INSTRUCTIONAL & TECHNOLOGICAL INNOVATIONS TO ATTRACT & RETAIN UNDERGRADUATES TO ENGINEER THE BUILT ENVIRONMENT

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Abstract *¾ Columbia University's Departments of Civil Engineering & Engineering Mechanics and Earth & Environmental Engineering and Center for New Media Teaching and Learning have recently partnered to develop instructional and technological innovations to develop reflective practitioners of engineering that are prepared for the engineering tasks of the 21st century. The partnership has begun a series of initiatives to develop a working prototype, called OPTIMUS, that simulates urban scenarios by integrating a three-dimensional interface of urban environments with underlying databases and models that represent components or systems within these environments. The prototype will become the central feature of a re-designed undergraduate curriculum that exposes students to the issues and variables of the built environment early in their undergraduate experience. The new curriculum is anchored by a sequence of classes in the first three years that progressively expose the students to a variety of civil & environmental engineering problems of regional and national interest in a case study mode. The proposed curriculum will be progressively specialized as one moves to the higher grades, offering a student the opportunity to explore a subsystem given an understanding of the larger context of the problem. The expectation is that this early exposure to the context of civil & environmental engineering problems will: (a) motivate students to enter and complete programs of instruction, (b) deepen student appreciation of the fundamental theories of mathematics and mechanics, and (c) better prepare students to analyze complex, multi-disciplinary problems.*

Index Terms ¾ civil & environmental engineering curriculum, education technologies, education simulations.

INTRODUCTION

The breadth of civil and environmental engineering (CEE) and its interactions with physical, chemical, ecological, social and economic systems pose tremendous challenges for the design of an undergraduate curriculum. The traditional, skill based curriculum has successfully trained a cadre of engineers who have designed and built reliable infrastructure that society takes almost for granted. Civil and environmental engineers, however, now face two substantial challenges: (1) re-engineering a massive, worldwide built environment that has deteriorated and needs rehabilitation or replacement, and (2) regaining professional prestige that has degraded through perceived, if not real, insensitivity to social and ecological issues and increased specialization that promotes commodity compensation. These circumstances have come to the fore when CEE undergraduate enrollments in the United States have been declining, and retention of women and other minorities lag expectations. Interviews with students reveal a strong interest in CEE subject matter, but a lack of knowledge regarding an engineer's role in society and a sense of ill-preparedness for the work force upon graduation that is often ascribed to abstract, process-based instruction.

A prevailing response to this situation is that an undergraduate engineering program cannot adequately provide the breadth and depth of coverage needed, particularly given the humanities, liberal arts and basic science requirements. Consequently, the MS is being proposed as the entry level professional degree and various mechanisms for combined BS-MS degrees, coursework only MS degrees and the like are being explored and implemented. While this conclusion and the resulting direction may be inevitable in the traditional education model, it is unclear that they constitute the best response for educating engineers as analysts and as "master integrators" or leaders in providing solutions for meeting the needs of managing a complex and changing system.

Columbia University's Departments of Civil Engineering & Engineering Mechanics and Earth & Environmental Engineering and Center for New Media Teaching and Learning have recently partnered to develop instructional and technological innovations to systematically address these issues. Still in its infancy, the partnership has begun a series of initiatives to develop a working prototype that simulates urban scenarios by integrating a three-dimensional interface of urban environments with underlying databases and models that represent components or systems within these environments, called OPEN PLATFORM FOR TEACHING INTEGRATED MODELING AND URBAN SIMULATION (OPTIMUS). The prototype will become the central feature of a re-designed undergraduate curriculum that exposes students to the issues and variables of the built environment early in their undergraduate experience. By presenting realistic engineering scenarios to either freshmen or sophomores, we expect this exposure to

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"de-mystify" the discipline, so students have a concrete understanding of the roles engineers play in the built environment. More importantly, students receive an introduction to problem solving that emphasizes an integrated and systems approach, so they recognize that the application of engineering expertise requires synthesis of topical knowledge.

