System Dynamics Group
Sloan School of Management
Massachusetts Institute of Technology

15.872 System Dynamics II

Fall 2010
Professor John Sterman

Assignment 1

From Mapping to Simulating Complex Systems*

Assigned: Session 1; Due: Session 3
This is an individual assignment.

In the first half of the semester you learned how to map the structure of complex systems, using stock-flow and causal loop diagrams. These qualitative maps are extremely valuable in surfacing mental models and improving them by expanding the boundary and identifying the critical feedback structures that generate the behavior of the system.

When we use a qualitative map to make inferences about how a system may behave or what the impact of a policy intervention may be we are mentally simulating how all the elements of the system interact to generate the system dynamics. While this is often valuable, policymakers usually require quantitative assessments of likely impacts of policies. Far more important, research shows that people's mental simulations are not reliable. For both these reasons, it is important to develop your ability to move from a qualitative map to rigorous specification of the processes and decision rules operating in the system, and then to use computer simulation to generate the dynamics resulting from your assumptions.

Here you develop your ability to formulate the equations for, simulate and analyze the behavior of dynamic models. These skills are important for everyone—whether you will build your own models in the future or not, all of us will be consumers of models and need to understand how they are built, simulated, and analyzed so that we can be intelligent model consumers and clients. Even more important, all of us need to develop our intuitive ability to relate the structure of dynamics models to their behavior. Practice with formulation, simulation and analysis is essential for both purposes.

* Prepared by John Sterman. Last Revision: October 2010

A. Simulation Tutorial: Using Vensim to simulate an epidemic

You already know how to use Vensim to create maps of the stock-flow and feedback structure of systems. Vensim also allows you to easily formulate, simulate, and analyze the behavior of complex systems. To develop your ability to do so, do the tutorial "Simulating Epidemics Using VensimPLE", available for download. You will also need to download a Vensim map of the SARS epidemic, also available (download instructions are in the tutorial). The tutorial provides step-by-step guidance as you convert the qualitative map into a fully specified model, simulate it, and analyze its behavior. Hand in the following:

a. a documented listing of your final model;

b. a table with the values of the parameters you prefer (those that give a good match between the behavior of your model and the data for the SARS epidemic in Taiwan);

☛ A reasonable fit between the model and data is sufficient for the purpose of the tutorial. Do not spend much time optimizing the fit of your model.

c. a graph showing the behavior of New Reported Cases with the parameters above and a graph showing the behavior of Cumulative Reported Cases, both compared against the data.

B. Models of simple systems

Now we will deepen your formulation and analysis skills by building and simulating models of important dynamic systems, starting from a blank screen.

❑ B1. Build and simulate a simple model of the US national debt and budget deficit.

☛ Follow the instructions below precisely. Do not add structure beyond that specified.

☛ Begin the simulation of the model in 1988 so that there is some replication of history. In Vensim, Select **Settings…** under the **Model** menu. Then set the Initial Time = 1988, Final Time = 2088, and Time Step = 0.0625 years. Check the box to save the results every Time Step. Finally, set the unit of measure for time to Years.

☛ To keep your model simple:

- Your model should have a single stock, the National Debt. The debt accumulates the Net Federal Deficit. The only flow altering the debt is the net deficit (do not represent the issuance and maturity of the debt as separate flows). In 1988 the national debt was approximately \$2.5 trillion (2.5E12).
- The net federal deficit is the difference between Government Expenditure and Government Revenue.
- Government Revenue is exogenous and constant. In 1988, revenue was approximately \$900 billion/year (900E9).

- Government Expenditure consists of Interest paid on the debt and Expenditures on Programs (all non-interest expenditures).
- Expenditures on Programs are exogenous and constant. In 1988 expenditures on programs were about $900 billion/year, about the same as Revenue.
- Interest payments are the product of the debt and the interest rate.
- The interest rate is exogenous and constant. In 1988 the average interest rate on the debt was approximately 7%/year (.07/year).

☛ As always, document your model and make sure every equation is dimensionally consistent.

☛ You may wish to review the discussion of reinforcing (positive) feedback systems in Business Dynamics (Ch. 8, pp. 263-274).

Answer the following questions.

- ❑ a. What kind of feedback loop is created in your model?
- ❑ b. What is the initial deficit (given the base case parameters)?
- ❑ c. How long does it take for the deficit to double?
- ❑ d. What is the relationship between the doubling time and the interest rate? (To discover a relationship, you may want to simulate with extreme interest rates—say, between 1% per year and 15% per year).
- ❑ e. Hand in your model (diagram and equation listing) and answers to the above questions. You need not hand in plots, but you should describe briefly how you arrived at your answers.

