CMPT 394 – Simulation Principles &
CMPT 858 (Special Topics in Operations Research – Modeling for Decision Making)

Course Contents

This course will introduce students to the theory and practice of dynamic modeling and simulation to inform decision making. In addition to covering elements common to diverse dynamic modeling traditions – including the challenges of framing dynamic hypotheses at varying degrees of abstraction, calibration, sensitivity analysis, parameter estimation, Monte Carlo method, and issues of metalinguistic abstraction – the course presents, compares and contrasts essential elements of three popular types of modeling for decision making: Agent-based modeling, System Dynamics modeling, and discrete event simulation.

Given that this is a graduate course, the need to substantively discuss the three types of modeling, and the fact that there are extensive online tutorials available offering training on use of the Anylogic software to accomplish many common tasks (most notably the youtube videos from the instructor – see Reference Resources), many sessions of this course will use an "inverted classroom" model, where students will be *required* to review relevant material prior to each such session, and most classroom time for these sessions will be devoted to activities that take key advantage of the shared classroom experience. These include – but are not limited to – addressing student questions regarding the materials, assisting students with exercises and (especially) with advancing their projects. Work on and completion of a project (as described below) will constitute a central component of the course.

Course Instructor

Nathaniel Osgood, Thorvaldson 280.6, 966-6102, *osgood@cs.usask.ca*
Office Hours: After class and by appointment.

Reference Resources

While the course will involve some lectures, this graduate course will limit the amount of training provided, and will tend to place greater emphasis on using the classroom time to take advantage of the unique opportunities available by in-person meetings. Students are required to take time outside of class sessions to review only materials. While the AnyLogic software comes with some excellent tutorials, students should refer to the following materials, which include detailed training sessions:

http://tinyurl.com/ConsensusABM

http://tinyurl.com/NCBootcampLinked

http://www.cs.usask.ca/faculty/ndo885/Classes/CMPT858LatestSDVersion/index.html

Reference Books

There is no required reference book for the class. Interested students may find the following books of value in understand elements of Agent-Based Modeling:

Railsback, S.F. and Grimm, V. *Agent-Based and Individual-Based Modeling: A Practical Introduction*. Princeton: Princeton University Press. ISBN 978-0-691-13674-5. 2012

Sterman, J. *Business Dynamics*. Boston: McGraw-Hill Higher Education. 2000.

Software

AnyLogic 7

Topic Plan

Key concepts to which students will be exposed in this class include those from programming languages (domain-specific languages, metalinguistic abstraction, event-based, generative and declarative programming), mathematics (state space, classes of networks, parameter spaces, glimpses of complexity theory, dynamic systems theory, ordinary differential equations and numerical integration), and software engineering (application of ideas from dependency injection, class- and functional- abstraction, encapsulation and interface-based programming for medium- and large-scale models, peer review and testing, UML diagrams).

Java tutorials will be available online and in specially scheduled sessions for students not from Computer Science background.

Student Evaluation

The proposed weighting for coursework varies for the two co-located courses is as follows. Please note that the estimated due dates may be off by a few days, and that additional material is anticipated for some graduate assignments.

CMPT 394 Option 1

Deliverable	**Detail**	**% Mark**	**Estimated Due Date**
Participation	In classroom and office hours	12%	N/A
Assignment 1	System Dynamics Exercise 1	10%	Feb 6
Assignment 2	Agent-Based Modeling Exercises 1	10%	Feb 14
Assignment 3	Agent-Based (&SD) Modeling Exercises 2	10%	Mar 6
Assignment 4	Agent-Based Modeling Exercises 3	10%	Mar 20
Pop Quizzes	Throughout Term, In Class	18%	TBD

Final Exam	Closed Book	30%	TBD

CMPT 394 Option 2

Deliverable	Detail	% Mark	Due Date
Participation	In classroom and office hours	10%	N/A
Term Project Part 1	Informal description of area in which you'd like to wor your model. Informal estimate of scope of model to be implemented. Further details on data sources planned f use. Causal loop and/or system structure diagrams	5%	TBD
Term Project Part 2	Informal mapping diagrams (stock and flow/statechart, object diagrams showing hierarchies, etc.) with equatio Descriptions of scenarios & sensitivity analyses that you plan to investigate.	5%	TBD
Pop Quizzes		10%	TBD
Term Project Part 4	Final report & end-of-term presentation	40%	TBD
Final Exam	Closed Book	30%	TBD