This paper describes these initiatives by: (a) reviewing the factors motivating these changes, (b) presenting a conceptual description of the urban simulation prototype, plans for its development and implementation, and progress to date and (c) outlining assessment and evaluation methods to be implemented to measure whether the effects intended have, in fact, been achieved. Our working hypothesis is that this early exposure to the context of civil & environmental engineering problems will: (a) motivate students to enter and complete our programs of instruction, (b) deepen student appreciation of the fundamental theories of mathematics and mechanics, and (c) better prepare students to analyze complex, multi-disciplinary problems.

BACKGROUND

Institutional Background

Columbia University has separate departments of Civil Engineering and Engineering Mechanics (CEEM) and Earth and Environmental Engineering (EEE) that work closely together. While the CEEM and EEE programs have been quite traditional, undergraduate students get comprehensive exposure to the basic science and liberal arts curriculum through a common core program for all majors for the first two years. Consequently, the primary contact that undergraduates have had with their engineering department in the first two years has been quite limited. Recently, both CEEM and EEE have introduced introductory level survey courses in the freshman year (*Design of Buildings Bridges and Spacecraft,* and *Earth Resources and the Environment*) that have been very popular relative to the size of each department. Despite the relative popularity of the courses the 'yield', measured in terms of the proportion of the class who remain as majors is low.

Recent Initiatives

The two departments secured an internal grant last year to initiate a comprehensive reformulation of the undergraduate curriculum to better address integrative, complex, earth systems problems. New faculty with relevant experience were hired during this period, and the initiative is strongly supported through the departments and upper administration.

One of the objectives of curriculum revision is to provide technical literacy to non-majors, and to recruit motivated students already admitted through a competitive process into our programs. Another goal is to position Columbia as a leading provider of state of the art instruction using multiple media and delivery mechanisms on issues pertaining to infrastructure and environmental management – areas identified as primary societal challenge for the 21st century and designated as focal points of the University's mission to its community. In interviews with entering freshmen, we have learned that this direction and the mandate of the engineering programs to develop solutions to such problems is of particular interest to women students. This interest is also manifest in the gender distribution of enrollment in the existing related classes. All students expressed a strong interest in early exposure to and involvement in the analysis of local, regional and global problems, and in working on projects with practitioners. Work on developing a new curriculum in this direction is underway; key elements are discussed later.

Engineering & CCNMTL Partnership

More recently, CEEM & EEE and the Columbia Center for New Media Teaching and Learning (CCNMTL) formed a partnership to produce a working simulation prototype, OPTIMUS, as an integral component in the redesign of the undergraduate curriculum, and to broadly disseminate resulting tools and outcomes. The CEEM and EEE Departments provide scholarship and engineering insight, while CCNMTL, with its programmers, designers, education technologists, and research and development staff, has expertise in knowledge architecture, interface and pedagogical design that will support the creation of the simulation and its pedagogical use.

PEDAGOGIC PHILOSOPHY

Underpinning these initiatives are two core principles: (1) problem-focused instruction and (2) utilization of technology. A brief discussion of each principle, including the motivation and the possibilities for its use, follows.

