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# New Course in Engineering Systems at Purdue University - Introduction to Civil Engineering Systems Design

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## ABSTRACT

*The large inventory and high value of civil engineering systems, coupled with the multiplicity of stakeholders and performance measures, necessitate a comprehensive yet integrated approach to the development and management of these systems. In wake of well-publicized failures, civil systems are facing scrutiny more than ever before, and engineers are increasingly being called upon to render account of their fiduciary stewardship of the public infrastructure and assets. This continues to be an important issue at the current time and in the foreseeable future due to ongoing trends such as aging infrastructure, limited funding, increasing user expectation, increased stakeholder participation, and greater desire for sustainable solutions. Also, due to the large expense involved in providing and operating civil systems, even marginal percentage savings earned by adopting systems approaches could translate into substantial amounts. Past evidence shows that such approaches are best appreciated and implemented when the development of civil facilities is viewed explicitly from a systems perspective. Over the last decade, many universities have sought to revive efforts that infuse "systems" perspectives to their traditional civil engineering curricula by establishing courses in that area. This paper describes a new course titled "Introduction to Civil Engineering Systems Design" that was introduced in fall 2003 as a required course in the undergraduate curriculum, at Purdue University's School of Civil Engineering. In viewing systems concepts explicitly from perspectives of systems phases, tasks, and tools, the course introduces a fresh paradigm to the way systems concepts are taught to civil engineering students. Specifically, the course presents the seven phases of civil systems development, five key tasks faced by the engineer at each phase, and the various tools needed to carry out these tasks. This course satisfies a significant section of current ABET requirements and ASCE rubrics for undergraduate civil engineering education.*

## KEY WORDS

Engineering systems, systems course, civil systems, engineering curriculum.

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## 1. Introduction

In 2003, as part of implementation of recommendations from the Curriculum Reform Committee of Purdue University's School of Civil Engineering, a new course "Introduction to Civil Engineering Systems Design" was developed for inclusion into the School's civil engineering curriculum. This was a revival of a similar course taught in the seventies at Purdue University but had been discontinued due to changes in the department's plans. The overall purpose of the new course was to impart techniques of operations research, financial engineering, and other systems concepts in the way undergraduate students plan, design, evaluate, and manage civil engineering structures and facilities. Also, it was envisaged that the new course would provide the future engineers with greater awareness of the consequences of their designs from the perspective of the ecology, the economy, the social and cultural environment, and other performance measures associated with sustainability. The course was approved by the University Senate in 2003. The establishment of the course at Purdue seems to be consistent with a global trend where civil engineering departments seek to infuse "systems" perspectives to their traditional civil engineering curricula. Obviously, this development arose out of the worldwide recognition that the developers of civil engineering systems need not only the traditional skills of physical or operational design or construction but also the skills to evaluate alternative designs, construction processes, and operational/maintenance techniques on the basis of a wide range of "external" performance measures.

This paper discusses the elements of the Introduction to Civil Engineering Systems Design course. These elements include motivation for establishing the course, basic course information, course content, and how this course differs from similar courses elsewhere. The paper also presents the mechanisms adopted for instructional delivery, the schedule of lectures, and the lessons learned after five years of course implementation. The course content is described in the context of the three key underlying themes that serve as the central philosophical pillar around which the course concepts revolve.

## 2. Motivation For The Course

In first lecture of the course, students are presented with the motivation for which the course exists. This is done for two reasons: Firstly, for students to acquire greater appreciation of ongoing and future developments that require them to infuse systems concepts in the way they will plan, design, construct, and operate the systems in their respective fields of civil engineering; and secondly, for students to be aware of the vastly advantageous position they stand to place in the industrial and academic communities when they are equipped with the concepts, tools, and perspectives offered by the course.

The motivation for the course rings across the entire terrain of civil engineering, in fields including structural, hydraulic, geotechnical, construction, environmental, transportation, and architectural engineering. For any real or virtual system in any of these fields of civil engineering, the system development cycle involves needs assessment, planning, design, construction, operations, monitoring, preservation, and termination. The technical design of specific elements of systems in these fields is well covered in traditional courses at Purdue

University as in most other universities. Most working engineers are typically involved in only one or two of these development phases of civil systems. However, it is beneficial for all engineers, particularly in the present era, to acquire an overall and explicit bird's eye view of all phases of the system development cycle so that decisions they make at any phase are holistic and within the context of the entire cycle.

