CHAPTER 1

Quality Fluctuations

This workshop uses a specific case study to explore several important issues in simulation modeling to support business process improvement or reengineering. Background is presented in the next section. In the following section, a simulation model for this case is investigated. Then a proposed process reengineering is considered. This case is adapted from Jarmain (1963), Problem 3.3.

1.1 Quality Image

Future Electronics Company is a medium-sized firm producing a line of specialized integrated circuits. Because of the delicate production processes involved, only 30 to 50 percent of the items produced prove usable. Therefore, all units produced must undergo testing before sale.

The management of Future has for some time been worried about their quality image. From time to time they have heard such statements from customers as: We are generally quite satisfied with your quality, and consider you one of our highest quality suppliers, but are bothered by some of the variations which occur. Every so often, we receive a series of poor shipments from you. These create a disruption of our production, and we are forced to find a supplier whose quality is more dependable, even if their best is not as good as yours. While customers are not always so outspoken, Future has noticed that at times customers return many defective units, but at other times these same customers return very few defectives.

The management of Future is quite sensitive to this situation and upon noticing increased complaints and returns, they hire more people to increase the thoroughness of the testing procedure. They base their hiring decision on the number of testers presently employed and on the frequency of complaints.

Learning the complex testing procedure requires several months training, although some trainees learn faster than others. The testers in training do not test parts for shipment, since Future does not wish to take the chance that inexperienced testers might let bad units get through. The new people are trained by experienced employees. An experienced tester assigned to the training of a new person must spend about half of his or her time in this capacity, and thus takes time away from actual testing.

Future has a policy against laying off testers, but will let natural attribution reduce an apparent excess. After becoming fully trained, a tester remains with Future an average of about three years.

At the present time, demand forces testers to attempt to keep up with production. Thus, the time spent on testing a unit depends on the volume of production. Future does not know a great deal about the policies of customers, but the company believes that customers take an appreciable amount of time to determine the quality of units which they receive.

1.2 First Simulation Model

The stock and flow diagram for a simulation model that is consistent with the information presented above for Future Electronics Company is shown in Figure 1.1. The IF THEN ELSE functions for the model are shown in Figure 1.2, and selected output from the model is shown in Figure 1.3.