Problem-Focused Instruction

Problem-focused instruction holds promise for improving student attraction, retention and performance. Many educational specialists are critical of passive, lecture based learning methods, so *active and cooperative learning* (ACL) approaches are recommended [4], [6]. Our own students often claim that they learn more from peers or from one on one interaction with the professor than they do from lectures. Further, research on classroom learning (see [2] and [5]) suggests that the traditional, abstract approach is more successful with male students, and that women prefer "*group discussions, simulations, panels and other activity based learning*" [2]. Roesset and Yao [7] observe, "*most teaching at present is abstract (principles rather than applications), verbal, deductive (going from general axioms to applications), and sequential*." The lecture format dominates, and exposure to problem formulation and solution in the first two years is lacking. When coupled with the inattention to the "*people serving dimension*" of the engineering profession, many students leave programs during this period [3], [9]. A keystone of our plan is to focus on the solution of infrastructure and environmental problems with an early exposure to systems analysis and problem formulation concepts using a case study approach to instruction. Unit process models are introduced in this context, rather than as primary building blocks. By presenting realistic engineering scenarios to students early in their undergraduate experience, we expect to provide them a concrete understanding of the roles engineers play in the built environment. More importantly, students receive an introduction to problem solving that emphasizes an integrated and systems approach, so they recognize that the application of engineering expertise requires synthesis of topical knowledge. In addition, this approach "opens" engineering to a larger student population thereby providing technical literacy to non-engineers and exposing engineering students to the values and competencies of non-technical disciplines.

Utilization of Technology

Technology enables the transformation of instructional methods and, more importantly, the practice of engineering. Recent advances in technology have fundamentally changed engineering methods, and the type of engineering education required. Traditionally, engineers have been trained as "*efficient solvers of routine problems*", using a mix of empirical rules and first-order principles. Today, software packages allow the parametric investigation of a range of engineering alternatives in minutes supplanting years of traditional office experience. Unfortunately, engineering curriculums have been slow to adapt to such technological changes. While technology has been used extensively in the development of K-12 learning modules, and to some extent in graduate science education, the basic instructional model for engineering education at the undergraduate level has only received recent attention. These trends are remarkable given the attendant technological and information explosion over this time period, and the emerging importance of using the increasing amounts of data to understand, resolve and manage spatial interactions between physical infrastructure and the environment.

Further, technology presents us with a marvelous tool, the digital computer simulation, with which to probe and learn about the mercurial nature of the built environment and engineering systems. Simulation is a cornerstone of discovery learning-styles where students are immersed in an environment that encourages them to infer concepts and to actively engage a problem [8]. More simply, students "learn by doing", and computer simulations have been used widely in education to provide experiential learning about the interplay of complex forces in a range of subjects: archaeology, architecture, science, and history. Computer simulation can be a laboratory for studying the informational structure of complex systems. The creation of silicon surrogates of real-world complex systems allows teachers and students, to perform controlled, repeatable experiments. Users can play myriad sorts of what-if games with genuine complex systems. Such simulations enhance learning through visualization, experimentation, and the creativity of play. Increased learning occurs by problem solving in a complex interactive environment and by "seeing" causal relationships between individual action and whole systems. The broader implications of using such simulations in engineering classrooms are for students to become more effective learners and thinkers enabling them to make connections across the curriculum.

PARTNERSHIP INITIATIVES

The proposed plan for developing and implementing a new curriculum facilitated by OPTIMUS is presented through an illustration of key factors. The structure of a desirable curriculum including its goals is identified first, which leads to a conceptual description of the software technology OPTIMUS. Methods for assessing the impact of the proposed curricular adjustment are then reviewed.

Curriculum Design

Discussing baccalaureate engineering education Bordogna [1] comments that it has been too focused on "*reductionistic science*" and too little on holistic elements. He notes that this approach drives many capable students away at the front end. For the 21st century, he argues that the engineer's essential role is an integrative one, and education needs to foster the capabilities summarized in Table I.

TABLE I
ENGINEERING SKILLS

20th Century Emphasis	**21st Century Emphasis**
In-depth thinking	*Functional Thinking*
Abstract Learning	*Experiential Learning*
Reductionism	*Integration*
Develop Order	*Correlate Chaos*
Understand Certainty	*Handle Ambiguity*
Analysis	*Synthesis*
Research	*Design/Process*
Solve Problems	*Formulate Problems*
Develop Ideas	*Implement Ideas*
Independence	*Teamwork*
Techno-Scientific Base	*Social Context/Ethics*
Engineering Science	*Functional Core of Eng.*

While 20th century education emphasized the left column, attention is now needed to the items in the right column. Developing contextual understanding, an ability to create, operate and sustain complex systems, skills for lifelong learning, and communication skills constitute the functional core of engineering.