CMPT 858 Option 1

Deliverable	Detail	% Mark	Due Date
Participation	In classroom and office hours	10%	N/A
Assignment 1	System Dynamics Exercise 1	12%	TBD
Assignment 2	Agent-Based Modeling Exercises 1	12%	TBD
Term Project Part 1	Informal description of area in which you'd like to wor your model. Informal estimate of scope of model to be implemented. Further details on data sources planned f use. Causal loop and/or system structure diagrams	0%	TBD
Assignment 3	Agent-Based (& SD) Agent-Based Modeling Exercises	12%	TBD
Term Project Part 2	Informal mapping diagrams (stock and flow/statechart, object diagrams showing hierarchies, etc.) with equatio Descriptions of scenarios & sensitivity analyses that you plan to investigate.	0%	TBD
Assignment 4	Agent-Based Modeling Exercises 3	12%	TBD
Pop Quizzes		10%	TBD
Term Project Part 4	Final report & end-of-term presentation	32%	TBD

CMPT 858 Option 2

Deliverable	Detail	% Mark	Due Date
Participation	In classroom and office hours	10%	N/A
Term Project Part 1	Informal description of area in which you'd like to wor your model. Informal estimate of scope of model to be implemented. Further details on data sources planned f use. Causal loop and/or system structure diagrams	0%	TBD

Term Project Part 2	Informal mapping diagrams (stock and flow/statechart, object diagrams showing hierarchies, etc.) with equatio Descriptions of scenarios & sensitivity analyses that you plan to investigate.	0%	TBD
Pop Quizzes		10%	TBD
Term Project Part 4	Final report & end-of-term presentation	80%	TBD

Please note that a significant fraction of students' grades will be based on class participation. In recognition of differences in communication styles and interests among students, this participation score will reflect interaction in class and in office hours and (where appropriate) tutorials.

The contents of the term project will be decided under discussion with the instructor.

Topic Plan

A preliminary schedule for topics is included below. This schedule is tentative and subject to change as student progress and discussion direction warrant. Note again that many sessions may be given in an "inverted classroom" model that requires student watching a video ahead of time.

Major section	Focus	Topics for discussion in class	Anticipated Date
Introductory topics	Orientation & Motivation	What to expect & what not to expect from this course. Complementary nature of systems-based and reductionist approaches. Emergence and "systems effects". Generating vs. "hardwiring" patterns.	Sep 4
	First Hands-On Exposure	Experiential encounter with some of the essential ideas of modeling & simulation	Sep 9
	Dynamic modeling process	Including the overview of qualitative mapping, model scoping, conceptualization & formulation, model testing, model use, phenomenology & pattern-oriented modeling. Incremental development & ongoing docking as a key to insight and containing process complexity.	Sep 11 (later revisit as time allows)
	Scoping a model	**Scoping a model: Tensions.** Causal interactions (both structured and random) between the parties, higher level environmental influences. Generating vs. "hardwiring" patterns. Key question: What is likely to be important to answer the research questions being asked? Endogenous/Exogenous/Ignored classification. Interaction Scenarios.	Sep 11 (later revisit as time allows)

		Breadth vs. depth. Opportunity costs. The critical role of incremental development.	
System Dynamics & Compartmental Modeling	System Dynamics modeling: Essentials	Feedback focus. Looking endogenously for the causes of behavior. "Structure drives behavior." Spectrum of qualitative to quantitative modeling. Stakeholder involvement in the modeling process. Incorporating less tightly known values. Models as thinking tools.	Sep 11
	Model mapping: Causal loop diagrams	Basics of qualitative and semi-quantitative sys thinking: diagramming feedback-rich systems influence & causal loop diagrams. Causal loop diagram examples. Limitations of causal loop diagrams.	Sep 11
	Stocks & flows 1: Basics	Structure as shaping behavior, stocks as accumulations, stock behaviour as a function of flows	Sep 16
	Mathematical underpinnings of stocks and flows	State equation formulation of stock & flow diagrams as Ordinary Differential Equations, simulation as numerical integration. Value of a formal mathematical framework.	Sep 23
	Stocks & flows 2: First Order Delays	Relation to stochastic processes, exponentially distributed residence times.	Sep 18 (via video)
	Stocks & flows 3: Higher order delays & Competing Risks	Erlang distributions	Sep 18 (via video)
	Delay-driven oscillations		Sep 23
	Non-Linearity	Complex emergent behavior as resulting from tipping points, equilibria, non-linearities, delays. Impact on dynamics, simulation, reasoning about management and interventions. Location of equilibria.	Sep 23
	Application of Stock & Flow Reasoning: Influence & Infection Spread	Essential dynamics of contagion, herd immunity.	Sep 23, 25
	Additional mathematics of Contagion	Assessing Stability and regions of stability in parameter space, endemic and disease-free equilibria	Separate tutorial around Sep