First Model Listing

```
(01) A = 0
(02) averaged complaints
        = SMOOTH(complaints, COMPLAINT AVERAGING DELAY)
(03) COMPLAINT AVERAGING DELAY = 2
(04) complaints = (3 / quality perceived by customers) - 2
(05) effective testing capacity = Trained Testers
        - 0.5 * Trainee Testers
(06) FINAL TIME  = 120
(07) HIRING DELAY = 2
(08) hiring rate
        = MAX(0, quitting rate
        + (testers needed - effective testing capacity) / HIRING DELAY)
(09) INITIAL TIME  = 0
(10) NOISE SEQUENCE SEED = 1013
(11) order rate = 10000 * quality perceived by customers
        * ( 1 + TESt variation)
(12) product quality
        = IF THEN ELSE(testing effort per unit shipped < 0.01,
            100 * testing effort per unit shipped,
            1 + 10 * (testing effort per unit shipped - 0.01))
(13) PRODUCTION DELAY = 3
(14) production rate
        = DELAY FIXED(order rate, PRODUCTION DELAY, order rate)
(15) quality perceived by customers
        = SMOOTHI(product quality, 6, 1)
(16) quitting rate = Trained Testers / 36
(17) SAVEPER  = TIME STEP
(18) TESt variation = STEP(0.2, 5) * ((1 - A)  + A
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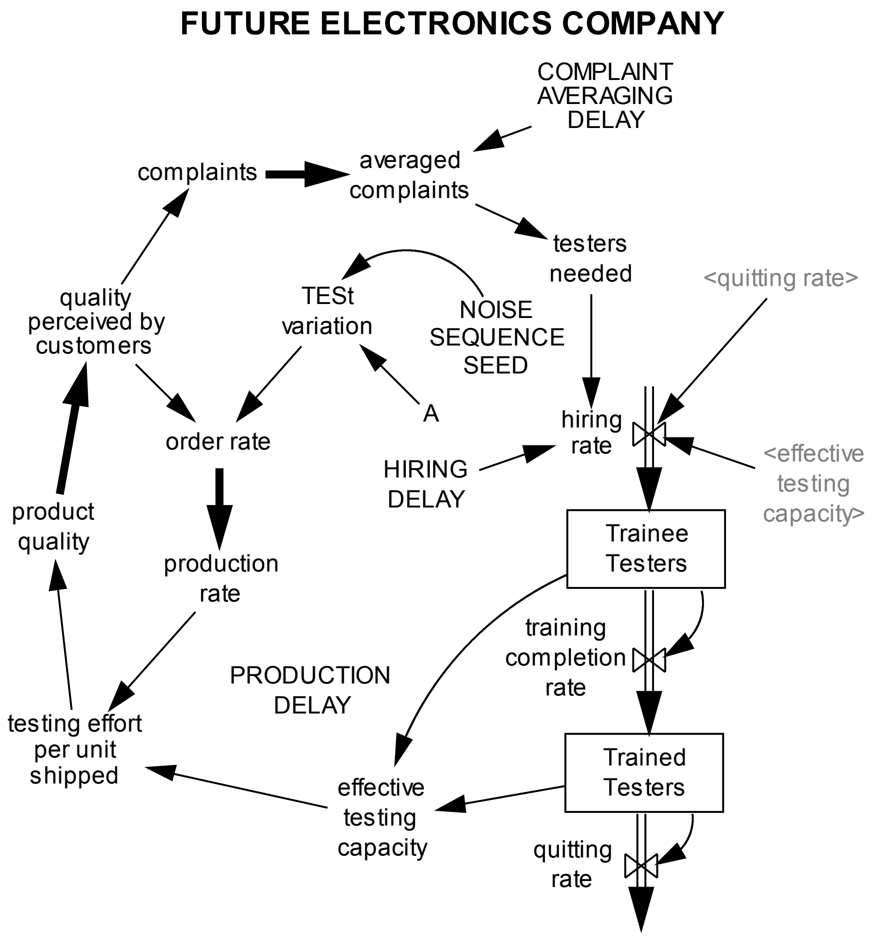

Figure 1.1 *First model*

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                      * RANDOM UNIFORM(-0.5, 0.5, NOISE SEQUENCE SEED))
(19) testers needed = IF THEN ELSE(averaged complaints < 0.5,
          0, 200 * (averaged complaints - 0.5))
(20) testing effort per unit shipped
          = effective testing capacity / production rate
(21) TIME STEP  = 0.125
(22) Trained Testers
          = INTEG(+training completion rate - quitting rate,
                  100 * 24 / 23)
(23) Trainee Testers
          = INTEG(hiring rate-training completion rate,
                  (3/36) * (100 * 24 / 23))
(24) training completion rate = Trainee Testers / 3
```
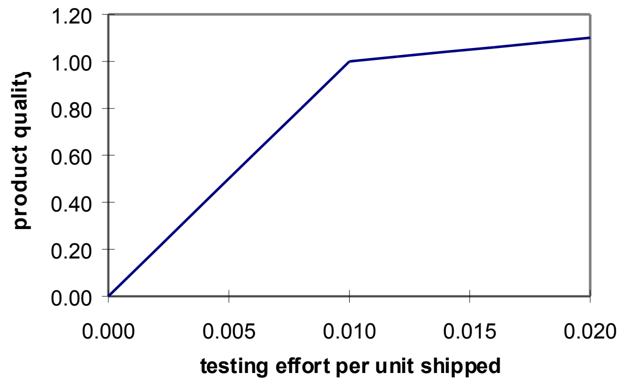
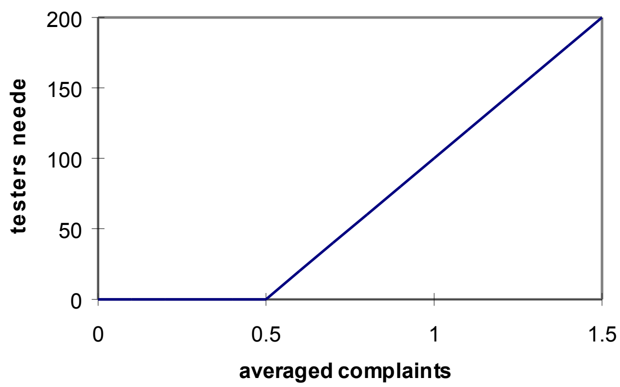



a. Product quality as a function of testing effort



b. Testers needed as a function of averaged complaints

Figure 1.2 *IF THEN ELSE functions*

1.3 Questions for First Simulation Model

1) Draw a causal loop diagram for the first simulation model. This causal loop diagram should include all the variables shown in Figure 1.1.