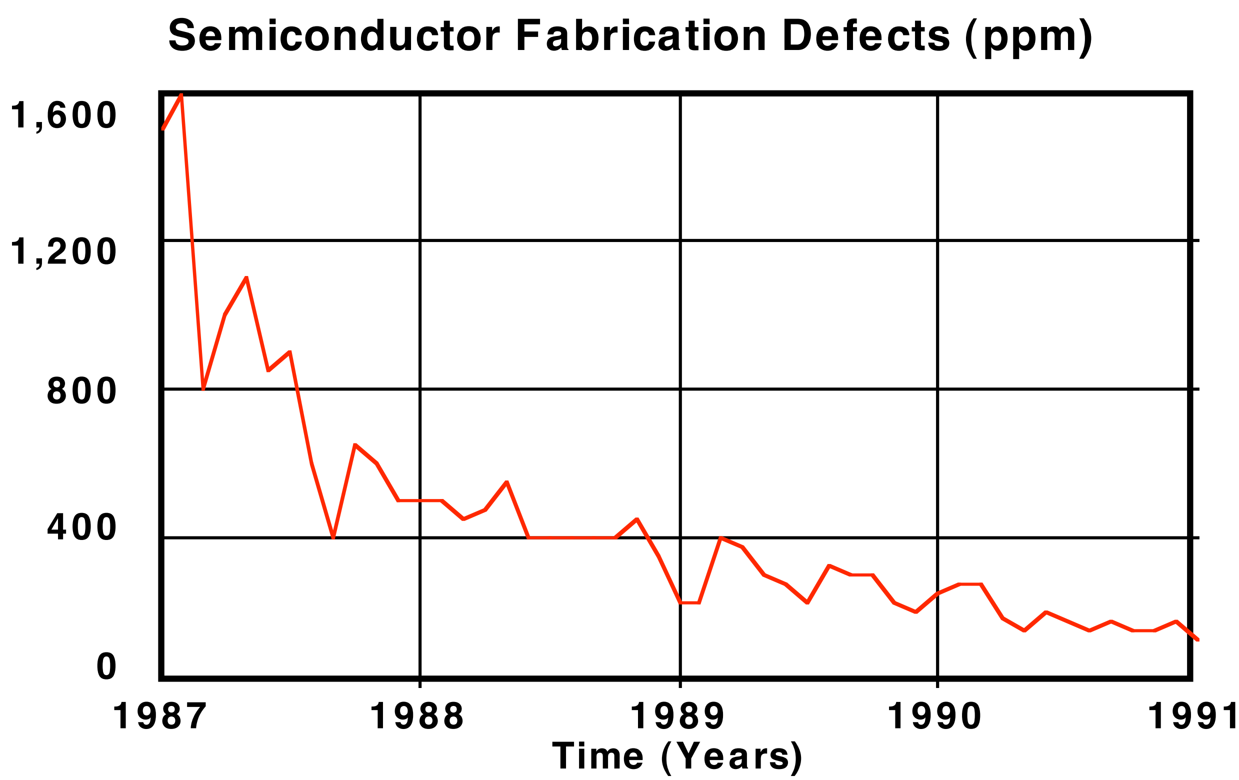
☛ To answer (d) you may want to use the Synthesim feature of Vensim (see the tutorial).

❑ B2. Build and simulate a simple model of process improvement in a firm.

All goal-seeking processes consist of negative feedback loops. In any negative loop, the system state is compared to a goal, and the gap or discrepancy is assessed. Corrective actions respond to the sign and magnitude of the gap, bringing the state of the system in line with the goal. Before doing this section you should review the material on negative feedback in Business Dynamics, section 8.3 (pp. 274-282).

For example, consider programs designed to improve the quality of a process in a company. The process could be in manufacturing, administration, product development—any activity within the organization. Improvement activity is iterative. Members of an improvement team identify sources of defects in a process, often ranking benefits of correcting them using a Pareto chart. They then design ways to eliminate the source of the defect, and try experiments until a solution is found. They then move on to the next most critical source of defects. Quality professionals refer to this iterative cycle as the "Plan—Do—Check—Act" or "PDCA" cycle (also known as the Deming cycle, for the late quality guru W. Edwards Deming). In the PDCA process, the improvement team: (1) identifies the root cause of a defect and plans an experiment to test an improvement idea, (2) does the experiment, (3) checks to see if it works, then (4) acts—either planning a new experiment if the first one failed or implementing the solution and then planning new experiments to eliminate the next most important source of defects. The team continues to cycle around the PDCA loop, successively addressing and correcting the root causes of. Such a learning loop lies at the heart of all process improvement methods, from Total Quality Management (TQM) to 6-σ.