	(Graduate Students only)		29
Agent-based modeling	Specific Motivations for ABM	Network & Spatial Context, Heterogeneity, individual decision making & preferences and longitudinal information, stakeholder understanding	Sep 30
	ABM Specific issues	Thinking in a structured way about the state of an agent (distinguishing static from dynamic), Representing Inter- and intra-individual Feedbacks in Agent-Based models. Key problem features motivating agent-based approaches. Multi-level interactions. High level summary measures/statistics.	Oct 2
	AnyLogic ABM core concepts	Core concepts for creating runnable agent-based models; separation of models & scenarios ("experiments") Design vs. execution environment. The notion of "builds", and components with representation at both design & execution time. Use of multiple types of UML diagrams to sketch agent class relationships & agent interactions.	Oct 2
	Computational Architecture of Agent-Based Models	Key classes for all types of models. Main, Agent classes, Presentations, Experiments. Relationship of classes, run-time objects & design-time objects. Expressing agent heterogeneity with subclassing vs. parameterization.	Oct 2
	Computational Components	Parameters & (State) variables. Methods/Functions. Inversion of control & "The Hollywood Principle". Action handler based code fragments (entering & leaving state, at transition, startup & destruction of Main & Person objects).	Oct 2
	Agent characteristics & heterogeneity	Parameters, Variables (dynamic & static). Creating heterogeneous populations.	Oct 7
	Specifying discrete intra-agent dynamics	Statecharts (UML State Diagrams) & transitions. Branching, sources & sinks. Transitions: Rates, Timeouts, Conditions, Message-Based.	Oct 7
	Discrete inter-	Messages: Broader motivations in	Oct 9 (via

	agent dynamics	Computer Science, sending & handling. Contagion of Pathogens & Ideas. Network neighbour selection options.	video)
	Events & Event-Driven Programming	Static events. Dynamic events & their uses. Event scheduling, the role of the scheduler.	Oct 14
	Environments	Networks & their relationships to populations. Topological (network) & geometric (regular & irregular spatial) context	Oct 16 (via video)
	Network environments	Networks: Structure and Dynamics • Network embedded agents, AnyLogic's built-in network types, and creating custom networks. • Network classes (Poisson Random, Ring lattice, Small World networks, Scale Free networks) • Mathematics of scale free networks • Impact on network dynamics Impact of network fitting and aggregation on results.	Oct 16 (via video)
	Population & structural dynamics	Implementing dynamically varying populations & dynamic networks.	Oct 21
	The Embedded Environment: Focus on Regular Spatial Embedding	**Regular spatial embedding (Cellular Automata)**: Neighbourhoods & inter-agent communication. Color. Boundary Conditions. Alternative tessellation schemes. Discrete & continuous geometries.	Oct 21
	Agent mobility & movement	Regular vs. irregular, discrete vs. continuous	Oct 23
Discrete Event Modeling	A Glimpse of Discrete Event Modeling & Simulation: Basics	The notion of process-centered modeling. Entities, resources, queues. Situations under which this is desirable.	Oct 28
	Taxonomy of resources and resource pools	Moving, portable, fixed. Resource interchangeability.	Oct 28
	Visualization	Representation of elements. Identification of visual representation with entities & resources. Paths for movement. Irregular geometries	Oct 28

Cross-methodology topics	Metalinguistic abstraction **(Graduate students only)**	Domain specific languages. Describing the "what vs. the "how": Declarative languages. Generative programming.	Separate Tutorials, Around Oct 30

	Customizing model appearance before & during execution	Creation of custom user-interface elements to
		• Present data via graphs & tables
		• Dictate assumptions via user input "widgets" (sliders, checkboxes, text fields, etc.)
		    ○ Initial assumptions (e.g. regarding parameter values)
		    ○ Live changes to assumptions
			Intermixed, starting Sep 16

