Analytical Methods for Complex Adaptive Systems (IGA-565)

Harvard Kennedy School

Course Syllabus – Fall 2019

Faculty: Afreen Siddiqi
Office: Belfer L-02A
Office Hours: https://calendly.com/iga565
E-mail: afreen_siddiqi@hks.harvard.edu

Faculty Assistant: Karin Vander Schaaf
Office: Belfer – B322
Phone: 617-496-5584
E-mail: karin_vander_schaaf@hks.harvard.edu

Teaching Fellow: Homa Koohi: hok958@student.hks.harvard.edu

Class Meetings: Mondays and Wednesdays 10:15am – 11:30am, L280

Review Sessions: Fridays 10:15-11:30am, Room: Rubenstein-306

Office Hours: Mondays 1:00-3:00pm by appointment (please sign up online)
TF office hours will be posted on the course website.

Course Description:

This course introduces theory and methods for quantitative analysis of complex, sociotechnical systems. The course will introduce complex adaptive systems theory and approaches for 'systems thinking' for analyzing modern systems that embody technological and social elements and operate within a changing environment. The methods will include Monte Carlo simulations, System Dynamics, and Agent-based Modeling. The focus of applications will be on water, energy, and transportation systems.

Complex adaptive systems theories provide a useful lens to understand why policy interventions in sociotechnical systems may produce delayed results, fail, or lead to unintended consequences. Key concepts of time lags in cause and effect, feedbacks, and adaptive behavior will be introduced and implications for policy and planning will be discussed. Applications will include analyzing infrastructure planning and capacity expansion under uncertainty, modeling future technology diffusion, and analyzing connections between water, energy, and food systems.

The assignments will step through the processes of problem definition, scoping, formulation, model creation, validation, analysis, and results presentation. The students will work in small teams for conducting in-depth analysis of system behavior, performance, and simulated outcomes.

The overall goal of the course is to enable students to: (1) Understand key properties of complex adaptive systems that can limit impact of interventions and policies; (2) Gain familiarity with methods and tools for studying system behavior and understand their strengths and limitations; and (3) Systematically conceptualize and build simulation models for conducting quantitative analysis.

Prerequisites

This class requires no programming experience. Students should understand introductory-level statistics (such as API-201 or equivalent courses), and should understand probability distributions. Students should also have basic knowledge of using MS Excel.

Target Students

This course is intended for students who seek to acquire skills in quantitative analysis and in using quantitative results to guide decisions and policy. Students from all programs are welcome.

Applications and Examples

The applications and example topics will include infrastructure planning under future uncertainties, diffusion of new technologies (such as of electric vehicles, autonomous cars, solar PV, water recycling and harvesting systems, groundwater pumping for agriculture, and desalination systems), analysis of the water-energy-food nexus, and contemporary issues in use of natural resources and sustainability.

Course Website:

The course materials will be posted on the IGA-565 CANVAS page.

Course Materials:

Required Textbook:

1. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill.

Additional required reading will draw from sections in the following texts:

a. *Engineering Systems: Meeting Human Needs in a Complex Technological World*, Olivier L. de Weck, Daniel Roos, and Christopher L. Magee, (2011), MIT Press.

b. An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo, Uri Wilensky and William Rand, (2015), MIT Press.

c. *Complexity: A Very Short Introduction*, John H. Holland**, (**2014). Oxford University Press.

d. *The Sciences of the Artificial*, Herbert A. Simon (1996), 3rd edition, MIT Press.

e. *Flexibility and Real Estate Valuation under Uncertainty*, David Geltner and Richard de Neufville, (2018). Wiley-Blackwell, John Wiley & Sons.

f. *Flexibility in Engineering Design*, Richard de Neufville and Stefan Scholtes, (2011). MIT Press.

g. *Data, Models, and Decisions: The Fundamentals of Management Science*, Dimitris Bertsimas and Robert M. Freund, (2004), Dynamic Ideas.

Required Software:

1. MS Excel.
2. Vensim PLE for simulations. It is available for free download at: https://vensim.com/free-download/

The assignments will require use of Excel and Vensim, and review sessions will include tutorials on using these two tools.

