I. GENERAL COURSE INFORMATION

VIRGINIA TECH
NORTHERN VIRGINIA CENTER
GRADO DEPARTMENT OF INDUSTRIAL & SYSTEMS ENGINEERING

ENGR 5104 APPLIED SYSTEMS ENGINEERING: System Dynamics and Systems Thinking

Fall 2006
Dr. Hazhir Rahmandad

Course Description

Why do so many business strategies fail? Why do so many others fail to produce lasting results? Why do many businesses suffer from periodic crises, fluctuating sales, earnings, and morale? Why many social and governmental programs fail to achieve their desired objectives and some create results counter to their goals?

To address these questions, in this course the basic concepts of systems thinking and system dynamics modeling will be introduced. In general, systems' thinking is a school of thought that focuses on recognizing the ***interconnection***s among the parts of a whole entity (the system) and synthesizing the interconnections into a ***unified view of the whole entity (the system)***.

System dynamics is a modeling process to quantify problems that unfold through time in mathematical models that are simulated to investigate sources of undesirable dynamics and find successful improvement strategies. System dynamics embodies an iterative process in which a ***problem*** that is pervasive throughout a system is defined, the ***structure of the system*** that generates the problem will be studied, and ***policies or practices*** that can change the system structure and behavior and therefore alleviate/solve the problem will be reviewed and introduced.

The understanding of the system structure requires the determination of how critical variables affect other variables, even if the other variables are downstream from the critical variables under consideration. To determine variable interrelationships, not only must the analyst establish the causal relationships among the elements of the system but also distinguish those among the ***physical, organizational, and decision-making*** relationships.

In this course, you will consider problems that manifest themselves in complex systems. Examples of these include but are not limited to: the performance degradation associated with the introduction of new technologies in organizations, the congestion associated with transportation networks, the lack of process performance improvement when introducing quality improvement interventions, fluctuating sales, production and earnings; the diffusion of new technologies; environmental challenges, and epidemics. You will use one of several simulation software packages throughout the course to understand, evaluate, and improve upon complex problems and establish a relationship between the real world and a virtual simulation world by generating and evaluating corresponding system simulation models.

Scope

Understanding the interrelationships among key concepts and variables can lead to the evaluation and improvement of complex enterprises and systems. Fundamentally, the decision-maker is forced to make decisions the consequences of which are separated from him/her both ***in time and space***. In order to deal with the dynamic complexity of the enterprise and/or system over time, decision-makers need to experiment in a virtual world where the impact of their decisions can be ascertained.

You will learn to visualize a social system in terms of the structures and policies that create dynamics and regulate performance. System dynamics allows us to create 'microworlds,' management flight simulators where space and time can be compressed, slowed, and stopped so we can experience the long-term side effects of decisions, systematically explore new strategies, and develop our understanding of complex systems. We use role playing games, simulation models, case studies, and management flight simulators to develop principles of policy design for successful management of complex strategies. Case studies of successful strategy design and implementation using system dynamics will be stressed. We consider the use of systems thinking to promote effective learning and policy design.

Justification

Accelerating economic, technological, social, and environmental changes challenge engineers and managers to learn at increasing rates. They must effectively learn how to ***design and manage*** complex systems with multiple feedback effects (loops), long time delays, and nonlinear responses to their decisions. Yet learning in such environments is difficult precisely because the decision-maker never confronts many of the consequences of his/her most important decisions. Effective learning in such environments requires methods to represent and assess ***dynamic complexity*** and require tools that managers and engineers can use to accelerate learning throughout an organization.

Major Course Concepts and Techniques

1. Modeling and Simulation.
2. Mental Models.
3. Virtual versus Real World.
4. Feedback
5. Double-Loop Learning.
6. Archetypal System Behaviors.
7. Non-Linear Relationships.
8. Causal Link and Loops.
9. Stocks and Flows.

10. Delays.
11. Aging Chains and Co-Flow Structures.
12. Higher-Order Systems.
13. Modeling Decision-making.
14. Group Modeling.
15. Knowledge and Equation Elicitation.
16. Policy and Practice Evaluation.
17. Model Validation.
18. Big-picture Thinking.

Educational Objectives

There are three broad educational objectives that relate to systems thinking and system dynamics modeling that are addressed in this course. These include: qualitative skills, simulation modeling skills, and personal insights. The course will focus primarily on the first two sets of qualitative and quantitative educational objectives and hopes to inspire continuous lifetime learning through the latter.

