Educating Students to Manage Civil Infrastructure Systems

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Abstract

In spite of increasing infrastructure preservation and improvement needs, limited agency budgets, and public resistance to new construction, civil engineering education focuses almost exclusively on teaching students to design new facilities. Analytical ability and knowledge of design standards and approaches are necessary but not sufficient tools for managing civil infrastructure in the 21st century. Students must learn to integrate this traditional civil engineering knowledge base with an understanding of deterioration science, economics, finance, decision and management theory, maintenance management, and public policy. This paper describes efforts to address this gap in civil engineering education. The authors began with a single course at Carnegie Mellon University and have modified the original material in different ways to serve the needs at other institutions.

Introduction

Over the past twenty years, civil infrastructure has received considerable attention in the popular press as bridges collapse or are closed, underground pipes burst, and trains derail. However, gradual deterioration has a more significant impact than catastrophic failure on facility users as pavements crack and develop potholes, waterways collect silt, lock gates bow, railroad ties rot, and rails wear. Individual users are delayed or without services, shippers experience additional crew costs, and vehicles are damaged. The American Society of Civil Engineers' *1998 Report Card for America's Infrastructure* gave US infrastructure a failing grade[1]. Furthermore, limited budgets, the need to accommodate existing users, and the challenges of rebuilding infrastructure in constrained situations mean that a knowledge of engineering, economics, financing, new technologies, and analytical tools are critical to being able to address infrastructure problems effectively.

In spite of increasing infrastructure preservation and improvement needs, limited agency budgets, and public resistance to new construction, civil engineering education focuses almost exclusively on teaching students to design new facilities. Analytical ability and knowledge of design standards and approaches are necessary but not sufficient tools for managing civil infrastructure in the 21st century. Students must learn to integrate this traditional civil engineering knowledge base with an understanding of deterioration science, economics, finance, decision and management theory, maintenance management, and public policy. This paper describes efforts to address this gap in civil engineering education. The authors began with a single course at Carnegie Mellon University and have modified the original material in different

ways at other institutions. The paper focuses on just one course rather than programs in civil infrastructure systems as the discipline is still emerging and most graduate programs have not been able to identify this as a specific area of graduate study.

What is Civil Infrastructure Systems?

There are many definitions of civil systems, civil infrastructure systems, infrastructure systems, and infrastructure management. Some examples are included in Table 1. In this paper we use these terms interchangeably.

The focus of this paper is also on graduate (or advanced undergraduate) classes. Therefore, these courses in civil infrastructure systems have evolved in parallel with research in the area. One of the basic premises of our civil infrastructure research is that many of the same principles apply to bridges, railroad track, pavement, roofs, buildings, and other types of infrastructure. This has proved to be an excellent foundation for the course in civil infrastructure systems. Topics, tools, and techniques are not characterized by the application area but by the process.

A Retrospective Look at Civil Systems Education

Civil systems education has its roots in urban engineering and pavement management courses. In the preface to his book *Infrastructure Engineering and Management*, Neil Grigg describes its roots in a 1970 "urban engineering" course at the University of Denver [2]. Similarly, Haas and Hudson provide a foundation for the discipline of pavement management in their 1978 book, *Pavement Management Systems*[3], then with the second edition in 1994[4], and finally with their 1997 text on infrastructure management[7].

Interest in infrastructure management was also accelerated by a conference organized by the Federal Highway Administration. The conference, titled "Transportation Management Systems Conference for Colleges and Universities" and held in Washington, DC, in 1992, brought together academics from across the U.S. to describe educational initiatives related to transportation management systems. In 1994, twenty-four colleges and universities were teaching courses on pavement management or related areas[5]. It is estimated that the number has now climbed to the mid-thirties.

Common elements in the courses being developed and offered are that they are aimed at graduate students, or upper level undergraduates, they have a strong interdisciplinary component, they use case studies and projects to illustrate concepts, and they encourage the students to tackle unstructured problems. Grigg summarizes the basic philosophy that is consistent with our experience:

> *I have found that students from the United States and from developing countries have the same need with regard to this material: to learn to analyze and apply basic principles of management to find solutions to difficult and unstructured problems facing infrastructure management to communicate the results effectively*[2].

