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 includes 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), this class will concentrate on the principles of dynamic modeling and simulation, rather than seeking to impart expertise in the particular software involved; it is expected that students will have the maturity to seek out the many resources on that software or acquire understand of its detailed operation. However, ongoing use of the software will be key to delivery of the course: a large fraction of the sessions of this course will use an "inverted classroom" model, where students will be *required* to attempt exercises (and sometimes review relevant online 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 hands-on exercises and with advancing their projects. Work on and completion of a project (as described below) will constitute a central component of the course.

Course Instructor

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Office Hours: Immediately after class (Thorv 386) 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/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. (Specifically for Agent-Based modeling).
>
> Sterman, J. *Business Dynamics*. Boston: McGraw-Hill Higher Education. 2000. (Specifically for System Dynamics modeling).
>
> Shiflet & Shiflet, *Introduction to Computational Science: Modeling and Simulation for the Sciences*, 2nd Edition, Princeton University Press. ISBN: 978-069116071. (System Dynamics and Agent-Based Modeling)

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, and students in each course may elect for a marking scheme that includes assignments, or those emphasizing projects. The breakdown 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	6%	N/A
At home exercises to support the "flipped classroom"	See description below	20%	Most weeks
Assignment 1	System Dynamics Exercise 1	11%	Sept 26
Assignment 2	Agent-Based Modeling Exercises 1	11%	Oct 17
Assignment 3	Agent-Based Modeling Exercises 2	11%	Nov 7
Assignment 4	Hybrid Modeling Exercises 1	11%	Nov 28
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 work. Informal estimate of scope of model to be implemented. Further details on interventions and other "what if" questions that will seek to ask and any data sources planned for use.	0%	Sept 27
Term Project Part 2	Informal mapping diagrams (stock and flow or agent- or hybrid-oriented mapping diagram, object diag showing hierarchies, etc.) with equations. Descriptions of scenarios & sensitivity analyses that you plan to investigate.	0%	Oct 10
Term Project Part 3	Interim Update	0%	Oct 31
Term Project Part 4	Final report	40%	Final day of class
At home exercises to support the "flipped classroom"	See description below	20%	Most weeks
Final Exam	Closed Book	30%	TBD

CMPT 858 Option 1

Deliverable	Detail	% Mark	Due Date
Participation	In classroom and office hours	5%	N/A
Term Project Part 1	Informal description of area in which you'd like to work. Informal estimate of scope of model to be implemented. Further details on interventions and	0%	Sept 19

	other "what if" questions that will seek to ask and any data sources planned for use.		
Assignment 1	System Dynamics Exercise 1	10%	Sept 26
Term Project Part 2	Informal mapping diagrams (stock and flow or agent- or hybrid-oriented mapping diagram, object diag showing hierarchies, etc.) with equations. Descriptions of scenarios & sensitivity analyses that you plan to investigate.	0%	Oct 3
Assignment 2	Agent-Based Modeling Exercises 1	10%	Oct 17
Term Project Part 3	Interim Update	0%	Oct 31
Assignment 3	Agent-Based (& SD) Agent-Based Modeling Exercises	10%	Nov 7
Assignment 4	Agent-Based Modeling Exercises 3	10%	Nov 28
Term Project Part 4	Final report (delivered for final exam)	35%	At final exam
At home exercises to support the "flipped classroom"	See description below	20%	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 interventions and other "what if" questions that will seek to ask and any data sources planned for use.	0%	Sept 19
Term Project Part 2	Informal mapping diagrams (stock and flow or agent- or hybrid-oriented mapping diagram, object diag showing hierarchies, etc.) with equations. Descriptions of scenarios & sensitivity analyses that you plan to investigate.	0%	Oct 3
Term Project Part 3	Interim Update	10%	Oct 31
Term Project Part 4	Final report (delivered for final exam)	50%	At final exam
At home exercises to support the "flipped classroom"	See description below	30%	TBD

For the take-home exercises, the goal is to engage seriously with the exercise, with marks being "Pass" or "Fail". *A pass will be granted as long as it appears that you have grappled seriously with the problem (regardless as to whether you provide a complete or even partial solution)*. The results should be handed in via moodle the evening before class.

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. Notion of models as thinking tools, operationally capturing theory.	Sep 6
	First Hands-On Exposure	Experiential encounter with some of the essential ideas of modeling & simulation	Sep 6
	3 central varieties of dynamic modeling	Agent-based modeling, System Dynamics modeling and Discrete Event Simulation: Commonalities and distinctions. Hands-on exposure to each. The state space perspective. (Those pursuing projects should use this opportunity to glimpse as to what modeling type might be most useful for your models).	Sep 8
	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 8 (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. Breadth vs. depth.	Sep 13 (later revisit as time allows)

