# Guided Study Program in System Dynamics
## System Dynamics in Education Project
## System Dynamics Group
## MIT Sloan School of Management[1]

Assignment #7

## Reading Assignment:

Please read the following:

- *Collected Papers of Jay W. Forrester*:[3] "Market Growth as Influenced by Capital Investment"
- Vensim PLE User's Guide: Section 7: Building a Function with Lookups (pp. 65 - 80)

Please refer to Road Maps 3: A Guide to Learning System Dynamics (D-4503-4) and read the following.

- *Study Notes in System Dynamics*,[4] by Michael Goodman: Section 3.12

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[3] Forrester, Jay W., 1975. *Collected Papers of Jay W. Forrester*, Portland, OR: Productivity Press. 284 pp.
[4] Goodman, Michael R., 1974. *Study Notes in System Dynamics*, Portland, OR: Productivity Press. 388 pp.

# Exercises:

1. Market Growth as Influenced by Capital Investment

A. This paper by Prof. Forrester presents the "Market Growth Model" as an example of modeling a complex system. The first several sections of the paper describe the structure of systems in terms of feedback loops and levels and rates. Read these sections carefully because they contain guidelines that will be useful to you when you build your own models.

The paper then proceeds to build the market growth model. You do not need to be able to build the model on your own. You should, however, try to understand the model structure, and how the structure creates the behavior generated by the model. Pay close attention to the table functions (multipliers) in the model. In this assignment, you will in fact build a part of the market growth model, and you will learn how to create such table functions in Vensim PLE. In later assignments, you will eventually build the full model.

B. In the section "Capital Investment," Prof. Forrester describes the dynamics of changing the delivery delay goal of the company. Such behavior is often referred to as "eroding goals."

Please give two examples of systems in which goals are constantly readjusted to match actual performance, and describe the behavior of those systems.

2. Vensim PLE User's Manual: Section 7: Building a Function with Lookups

A. Follow the instructions to build the delivery delay model. In your assignment solutions document, please include the model diagram, documented equations, a graph of the delivery delay lookup function, and a graph of the behavior of "Backlog."[5] After changing the lookup function, submit the new lookup graph, and a graph of behavior of "orders" from the two simulations. Explain how the change in the lookup function changed the behavior of "orders."

B. The section "Normalizing the Lookup" on page 68 explains that the input and output values of a lookup function should be normalized. Explain why you think that normalizing the values is important. Give separate reasons for the input and output values.

C. In system dynamics literature, the lookup functions are often called "table functions" or "multipliers." Why would you use a table function in a model? Describe two table functions that you would use in models of your choice. You do not need to build the models or the table functions, only describe the system and the table function in words.

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[5] Please refer to the document "GSP-VensimHelp.pdf" for tips on how to submit graphs of table functions.

3.  Study Notes in System Dynamics, Section 3.12

A.  Build the basic linear pollution model, as shown in Figure 3-17 (a), and make sure the model generates the behavior shown in Figure 3-19.

B.  After reading the description of the nonlinear pollution model, build the complete model, as shown in Figure 3-21 (a).  Notice, however, that the nonlinear table function for "pollution absorption time" shown in Figure 3-20, does not have a normalized output.[6]  Following the instructions from section 7 of the Vensim PLE User's Manual, make sure that the lookup function in your model has normalized input and output values. To do this, you will need to define several additional variables, not shown in the model in Figure 3-21 (a).  The "effect of pollution ratio on absorption time lookup" should look the same as the table function in Figure 3-20, and should be dimensionless.  This variable corresponds to the "effect of delivery delay on orders lookup" in the delivery delay model.  To help, the equations for the additional variables are given below:

- effect of pollution ratio on absorption time = effect of pollution ratio on absorption time lookup (pollution ratio)
  Units: dmnl
  This variable corresponds to the "effect of delivery delay on orders" in the delivery delay model.
- pollution absorption time = NORMAL POLLUTION ABSORPTION TIME * effect of pollution ratio on absorption time
  Units: year
- NORMAL POLLUTION ABSORPTION TIME = 1
  Units: year

With the above equations, the model should be dimensionally consistent, and the lookup function has normalized input and output values.

In your assignment solutions document, please include the model diagram, documented equations, a graph of the lookup function, and graphs of the behavior of the "normal system" and the "overstressed system."

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[6] Also note that the input to the table function in Figure 3-20 should be "POLR pollution ratio," not "POLR pollution rate."