Qualitative and Simulation Modeling Educational Objectives

1. Appreciation for systems thinking, causal loops, stocks and flows and feedback dynamics.
2. Define a problem, a system and hypothesize its behavior that is responsible for the problem.
3. Use of behavior over time graphs.
4. Identify the physical, organizational, decision-making structures within systems.
5. Identify critical variables in a system and their relationships to other variables.
6. Draw and interpret causal loop and stock and flow diagrams.
7. Identify and define stocks and flows.
8. Formulate robust, small, models.
9. Define the dynamic behavior of systems.
10. Identify and define delays in systems.
11. Understand how to elicit tacit knowledge.
12. Complete policy analysis.
13. Work within a group-modeling framework.
14. Complete model validation.
15. Test models using simulation software. (iThink, Powersim, and VENSIM are available with the text.).
16. Appreciate of how stock-and-flow and feedback structures containing delays and non-linear relationships can create non-intuitive behaviors over time, and therefore demand simulation for better thinking about, and solutions to, dynamically complex problems.
17. Become in-house trainers of system dynamics principles and modeling.

Prerequisites

Graduate standing in the industrial and systems engineering degree programs. (3H, 3C)

Professor

Hazhir Rahmandad
Office: Falls Church Center, Room 430
Office Phone: 703.538.8434
Office Hours: Thursdays 3:30-5pm
E-mail: hazhir@vt.edu

GA

Mike Sallada

Phone: 703-408-4608
Office Hours: By Appointment
E-mail: msallada@vt.edu

Student Services Assistant

Virginia Allen
424 Graduate Center Building
Office Phone: 703-538-8431
E-mail:vallen@vt.edu

Class Meeting Time and Place

Thursday: 7:00 p.m. - 9:45 p.m.
Blacksburg: Room Whit 281
Falls Church: Room 113

Required Texts

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

2. Richmond, Barry (2000), *The "Thinking" in Systems Thinking: Seven Essential Skills*, Pegasus Communications, Inc., Waltham, MA.

Supplementary Texts and Readings

1. Richardson, P. George, and Pugh, L. Alexander, III (1981), *Introduction to System Dynamics Modeling with DYNAMO*, The MIT Press, Cambridge, MA.

2. Senge, Peter M., Art Kleiner, Charlotte Roberts, Richard B. Ross, and Bryan J. Smith (1994), *The Fifth Discipline Field book*, A Currency Book, ISBN: 0-385-47256-0.

3. Warren, Kim (2002), *Competitive Strategy Dynamics*, John Wiley & Sons, Ltd.

4. Road Maps, Website for MIT, http://sysdyn.clexchange.org/road-maps/rm-toc.html.

3. O'Connor, Joseph and Ian McDermott (1997), The Art of Systems Thinking: Essential Skills for Creativity and Problem Solving, Thorsons, ISBN: 0-7225-3442-6.

In addition, modeling software will be used in the course. Several excellent packages for system dynamics simulation are now available commercially, including **iThink**, from High Performance Systems, **Powersim**, from Powersim Corporation, **Professional DYNAMO**, from Pugh-Roberts Associates, and **VENSIM**, from Ventana Systems. All are highly recommended. You may wish to learn more about these packages, as all are used in the business world and potential employers are increasingly seeking expertise in them. For further information, see the following resources:

iThink: See the High Performance Systems web site at <http://www.hps-inc.com/index.html>

Powersim: See the Powersim web site at http://www.powersim.no

Professional DYNAMO: Contact Pugh-Roberts Associates, 41 William Linskey Way, Cambridge, MA 02142, 617/864-8880

VENSIM: See the Ventana Systems web site at <http://www.vensim.com/>

In this course, the **VENSIM** Personal Learning Edition (**VENSIM PLE**), a FREE package offered by Ventana Systems will be used. VENSIM PLE is available for both Windows and Macintosh. Models created with it are fully convertible across platforms. VENSIM PLE comes with on line user's guide and help, and also a folder of demo models. Download VENSIM PLE from the VENSIM web site at <http://www.vensim.com/venple.html>.

Course References:

The systems thinking and system dynamics literature has a plethora of reference materials since it spans over forty years of academic and empirical work. The references presented subsequently have provided some of the background information that serves as the foundation of the course notes. You are encouraged to consult these references and other materials that complement the following reference list.

