Civil and Environmental Engineering 483
Infrastructure Systems Analysis
Winter 2024

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Class Times and Locations:	Tu, Th 9:30–10:50 (Tech, L170), F 10–10:50 (Tech, MG28)
Class Website:	Northwestern Course Management System `http://canvas.northwestern.edu`

Course Description

The course introduces students to the formulation and analysis of mathematical models to address tactical and strategic problems in the context of planning and managing civil infrastructure systems. The methodological tools are drawn from decision analysis, dynamic programming, Markov decision processes (MDPs), and game theory. Applications and topics include: structural estimation (of MDPs) in the context of statistical modeling of infrastructure performance, shortest path problems, production/inventory management, and maintenance optimization. The course integrates methodological tools with applications.

Intended Audience

1. Students who are interested in the issues and challenges (economic, technical, environmental, political, etc.) involved in the planning and managing transportation/civil infrastructure systems, and the development of mathematical models to support associated decisions.
2. Students who are interested in learning how to use mathematical models to analyze and solve sequential decision-making problems (under uncertainty). In particular, we will focus on tools often used in the management sciences, such as dynamic programming and game theory to develop insights about the structure of problems and ensuing (optimal) policies.

Objectives

1. To encourage the development of a "systems perspective" necessary for the planning and management of large-scale and complex civil and environmental engineering systems;
2. To introduce students to the formulation and analysis of mathematical (descriptive, predictive and prescriptive) models for planning and management of (civil) infrastructure systems such as bridges, roads, power generation/transmission and telecommunication networks, rail and aviation systems, schools, hospitals, hotels, factories, airports, etc. The methodological tools that will be covered are actually quite general and useful in many planning and management situations; and,
3. To expose students to recent research in the management of civil infrastructure systems.

Course Materials

Reference materials for the course will be provided as needed and made available online. Over the years, students have been "scribing" lecture notes. As much as possible, updated notes will be made available through Canvas prior to each lecture. Overall, the course builds on material that appears in the following references: (i) Appendix G from *Dynamic Programming and Optimal Control* by Bertsekas; (ii) chapters 1, 2, 4, 9, 10, and 11 from *The Art and Theory of Dynamic Programming* by Dreyfus and Law; and (iii) research papers related to infrastructure planning and management to be presented in class. Other reference texts include:

1. Keeney, R.L. and Raiffa, H. (1993); *Decisions with Multiple Objectives: Preferences and Value Trade-offs*; Cambridge University Press.

2. Bikhchandani, S., Hirshleifer, J., and Riley, J. (2013); *The Analytics of Uncertainty and Information*; Second Edition, Cambridge University Press.

3. Hillier, F. and Lieberman, G. (2015); *Introduction to Operations Research*; Tenth Edition, McGraw-Hill.

4. deNeufville, R. (1990); *Applied Systems Analysis*; McGraw Hill.

   `http://ardent.mit.edu/real_options/ASA_Text/asa_Text_index.html`

5. Revelle, C.S., Whitlatch, E.E. and Wright, J.R. (2004); *Civil and Environmental Systems Engineering*; Second Edition, Pearson – Prentice Hall.

6. Dreyfus, S. and Law, A. (1977); *The Art and Theory of Dynamic Programming*; Academic Press.

7. Bertsekas, D. (2017); *Dynamic Programming and Optimal Control*; Volume I, Fourth Edition, Athena Scientific.

8. Bather, J. (2000); *Decision Theory: An Introduction to Dynamic Programming and Sequential Decisions*; John Wiley & Sons, Ltd.

9. Gibbons, R. (1992); *Game Theory for Applied Economists*; Princeton University Press.

Reference 1 is a/THE comprehensive book about Decision Analysis. Reference 2 presents in-depth coverage of the economics of uncertainty and information. References 3, 4, and 5 are introductory texts that present coverage of the methodology that we will be studying. Reference 6 is an intermediate level text in Dynamic Programming. It focuses on the art of formulating sequential decision problems. The next two references are advanced references on Dynamic Programming and Optimal Control Theory. Reference 9 provides an intermediate level coverage of Game Theory. Many interesting and relevant articles can be found in the Journal of Infrastructure Systems available online through the ASCE website (`www.asce.org`).

Course Assessment

The course integrates methodological tools with applications. Lectures will be devoted to learning the tools and solving problems to reinforce the material. In addition there will be sessions dedicated to the presentation and discussion of recent, relevant research papers.

1. Homework assignments (20%). Homework will be submitted via Canvas according to the schedule appearing in the following page. Solutions to the assignments will be posted on the day the assignment is due. Therefore, no late homework can be accepted. Only the best 4 of the 5 for-credit assignments (by percentage) will count toward the final homework score. You should start working on the homework early so that you have time to ask questions before it is due. Please feel free to work in groups or to ask for help from fellow students or the instructor. Each student must submit his/her own work unless otherwise stated.