## 4. Independent modeling exercise

This exercise will develop a simple model of the absorption of CFCs (chlorofluorocarbons) in the atmosphere.[7]

Some background:

CFCs are halogenated hydrocarbons that are used extensively as propellants in aerosol spray cans, coolants in refrigerators and air conditioners, solvents, and plastic foam products such as Styrofoam cups. The usefulness of CFCs lies in their nontoxic and nonflammable properties, as well as the ease with which they can be converted from a liquid to a gas and vice versa. CFCs became widely used after World War II.

Although CFCs are very useful in commercial and industrial applications, they pose a serious threat to the environment. In the 1970s, scientists discovered that after CFCs are released into the atmosphere, they pass through the troposphere and accumulate in the stratosphere. In the stratosphere, solar ultraviolet radiation breaks down the CFC molecules, releasing their constituent chlorine atoms. These then react with the ozone molecules, destroying the ozone layer.

The stratospheric ozone layer shields living organisms on Earth from the Sun's ultraviolet radiation. The radiation is associated with dangers such as skin cancer, cataracts, genetic disease, and weaker immune systems. Because of a growing concern over ozone depletion, in the late 1970s the United States, Canada, and the Scandinavian countries imposed a ban on the use of CFCs in aerosol-spray dispensers. In 1990, 93 nations agreed to end production of ozone-depleting chemicals by the end of the century, and in 1992, most of those same countries agreed to end their production of CFCs by 1996.

This exercise will study how the amount of CFCs in the atmosphere changes as the production of CFCs is restricted. When CFCs are released they first ascend into the troposphere. After an average of five years, the CFCs migrate to the stratosphere. The CFCs reside in the stratosphere on average 55 years before they are destroyed.

A. The model will contain the elements listed below. Identify each element as either stock, flow, or constant, and label its units. For each stock, determine its inflows and outflows.

- time to rise to stratosphere
- CFC 11 destruction
- CFC 11 release pattern
- CFC 11 in stratosphere
- atmospheric CFC 11 releases
- lifetime of CFC 11 in stratosphere
- CFC 11 in troposphere

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[7] The CFC model, system description, and data are based on information gathered in *Britannica Online*, *Biology: The Unity and Diversity of Life* by Starr and Taggart, and materials provided by Ventana Systems.

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- migration to stratosphere

B. Using Vensim PLE, combine the elements to represent the structure of the system. In your assignment solutions document, please include the model diagram.

C. Using the system description and the table provided below, define the equations for each flow. Then supply the constants and initial values of the stocks. In your assignment solutions document, please include the documented equations and a graph of the lookup function.

| Year | CFC production (Mkg/year) |
|------|---------------------------|
| 1940 | 0 |
| 1945 | 0 |
| 1950 | 5 |
| 1955 | 20 |
| 1960 | 40 |
| 1965 | 110 |
| 1970 | 200 |
| 1975 | 310 |
| 1980 | 250 |
| 1985 | 280 |
| 1990 | 220 |
| 1995 | 100 |
| 2000 | 0 |
| 2005-2140 | 0 |

*Hint: To define the rate at which CFC 11 is released into the atmosphere, you will need to use a lookup function. The input to the lookup will be the current time; in this case, you do not need to make the input dimensionless. You will need to use the shadow variable tool to add <Time> to the model diagram. To use the shadow variable tool, click once on the shadow variable icon, position the pointer on the diagram, and click once. You will then be able to choose "Time" from the list of all variables used in the model.*

D. Before you simulate the model, draw reference modes for the stocks. You do not need to include these in your assignment solutions document, but you do need to draw them in order to be able to answer the next question.

E. Simulate the model from 1940 to 2140. In your assignment solutions document, please include graphs of the behavior of all stocks. Did the model generate the behavior you predicted? Why or why not?

F. What would have happened if, in 1990, all countries had agreed to end production of CFCs immediately, instead of by the end of the century? Change the model to reflect the new scenario. Draw reference modes for each stock. Create a new dataset and simulate the model. In your assignment solutions document, submit graphs that contrast the behavior of the stocks from the two simulations. Did the model generate the behavior you predicted in the reference modes? Why or why not?

G. Return to the original data for CFC production. This time, however, imagine that in the year 2000, scientists develop a chemical that, when released into the stratosphere, decreases the average lifetime of CFCs from 55 to 20 years. Change the model to reflect this scenario and draw reference modes. Create a new dataset and simulate the model. Submit graphs that contrast this simulation with the original one. Did the model generate the behavior you predicted in the reference modes? Why or why not?

H. If in 1990, you were an advisor to the worldwide commission on CFC production, what policy would you recommend? Why?