Massachusetts Institute of Technology
Sloan School of Management

15.879 Bringing Data into Dynamic Models
Fall 2022

Hazhir Rahmandad
Last Updated: August 29, 2022

I. GENERAL INFORMATION

Course Description and Objectives

In this course, we introduce the basic tools for bringing quantitative data into building and estimating System Dynamics models. We will discuss various tools related to model calibration/estimation spanning optimization methods, Maximum Likelihood, Method of Simulated Moments, Markov-Chain Monte-Carlo, Kalman filtering and state resetting, Hierarchical Bayesian methods, and the modeling and computational infrastructure needed for scaling these methods. Students will collaborate in applying these techniques to a handful of classical System Dynamics models, with the aim of developing research paper(s) jointly authored by active class participants. While having taken 15.873/2 would be valuable, this course does not have those as a required pre-requisite. That said, the course is hands-on, research focused, and most suitable for PhD students and others considering rigorous merging of SD models with data. The course is open to non-MIT graduate students to audit but given limited bandwidth for weekly presentations, in case more than a handful of students participate, the priority for weekly presentations will be given to the formally registered students.

Grading is largely based on weekly Assignment assignments and presentations which also contribute to building the knowledge based for the joint publication(s) to be developed in the class.

Instructor

Hazhir Rahmandad, E62-432
617.258.8912 (v), Hazhir@mit.edu

Teaching Assistant

Angie Moon: amoon@mit.edu

Class Meeting Time and Place

Fridays: 9 am- 12 pm

Room E62-450 and Zoom (https://mit.zoom.us/j/94781783836):

Primary Textbooks

1. H. Rahmandad, Oliva, R., Osgood, N. 2015. Analytical Methods for Dynamic Modelers. MIT Press, Cambridge, MA. (Abbreviated as AMD)

2. Sterman, John D. (2000), *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin McGraw-Hill, ISBN: 0-07-231135-5. (Abbreviated as BD)

Other readings will be posted on Stellar.

Software

Vensim DSS (Decision Support System**).** Vensim DSS is Ventana's top-of-the-line version. Ventana generously allows the students taking this course to use the software *for academic purposes only* without charge. Use the link below for downloading the Vensim DSS: http://www.vensim.com/mit.html

Hardware

Many class exercises will require the use of a computer, so please bring your own laptop, with Vensim DSS installed on it, to class. We will also require computational work for weekly assignments, some of which may be computationally intensive. We have access to some Sloan virtual machines for more intensive computational work, which we will utilize for the final analyses for our joint publication(s), and occasionally may benefit from those if personal computers are not sufficient for your weekly assignments. Please work with instructor and TA to utilize these resources.

Assignment Assignments and Weekly Presentations

The topics we cover require hands on practice to master. The weekly Assignment assignments are the primary learning opportunity for students. These assignments are designed to utilize and practice various tools and methods we learn about, and to put them to work for addressing a set of concrete research questions which we plan to turn into publications. As such, completing them is central to the course, and they require significant amount of work. The detailed class schedule specified not only the date for finishing the assignment, but also suggests a start date, as some assignments are lengthier than others and you need to start them more than a week before. You are encouraged to collaborate with others in the class, to share code and reuse code, and find ways to enhance your learning experience and its efficiency as you see fit: there is no cheating for these assignments. Canvas 'Discussions' section provides a mechanism to discuss and share ideas and get your questions answered by the instructor and other classmates.

These assignments are opportunities for learning-by-doing, learning from colleagues, and getting feedback. For the latter two purposes each student is expected to provide a brief (10-15 min) presentation of what they have done for the assigned Assignment for the week, what they have learned, and what questions they may have. We kick off the class with these presentation/discussions. Presentations will go over similar questions but applied to different seminal models in the field, offering valuable comparative studies each week. Individuals should upload their presentations and any relevant file to class's shared canvas folder under the relevant assignment and a folder named after the student. Name your files as: <LastName>-S<session>.pptx, e.g. Rahmandad-S5. Besides the presentation files you may want to upload your updated models, code, and other relevant files both to enable faster feedback and to help others see your work and learn from it. These files will be accessible to everybody in the class and you are welcome to share your feedback to colleagues both during individual presentations and afterwards.