The figure below shows data on defects from the wafer fabrication process of a mid-size semiconductor firm (from Figure 4-5 in *Business Dynamics*). The firm began its quality improvement program in 1987, when defects were running at a rate of roughly 1500 parts per million (ppm). After the implementation of quality program, the defect rate fell dramatically, until by 1991 defects seem to reach a new equilibrium close to 150 ppm—a spectacular factor-of-ten improvement. Note that the decline is rapid at first, then slows as the number of defects falls.



❑ a. Create a model of the improvement process described above and compare its behavior to the data for the semiconductor firm. As always, specify the units of measure for every element of your model and provide an appropriate explanation for each element. Make sure your model passes the dimensional consistency test. Hand in: (1) the diagram for your model and (2) a documented model listing.

☛ Follow the instructions below precisely. Do not add structure beyond that specified.

- Under model settings, choose values so that your simulations will begin in 1987 and end in 1991. Use a time step ("dt" or delta time) of 0.125 years.
- Before running your model, load the dataset "defects.vdf", which contains the historic data for the firm's defect rate shown in the figure above. You can download the defects.vdf file from the class Stellar site.
- The state of the system is the defect rate, measured in ppm. Create a stock called "Defects" to represent the defect rate. Use the variable name "Defects" exactly so that you will be able to compare the behavior of your model against the data. The defect rate in 1987 was 1500 ppm.
  - ☛ The defect rate is not a rate of flow, but a stock characterizing the state of the system—in this case, the ratio of the number of defective products to the number produced.
- The defect rate decreases when the improvement team identifies and eliminates a root cause of defects. Denote this outflow the "Defect Elimination Rate."
- The rate of defect elimination depends on the number of defects that can be eliminated by application of the improvement process and the average time required to eliminate defects.
- The number of defects that can be eliminated is the difference between the current defect rate and the theoretical minimum defect rate. The theoretical minimum rate of defect generation varies with the process you are modeling and how you define "defect." For many processes, the theoretical minimum is zero (for example, the theoretical minimum rate of late deliveries is zero). For other processes, the theoretical minimum is greater than zero (for example, even under the best imaginable circumstances, the time required to build a house or the cycle time for semiconductor fabrication will be greater than zero). In this case, assume the theoretical minimum defect level is zero.
- The average time required to eliminate defects for this process in this company is estimated to be about 0.75 years (9 months). The average improvement time is a function of how much improvement can be achieved on average on each iteration of the PDCA cycle, and by the PDCA cycle time. The more improvement achieved each cycle, and the more cycles carried out each year, the shorter the average time required to eliminate defects will be. These parameters are determined by the complexity of the process and the time required to design and carry out experiments. In a semiconductor fab, the processes are moderately complex and the time required to run experiments is determined by the time needed to run a wafer through the fabrication process. Data collected by the firm prior to the start of the TQM program suggested the 9 month time was reasonable.
- Equipment wear, changes in equipment, turnover of employees, and changes in the product mix can introduce new sources of defects. The defect introduction rate is estimated to be constant at 250 ppm per year.

- ❑ b. Run your model with the base case parameters, and *hand in the plot*.
- ❑ c. *Briefly* describe the model's behavior. How well does your simulation match the historical data? Are the differences likely to be important if your goal is to understand the dynamics of process improvement and to design effective improvement programs?
- ❑ d. Does the stock of defects reach equilibrium after 9 months (the average defect elimination time)? Referring to the structures in your model, explain why or why not.
- ❑ e. Experiment with different values for the average defect elimination time. What role does the defect elimination time play in influencing the behavior of other variables? You will find Vensim's Synthesim feature is helpful for this purpose.
- ❑ f. Any stock reaches equilibrium when its inflows equal its outflows. Set up that equation for the defect rate and solve for the equilibrium defect rate in terms of the other parameters.
- ❑ g. What determines the equilibrium (final) level of defects? Why?
- ❑ h. Does the equilibrium defect rate depend on the average time required to eliminate defects? Why/Why not?
- ❑ i. Explore the sensitivity of your model's results to the choice of the time step or "dt" (for "delta time").
  - ☛ Before doing this question, read Appendix A in *Business Dynamics*.
- ❑ j. Change the time step for your model from 0.125 years to 0.0625 years. Do you see a substantial difference in the behavior?
- ❑ k. What happens when dt equals 0.5 years? Why does it behave as it does?
- ❑ l. What happens when dt equals 1 year? Why does the simulation behave this way?