Optional Software: Students who have experience and preference for python, R, Matlab, or other programming languages are welcome to use them.

Assignments and Grading:

Class grades will consist of the following components:

10%	Class participation
70%	Problem Modeling and Analysis – (seven assignments will be given)
20%	Final Project

Class participation includes attending lectures, completing pre-class assignments, and engaging in discussions.

There are 7 assignments of modeling and analysis given throughout the term and a final project. Most of the assignments will involve a series of tasks ranging from model conceptualization, scoping, development, and analysis. The students are expected to work as a team in several assignments, and will jointly develop the models, collaborate on running simulations, and conduct analysis. The students will be required to write up ***individual reports*** on explaining the simulations and results. Detailed instructions regarding collaboration and individual work will be provided for each assignment.

The teams will have the option to pick a topic of their own choosing for in-depth modeling and analysis for the final project.

Students are expected to follow Kennedy School and Harvard University rules when preparing their reports. Any text used in explaining the results must be cited if it is drawn from someone else, or published or un-published material. All sources of information and data must be fully cited and credited.

The final course letter grades will be based on the Dean's recommended grade distribution. See: https://knet.hks.harvard.edu/DPSA/Registrar/Exams-Grading/Pages/default.aspx

Office Hours

Meeting times during regular office hours can be reserved here by clicking the 'office hours' link on this website: https://calendly.com/iga565/office-hours/

Review Sessions:

The review sessions in this course will consist of a combination of structured reviews of the course lecture contents, as well as sessions that will be focused on implementing operational models. The review sessions will include tutorials on using Excel functions, and on creating causal loop diagrams and stocks and flow models in Vensim.

Class Outline and Tentative Schedule: There may be some adjustments to the lecture topics and schedule during the course of the semester. *Please refer to the online version of the schedule for the most up to date information*.

Date – [#]	Topic	Assignment
	COMPLEX SYSTEMS ANALYSIS	
F 9/6 - [1]	Introduction to Complex Adaptive Systems	
M 9/9 – [2]	Creating Models for Simulation	PS1 Out
W 9/11 - [3]	Modeling Uncertainty	
	STOCHASTIC ANALYSIS	
M 9/16 - [4]	Simulating Growth and Progression	PS1 Due, PS2 Out
W 9/18 – [5]	Application Case – Capacity Planning	
M 9/23 – [6]	Understanding Extremes	PS2 Due, PS3 Out
W 9/25 – [7]	Validation and Error Analysis	
	SYSTEMS DYNAMICS	
M 9/30 – [8]	Policy Resistance in Complex Adaptive Systems	PS3 Due, PS4 Out
W 10/2 – [9]	Causal Loop Diagrams	
M 10/7 – [10]	Structure and Behavior	PS4 Due, PS5 Out
W 10/9 – [11]	Stocks and Flows	
FRI 10/18 – [12]	Dynamics of Stocks and Flows-I	PS5 Due, PS6 Out
M 10/21 – [13]	Dynamics of Stocks and Flows-II	
W 10/23 – [14]	Growth and Diffusion	
M 10/28 – [15]	Path Dependence and Delays	PS6 Due
W 10/30 - [16]	System Instability	Final Project Out
M 11/4 - [17]	Simulators - electric vehicles adoption	
W 11/6 - [18]	Simulators – sustainability (marine fisheries)	
	AGENT-BASED MODELING	
W 11/13 – [19]	Agent-Based Modeling (ABM)	PS7 Out, Project Plan Due
M 11/18 – [20]	ABM – simulating diffusion	
W 11/20 – [21]	ABM – simulating natural resource use	PS7 Due
M 11/25 – [22]	ABM – simulating future mobility (self-driving cars)	
M 12/2 – [23]	Models for Policy - Strengths & limitations	
M 12/4 – [24]	Lightning Presentations on Class Projects	
M 12/16 – FINAL	Final Project Report Due at 5:00 PM	Final Report Due 5:00 PM

Lecture Topics and Readings

1. Introduction to Complex Adaptive Systems

Topics: Introduction to complex systems analysis, definitions of systems, complexity, complex systems; complex adaptive systems theory, sociotechnical systems.
Readings:

a. *Complexity: A Very Short Introduction*, John H. Holland**,** 2014. Oxford University Press, Chapter 1, pp 1-12, and pages 24-25, 42-44.
b. *Engineering Systems: Meeting Human Needs in a Complex Technological World*, Olivier L. de Weck, Daniel Roos, and Christopher L. Magee, (2011), MIT Press, Chapter 1, pp 1-25.