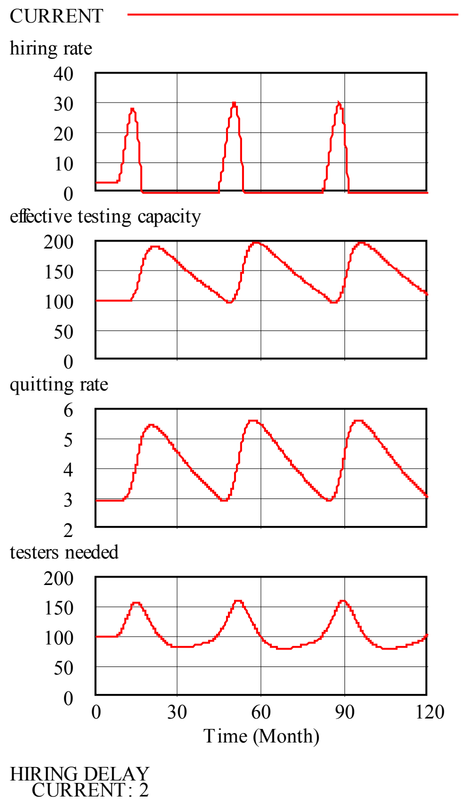


Figure 1.3 *First model output*

Questions Related to Setting Initial Conditions

Study the model presented above as background to answer the following questions. As part of your background study, you will probably want to run the simulation and review the behavior of various key variables.

In this model, time is measured in months. Quality for the product is measured by an index such that when customers perceive a quality of one there is one complaint per month to Future Electronics Company. At the beginning of the simulation run, the effective testing capacity is set such that the product quality is one, and therefore complaints is also equal to one.

Thus, if there is no variation in the order rate, then everything else in the process will also stay constant. That is, the number of Trainee Testers and Trained Testers will remain constant, and hence the effective testing capacity will also remain constant. Because of this, so long as there is no variation in the order rate, the product quality will remain at one, and hence the complaints will remain at one per month. A process where the variables have an internally consistent set of values like this is said to be in equilibrium. In the absence of any variations, all of the variables will remain constant indefinitely.

In this model, a variation is introduced by changing TESt variation from its initial value of zero. The constant A is used to change the nature of the variation that is introduced. When A is zero (which is the initial setting in the model), then TESt variation changes from zero to 0.2 at five months. When A is equal to one, TESt variation changes at five months from zero to a random variation over time which has values between −0 1 and 0.1 with an average of zero.

2) Modify TESt variation so that it is equal to zero for all time. Confirm that under these conditions all the variables in the model remain constant for the entire simulation run. (Hint: You can make the required modification to TESt variation by multiplying the expression in equation (18) by zero. This approach will make it easy to restore the original expression later.)

It is often useful to set up a simulation model so that it is initially in equilibrium. If this is not done, then when a simulation run is started there will be changes in various model variables as the process seeks to bring itself into a condition which is internally consistent. Such variations will occur spontaneously in the same way that a ball which is lifted and released will fall to the ground the physics of a process only allows certain process configurations to be stable.

Establishing internally consistent initial conditions for a process model sometimes can require calculations. For example, examine the expressions for the initial values of Trained Testers and Trainee Testers shown in equations (22) and (23) above.

3) Explain why these somewhat mysterious expressions result in an effective testing capacity that is just equal to the number of testers needed to establish a product quality of one and also have the model in balance. Given that we wish to have an initial value for product quality of one, show how the initial condition expressions shown in equations (22) and (23) were established for Trained Testers and Trainee Testers.
4) Change the initial condition for Trained Testers so that there are initially 150, rather than the number shown in equation (22) above. Continue to use a TESt variation equal to zero, and run the simulation. Examine the behavior over time of various variables. You will see that the process oscillates. This is because the initial values were not consistent, and the process adjusts variable values in an (unsuccessful) attempt to obtain consistency. **Important:** After making this test, change TESt variation and Trained Testers back to the forms shown in equations (18) and (22) above.

Another issue in setting initial conditions is that you cannot have initial conditions which mutually depend on each other so that simultaneous equations would have to be solved to determine these initial conditions. In many models, this is not a problem because once you set the initial values for the stock variables, Vensim can determine the initial conditions for all the other variables.

However, in the model listed above, there is a feedback loop through the following variables: quality perceived by customers, order rate, production rate, testing effort per unit shipped, and product quality. Thus, the initial values for all these variables depend on each other, and Vensim cannot determine these initial values.

In order to set the initial values for these variables, we need to break the feedback loop when the simulation run starts by specifying an initial value for one of the variables. Once this is done, Vensim can determine the initial values for the other variables in the feedback loop. To address this difficulty, Vensim provides a version of the SMOOTH function, called SMOOTHI, that allows you to specify the initial output of the SMOOTH. (The standard version of SMOOTH gives the initial value of the input to a SMOOTH as its output.) The use of SMOOTHI is demonstrated in equation (15) above. The third argument of SMOOTHI is the value to be used as the initial output of the SMOOTHI.

Thus, equation (15) specifies that the initial value for quality perceived by customers is one, which we know from the discussion above is the initial value we want for this variable. Once this value is set, Vensim can determine the initial values for the other variables in the feedback loop involving quality perceived by customers.

