frames. After recreating the scenario of the halls, each student proposed a new lighting system considering the requirements and flexibility of a museum together with its lighting needs and energy saving improvements respect to the original system (Fig. 2-3).

Figure 2 – Original lighting design of one room of the Worcester Art Museum
Fig. 3 – New student lighting design of the same room of Fig. 2 in the Worcester Art Museum

Fig. 4 shows the improvements of values and homogeneity of the illuminance on a painting in the museum after the redesign of the lighting system. Most of the students promoted solutions which increased the long term sustainability of the lighting systems, by selecting new technology lamps which were able to guarantee long life and energy saving up to 80% of the actual consumption of the museum.

Also for this course, students presented their work in a poster session organized within the department and open to the public. This occasion encouraged a sense of professional competition among students who tried to distinguish and defend their new design not only from an aesthetical point of view but, above all, for their energy saving goal. The success of this experience was confirmed by the attention for the students’ posters of the director of the museum who agreed to host the posters on the museum web-page.

Fig. 4 – False color rendering of the illuminance of a hall in the Worcester Art Museum before (left) and after (right) the improvements
EDUCATIONAL OPPORTUNITIES THROUGH THE ARCHITECTURAL ENGINEERING EDUCATION

The opportunity and need to offer new courses within the new AE program has been the stimulus to reflect about future directions of AE. In particular, the discipline worldwide known as “building physics” has been pointed as one of the most promising areas for AE. In fact, being strongly based on physics, it applies engineering knowledge to the buildings and architectures.

This area is often represented by traditional courses of energy, thermal conductivity and lighting. However, the possibility to offer a course in acoustics is generally limited by the availability of faculty members with this expertise. This situation of AE education is similar to other countries, such as England and Italy, where courses about building physics are often limited to energy modeling (including thermal and lighting topics).

It appears important to underline that the general request for introducing sustainability in engineering education may fruitfully be satisfied by experience like that at WPI [10]. In fact, the experiences reported in this paper have shown the potentiality that courses of lighting and acoustics may have in developing an attention to real buildings, which have been used as scenarios for retrofitting actions based on sustainability principles such as energy saving and comfort improvements [11].

The courses have also revealed that the use of a case study approach may help students to integrate in a building physics class a discussion of historic and modern architecture, and through these increasing their awareness of the fascinating world of the architecture. This is a necessary step in the AE education which more and more is requiring to create a generation of professionals with the capability to communicate within the overall architectural network.

The Opportunity of the Solar Decathlon 2013

WPI, in cooperation with NYU Poly and Ghent University in Belgium, are competing in the Solar Decathlon China 2013. This is a precious opportunity for students to apply theory into practice into a high experimental project where the expertise of university courses is integrated [12]. The goal of the Solar Decathlon is to build a family house that uses solar energy as a primary source for its need.

Many challenges are emerging in the different steps of this project. In general, students and faculties revealed the importance of acquire a holistic thinking to building design. Students with different majors, and from different schools (and countries) are working together to make the house functional. Students learn as they work both from the project itself and the courses they are attending.

In this alive and stimulating context, the courses of acoustics and lighting have already revealed a huge potential. Students were in fact able to choose among the different types of lamps according to energy consumption and daylight condition in the house, and predict with simulations the final result of the artificial/natural lighting system. The acoustics course has offered insight about the sound transmission in the house, and is helping the evaluation of the technology details of the partitions. The Solar Decathlon project is hence setting a platform for students to practice an holistic thinking where the AE courses are immediately integrated within sustainability, energy saving and comfort choices.

CONCLUSIONS

This paper has described the challenge of two new courses in a new AE program. The courses of Building Electrical & Lighting Systems and Building & Architectural Acoustics are project oriented and are both strongly based in showing students real buildings where they can appreciate the application of physics aspects to buildings. In both courses, measurements and software simulations are used to face and solve real life problems. This approach has shown to develop a professional attitude in the students without limiting their theoretical background. The experiences of solving the problems of the illumination in the Worcester Art Museum and the acoustics in a few classrooms of the Worcester Polytechnic Institute have been exciting and have offered students a live contact outside the academia. Moreover, the project based approach has allowed students to present their activity publically and to compare the solution that each student had proposed. These experience may create a stimulus in the students which can develop the different attitudes required by the ABET accreditation (engineering science and engineering design + general education that complements the technical content of the curriculum) in the same course. In fact, these courses have created an ability of students to work within the overall architectural design, considering fundamental attributes of building performance and sustainability, including computer-based technology, without renouncing communication and collaboration skills.
REFERENCES


Umberto Berardi

Umberto Berardi is an assistant professor at the Worcester Polytechnic Institute (MA, USA). He teaches the courses of Introduction to Architectural Engineering Systems, Building Electrical & Lighting Systems, Building and Architectural Acoustics, and Sustainable Construction. He was awarded an MSc from the University of Southampton (UK) and a PhD at the Scuola Interpolitecnica in Italy. Before joining the WPI, he had research experiences in Spain and Netherlands, and was active as a lecturer in Italy. His research areas are related to building acoustics and several energy saving technologies. Has has published 20 papers in peer reviewed journals, among which the Journal of Building Performance Simulation, International Journal of Low-Carbon Technologies, Journal of Mechanical Science and Technology, Sustainable Development, and Intelligent Buildings International.
Course Project: Classroom Acoustical Performance and Software Simulation
Instructor: Prof. Umberto Berardi, Ph.D.
Student: Taoning Wang

Introduction
The purpose of the project is to use CATT software simulating the room we daily studied in and study the acoustical performance of the room. By using the software, we can visualize the acoustical performance and get insight of the acoustical function of each component in the room.

Room Floor Plan

Room with furniture
Workstations and desk were added to the room. On the left, 2000 rays were simulated transferring across the room from the source.

Method
We approach the problem by following an order of simple-to-complex. First, we simulate the room without any furniture or equipment, and we obtain the crude data of the acoustical performance of the room. Then, we add critical components that affect the acoustical performance of the room.

Result
Simple box

On the right, the echogram and SPL of the simple empty room.

C 50 measure the clarity of room whose major acoustical usage is for speech. Generally, the color of the C 50 at 500 Hz between before and after we added the furniture. Commonly, the C 50 is suggested to be greater than 3 dB for learning space.

Scenario Study of Speech Intelligibility
Sound Transmission Index is parameter that measures the speech intelligibility. ISO suggested that the recommended background noise level is 35 dB for learning space. On the top, we have the color map of the STI in room under 35 dB background noise level. There are cases that the background noise level cannot be controlled under 35 dB. Those case may cause the background level to rise. On the bottom, we have the color map of STI under the background level of 58 dB. ISO suggested the rating of STI, and divided them into excellent, good, fair, poor, and bad.

On the right, SPL at 500 Hz (top), reconstruction time comparison between calculated and simulation (middle), SPL at receiver at different locations (bottom).