Optional Readings:

c. *The Sciences of the Artificial*, Herbert A. Simon (1996), 3rd edition, MIT Press. Pages 172-181.
d. Boulding, K., "General Systems Theory: The Skeleton of Science", *Management Science*, (1956) 2: pp 197-208.
e. Szlezak, N. A., Bloom, B. R., Jamison, D. T., et al. "The Global Health System: Actors, Norms, and Expectations in Transition", PLoS Medicine, (2010) 7(1), pp1-4.

2. <u>Creating Models for Simulation</u>

Topics: Systems analysis, purpose of modeling (possibilities and limitations), types of analytical methods and tools, study emergent properties such as resilience, stability, adaptability, and behavior over time, examples of model-based analysis. Setting up a model: purpose and scope (boundary, time resolution and horizon, inputs and outputs), N^2 diagram, key equations, results summarization, examples of system models.

Readings:

a. *Engineering Systems: Meeting Human Needs in a Complex Technological World*, Olivier L. de Weck, Daniel Roos, and Christopher L. Magee, (2011), MIT Press, Chapter 3, pp 60-82, pp 97-103, and 109-120.

b. *The Sciences of the Artificial*, Herbert A. Simon (1996), 3rd edition, MIT Press. "Understanding by simulating", pp 13-18.

c. William C. Clark, Lorrae van Kerkhoff, Louis Lebel, and Gilberto C. Gallopin, (2016), "Crafting usable knowledge for sustainable development". *Proceedings of the National Academy of Sciences*, Vol 113 (17), pp 4570-4578.

Optional Reading:

a. Ackoff, R. L., "Towards a System of Systems Concepts", *Management Science*, (1971) 17(11): pp 661-671.

3. <u>Modeling Uncertainty</u>

Topics: Identifying uncertainties, classifying uncertainties, intro to Monte Carlo simulations, white noise, random walks, examples

Readings:

a. "Explained: Monte Carlo simulations", MIT News, http://news.mit.edu/2010/exp-monte-carlo-0517
b. *Flexibility and Real Estate Valuation under Uncertainty*, David Geltner and Richard de Neufville, (2018). Wiley-Blackwell, John Wiley & Sons. Chapter 5, pp 33-40, and Chapter 6, pp 41-45.
c. *Flexibility in Engineering Design*, Richard de Neufville and Stefan Scholtes, (2011). MIT Press. Chapter 4, pp 65-97, "Estimating the distribution of Future Possibilities".

Optional Reading:

d. *Flexibility in Engineering Design*, Richard de Neufville and Stefan Scholtes, (2011). MIT Press. "Recognition of uncertainty", Chapter 2.
e. *Theory and Practice in Policy Analysis: Including Applications in Science and Technology*, M. Granger Morgan (2017), Cambridge University Press. "Characterizing, Analyzing, and Communicating Uncertainty", Chapter 8.

4. Simulating growth and progression

Topics: growth models, linear, exponential, logistic, population growth, technology progression

Readings:

a. *Models, and Decisions: The Fundamentals of Management Science*, Dimitris Bertsimas and Robert M. Freund, (2004), Dynamic Ideas. “Generating random numbers obeying a discrete probability distribution”, Ch 5.1-5.6, pp 195-210.
b. *Flexibility and Real Estate Valuation under Uncertainty*, David Geltner and Richard de Neufville, (2018). Wiley-Blackwell, John Wiley & Sons. “Modeling Price Dynamics”, Chapter 7, pp 47-52.

c. *Flexibility in Engineering Design*, Richard de Neufville and Stefan Scholtes, (2011). MIT Press. Appendix E, pp 251-263, “Dynamic Forecasting.”