Ackoff, L. Russell (1993), Beyond Total Quality Management, *Journal for Quality and Participation*, March, pp. 66-78.

Andersen, F. David and Richardson, P. George (1997), Scripts for Group Model Building, *System Dynamics Review*, Vol. 13, No. 2, Summer, pp. 107-129.

Beer, Michael (1980), *Organization, Change, and Development: A Systems View*, Scott, Foresman and Company, Glenview, Ill.

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Detert, R. J., Schroeder, G. R., and Mauriel, J. J. (2000), A Framework for Linking Culture and Improvement Initiatives in Organizations, *Academy of Management Review*, Vol. 25, No. 4, pp. 850-853.

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Forrester, W. Jay (1971), Counterintuitive Behavior of Social Systems, *Technology Review*, Vol. 73, No. 3, Jan, pp.52-68.

Kaufman, S. Robert (1992), Why Operations Improvement Programs Fail: Four Managerial Contradictions, *Sloan Management Review*, Fall, pp. 83-93.

Keating, E., Oliva, R., Repenning, N., Rockart, S., and Sterman, J. (1999), Overcoming the Improvement Paradox, *European Management Journal*, Vol. 17, No. 2, pp. 120-134.

Kim, H. Daniel (1990), Toward Learning Organizations: Integrating Total Quality Control and Systems Thinking, *Pegasus Communication*, Cambridge, MA, pp. 1-17.

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Kothari, V. (2004), Analysis of the impact of Maintenance Functions on the System Performance: A System Dynamics Approach, MS Thesis, *Virginia Tech, Grado Department of Industrial and Systems Engineering, System Performance Laboratory*.

Monga, P. (2001), The Implementation of New Technologies on Ship Systems: A System Dynamics Approach for the Development of New Technologies, MS Thesis, *Virginia Tech, Grado Department of Industrial and Systems Engineering, System Performance Laboratory*.

Monga, P. and Triantis, K. (2002), A Dynamic Model for the Development of New Technologies for Ship Systems, under review, *System Dynamics Review*.

Morecroft, D. W. John, and Sterman, D. John (1994), *Modeling for Learning Organizations*, Productivity Press, Portland, Oregon.

O'Connor, Joseph, and McDermott, Ian (1997), *The Art of Systems Thinking*, Thorsons, Hammersmith, London.

Oliva, Rogelio, Sterman, D. John (2001), Cutting Corners and Working Overtime: Quality Erosion in the Service Industry, *Management Science*, Vol. 47, No. 7, July, pp. 894-914.

Repenning, P. Nelson (2000), Drive Out Fear (unless you can drive it in): The Role of Agency and Job Security in Process Improvement, *Management Science*, Vol. 46, No.11, November, pp. 1385-1396.

Repenning, P. Nelson (2001), Nobody Ever Gets Credit for Fixing Problems that Never Happened: Creating and Sustaining Process Improvement, *California Management Review*, Vol. 43, No. 4, Summer, pp. 64-92.

Richardson, P. George (1986), Problems with Causal-Loop Diagrams, *System Dynamics Review*, No. 2, Summer, pp. 158-170.

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Richmond, Barry (2000), *The "Thinking" in Systems Thinking: Seven Essential Skills*, Pegasus Communications, Inc., Waltham, MA.

Roberts, E. B. (1964), *The Dynamics of Research and Development*, Harper & Row: New York.

Roberts, N., D. F. Andersen, R. M. Deal, M. S. Grant, and W. A. Shaffer (1983), *Introduction to Computer Simulation: The System Dynamics Modeling Approach*, Addison-Wesley: Reading, MA.

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Warren, Kim (2002), *Competitive Strategy Dynamics*, John Wiley & Sons, Ltd.

Wolstenholme, F. E. (1999), Qualitative vs. Quantitative Modeling: The Evolving Balance, *Journal of Operational Research Society*, Vol. 50, April, pp. 422-428.