The current Columbia curriculum invests the first two years largely in science and humanities courses that provide valuable but seemingly disjointed knowledge. The subsequent years provide exposure to unit process skills culminating in a capstone design project. For example, a student may learn to analyze and design structural elements, and in an advanced class procedures for structural response to acceleration (earthquake), but he/she will rarely be exposed to the issue of the attendant water, electric, transportation system failures and fires. Yet, with existing infrastructure the synthesis of a response to such a hazard across all these elements is likely to be more valuable.

Our plan focuses upon the solution of infrastructure and environmental problems with an early exposure to systems analysis and problem formulation concepts using a case study approach to instruction. This approach necessitates a significant change in the existing curriculum (and in the method of instruction) as illustrated *in concept* for the EEE program in Figure 1. A similar structure will evolve for the CEEM program. The existing curriculum is marked by skill or process based classes. The new curriculum is anchored by a sequence of classes in the first three years that progressively expose the students to a variety of EEE problems. The proposed curriculum gets progressively specialized as one moves to the higher grades, offering a student the opportunity to explore a subsystem given an understanding of the larger context of the problem. For instance, hydrology is now taken in the senior year with no prior context. In the new curriculum, the student will have experienced hydrologic analyses several times by the time a formal hydrology class is taken. This will allow us to teach hydrology in a much more sophisticated manner.

The systems approach is first introduced at the freshman level, as a formalism for identifying the salient aspects of the problem, defining key state and control variables, and identifying the type of scenarios to generate given the objectives or goals of the stakeholders. An exposure to the complexity of the coupled systems, the interplay of scales, and the emergent uncertainties is provided. The role of different bodies of knowledge (e.g., physics, statistics, economics, sociology) emerges naturally. EAEE 1100 Earth Resources & Environment was introduced in the spring of 2002, and information about this class can be obtained from the project's web-site. Analysis of infrastructure systems and their design and management to support a livable city follows. The third class in the sequence reinforces systems engineering skills through the application of numerical, optimization and Monte Carlo simulation tools. Sub-system theme classes follow.

Simulation Prototype: OPTIMUS

Technology can facilitate our goal of producing reflective practitioners of engineering that are prepared for the engineering tasks of the 21st century. Computers provide a conversational environment in which the learner can apply knowledge to problems and consider their actions as reusable events. Learners can control their learning, learn from others and develop reflection in action and reflection on actions as metacognitive skills.

A gaming system will be used to develop and introduce the concept of a system and interacting subsystem, as well as basic ideas of mathematical and symbolic modeling and their relationship to data. Concepts of risk and uncertainty will be illustrated through the relationship of events generated stochastically, their expected frequencies and the spatial impact. Vulnerability and exposure to natural and environmental hazards will be made explicit in a spatial context.

The *SimCity* (copyright Maxis) gaming environment is appealing as a building block. It is a "god game", in which the player assumes the role of master controller (mayor) and directs the simulation through the design of a city (power, water, waste, education, fire, etc subsystems) and its operation (budgeting, ordinances, environmental investments). Feedback on the mayor's performance is