		Opportunity costs. The critical role of incremental development.	
System Dynamics & Compartmental Modeling	System Dynamics modeling: Essentials & Model mapping: Causal loop diagrams	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. Basics of qualitative and semi-quantitative systems thinking: diagramming feedback-rich systems with influence & causal loop diagrams. Causal loop diagram examples. Limitations of causal loop diagrams.	Sep 15
	Stocks & flows 1: Basics	Structure as shaping behavior, stocks as accumulations, stock behaviour as a function of flows. Separation of models & scenarios ("experiments"). Key classes for all types of models. Main, Agent classes, Presentations, Experiments. Expressing agent heterogeneity with subclassing vs. parameterization. Futility of just adding more capacity in the stock when outflow is greater than inflow.	Sep 20
	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. State space (phase space) depiction of a system's state; trajectories and their relations to derivatives.	Sep 22
	Stocks & flows 2: First Order Delays	Relation to stochastic processes, exponentially distributed residence times. Key notion of a memoryless transition process – for a fixed transition rate (or mean residence time), the probability of leaving the "well-mixed" stock is independent of how long one has been present. Distinguishing hazard rate (probability per unit time) from probability of transition over entire interval. Conceptualizing in terms of feedbacks, inflows and outflows. Equilibrium behaviour and stability. Dissipative models: Insensitivity to initial	Sep 22

		state. State space depiction of system dynamics.	
	Stocks & flows 3: Higher order delays & Competing Risks, Delay-driven oscillations	Capturing heterogeneity and non-well-mixed populations via disaggregation. Mixing matrices. Erlang distributions with aging chains. Competing risks. Origins of oscillation in delayed balancing feedbacks. State space depiction of system dynamics.	Sep 24
	Reinforcing feedback	Exponential (log-linear) growth and limits to growth, instability of equilibria. History dependence.	Sep 24
	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 27
	Application of Stock & Flow Reasoning: Influence & Infection Spread	Essential dynamics of contagion, herd immunity. State space depiction of system dynamics. History dependence. Key role of the fraction of susceptibles in governing dynamics. The key threshold of herd immunity.	Sep 27
	Key concepts in contagion models	The basic and effective reproductive constants. Understanding effects of open and closed populations (state space depiction of system dynamics of each). Critical immunization fractions.	Sep 29
	Additional mathematics of contagion	Mathematics of equilibria. Endemic and disease-free equilibria. Assessing stability of equilibrium and surrounding regions in parameter space. General reasoning about system behaviour (abstracting away from particular parameter values) for position and stability of equilibria and trajectories. Formal analysis of loop gain and parameter influence.	Sep 29
	Numerical calculation considerations	Brief look at accuracy considerations from a numerical analysis standpoint. The integration algorithm, fixed and variable step-sizes, stiff and non-stiff systems	Oct 4
Agent-based modeling	Specific Motivations for ABM	Key problem features motivating agent-based approaches. Network & Spatial Context, heterogeneity, individual decision making & preferences and longitudinal	Oct 6

		information, stakeholder understanding. Multi-level interactions.	
	ABM Specific issues	PARTIES framework for model conceptualization and mapping. 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. High level summary measures/statistics. Continued relevance of stock & flow lens.	Oct 6
	AnyLogic ABM core concepts	ABM Vocabulary: A quick glimpse, and contrast with stocks & flows.	Oct 6
	Computational Architecture of Agent-Based Models	Inversion of control & "The Hollywood Principle". Action handler based code fragments (entering & leaving state, at transition, startup & destruction of Main & Person objects).	Oct 11
	Agent characteristics & heterogeneity	Parameters, Variables (dynamic & static). Creating heterogeneous populations. Importance of heterogeneity. Comparison with how heterogeneity is captured in stock & flow models. *Students needing more familiarity with AnyLogic mechanisms are referred to my youtube videos on the subject*.	Oct 11
	Specifying discrete intra-agent dynamics	Statecharts (UML State Diagrams) & transitions. Branching, sources & sinks. Transitions: Rates (hazards), Timeouts (fixed or drawn from probability distribution), Conditions, Message-Based. Understanding the semantics of each transition times. Again distinguishing hazard rate (probability per unit time) from probability of transition over entire interval. Comparison with dynamics in stock & flow models. *Students needing more familiarity with AnyLogic mechanisms involved are referred to my youtube videos on the subject*.	Oct 11
	Events & Event-Driven Programming	Static events. Mention of dynamic events & their uses and event scheduling, and the role of the scheduler (with more for later). Use of events in reporting. *Students needing more familiarity with AnyLogic mechanisms involved are referred to my youtube videos*	Oct 13

		on the subject.	
	Using the state space (Phase space) and stock-and-flow lens for agent-based models	State space depiction of system dynamics, and reasoning about stocks and flows to understand observed dynamics.	Oct 13
	Environments	Significance of context: As governing factor, and as affected by model governing processes. Comments on reifying topological (network) & geometric (regular, GIS & irregular spatial) context.	Oct 13
	Discrete inter-agent dynamics	Messages: Broader motivations in Computer Science, sending & handling. Notion of message passing as robust way of communicating between asynchronous agents. Contagion of Pathogens & Ideas. Network neighbour selection options. *Students needing more familiarity with AnyLogic mechanisms involved are referred to my youtube videos on the subject*.	Oct 18
	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) • Impact on network dynamics Network metrics (degree, betweeness centrality, density, connectedness, etc.). Different degree distributions associated with different networks. Impacts on state space depiction of system dynamics. heterogeneity and its effects on network dynamics. Impact of network fitting and aggregation on results. Multiple types of networks, and competing network dynamics	Oct 18/20
	Scale free networks: Structure, properties, and dynamics	Preferential attachment. Mathematics of scale free networks: Power-law distributions in degree (numbers of neighbours per person), extreme variation in small segment of the population.	Oct 20