Table 1 – Definitions

• *The nation's infrastructure is its system of public facilities, both publicly and privately funded, which provide for the delivery of essential services and a sustained standard of living. This interdependent, yet self-contained, set of structures provides for mobility, shelter, services and utilities. It is the nation's highways, bridges, railroads, and mass transit systems, and reservoirs. It is our dams, locks, waterways, and ports. It is our electric, gas, and power-producing plants. It is our court houses, jails, fire houses, police stations, schools, post offices, and government buildings. America's infrastructure is the base upon which society rests. Its condition affects our life styles and security and each is threatened by its unanswered decay*[6].
• *... combined facilities that provide essential public services of transportation, utilities (water, gas, electric), energy, telecommunications, waste disposal, park lands, sports and recreation, and housing. Infrastructure also provides the physical systems used by other services to the public through economic and social actions*[7].
• *...infrastructure's diverse modes function as a system, providing supporting services to a wide range of economic and social activities, a crucial enabling environment for economic growth and enhance quality of life*[8].

A Snapshot of Activity in U.S. Colleges and Universities

An informal survey, conducted during September and October 1999, examined fifty-one Civil and Environmental Engineering programs nationwide to determine the level of academic activity in infrastructure management/systems and the content of these courses as deciphered from web-based course descriptions. The characteristics of the institutions that were surveyed are summarized in Table 2 and indicate that, while the sample was not drawn randomly or using experimental design, it is fairly representative geographically. Thirteen out of the fifty-one programs reviewed had at least one course in infrastructure management and/or systems (Table 3). Based on course descriptions provided through the world-wide-web, five major categories describe the content of these courses reasonably well:

1. Data Collection Methods (including condition surveys, sampling, and inspections)
2. Analytical Methods
   i. Performance and deterioration modeling tools
   ii. Decision-making tools for economic evaluation and selection of projects (including optimization and prioritization techniques); one course included environmental and social impact assessment
3. Technologies
4. Computerized Management Systems (or Decision Support Systems)
5. Institutional Factors

Table 2 – Profile of Universities used in Infrastructure Management/Systems Survey

Characteristics of Institution		
Geographic Location	Northeast Southeast Midwest Southwest Northwest	33% 16% 25% 14% 12%
Public/Private Institution	Public Private	71% 29%
Carnegie Classification of Universities	R1 R2 D1 D2	74% 22% 0% 4%
Universities with Infrastructure Management/Systems Course Universities without Infrastructure Management/Systems Course		25% 75%

Table 3 – Universities With Infrastructure Management Courses

University	Public/ Private	Location	1994 Carnegie Classification	Title of Infrastructure Management/Systems Course
Carnegie Mellon University	Private	NE	R1	Infrastructure Management
Colorado State University	Public	MW	R1	Infrastructure Engineering and Management
Columbia University	Private	NE	R1	Civil Engineering Management
Georgia Institute of Technology				
				Pavement Performance and Management Systems
New Jersey Institute of Technology				
Polytechnic University	Private	NE	R2	Infrastructure Systems Analysis
University of Arkansas at Fayetteville				Infrastructure Management with GIS and Databases
University of California at Berkeley				
University of Massachusetts at Amherst				
University of Missouri-Columbia				
University of Wisconsin at Madison				
Virginia Polytechnic and State University				

Infrastructure Management at Carnegie Mellon

The Department of Civil and Environmental Engineering has offered the course Infrastructure Management eight times over the past 11 years, serving a total of 115 students, largely graduate students and some graduating seniors. Each year, the class has included one or two participants from outside Civil Engineering, such as Engineering and Public Policy or the Heinz School of Public Administration, and one or two part-time students. While the majority of the graduate students would be classified as focusing on Engineering Planning and Management, students are also drawn from the other disciplines offered, namely Environmental Engineering, Computer Aided Engineering, and Computational Mechanics. The course has also served as a core course for the National Science Foundation funded Graduate Research Traineeships "Integrating Science, Technology and Management in Global Civil Infrastructure Systems."

The parent of this course is a course initiated in the Department of Civil Engineering at Massachusetts Institute of Technology in 1985. The course, "Highway Systems Analysis and Technology," was team-taught by Ben-Akiva, Markow, Humphrey, and McNeil. In 1986, McNeil took responsibility for the course, and renamed it "Transportation Infrastructure Systems." The course focused on four areas:

- an introduction to infrastructure,
- infrastructure performance,
- infrastructure management, and
- resources, including technology and finance.

While the specific topics covered change each year, the basic concepts and areas are still consistent with the original course.

The current course is taught once a week as an evening course to encourage participation from other disciplines and part time students, as they bring a breadth of experience to the classroom. The class is broken into two periods. The first period has a lecture format; readings are assigned in advance, and PowerPoint notes are provided and projected directly from the computer in the classroom. The second period is a mix of class activities, videos, or software demonstrations.