II. OUTLINE OF TOPICS AND READINGS

Program of Study

Date	Class	*Topic*	Reading Due	Assn Out	Assn Due
8/24	1	Introduction and Overview of the course; System dynamics overview: SARS case; Systems thinking: Policy resistance	Richmond *Business Dynamics* [BD], Ch. 1	**#0**	
8/31	2	The Beer Game: Part one Systems thinking and system dynamics tools: Reference modes and problem definition	Read BD, Ch. 3, Ch. 4	**#1**	**#0**
9/7	3	The Beer Game: Part two: Results; Systems thinking and system dynamics Tools Part 2: Building theory with causal loop diagrams	Read BD, Ch. 5 (Skim sections 5.4, 5.6)		
9/14	4	System Dynamics Tools Part 3: Mapping the stock and flow structure of systems; Dynamics of Stocks and Flows	Read BD, Ch. 6 (Skim sections 6.2.7, 6.2.8, 6.2.9, 6.3.4, 6.3.6), Ch. 7	**#2**	**#1**
9/21	5	System Dynamics Tools Part 4: Linking feedback with stock and flow structure	Read BD Ch. 8	**#3**	**#2**
9/28	6	System Dynamics Tools Part 5: Material and Information Delays, Coflows and Aging Chains	Read BD Ch 11 and Ch 12	**#4**	**#3**
10/5	7	Dynamics of Growth: Epidemics, diffusion and modeling the growth of new products; Network externalities, complementarities, and path dependence;	Read BD Ch. 9.1 (Skim 9.1.2, 9.1.3); 9.2, 9.3 (Skim sections 9.3.5 - end) Read BD Ch. 10 (Skim section 10.2)	**#5**	**#4**
10/12	8	System Dynamics in Action: Applications of System Dynamics to Environmental and Public Policy Issues	Read Meadows, et. al., "Groping in the Dark: The First Decade of Global Modeling" (excerpts), Meadows, "The Global Citizen" (selections)		
10/19	9	Managing Instability Part 1: Formulating and testing robust models of business processes, modeling supply line	Read BD, Sections 13.1, 13.2.1-13.2.7, 13.3 and 13.4, 14.1	**#6**	**#5**
10/26	10	Managing Instability Part 2: Supply chains, forecasting and feedback	Read BD, Sections14.1, 17.1, 17.2 and 17.3, Ch 16		

11/2	11	Projects, Products, and Processes: The dynamics of project management— On time and under budget Process improvement and product development	Read BD, Sections 2.3 and 6.3.4	**#7**	**#6**
11/9	12	Interactions of Operations, Strategy, and Human Resource Policy: People Express and its lessons			**#7**
11/16	13	Truth and beauty: building confidence in models Being a savvy user of models	Read BD Ch 21		**PP**[1]
11/23		**Thanks Giving holiday, No Classes**			
11/30	14	The implementation challenge, Conclusion: How to keep learning, follow-up resources and courses	Read BD Ch 22		
12/6		**No Classes**			**PC**[2]

Reading Assignments

You should expect to read each assignment from Sterman thoroughly. Reading Sterman is like reading a calculus book in that you will need to ponder over equations, graphs, and diagrams. Readings will help you with the assignments and with a better understanding of the course material, they do not directly count as part of the course grades. Also, for those of us who like tutorials, the MIT Road Maps are very helpful (Road Maps: http://sysdyn.clexchange.org/road-maps/rm-toc.html). The order in the class syllabus matches what is being focused on in Sterman. Many websites provide additional material for readings on systems thinking and system dynamics. Some examples include http://www.pegasuscom.com , http://www.outsights.com/systems/welcome.htm, or http://www.lambent.com .

Policy for Assignments

You are expected to work on your own for the first few assignments, later assignments are group based. Groups can have two or three students. System dynamics is a team sport in the sense that it is about learning and you will learn best working on tough problems together. The challenges will be submitted through **Blackboard** (www.learn.vt.edu). Each individual (group) assignment has to ***have the following naming convention***: Last Name (or Group Name)_Site_Date of Assignment (for example, Rahmandad_NVC_9_15_06 or NVC01_9_15_06)

20% of the total points assigned to an assignment will be forfeited for the first assignment handed in late. Assignments handed in late subsequently will receive no credit. Assignments handed in that are not consistent with the naming convention will receive no credit. *This policy will be strictly enforced.*

[1] Personal Projects are due
[2] Project Critiques are due

III. Personal Project and Project Critique Description

Overview

The goal of the personal project is to provide an opportunity to apply the skills you learn in this course to a problem that you care about. The main value of the project is in practicing systems thinking and system dynamics modeling in a step-by-step process during the semester. The projects are relatively small in scope and workload, moreover they focus on a problem of interest to you, therefore they are individual based.
The project critique provides you with an opportunity to critique other projects in terms of quality of model, analysis and modeling process, generation of insights, and clarity of presentation. The critique makes you a more cognizant user of models and helps you improve your own modeling capabilities.