Based on what we learn from these exercises, we may then identify scientific contributions of broader interest to the System Dynamics community which underpin specific research papers we will work on.

Candidate Models

Weekly assignments are organized around classical SD models, and each student will be picking up a model and conducting her assignment for each week using that model. Here is a menu of potential models to choose from sorted based on complexity of the models; we will finalize the model assignments in the first session of the class:

- Stock management structure (demo model which we will work on throughout class exercises; not available for individual work)
- SEIR with behavioral feedback from Rahmandad et al 2022
- Longwave model from Sterman 1985
- Project management model from Ford and Sterman 1998
- Market Growth model (from BD, originally by Forrester)
- Commodity Cycles model (from BD)
- Service Quality model by Oliva and Sterman 2001
- Urban Dynamics (could accommodate 2 people)
- World 3 model from Limits to Growth 30 year update (could accommodate 2 people)

Research Paper(s)

The topics we cover in this course are explored in depth in various communities focused on statistical and operations research methods, yet their applications to SD models remain sparse. For example, we don't have clear guidance on questions such as "*What optimization algorithms are best suited for calibration of SD models?*"; "*How much quantitative data is needed to reliably infer parameters of an SD model?*";"*What features of the model determine the value of including state resetting and filtering methods in the calibration process?*"; "*What estimation methods provide reliable confidence/credible intervals for estimated parameters?*" among others. These research gaps provide contribution opportunities for class participants. Specifically, by addressing these and similar questions in the context of a few well-known SD models in weekly assignments, the students will accumulate the knowledge base needed to systematically address these research questions. Based on the speed of progress, the novelty of emerging findings, and the team's bandwidth, the instructor will coordinate the development of one to three research papers jointly co-authored by class participants. While the primary work for the analysis going into these papers is happening during the weekly assignment work, developing and writing full research papers and shepherding them through the review process will extend beyond the duration of this course. Therefore, participants interested to be co-authors will need to remain engaged with the ongoing paper(s) beyond this semester.

Reading Assignments

We largely flip the classroom, so class work relies on the assumption that you have done the readings and we can build on that basic knowledge.

Class Exercises

Readings would prepare you to apply the various techniques in simple problems. We typically spend the class time beyond project presentations addressing your questions on different methods, discussing the readings, and working on a few exercises to apply those methods. Your active participation in these activities contributes to your classroom participation component of the grade.

II. OUTLINE OF TOPICS AND READINGS

Subject to change. Please check for latest version on canvas. References at the end of syllabus.

Date	Class	Topic	HW to Start	Reading, Assignment Due
9/9	1	Intro; Choosing Models, Measurement and Process Noise; Model parameters; Data types	**1 and 3**	**Readings**: BD Appendix A Industrial Dynamics, Appendix O AMD Introduction
9/16	2	Vensim Tips and Tricks: Subscripts, Data Connections; Sensitivity Analysis; Optimization Analysis workflow	**2**	**Assignment 1**: Identifying data and parameter types, measurement and process noise. **Readings**: Industrial Dynamics Appendix K; BD Appendix B
9/23	3	Model Analysis Process; Equilibrium; Synthetic Data Experiments	**4**	**Assignment 2**: Setting subscripts for a multi-level model **Readings:** (Gelman, Vehtari et al. 2020)
9/30	4	Functional forms, Allocation, Coflow	**5**	**Assignment 3**: Setting up ***two*** python-based methods for automated simulation workflows **Readings**: Rios-Ocampo and Gary 2022; Vensim Allocate by Priority help
10/7	5	Optimization and Calibration		**Assignment 4**: Exploring the modes of behavior from the model; Creating Synthetic Data **Readings:** (Amaran, Sahinidis et al. 2016)
10/14	6	Likelihood-based error terms and Bayesian introduction	**6 and 7**	**Assignment 5:** Calibrating to synthetic data, comparing optimization algorithms **Readings:** (Vrugt 2016)
10/21	7	MCMC; HMC	**8**	**Assignment 6**: Maximum Likelihood Estimation **Readings:** (Betancourt 2017)
10/28		**No class. SIP**		
11/4	8	Hierarchical Bayesian		**Assignment 7:** MCMC and comparison with HMC **Readings:** (Gelman, Bois and Jiang 1996); (Huang, Liu and Wu 2006)
11/11	9	Method of Simulated Moments and Indirect Inference	**9**	**Assignment 8:** Hierarchical Bayesian Estimation **Readings:** (Hosseinichimeh, Rahmandad et al. 2016);
11/18	10	State resetting and Kalman filtering	**10**	**Assignment 9:** Indirect Inference Estimation **Readings**: (Eberlein 2015(AMD Ch. 4))
11/25		**No class. Thanksgiving**		
12/2	11	Building a SD workflow; Simulation-based Calibration	**11**	**Assignment 10:** Estimation with extended Kalman filtering **Readings**: (Talts, Betancourt et al. 2018)
12/9	12	Hands-on: Developing papers		**Assignment 11:** Bringing it together. Paper outlines.