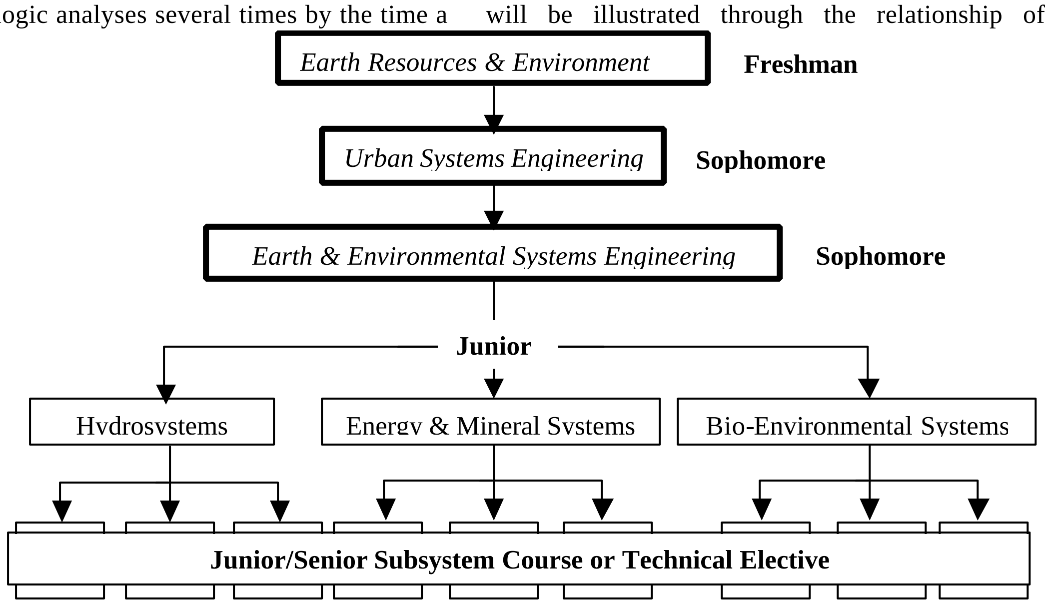

FIGURE 1
PROPOSED EARTH & ENVIRONMENTAL ENGINEERING CURRICULUM

provided continuously through spatial maps of pollution, growth measures for residential, commercial and industrial sectors, fires that break out in areas outside the range of designed service, and pop up windows that represent citizen concerns. The player functions as an implicit optimizer seeking to grow the city to a high degree of affluence and population, accomplished by balancing growth amongst sectors and maintaining a good environment.

Students often have considerable experience with such games and adapt very quickly to interacting with them. Currently, *SimCity* lacks the open architecture to add modules and extract state variables. In addition, multiple roles are not a part of the current platform. The addition of multiple roles would allow student teams to participate in a simulation as a city public works engineer, a water systems manager etc., and explore what is involved in designing a system and interacting with the institutional and regulatory setting. A limited capability to import GIS terrain and land use data directly into *SimCity* already exists. Palettes to change the landscape, easily add infrastructure elements and the like already exist. They could be enhanced to enable realistic specification of components (e.g., conveyance pipes). Consultants familiar with *SimCity* and its architecture have graciously agreed to assist in the development of OPTIMUS.

SimCity uses Cellular Automata (CA) as the underlying modeling structure, which allows spatial interaction and space-time evolution. Classical models for fluid and heat transfer based on partial differential equations are readily recast as CA models, enabling the instructor to start introducing these concepts early in the curriculum. CA models are also used extensively for spatially extended ecological, environmental and social modeling. Local (in space and time) rules are used to identify the evolution of the system from one time to the next. The CA framework appears to be very useful as a building block for spatial models and for teaching material on interacting subsystems.

Integrating a visual platform with data and models that represent the socioeconomic, natural and physical fabric of an urban center holds substantial promise for engineering instruction. Students can be exposed to various scenarios within a realistic setting and then be given the opportunity to investigate, design and implement changes to the natural and built environment; subsequently, they will also have the chance to observe the effects of the strategies that they implement. *SimCity*'s spatial and visual platform provides a ready vehicle for integrating data sources and models to represent the social and physical systems that embody an urban center. Once links are established between three-dimensional images of systems or components and databases or models that store information or represent physical behavior, the possibilities as an instructional tool are quite exciting.

Interaction with the tool could take a number of forms. Students could access a database from the visual simulation window by selecting an object in the 3D environment of an urban neighborhood. This could highlight 2D GIS maps and data tables in a separate window. Students could then query and analyze demographic, economic or technical data in the region of interest. In addition, students could investigate and study changes in the urban landscape by "picking" objects from a 3D scene. Once selected, an object could be removed from the scene (simulating, for example, the removal of a building from a lot) or alternative models could be substituted for the object. Students could easily design and review different options for a particular site or region.