   In addition to the required problems, the assignments may have some in-depth problems that will be labeled "Extra credit +" or "Extra credit ++". Problems labeled "+" are what one would expect in take-home exams or for PhD entrance exams. Problems labeled "++" could be topics for research papers. You may earn extra-credit by trying these problems. Only careful solutions submitted along with complete assignments will be evaluated. Complete the required parts of the assignment before you spend time on the extra-credit problems.

2. Research exposure (10%). Dynamic Programming/Backwards Induction/Markov Decision Processes are used as a research tool to model/analyze systems/problems in a variety of contexts. The assignment consists of identifying a paper published in the last 10 years that addresses an application you are interested in outside of maintenance optimization. Examples include scheduling, routing, production planning, finance, marketing, economics, public health, organ replacement, video game design, etc. You will then write a 3-5 page review that (i) explains why the problem being studied is important, (ii) the key contribution(s) to the literature of the paper you selected, (iii) states the key assumptions, (iii) presents the (main) DP/BI/MDP formulation (using the notation from our class), (iv) describes the main analytical/computational results, and, (v) identifies limitations or opportunities for additional research. These opportunities may be explored by MS students as part of their Research Analysis papers. There may be an extra-credit opportunity by preparing a presentation for the class. Additional guidance will be provided in a separate document.

3. Research presentation (20%). Lead discussion of a set of technical papers assigned by the instructor (in groups). Precise instructions, including group assignments, will be distributed by the end of the second week of the quarter. In short, this should not be a lecture; discussion leaders should ensure that the main points of the paper are clearly elicited. In addition, it is expected that directions for additional research will be identified and discussed. MS students may wish to pursue these directions in their Research Analysis papers. **The leaders must prepare a draft of the presentation or a detailed outline to be distributed to the class, and have it approved by the instructor at least one week in advance of the discussion. Groups that do not prepare a draft or outline will not be allowed to present and will receive a grade of 0.**

4. Paper review (10%). Each of the assigned groups will have to prepare detailed reviews for 1-2 additional papers. The reviews will follow the format described for the research exposure exercise. The reviews will be due 1 week the paper is presented to the class. Instructions will be given in the document describing the presentations.

5. In-class examinations (20% each). The examinations will be open-book/notes and will be designed to test your understanding of the methodological material presented in class, in the homework assignments, and in the readings. The dates for the exams are printed in the class schedule.

   Special arrangements for the exams must be discussed with the instructor 2 weeks prior to the exam's scheduled date. Travel arrangements ARE NOT sufficient to warrant special accommodations.

Course Schedule

A detailed schedule is presented below. Exam dates are fixed. Please take note that the second exam is scheduled for the last week of the Quarter. There may be a need to move individual classes or group presentations. I will try and notify you of any changes as soon as possible. As you can see, we have some slack to accommodate.

COURSE SCHEDULE			
Date:	**Topics**	**Hand-ins**	**Handouts**
01/04	Introduction & Organization Introduction to Infrastructure Systems Analysis		Syllabus
01/05			
01/09	No class – TRB Annual Meeting		
01/11	No class – TRB Annual Meeting		
01/12	No class – TRB Annual Meeting		
01/16	Introduction to Decision Analysis		HW1
01/18	Value of Information and Options		
01/19	Value of Information and Options (cont.)		
01/23	Introduction to Dynamic Programming		HW2
01/25	Introduction to Dynamic Programming (cont.)	HW1	Sol1
01/26	Introduction to Dynamic Programming (cont.), if needed		
01/30	Deterministic DP Applications		
02/01	General Discussion on Shortest Path Problems		
02/02	Stochastic Dynamic Programming & Exam Review	HW2	Sol 2
02/06	EXAM 1 (Decision Analysis and Deterministic Dynamic Programming – material covered through 02/01)		
02/08	Stochastic Dynamic Programming (cont.)		HW3
02/09	Stochastic Dynamic Programming (cont.), if needed		
02/13	Stochastic Equipment Replacement		
02/15	Stochastic DPs with special structures Infinite planning horizons	HW3	Sol3, HW4
02/16	Adaptive Dynamic Programming		
02/20	Introduction to Game Theory Nash Equilibrium & Subgame perfect Nash Equilibrium		HW5
02/22	Sequential and Simultaneous move games	HW4	Sol4
02/23	Applications: Credibility and SPNE Bargaining		
02/27	Presentations		
02/29	Presentations	HW5	Sol5
03/01	Presentations		
03/05	Presentations & Exam Review		
03/07	EXAM 2		