IV. COURSE GRADING

Grade Distribution	**% of Final Grade**
Class Participation and Classroom Exercises	25
Assignments and Presentations	75

V. OTHER IMPORTANT ISSUES

Academic standards

We expect the highest standards of academic honesty and behavior from all participants in class. Our course Stellar site contains a link to an important document describing the academic and personal values we uphold at MIT Sloan. Sloan Classroom Policies and Norms, presents standards for individual and group work as well as those for citing the work of others (proper referencing to avoid plagiarism) and for personal conduct in the classroom and as a member of our community. Be sure to read this document. If you have any questions about standards and expectations regarding individual and team assignments, please ask us after you have read the standards and before doing the assignments.

References

Texts

Rahmandad, H., Oliva, R., & Osgood, N. (Eds.). (2015). *Analytical Methods for Dynamic Modelers*. Cambridge, MA: MIT Press.

Sterman, J. (2000). *Business dynamics: systems thinking and modeling for a complex world* (1 ed.). Boston: McGraw-Hill/Irwin.

Forrester, J. W. (1961). *Industrial Dynamics* (1 ed.). Cambridge: The M.I.T. Press.

Papers

Amaran, S., N. V. Sahinidis, B. Sharda and S. J. Bury (2016). "Simulation optimization: a review of algorithms and applications." Annals of Operations Research **240**(1): 351-380.

Betancourt, M. (2017). "A conceptual introduction to Hamiltonian Monte Carlo." arXiv preprint arXiv:1701.02434.

Eberlein, R. (2015). "Working with noisy data: Kalman filtering and state resetting." Analytical methods for dynamic modelers.

Gelman, A., F. Bois and J. Jiang (1996). "Physiological pharmacokinetic analysis using population modeling and informative prior distributions." Journal of the American Statistical Association **91**(436): 1400-1412.

Gelman, A., A. Vehtari, D. Simpson, C. C. Margossian, B. Carpenter, Y. Yao, L. Kennedy, J. Gabry, P.-C. Bürkner and M. Modrák (2020). "Bayesian workflow." arXiv preprint arXiv:2011.01808.

Hosseinichimeh, N., H. Rahmandad, M. S. Jalali and A. K. Wittenborn (2016). "Estimating the parameters of system dynamics models using indirect inference." System Dynamics Review **32**(2): 156-180.

Huang, Y., D. Liu and H. Wu (2006). "Hierarchical Bayesian methods for estimation of parameters in a longitudinal HIV dynamic system." Biometrics **62**(2): 413-423.

Talts, S., M. Betancourt, D. Simpson, A. Vehtari and A. Gelman (2018). "Validating Bayesian inference algorithms with simulation-based calibration." arXiv preprint arXiv:1804.06788.

Vrugt, J. A. (2016). "Markov chain Monte Carlo simulation using the DREAM software package: Theory, concepts, and MATLAB implementation." Environmental Modelling & Software **75**: 273-316.