Most newcomers to engineering, and more broadly the general public, are interested in failures of the built environment rather than successes (which are often taken for granted). A proposed simulation scenario is an urban earthquake disaster, which possesses characteristics that align with the project's pedagogical objectives. The scenario demonstrates the *interdependency* of infrastructure systems, the effects of *spatial distribution*, and the *uncertainty* of natural hazards. For instance, during an earthquake, structures will suffer varying degrees of damage or potentially total collapse depending on the structure type, location relative to the epicenter, the soil conditions at the site of the structure and many other factors. An existing software tool HAZUS, which was developed by FEMA as their "Natural Hazard Loss Estimation Methodology" for the United States, could be linked to the basic SIM package with which the students interact. HAZUS generates damage distribution output for a scenario earthquake. Estimates can be made for dollar and/or life losses.

The basic data required by HAZUS includes the distribution of soil types and building stock (e.g., single story, high-rise, mid-rise apts. etc.). Such data would remain fixed, and students could study the consequences of different magnitudes and earthquake epicentral locations relative to the city being considered. More importantly, basic engineering concepts can be introduced such as what pre-emptive measures designers could take to mitigate the effects of such a natural disaster. Naturally costs would be associated with these design choices, and students could evaluate the cost/benefit of the design choices with the expected losses estimated by the HAZUS loss estimation kernel. In addition, this result emphasizes the insurance and public policy aspects of basic design issues in civil engineering.

Assessment and Evaluation

Once we have implemented the prototype simulation along with the curricular changes in the classroom, we must insure that the effects intended have, in fact, been achieved. Obvious metrics that are easily observed such as student enrollment, retention and graduation rates will be tracked after implementing the adjustments proposed, but assessing the impacts of OPTIMUS and the curricular change upon student learning processes is far more important, as well as more difficult. Evidence to gauge the quality of the education given and, if necessary, to improve it, will be collected from three sources: the learning effect, controlled using written examinations and group reports/presentations; the observations of the teacher and teaching assistants (if present); and a users' analysis (student opinions of the teaching provided). The simplest way of performing a users' analysis is to provide a questionnaire to all the students and follow this up with a focused task analysis with selected users. Using these techniques, information can be acquired about the clarity of materials, the relation of materials to other elements of instruction, the degree of difficulty relative to the target group, and the desirability of chosen teaching methods.

PROGRESS TO DATE

A grant from the U.S. National Science Foundation was recently acquired by the project team, so development of the prototype simulation tool will begin in earnest in the fall of 2002. Currently, the design and integration challenges of the simulator are the principle subjects of interest, and the team plans to settle upon a basic architecture for OPTIMUS by the end of the summer. Once complete, development activities will commence. The goal is to have a working prototype which has the data and models necessary to support several engineering scenarios available for the classroom by 2004. Content and materials for the new undergraduate courses will be developed concurrently. Project information will be made available through a web-site; links to the site can be found from the CEEM and EEE department web-pages.

CONCLUSION

The initiatives described take a fresh look at the undergraduate education of the CEE and develop technological innovations that support curricular redesign and student learning. The proposed technological innovations are designed to: a) make the analysis of infrastructure and environment in the proper social and spatial context accessible, b) emphasize the use and collection of data, c) stimulate in-depth and creative research, and d) involve students in solutions to community problems so that they appreciate their historical and cultural context. The spatially explicit simulator under development will combine a variety of interacting infrastructure and environmental components and will be used as a vehicle to introduce broad problem contexts and to bring case studies to life. Student teams will use them to explore historical data, as well as the effects of both policy and structural measures for a range of problems (e.g., natural and environmental hazards) on the long term functioning of the infrastructure, the environment and interacting social systems. As a result, we expect to improve student learning and to generate the student excitement that the field of civil & environmental engineering warrants.

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