Process

Different steps of the project accompany the assignments during the semester. Along with each assignment a new step for the project is discussed and a short progress update is due. These updates do not impact the final project's grade, however, they signify your active class participation. The final project report and model are due on **November 16th**. Late project reports are accepted only until **November 20th**, and will **lose 20%** of the project grade. Instructions for preparation of final project report are discussed below, please follow these instructions carefully.

Each of you will be randomly assigned to critique three project reports and their accompanying models. The critique process is double-blind (the author of the report and the reviewer will not know each others' identity). Critiques assess the quality of model, analysis and modeling process, generation of insights, and clarity of presentation. Instructions for submission of project critiques are discussed below. Critiques are due on **December 6th**. **Late critiques are not accepted.**

Project critiques are graded as pass/fail. Critiques that do not include detailed assessments of different aspects of the project under consideration will fail. The project grades are calculated based on the average of the project grades provided by project critiques. Only those critiques that have passed will be included in the averaging.

Project Report and Model

The project report is short and the material is developed during the semester. The final report is in fact an assembly of what you have already put together for shorter progress updates. Project reports can take the form of power-point presentations or papers. The **maximum** size for the former is **15 slides** and for the latter **10 pages** (font size 12, times new roman, 1.5 line spacing, margins of 1" on all sides), including pictures. Power point slides can have descriptions on the note page up to 200 words per slide. Longer reports will lose points. Appendix A includes a suggestive framework for the project report.

Submitting the model:
You should submit any simulation model that you develop for your project along with the final project report. Submit a Vensim version of the model. If you are using other software for the development of your models, it should be an easy task to rewrite the final model in Vensim. You can get help from a class mate who has been using the Vensim during the semester. To get their full grade, models should follow all the good modeling practice guidelines discussed during the semester. The checklist for evaluation of project reports discusses some of these items.

Convention for naming and submitting the project report and model:
You will be assigned a unique number to use for submission of your project reports and models. **Do not share this number** with others to ensure a high-quality review process. The final project report and the final model should be named as xyz.doc (or .pdf, .ppt, .mdl etc) where xyz is your unique submission number. If you need to submit more than one file of the same type, use numbering convention of xyz-1.doc, xyz-2.doc, etc.
Your project report and your model should be free of any other identifying information. Please do not include in your files your name, student ID, E-mail address, or any other information that identifies you as the author of the report or model. Make sure you remove any such information that is automatically included by Word, Powerpoint, or Acrobat by going to file>Properties. **Reports and models with identifying information will lose 20% of their final grade.**

<u>Project Critiques</u>
Projects are evaluated based on four major criteria: quality of model, quality of hypothesis building and analysis, generation of insights, and clarity of presentation. The list in Appendix B describes what questions to ask in order to evaluate a model/project report on each dimension. For each critique you will be reporting four numbers (between 0-10) as well as a written critique that explains major strengths and weaknesses of the project report and model. **The written critique is limited to 700 words and should not include figures or special characters.** The four numbers are weighed as listed in Appendix B and constitute the project grade from your critique. The average of grades assigned by the three project critiques, constitute the project grade. You will receive the written critiques for your project at the end of semester.
Project critiques will be submitted online. Instructions will be provided by the deadline for submission of projects.

IV. COURSE GRADING

Grade Distribution	% of Final Grade
Class Participation	10
Assignments	50
Project	30
Project Critique	10

Grading Policies:

Class participation: Throughout the semester you will be called upon to contribute to the class discussion. If you are called upon and do not respond because you are not in class more than three times during the semester you will receive one letter grade less than you would otherwise receive. If you are called upon and do not respond because you are not in class more than four times during the semester you will receive two letter grades less than you would otherwise receive.

Challenges: 20% of the total points assigned to a set of challenges (which constitutes an assignment) will be forfeited for the first assignment handed in late. Assignments handed in late subsequently will receive no credit. Assignments handed in that are not consistent with the naming convention will receive no credit.

Project: The final document for the project is due on November 16. Projects handed in late will forfeit 20% of the project grade. Projects will not be accepted after November 20.