Major motivations for using systems concepts in civil engineering include the large inventory and high value of civil engineering systems, the large volume of funding for their preservation and operations, and the multiplicity of interested parties and stakeholders. These necessitate a comprehensive yet integrated approach to the design, analysis, evaluation, and implementation of these systems. Thus, civil engineering systems are facing scrutiny more than ever before. Civil system engineers are increasingly being called upon to render account of their fiduciary stewardship of the public infrastructure and assets at both network level and facility level, and the biggest bang is now sought for every dollar spent on these systems. This is important at the current time and in the foreseeable future primarily due to global trends (aging infrastructure, limited funding, increasing user expectation, increased stakeholder participation, greater desire for sustainable solutions, etc.), but also because of the typically large expense involved in providing civil systems. Every year, several billions of dollars are invested worldwide in civil engineering systems, to build new facilities or to preserve or operate existing ones. Even marginal percentage savings earned by adopting optimal practices can translate into large amounts.

Another motivation is that the costs and benefits of civil engineering investments permeate every sphere of our lives including safety, mobility, security, and the economy, and thus need to be assessed comprehensively in any decision-making at any phase of civil systems development. Also, the adverse impacts of civil systems, such as environmental degradation and community disruption are often evident and need to be assessed and mitigated proactively.

This course demonstrates that these motivations can be addressed when civil engineers view explicitly the development of their systems within a phasal framework, and when they acquire the requisite tools needed to address the tasks at each phase.

## 3. Basic Course Information

*3.A. Course Objectives*

The objectives of the new course are as follows:

1. Provide the civil engineering undergraduate with an overall picture of the development of systems in their respective areas of civil engineering, from the initial phase of needs assessment, to planning, design, implementation (construction), operations, monitoring, maintenance, and termination.

2. Expose the civil engineering undergraduate to the various tasks and challenges faced by civil engineers at each phase of the systems development process, such as description, analysis, optimization, evaluation, of various processes and physical elements.

3. Equip the student with the requisite analytical tools needed to carry out the tasks that will be encountered at various phases of the system development process.

4. In the course of addressing (1 to (3), expose the student to concepts such as engineering economy, probability and statistics, operations research, environmental impacts, uncertainty analysis, and sustainability

5. Address professional issues such as ethics, legal issues, and management

6. Help the civil engineering undergraduate to develop vital skills of report-writing and technical presentation, as a prelude to the senior design course.

7. Serve as an integrated part of a three-course sequence: (Semester 6) Systems Design, (Semester 7) Management and Communication, (Semester 8) Senior Design.

The course is intended for college instructors and students in the areas of civil engineering systems and can be taken by advanced undergraduate and beginning graduate students. All the material could be covered in one semester on condition that there are no less than three credit hours per week for the course. Also, the material taught in the course is expected to be useful to practicing civil engineers, civil systems managers and policy makers in general at private and non-governmental organizations, consultants, public policy makers, and other institutions involved in various phases of civil systems development. Such institutions include public entities such as state and local (city and county) departments, municipal authorities, public works departments, regional planning agencies, and metropolitan planning organizations. This course provides fundamentals for understanding the issues involved in developing the civil systems at these organizations.

*3.B. Brief Description of the Course*

This course introduces the fundamental concepts associated with civil engineering systems design from needs assessment to implementation. The topics covered are: the phases of systems development, tasks faced at each phase (such as description, optimization, and evaluation), and tools needed to address these tasks (such as benefit cost analysis, optimization, multiple-criteria analysis, etc.). The course applies the concepts to problems in the various areas of civil engineering and provides an array of case studies in various civil engineering disciplines. The course comprises lecture presentations, quizzes, guest presentations, video shows, homework assignments, and a term project with oral presentation.

*3.C. Course Material*

*Main textbook*: Introduction to Civil Engineering Systems, by S. Labi, Wiley & Sons (currently available online for Purdue students, due for release 2010).

*Additional texts*: (1) Systems Analysis for Engineers and Managers, DeNeufville and Stafford, 1974. (2) Fundamentals of Systems Engineering, by Khisty and Mohammadi, 2001. (3) Design and Planning of Engineering Systems, by Meredith, Wong, Woodhead, Wortman, 1985. (4) Civil and Environmental Systems Engineering, by Revelle, Whitlatch, Wright, 2003.

*3.D. Grading Policy*
This course has one mid-term exam and a final exam which are worth 30% each. The term project is worth 20%, and the homework is 10%. Quizzes and class participation are 5% each.