	Analyzing & reporting data	Reporting data for analysis • Built-in Statistics • Custom statistics & stratification • Event use • Visualization in state space	Oct 30
	Model Debugging	Distinguishing the failure from the fault. Tracing. Isolation. Binary search. Common defects. Remote debugging via Eclipse. Basic principles & practices of debugging Tips and techniques for effective debugging Debugging build problems Mechanisms for logging & tracing Multiple debugging methodologies	As possible
	Sensitivity Analyses	Parameter, structural, automated & manual, one way & multi-way. Parameter uncertainty & model uncertainty Stochastics: Uncertainty in evolution over time . 2D Histograms: Understanding the dynamic response of the model under uncertainty • Empirical fractiles • Plots of per-realization behaviour	Nov 4
	Model parameter estimation	Diverse sources of parameters. Challenges of network data. Opportunities for employing novel data collection mechanisms. Tie-in with Sensitivity analysis	Nov 4
	Calibration	Adjusting assumptions to best match	Nov 6 (via

		historical data & behavioural reference modes
		• Basic concepts of calibration
		  o Parameter space
		  o Objective function & the implied error model & MLE
		  o Weighing multiple matches
		  o Optimization algorithm
		• Assessing convergence & handling pathologies
		• Calibration differences between stochastic & deterministic models
			video).

	Multiple systems science methods	Complementary strengths and weaknesses Building AnyLogic models incorporating multiple modeling approaches. Stocks & flows in ABM: Why & how. Using several sorts of models together as synergistic lenses. Presentation of four effective hybrid modeling strategies. When to best characterize structured, individual-level processes within an ABM or within a discrete event model	Nov 18
	Additional coverage of hybrid systems science methods **(Graduate students only, separate tutorial)**	Building up 4 types of hybrid modeling strategies	Around Nov. 19, by video
	Modeling for Dynamic Decision Problems	Linkages of simulation models with other modeling techniques such as multi-attribute decision theory. Theoretical and practical basis for tying together decision trees & simulation models.	Nov 20
	Best Practices, Overview and Process-Oriented	Peer reviews, Version control (Versioning, Check-in (commit)/check out (locking)), Incremental delivery, YAGNI Principle, Continuous Integration & smoke testing, Refactoring. Unit checking. Brief exposure to principles of testing (test drivers, harnesses, mocks/fakes, unit tests), Risk Management. Continuous process improvement.	Nov 25

	Best Practices, Technical	Eliminating manifest constants. Assertions. ABM as realization of mathematical process; documenting mathematical description & Checking adherence of code to mathematical specification. Reducing software engineering complexity via modularity & model transparency. Trajectory Recording, abstraction using methods & classes, separating interface specification & implementation. Commenting. Using intention-revealing naming conventions. Individual versioning. Mocks & Fakes. Incremental delivery. Change & configuration management. Exceptions vs. return codes. Clean coding suggestions. Test-first coding.	Nov 27
	Dimensional Reasoning and Dimensional Homogeneity Testing	Understanding and using dimensional systems. Dimensions and Unit. Expressing dimension of a quantity as a product of powers of dimensions. The impact of the power of a dimension on unit change for that dimension. The privileged character of quantities of unit dimension ("dimensionless" quantities).	Dec 2
	Dimensional Analysis 2, de-dimensionalizing and Scale Models	Identification of parameters of unit dimension by defining known blocks of dimensional matrices and solving for remaining block. Buckingham's Π Theorem & capacity to lower parameter count by de-dimensionalizing. Risk of changing parameters of non-unit dimension; creating scale models so as to enable controlled experiments.	Dec 4

NB: The schedule above is subject to change. On occasion, updated schedules may be provided.

Lectures slides will be provided via the course website on Moodle. We will seek to have all course sessions recorded as screencasts for later viewing on youtube.

Project

The completion of a project forms an important – but optional – part of the class. The project type and topic will be chosen by the students in conjunction with the instructor. Because of the steepness of the learning curve, and the benefits of assembling team members with complementary backgrounds, we recommend pursuing group projects with 2 or 3 students. Projects should have a client associated with them. Individual projects may be pursued with instructor permission. We also strongly recommend projects which have an external client. Contact information for clients associated with many possible project are included in a separate document. Based on verbal discussion and on a series of incremental deliverables submitted during the term, the instructor will help guide the students on the project. (Please note that these early deliverables for the project may be informal and rough. While all deliverables should attempt to communicate material, no focus on creating a careful presentation of these materials is required prior to the final report for the project.) The project emphases may vary, but most projects should include the following:

1. Creating one or more simulation models that describe these phenomena, or adapting a particular model to a different context.
2. Placing data into the model to customize it to a particular context.
3. Running a "baseline" scenario with the existing model parameters, and commenting on its plausibility.
4. Running one or more "what if" scenarios with the model to explore different possible situations. These situations could reflect the results of implementing different policies, or different possible external conditions.
5. Performing one or more "sensitivity analyses", in which assumptions in the model (in the form of parameter values, or structural elements of the model) are changed.
6. A well-structured written report describing the above (see below).
7. An in-class 30-minute presentation where you summarize the model, its construction and findings.