5. Simulation – Application Case (capacity planning)

Topics: Application: capacity planning (real-estate and infrastructure examples)

Reading:

a. *Flexibility in Engineering Design*, Richard de Neufville and Stefan Scholtes, (2011). MIT Press. Appendix D, pp 217-249, “Monte Carlo Simulations.”

6. Understanding Extremes

Topics: long-tailed distributions, fat-tailed distributions, understanding extremes for planning and policy, examples: climate change, heat waves, floods, financial risks

Readings:

a. *Flexibility in Engineering Design*, Richard de Neufville and Stefan Scholtes, (2011). MIT Press. “Flaw of averages”, Appendix A, pp 187-194.
b. “The trinity of errors in financial models”, https://medium.com/tensorflow/the-trinity-of-errors-in-financial-models-an-introductory-analysis-using-tensorflow-probability-9fdefb4d283d

Optional Reading:

c. McKelvey, B., and Andriani, P., “Why Gaussian statistics are mostly wrong for strategic organization”, Strategic Organization (2005) Vol 3(2): pp 219-228

7. Validation and Error Analysis

Topics: Validation of simulation models, limitations, common error quantification metrics, uncertainty in simulation results

Readings:

a. Kevin Anderson and Jessica Jewell, "Climate-policy models debated" *Nature,* Vol. 573, September 19, 2019, pp. 348-349.

8. Systems Dynamics – Policy Resistance

Topics: Policy resistance, unintended consequences, feedback in systems, intro to systems dynamics

Readings:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapters 1 and 3.

Optional Readings:

b. Alcott, B. (2005), “Jevons’ Paradox”, *Ecological Economics*, 54: pp 9 -21
c. *Theory and Practice in Policy Analysis: Including Applications in Science and Technology*, M. Granger Morgan (2017), Cambridge University Press. “A few key ideas from the history and philosophy of science”, Appendix 1, pp 567-576.

9. Introduction to Causal-Loop Diagrams (CLDs)

Topics: Introduction to Causal-Loop Diagrams (CLDs), rules for CLDs, formulating hypotheses with CLDs, examples

Readings:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapters 5-6.

Optional Reading:

b. Sterman, J., System Dynamics at sixty: the path forward, *Systems Dynamics Review*, (2018)

10. Structure and behavior in dynamic systems

Topics: Structure and behavior in dynamic systems: growth, goal seeking, oscillation, S- shaped growth, collapse

Reading:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapter 4.

11. Stocks and flows

Topics: Stocks and flows, system memory, delays

Readings:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapter 6
b. Richardson, G. P., "Problem with causal-loop diagrams", *Systems Dynamics Review* (1986), 2 (2):158-170.

Optional Reading:

c. Sterman, J., Sustaining Sustainability: Creating a Systems Science in a Fragmented Academy and Polarized World, in *Sustainability Science: The Emerging Paradigm and the Urban Environment*, (2012) Springer.

12. Dynamics of stocks and flows -I –NOTE: CLASS ON FRIDAY OCTOBER 18th at 10:15 AM – 11:30 AM – CLASS MEETS IN R-306

Topics: Dynamics of stocks and flows, first order systems

Readings:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapter 7.

13. Dynamics of stocks and flows - II

Topics: Dynamics of stocks and flows, higher order systems

Readings:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapters 8.

Optional Reading:

b. "Systems Thinking and Modeling for Public Health Practice", Editorial, *American Journal of Public Health* (2006) 96(3): 403-405

14. Growth and diffusion

Topics: Growth and diffusion, examples of infectious disease, technology diffusion, SIR model

Readings:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapter 9.