## 4. Course Content

This course introduces a paradigm in the way systems concepts are taught to civil engineering students: a deliberate and explicit effort is made to present the phases of civil systems development, the tasks and challenges faced by the engineer at each phase, and the tools needed to carry out these tasks. Also, vital issues associated with civil systems development, such as ethics, legal issues, communication, and sustainability, are given due prominence in the course. The modules are herein described.

*4.A. Module 1 – Introduction (Systems Concepts)*
The first module discusses details and evolution of the various engineering disciplines and general concepts of systems. This includes formal definitions, classification of systems, general and specific examples of systems in civil engineering, and attributes of a system. The module also identifies the various phases of civil systems development and provides a general discussion of challenges faced the by civil systems engineer at each phase.

*4.B. Module 2 – Phases of Systems Development*
In this module, students are presented with the sequence of development of a civil engineering system, starting from an assessment of the need for the system, to system planning, system design, system construction or implementation, system operation, system preservation, system monitoring (of physical condition and operation usage) and system termination (Figure 1).

*4.C. Module 3 – Tasks at Each Phase of Systems Development*
This module describes the tasks faced by civil engineers at each phase of system development, including the tasks of systems description/prediction, analysis, evaluation, and optimization, and selection. Systems description is often needed for purposes of monitoring and communication while systems analysis, evaluation and selection are needed for decision-making. The trio of the processes of analysis, evaluation, and selection (of the best course of action), is typically termed systems optimization. The feedback task (not shown in Figure 1) can be represented by arrows from any phase to the preceding phases. Lessons learnt from an antecedent phase are always needed so that the preceding phases can be enhanced. Such feedback is an application of systems dynamics that is necessary for adaptive systems development.

*4.D. Module 4 – Necessary Tools for the Systems Tasks*
In order to carry out the tasks identified in the preceding Section, engineers need to be equipped with a certain set of tools. For example, in order to describe how a system works, the engineer may need to use computer simulation; in order to arrive at the best option under different objectives and constraints, the engineer may need to use tools of optimization. This module presents the tools that civil engineers need in order to execute their tasks at the various phases of systems development. The tools include probability, statistics, modeling and simulation, economics, multiple criteria analysis, optimization, reliability/risk analyses, and communication.

*4.E. Module 5 – Application of the Tools*
The fifth module discusses how these tools are applied practically to address specific tasks, and this is done for each phase of the systems development process. Examples are provided using two common configurations of civil systems – queuing systems and network systems.

*4.F. Module 6 – Peripheral Topics*
Finally, topics that are considered peripheral but are critical to civil systems development, such as legal issues, ethics, communication and management, etc. are discussed.