This course continues to evolve and reflect the emerging discipline in this area. Students in practice call to say that they found this course extremely valuable as they "manage infrastructure" in their jobs.

Four Experiences

The Carnegie Mellon infrastructure course serves as a foundation for other courses. The authors have either been an instructor or student in the Carnegie Mellon course and have subsequently developed courses to serve other institutions. The institutions, and therefore the audiences for the courses, represent a range of types, from a U.S. land-grant university to an Asian graduate institute. The content and focus of the courses, as well as the teaching methods used, vary accordingly. Each of these courses is described below.

Asian Institute of Technology – Pannapa Herabat

The Asian Institute of Technology (AIT) focuses only on graduate studies leading to the master and doctoral degrees. Recently, the School of Civil Engineering revised some of its curriculum, particularly in the area of Infrastructure Engineering. In the revised curriculum, Infrastructure Engineering (IE) is offered as a combined program with Transportation Engineering, and the resulting program is called "Transportation and Infrastructure Engineering (TIE)." There are three minor fields of study in IE at AIT, which are infrastructure management, infrastructure demand analysis, and infrastructure economics. Many classes are offered to support these three fields of study. Students are required to take selected courses in both Transportation and Infrastructure Engineering. Most of the students at AIT come from within the Asian region, and approximately 25 different nations are represented in the School of Civil Engineering. The countries in the Asian region vary significantly from well-developed and developing countries to underdeveloped countries, and the goal of the TIE program is to meet the varying needs of these countries.

One of the core courses that the students are required to take in the first term of the program is Infrastructure Maintenance Management. This class was revised and redesigned based on the Infrastructure Management course offered at Carnegie Mellon University. The revised course has been offered for the past two terms and will be offered regularly in each September term. This class focuses on fundamental concepts in managing, planning and maintaining infrastructure in a cost-effective manner. The revised course better addresses the issues and areas of applications that are relevant to the Asian region. In addition, the course places a strong emphasis on areas of expertise of the instructor such as pavement management systems, bridge management systems, deterioration models, inspection processes, and data collection processes.

Some recurring problems in the Asian region are the lack of data for many types of infrastructure and the lack of systematic procedures for inspection and management. These problems are addressed in case studies in the course and help the students to better understand the concept of infrastructure maintenance management. One approach that is often used in the class is to step back and focus more on the fundamental principle of how to effectively maintain the infrastructure facilities by starting with data collection, inspection, planning, scheduling, maintenance, and management. This ties in to the many research activities that are on-going in Infrastructure Engineering at AIT, such as asset management, performance measures, condition assessment, and management systems.

Georgia Institute of Technology – Adjo Amekudzi

Infrastructure and Systems Management will be offered for the first time at Georgia Institute of Technology, in the spring of 2000, as part of the Transportation Systems program in the School of Civil & Environmental Engineering. This is the second course that will be introduced as part of an ongoing initiative to develop an infrastructure systems program component in the School of Civil and Environmental Engineering. In the fall of 1999, the Civil Engineering Systems course was introduced at the undergraduate level. The intent of Civil Engineering Systems is to introduce students to a systems perspective in planning, design, operations, and management of civil engineering systems, at the beginning of the

curriculum. Infrastructure and Systems Management introduces graduate level students to the systemic management of deteriorating infrastructure.

Infrastructure Systems Management expands upon the original framework and content of the Infrastructure Management course taught at Carnegie Mellon University. Like the original course, this course presents an integrated treatment of the models, methodologies, tools and techniques that assist with assessing and controlling infrastructure degradation. Building on Amekudzi's Ph.D. dissertation research, this course develops more detailed treatments of uncertainty, risk, and information quality assessment in infrastructure decision support systems. The intent is to integrate research and teaching activities by sharing research results as part of the class and encouraging students to develop term projects around specific research questions in this area.

Infrastructure and Systems Management also expands the framework of the original course to include smart growth initiatives and sustainability. Smart growth initiatives are introduced to encourage students to think more seriously about behavioral solutions to infrastructure problems, as well as to explore the impacts of such initiatives on transportation-related problems. Sustainability is introduced as a timely paradigm to encourage students to explore project opportunities for incorporating sustainability into performance evaluation of infrastructure. Future plans include offering this course as a continuing education course as it continues to evolve to include more local examples of more and less effective infrastructure management in the rapidly growing Atlanta Metropolitan Area.