Optional Reading:

b. Bass, F. 1969, "A new product growth model for consumer durables," *Management Science,* Vol. 15, no. 4, pp. 215-227
c. Bass, F., Krishnan, T. and Jain D. 1994, "Why the Bass model fits without decision variables," *Marketing Science*, Vol. 13, no.3, p.203-223.

d. Anadon, L. D., Chan, G., Harley, A., Matus, K., Moon, S., Murthy, S., and Clark, W., "Making technological innovation work for sustainable development", *Proceedings of the National Academy of Sciences*, (2016) 113(35): 9682-9690.

15. Path dependence and Delays

Topics: Dynamic behavior: path-dependence, and lock-in, Modeling delays in system processes

Readings:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapter 10, 11, and 13.

Optional Reading:

b. Dangerman, A. T. C. J., and Schellnhuber, H. J., Energy systems transformation, *Proceedings of the National Academy of Sciences*, (2013) 110 (7) E549-E558.

16. Instability in systems

Topics: Instability in systems: bullwhip effect in supply chains

Readings:

a. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John Sterman, 2000, McGraw-Hill. Chapter 17.

17. Simulators – Electric Vehicles Adoption (Driving the Future)

Reading:

TBD

18. Simulators - Sustainability (FishBanks)

Reading:

a. Hardin G. "The tragedy of the commons" (1968), *Science* 162: pp 1243–48

Optional Reading:

b. Sterman, J., Interactive web-based simulations for strategy and sustainability, Systems Dynamics Review, (2014), 30: 89-121.

19. Agent Based Modeling (ABM)

Topics: Heterogeneity in agents and complex behavior; introduction to agent-based modeling (ABM)

Reading:

a. An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo, Uri Wilensky and William Rand, (2015), MIT Press. Chapter 0, pp 1-20, and Chapter 1, pp 21-43.

Optional Reading:

b. Bonabeau, E., Agent-based modeling: Methods and techniques for simulating human systems, *Proceedings of the National Academy of Sciences*, 2002, pp: 7280-7287

20. Application of ABM: simulating diffusion

Topics: Application of ABM: tipping points (with example of forest fires), simulating diffusion, Schelling's model of segregation

Readings:

a. An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo, Uri Wilensky and William Rand, (2015), MIT Press. Chapter 2 and 3.

Optional Reading:

b. Schot, J., and Kanger, L., "Deep transitions: Emergence, acceleration, stabilization and directionality", Research Policy (2018), 47: 1045-1059

21. Simulating economies and natural resource use

Topics: Application of ABM: simulating economies, Wilensky chapter 2 pp 87-96 (A Simple Economy), Epstein's and Axtell's SugarScape, natural resource use and "tragedy of the commons"

Readings:

a. Castilla-Rho, J.C., et al. "An agent-based platform for simulating complex human-aquifer interactions in managed groundwater systems", Environmental Modeling and Software, (2015) 73: 305-323.

Optional Reading:

b. Deguchi. H., "The tragedy of the commons and its agent-based and gaming modeling", in *Economics as an Agent-Based Complex System*, Springer (2004).

22. Simulating the future of mobility: self-driving cars

Topics: Application of ABM: traffic simulations, simulating 'emergent behavior' (self-driving cars)

Reading:

a. Litman, T., (2019) Autonomous vehicle implementation predictions, Victoria Transport Policy Institute.

Optional Reading:

b. Zakharenko, R., "Self-driving cars will change cities", Regional Science and Urban Economics, (2016), 61: 26-37

23. Strengths and limits of models for policy

Topics: Modeling for policy and decision making; limitations; strengths; key take-aways

Readings:

a. Paul P. Craig, Ashok Gadgil, and Jonathan Koomey, (2002), "What can history teach us? A retrospective examination of long-term energy forecasts for the United States". *Annual Review of Energy and the Environ*ment, 27:83–118

b. Pindyck, R. S., (2017), The Use and Misuse of Models for Climate Policy, *Review of Environmental Economics and Policy*, Vol 11(1):100-114.

Optional Reading:

c. *Theory and Practice in Policy Analysis: Including Applications in Science and Technology*, M. Granger Morgan (2017), Cambridge University Press. "The use of models in policy analysis", Chapter 11, pg323-339.

24. Final Presentations