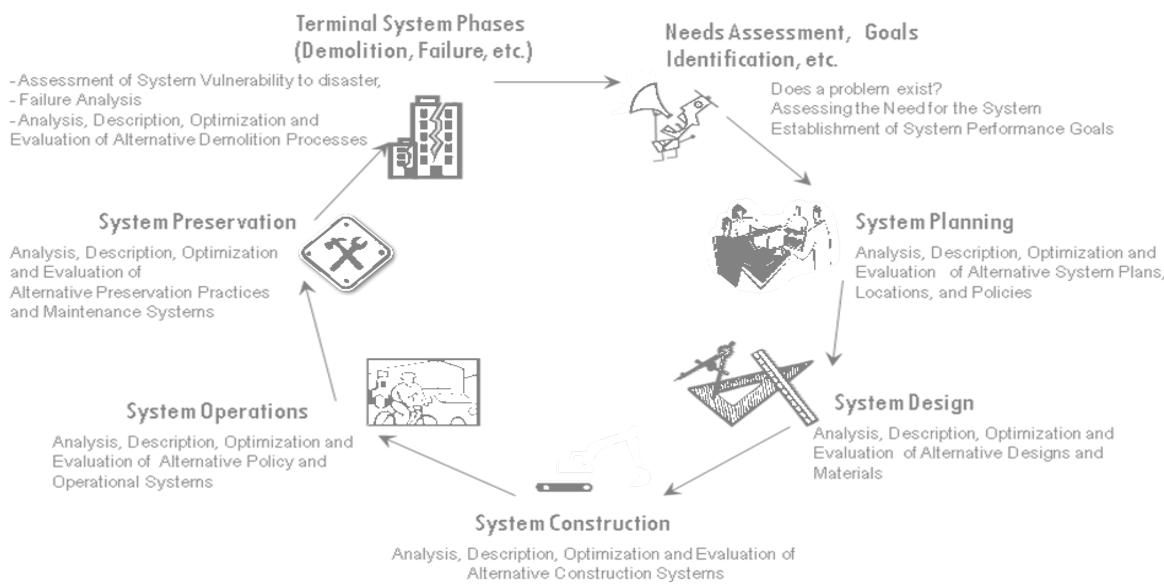


Figure 1: Phases of civil systems development and tasks at each phase

## 5. How This Course Differs From Similar Other Courses Elsewhere

This course is similar to other similar courses in that it presents the tools needed for infusing systems concepts in civil engineering. However, the course differs from other similar past courses in a variety of ways. First is the content itself: in traditional civil systems courses, it is the tools that are mostly presented, without adequate or explicit identification of the phases of civil systems development or the different tasks and tools that are needed at each phase. Thus, in past courses, students have been exposed to an array of techniques without acquiring a deep appreciation of the context within which such tools are to be applied. This course makes a deliberate and explicit effort to not only to present the phases of civil systems development but also the tasks or challenges faced by the systems engineer at each phase. It is only after these two critical foundations are laid that the course discusses the tools needed to carry out these tasks.

Also, the course duly and explicitly discusses non-traditional but vital tools needed for civil systems development, such as legal issues, management and communication skills, and environmental sustainability. This is in recognition of the fact that the current problem of aging infrastructure is exacerbated by increased demand and loading, increasing user expectations of facility performance, increased desire of stakeholder participation in the decision-making process, terrorism threats, the increasing specter of tort liability, and above all, inadequate funding for sustained infrastructure preservation and renewal. As such, civil engineers of today need to develop skills not only in the traditional design areas but also in other related areas such as operations research, economics, law, finance, communication, and other areas that would facilitate a comprehensive and holistic approach that is systems-based and considers the real options faced by the engineer at any phase of the systems development cycle. This way, civil systems can be constructed, maintained, and operated sustainably and cost-effectively with maximum appreciation from legislature and the general public, minimal damage to the environment, maximum system longevity, reduced exposure to tort suits, and optimal use of the taxpayer dollar. This course duly presents its material with explicit consideration of these issues.

Thirdly, the course explicitly addresses a growing void in the subject area that is evolving in response to ongoing developments in the global infrastructure environment: viewing each system not as a standalone but as a part of a larger supersystem of civil assets. Consistent with such consideration are: the need to prioritize systems slated for some improvement in a manner that optimizes some systemwide benefits under given budgetary constraints; and needed capability of systems managers to assess trade-offs among cost and performance attributes of their systems. This is particularly important at the current time of increasing need vis-à-vis reduced resources, as discussed in the previous paragraph. The issue of increasing needs, for example, is a stark reality facing many civil engineering agencies at the current time. In the United States, for example, a large number of civil infrastructure systems – dams, bridges, roads, sewers, etc. – are approaching the end of their design lives and need rehabilitation or replacement. The issue of aging civil infrastructure has deservedly gained national attention due to a series of well-publicized engineering system failures, such as the New Orleans levees, the Minnesota I-35W bridge, and the recent New York City and Dallas sewer ruptures.

Furthermore, this course satisfies a significant section of current ABET requirements and ASCE rubrics for undergraduate civil engineering education. These include problem solving, experiments and simulations, data analysis, optimization and financial analysis, and systems approach in design of facility components and processes. Also, the course addresses socially and environmentally sustainable design, engineering practice and licensure issues, ethics, communication and managerial skills, and working in multidisciplinary teams.

## 6. Mechanisms for Instructional Delivery and Didactic Resources

The subject of civil engineering systems is indeed a broad subject that could fill several courses. As such there is a limitation to the scope and depth that can be provided in a single course. This course therefore not only provides a fresh perspective that streamlines the acquisition of a basic fundamental understanding of civil systems (namely, phases, tasks, and tools) but also serves as an avenue for establishing a central repository of references for persons interested in further inquiry. The course focuses on providing the student with a clear and understandable material that presents well-explained methodologies and procedures useful for addressing tasks at each phase of civil systems development. The course also helps to translate the findings of useful past and recent research and technical tools that have been developed for enhanced civil engineering systems development. Throughout its sections, the course emphasizes practical applications of the concepts. Theoretical backgrounds are provided to enable the reader to enhance their understanding of the concepts and to recognize the merits and demerits of alternative concepts in solving a particular problem. The chapters and concepts are presented in a sequence and style that are expected to encourage the student to define and solve problems with requisite tools in a manner consistent with engineering and professional responsibility.