	Percolation effects in networks	Looking beyond aggregate population fractions of susceptibles to connectivity as a major factor governing network dynamics.	Oct 25
	Population & structural dynamics	Impact of network dynamics and concurrency on contagion. Implementing dynamically varying populations & dynamic networks.	Oct 25
	General comments on spatially explicit and implicit models	Notion of endogenizing space (tradeoffs -- retaining understanding of spatial resources, contacts as emerging from mobility, spatial analytics, greater detail required, level of confidence secured from stakeholders)	Oct 27
	The environment: Focus on Regular Spatial Embedding	Regular spatial embedding (Cellular Automata): Neighbourhoods & inter-agent communication. Boundary Conditions. Alternative tessellation schemes. Discrete & continuous geometries, discrete & continuous time, deterministic and stochastic dynamics	Oct 27
	Agent mobility & movement	Regular vs. irregular, discrete vs. continuous	Oct 27
	Leveraging geographic information systems for dynamic models	Resource placement, reasoning about distance, continuous movement along stylized and route-specific paths	Nov 1
Discrete Event Modeling	A Glimpse of Discrete Event Modeling & Simulation: Basics	The notion of workflow-centric modeling. Entities, resources, queues. Situations under which this is desirable. Queuing behaviour. Importance of stochastics of even brief transients when inflow and outflow are well-balanced. Endogenizing resource representation, travel time. Modeling language universality. Metalinguistic abstraction.	Nov 3
	Taxonomy of resources and resource pools	Representation of entity and resource movement. Moving, portable, fixed. Resource interchangeability.	Nov 8
	Visualization	Representation of elements. Identification of visual representation with entities & resources. Paths for movement. Irregular geometries	Nov 8
Ret ros pec	Model scope revisited	Impact of endogenizing (contact patterns as "well mixed", network based or emerging	Nov 10

		from mobility; space; resources; movement, travel time).	
	Metalinguistic abstraction	Domain specific languages. Describing the "what vs. the "how": Declarative and non-declarative languages. Generative programming.	Nov 10
	Abstractions of time	Discrete time, Continuous time with discrete events, continuous processes: further discussion of implications (need to broker events within discrete periods of time)	Nov 10
	Modeling process revisited	Choosing model scope, but also areas following model formulation	Nov 22
Hybrid Modeling		Motivations for hybrid modeling. 5 types of hybrid modeling strategies. 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 22

Cross-methodology topics	Importance of model visual interface for communication	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 with above

	Analyzing & reporting data	Reporting data for analysis • Built-in Statistics • Custom statistics & stratification • Event use • Visualization in state space	Intermixed with above
	Sensitivity	Parameter, structural, automated & manual,	Nov 24

	Analyses	one way & multi-way, deterministic & Monte Carlo. 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	
	Calibration	Adjusting assumptions to best match 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	Nov 29
	Simulation mechanisms: Beneath the hood	Event schedule. Supporting continuous time & discrete time abstractions. Concept of event scheduling, event-driven performance, event descheduling and pre-emption, dynamic and static scheduling of events, event queues	Dec 1
	Model performance	Cross-platform performance. Scaling with population and heterogeneity. Events and model performance. Memory needs. Parallelism and dependencies, time granularity, number of events.	Dec 1
	Dynamic modeling frontiers	Where rapid advances in simulation modeling can be expected: Model integration with machine learning algorithms and “big data”, hybrid modeling, declarative modeling languages, collaborative modeling, agile modeling, behavioural modeling, and modeling in the cloud	Dec 6
	Model Debugging	Distinguishing the failure from the fault. Tracing. Isolation. Binary search.	As opportunities

		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	arise during term
	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.	Dec 8
	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.	Dec 8
	Wrap-up and resources for learning more		Dec 8
As opportunities arise or project needs dictate	Model parameter estimation	Diverse sources of parameters. Challenges of network data. Opportunities for employing novel data collection mechanisms. Tie-in with Sensitivity analysis	
	Modeling for Dynamic Decision	Linkages of simulation models with other modeling techniques such as multi-attribute decision theory. Theoretical and practical	

	Problems	basis for tying together decision trees & simulation models.	
	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).	
	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.	
	TBD		

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 to 4 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).

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. Individual student projects should be no longer than 15 pages; group projects should be no longer 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 Simulation)

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.