Please note that while most projects will fall into the framework described above, the instructor is open to the idea of students exploring alternative methodologically oriented project types. These could include (but are not limited to) investigation of meta-level issues in modeling (e.g. challenges in characterizing a certain dynamic phenomenon in different modeling frameworks), or an analysis of or proposal for innovations involving the modeling tools and methodologies used for simulation modeling. If you wish to pursue one of these other types of projects, please discuss your interests with the instructor.

Final Report

The emphasis for the final report will be on quality of reflection and depth of the comments, rather than on length. Conciseness in text is a virtue. While bearing this in mind, it would be somewhat unusual for the length (ignoring figures) to be less than 10 pages or more than 30 pages.

The level of the report should be such that it would speak to other course members.

The report should include an abstract.

The outline below provides an idea of what the report could cover. It does not specify what is required in the report, nor is it comprehensive. The template should be used to stimulate ideas, not as a rigid template or requirement.

Please note that while the sections below are numbered, individual reports are not expected (or required) to use this numbering system. A given document may well omit certain of the sections below, based on the specific circumstances of that project. There are also quite a few considerations that could be fruitfully included in many reports that are not reflected below.

The project emphases may vary, but many projects would include the following:

0) **Abstract** (mandatory)
1) **Background**. While the instructor often does not require this knowledge per se, it can help convince the instructor that you have a strong grasp of this material. It can also help frame the scoping of the model, and of the scenarios. This should characterize factors such as

a) Motivation

b) Context

c) Goals of model

1) Is this a model primarily geared at providing higher-level insights without focusing on a particular external situation, or does it aim to characterized some particular external situation?

2) Research questions/hypotheses of greatest interest.

2) **Model.** This section of the report describes the model that was created:

a) Model scope: High level description of what is included, considered and left out of the model. I would suggest use of the endogenous/exogenous/ignored distinction introduced in the first or second lecture of class.

b) Model architecture. This should address the choice of modeling approach or approaches (e.g. System Dynamics, Agent-Based Modeling, Discrete Event Modeling)

c) Model formulation. For an agent-based model, you might consider using the ODD protocol to

1) High level. This could include stocks & flow diagrams, state charts, a description of the various sectors ("views") in the model or various agents or (in discrete event modeling) networks represented, variables or parameters associated with them, key outputs and dependencies on any input data. Discussion of how the initial state is selected: what particular situation (if any) is depicted in the initial state of the model,.

2) Lower-level. Formulation of key transitions or flows within the models. Discussion of general approach used.

3) **Calibrations** Any calibrations (by hand or automated) performed.

4) **Sensitivity Analyses**. These could be

a) Structural sensitivity analyses (certain areas of the model are altered or disabled)

b) Parameter sensitivity analysis

c) Extreme value tests conducted (as part of model testing or out of curiousity). These would test or seek to understand model behavior in "extreme" conditions (e.g. where one or more regions of the model are disabled)

5) **Scenarios**

a) Scenario Descriptions: Description of one or more "what if" scenarios with the model to explore different possible situations.

1) Describe the a "baseline" scenario, and the motivation for choosing it
2) Alternative situations examined. These situations could reflect, for example
   a) The results of implementing different policies
   b) Different possible external conditions.
   c) Understanding behavior

b) Findings from scenario runs

1) Findings related to the domain area (from insights from the runs)
2) Findings related to the model
3) Other findings

7) **Learning**. Insights and learning from different aspects of the project. This could include, for example, learning about

What would you do differently if you were to undertake this project again?

What other approaches might you take?

How might you change the scope or architecture of the model?

How might you approach the steps of modeling differently? What different steps might you use in assembling the model?

a) The domain area (from insights from the runs)

b) Learning about technical challenges of modeling

1) What was easy, what was hard?
2) Learning about tradeoffs between model architectures

c) Learning about the process side of modeling, for example

1) What makes modeling easier/harder?
2) What processes help lower risk of error?
3) What processes help identify errors earlier?

8) **Future work.** Promising avenues for future work

9) **Conclusions**. Highest level key points that you'd like to convey to someone from this project. These could cover issues included anywhere in the above.