Project Critique: The project critiques are due on December 6. Late critiques are not accepted.

Re-evaluation Requests: All re-evaluation requests of any graded assignments should be communicated no later than one week after the graded assignment has been initially returned otherwise they will not be considered.

All of these grading policies will be strictly enforced.

Appendix A- Project Report Format

It is suggested that the project report includes the following sections, however, feel free to use a different presentation structure if you find it more appropriate; after-all your class-mates are the final judge:

Problem definition/statement and reference modes: Elaborates on the motivating problem for the project and the important reference modes for how critical variables have been changing over time. Pictures are as useful, if not better than, texts. Given the time constraints, you are discouraged to look for exact numerical data for the reference modes. A qualitative sketch of how things have been changing through time (e.g. increasing, decreasing, oscillating) will suffice.

Main feedback loops: The set of important feedback loops, or dynamic hypotheses, which are good candidates for explaining the sources of the problem. Try to generate as many feedback loops as possible, though you can only discuss the major ones in your report.

Model: Discuss the stock and flow structure pertaining to the part of dynamic hypotheses you have decided to model. Your model does not need to include all the loops, in fact, it is recommended to only include a few central structures and keep the model simple and focus on analysis.

Analysis: The analysis section explains 1-Why the model does what it does? How the structure of the model generates the observed behavior? 2- How does the behavior of the model inform the real problem you care about? What are the policy ramifications of the analysis?

Personal Insights: In this section you discuss what ***you*** have learnt in the modeling process. Insights, new understandings with respect to some aspect of the problem, come at every stage of the modeling process. However, they are fleeting because once you notice them they lose their novelty and therefore their quality as an insight. As a result, it is extremely important to record your insights at every stage of the project, at the very time you have the “Aha!” feeling. Use the progress updates to be submitted with the assignments to identify what you have learnt in the process before it becomes mundane.

Appendix B- Checklist of questions for project critique

These questions provide you with a guideline for how to assess the quality of a project. They therefore are helpful for you in crafting your own project report and in building your own model as well. On each of the four dimensions you will give a assessment between 0 and 10 (10 for a very good project that passes most of the critique questions):

1- Model quality (40%)

- Basic tests before simulation:
  - Does the model have unit consistency? (Use Model>Units Check in Vensim to test for this)
  - Are model variables named correctly? (Variables can increase or decrease with a clear direction)
  - Are polarities of different links assigned correctly?
  - Are different loops identified and named properly? (Loops should be identified with Reinforcing or Balancing signs as well as a name)
  - Is model well documented, e.g. variables defined in the comment section of the equation editor?
- Model structure tests:
  - Are stocks and flows conceptually sound and appropriate for the model purpose?
  - Are the intended feedback loops captured in the model?
- Formulation robustness tests
  - Are decision rules formulated well? Are they reasonable representations of how decisions could be made in the specific setting? See chapter *** for specific issues on formulating decision rules.
  - Are formulations simple enough? For example, it is a good practice to keep the number of inputs into any equation below 3 and avoid complicated equations with If Then Else and Min/Max functions.
  - Are table functions robust and well formulated? See chapter *** for specific points on formulation of table functions.
- Time step test:
  - Is the model time step short enough. To test this, divide the time step (Go to Model>Settings>Time Bounds) by two and run the model, if there is a change in behavior of the model, the initial time step has not been short enough.
- Model behavior tests:
  - Does the model start from equilibrium in the base case?
  - Think of a few extreme condition tests (see pages *** in sterman) and apply them to the model. Does the model behave robustly, that is, the behavior remains reasonable and in the expected domain?
  - Do all physical stocks remain positive, or can they go negative? Do stocks have first order controls?

2- Hypothesis building and analysis (30%)

- Does the set of dynamic hypothesis (loops and basic structures hypothesized to explain the problem at hand) look reasonably broad and comprehensive?
- Are loops named properly and have the correct sign (Reinforcing or Balancing)?
- Does the analysis provide a good explanation of why the model behaves the way it does?

- Does the analysis provide a good connection between the modeling work and the real world problem which has motivated the model?
- Are there any discussions of potential improvement strategies?

3- Generation of insights (15%)

- Are the insights of the project documented?
- Do you, as the reviewer of the project, find interesting points in the project and modeling work?

4- Clarity of presentation (15%)

- Was the report and model clear and understandable?
- Did you feel interested to follow the presentation