University of Missouri-Columbia – Kristen Sanford Bernhardt

Infrastructure Management was taught at the University of Missouri-Columbia for the first time in the spring of 1999. The course was listed as a "special topics" course, and enrolled 9 students – three graduate students and six undergraduate students. The three graduate students are all working toward transportation-related M.S. degrees, and the six undergraduates were all within three semesters of graduating. Several of the undergraduates had interned with the Missouri Department of Transportation. The course will be taught again in Fall 2000 as a special topics course, and application has been made for a permanent course number. The number of students enrolled is expected to increase as students become familiar with course content and graduate student enrollment rises.

Sanford Bernhardt designed the course to be similar to the original Carnegie Mellon course. The intent of this course is to broaden students' perspective from focusing on one type of facility or one aspect of civil engineering (such as soil mechanics or steel design) at a time, and instead to focus on the interaction of these system components. For graduate students it provides a foundation for preliminary thesis research, familiarizing them with the terminology and background needed to conduct their research. For the undergraduates, it introduces a critical aspect of civil engineering not found in other courses.

The course is currently undergoing revision from primarily lecture/discussion with projects at the end to a more case-based or problem-based learning format. In addition, Sanford Bernhardt is marketing the course to graduate students in other areas of Civil Engineering

and other departments across the university, recognizing that it is not only civil engineers who mange civil infrastructure. Discussions are also ongoing about the possibility of using distance-learning techniques to extend the course to interested students at the University of Missouri-Rolla and/or to employees of the Missouri Department of Transportation.

University of Minnesota – Sue McNeil

In the spring of 2000, the University of Minnesota began offering a professional masters program in Infrastructure Systems Engineering. The program is open to engineers and professionals in public works, transportation, consulting, and related areas with sponsorship from employers. It is a two-year course of study, requiring work release every second week and Saturday classes every other week. The initial cohort is about twenty students. It is intended that each cohort will progress through the program as a unit.

The course, Infrastructure Systems Engineering Management, is a core course and will be taught by McNeil in the spring 2000 semester. It is modeled after the Carnegie Mellon course, with an emphasis on the systems aspects of infrastructure, that is, the elements, concepts, and analysis tools common to different types of infrastructure. It also tailors projects to the interests of individual students. Students will be asked to identify a type of infrastructure at the beginning of the semester and, as the semester progresses, to develop components for an integrated plan for managing that type of system as specific topics are covered in class. Students may use work-related experience or a hypothetical system as the focus for their plan.

Pavement Management, Maintenance and Rehabilitation, and Computer Applications will also be offered the same semester. Exercises in the computer applications class will use concepts presented in Infrastructure Systems Engineering Management. For example, the students will use Excel to compute the progression of deterioration using a Markov model. Subsequent courses in the program will address specific types of infrastructure (bridges, water distribution, sewer collection, water treatment), project management, geographic information systems, and finance. It is hoped that this program will fill a critical need in the education of infrastructure professionals. The program was developed by the Department of Civil Engineering and the Center for the Development of Technological Leadership, with input from Minnesota Department of Transportation and the broader professional community.

Conclusion

There is an ongoing paradigm shift in engineering education – from the purely technical to a more multidisciplinary and well-rounded model. For example, as stated in a recent article in the ASCE Journal of Professional Issues in Engineering Education and Practice[9]:

> *"Engineering appears to be at a turning point. It is evolving from an occupation that provides employers and clients with competent technical advise to a profession that serves the community in a socially responsible manner. Traditional engineering*

education caters to the former ideal, whereas increasingly both engineers themselves and their professional societies aspire to the latter. Employers are also requiring more from their engineering employees than technical proficiency. A new educational approach is needed to meet these changing requirements."

The introduction of courses such as Infrastructure Management embraces this shifting paradigm.

A systems approach to infrastructure management provides students with a valuable perspective not presented in most civil engineering courses. While the courses described do not address "design" in the sense of selecting the material for and dimensioning a beam or a column, they do present students with open-ended, complex problems. The ABET 2000 criteria change the de-facto definition of "design" in the curriculum that many institutions have been following to allow a more liberal interpretation, and the types of activities in these courses certainly qualify. They present students with an interdisciplinary approach, forcing them to tie together basic engineering knowledge with economics, management, and other skills.

The challenge in these courses is to engage both student and faculty interest and to address the topic in sufficient breadth for the students to appreciate the interdisciplinary linkages while providing sufficient depth so that the students can apply what they've learned.

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