Each section is an integrated mélange of theory and practice, and numerous examples have been provided. Recognizing that only a limited number of examples and tools can be included within the content constraints in a single semester, the student who wishes to acquire further knowledge on the subject is provided a set of useful resources at the end of each lecture. As students learn better when they are asked to apply the concepts to real-world problems, a term project is administered as part of this course. The term project deals with any type of civil engineering system, phase, task, or tool. Project topics include civil engineering related problems on campus or elsewhere that are chosen to stimulate student interest. Also, additional information on each module or lecture, such as updated analytical tools, recent research findings, and news items relating to civil systems development worldwide, are posted on a website established purposely for this course.

## 7. Schedule of Lectures

Section 1 Introduction – Systems Concepts

- Lecture 1 Civil Engineering (CE) Disciplines, their Evolution, and Future Prospects
- Lecture 2 What is a System? What are System Phases, Tasks, and Tools?
- Lecture 3 Civil Engineering System Goals and Objectives

Section 2 The Tasks at Each Phase of CE Systems Development

- Lecture 4 Description/Prediction of Facilities and Processes, and their Outcomes
- Lecture 5 Evaluation of Alternatives and Decision-making for Best Action/Policies
- Lecture 6 Communication within Phases and Feedback between Phases

Section 3 The Tools Needed to Carry Out the Tasks

- Lecture 7 Probability
- Lecture 8 Statistics
- Lecture 9 Modeling and Simulation
- Lecture 10 Engineering Economics
- Lecture 11 Multiple Criteria Analysis
- Lecture 12 Optimization
- Lecture 13 Reliability and Risk Analyses
- Lecture 14 Communication Tools

Section 4 Application of the Tools at Each Phase of CE Systems Development

- Lecture 15 Needs Assessment
- Lecture 16 Systems Planning
- Lecture 17 Systems Design and Cost Estimation
- Lecture 18 Systems Construction/Implementation
- Lecture 19 System Operations
- Lecture 20 Systems Monitoring and Preservation
- Lecture 21 Systems Termination

Section 5 Other Topics in Systems Development

- Lecture 22 Incorporating Sustainability in Systems Development
- Lecture 23Vulnerability Analysis for Civil Facilities
- Lecture 24 Legal Issues in Systems Management
- Lecture 25 Ethics in Civil Engineering
- Lecture 26 Management and Administration

## 8. Lessons Learned After Five Years of Course Implementation

A variety of techniques learned from the literature were used to generate feedback information from the students before, during and after the course. The formal end-of-semester student course evaluations yielded critical information by identifying areas that could be further enhanced to facilitate and streamline the instructional process: this information included quantitative data and well as qualitative assessments. The informal start-of-semester and mid-semester evaluations provided useful hints on students' background strengths and interests. The evaluations helped in streamlining and enhancing the course further. It was found that the term projects particularly play a valuable role in the didactic experience: students stated that this component of the course provided a pedestal for them to think in perspectives other than technical performance and thus earned greater appreciation of the need to duly incorporate a suitable range of performance measures at any phase and in any task of systems development. They gained appreciation of the need to consider performance measures such as user costs, environmental impacts, and sustainability in general. Also, it was learned that the term projects helped students acquire the confidence to translate real world problems into solvable constructs using mathematical modeling or simulation. Many students who took the course indicated that they benefitted greatly from the course concepts, particularly the explicit explanation of civil systems development from the perspective of phases, tasks, and tools. A number of students opined that the course is one of the most important courses of their undergraduate years at Purdue University and expressed a desire to pursue further studies in engineering systems at Purdue or elsewhere.

## 9. Summary

This paper presents an overview of the "Introduction to Civil Engineering Systems Design" course at Purdue University, a core requirement in the undergraduate curriculum of Purdue's School of Civil Engineering since 2004. The course was established as part of implementation of the School's 2003 strategic plan that sought to address new challenges in a rapidly changing professional, educational and institutional environment. The paper discusses the motivation for the course, course information, the course content, continuing concepts and paradigms, mechanisms utilized for instructional delivery and didactic resources, schedule of lectures, lessons learned after five years of course implementation, and ongoing development of the course.

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