5) Modify equation (15) for quality perceived by customers by replacing the SMOOTHI function with a SMOOTH function. Confirm that with this change Vensim generates an error message and is unable to start a simulation run. Describe what error message is displayed. **Important:** Restore the original version of equation (15) after you are done answering this question.

Questions Related to IF THEN ELSE Functions

IF THEN ELSE functions can be used to model some situations where one variables depends on another variable in a nonlinear manner (that is, in a manner such that it is not possible to draw a graph of the relationship between the two variables which is a straight line). There are two equations with IF THEN ELSE functions in the model given above, which are numbered (12) and (19).

6) Describe the qualitative manner in which product quality depends on testing effort per unit shipped, as shown by equation (12) and Figure 1.2a. In particular, note that the impact of increases in testing effort per unit shipped on product quality differs depending on whether testing effort per unit shipped is less than or greater than 0.010 person-months per unit. What level of product quality does this 0.010 level of testing effort per unit shipped correspond to?
7) In a similar manner, describe qualitatively how testers needed depends on averaged complaints, as shown by equation (19) and Figure 1.2b.

Questions Related to Delay Functions

There are two types of material delay functions that are most often used in models, the DELAY3 and DELAY FIXED functions. In many cases, the modeled process behavior will not differ greatly if either of these two functions is used.

8) There is a DELAY FIXED function in this model in equation (14) for production rate. Demonstrate that there is little impact on the model behavior from changing this function to a DELAY3 function. When you use a delay function, you must specify what the output of the function will be from the start of a simulation run until there has been time for input to reach the output of the fixed delay. Explain what the output is for the DELAY FIXED function in equation (14) during this period, and what it is for the DELAY3 function that you use as a replacement. **Important:** When you are done answering this question, restore the DELAY3 function to a DELAY FIXED. [Hint: You may need to refer to the Vensim online documentation to determine what the output is for a DELAY3 function during the initial period. The expression that you need to insert to replace the DELAY FIXED expression in equation (14) is DELAY3(order rate, PRODUCTION DELAY).]

Note that under some conditions using the DELAY FIXED function can lead to difficulties in solving the model using certain integration procedures. It is generally recommended that you use the Euler integration procedure if you are using DELAY FIXED functions.

Questions Related to Continuous Improvement

Important: Before answering the following questions, make sure that you have restored the model to agree with the listing given above in Section 1.2.

9) Determine the average delay from the time that product quality declines until this impacts a) order rate, b) hiring rate, and c) improvement in effective testing capacity. (Hint: The average delay through an exponential smoothing function or material delay is equal to the delay constant. You do not have to make any simulation runs to answer this question.)
10) Note that the Figure 1.3 output shows that this process substantially overshoots in hiring additional testers. Given the change in the order rate at time 5 that is shown in equations (11) and (18), determine how many additional testers are needed to maintain a product quality equal to one, and compare this with how many are actually hired. (Hint: Determining how many additional testers are needed is easy; it does not require making model runs. You may find helpful to use the Vensim Table capability while answering this question.)
11) As noted above, when A is changed from 0 to 1, TESt variation becomes a random variation with an average value of zero. Discuss how the model behavior changes when A is changed from 0 to 1. Include simulation output graphs with your answer which illustrate the main points in your discussion. Specifically, make two simulation runs, one with A equal to zero and one with A equal to one, and then compare the results

of these runs. You should examine the behavior of several variables, including at least order rate, production rate, product quality, quality perceived by customers, and hiring rate. Specifically discuss the impact of the SMOOTH functions on the random variations. That is, compare the inputs to the SMOOTH functions with their outputs. (Hint: The qualitative behavior of many variables in the process remains similar when the step input TESt variation is replaced with the random input.) **Important:** Change A back to 0 after you are done answering this question.

12) Discuss the impact of varying the constants HIRING DELAY, PRODUCTION DELAY, AND COMPLAINT AVERAGING DELAY on the model behavior. In particular, it may seem logical that decreasing these constants will reduce the overshoot in hiring, since decreased values correspond to faster responses to changes in the order rate. Does this actually happen? (Hint: Try cutting each of these delays in half one at a time, and then try doubling each of them, one at a time. There is relatively little impact from making these changes. In some cases, reducing the delay actually makes the oscillations worse.)
13) Discuss what factors lead to the oscillations in this process and why these oscillations occur. (Hint: While a number of features combine to produce the oscillations, an important factor is the policy used to set the number of testers needed. Consider how this policy helps to produce oscillations.)

1.4 Second Simulation Model

The changes considered above to the various process delays correspond to a typical continuous improvement program in a business. In many such programs, efforts are made to reduce delays in order to improve process performance. The analysis completed in the preceding section shows that such reductions in delays do not significantly improve the situation for Future Electronics Company. In this section, a more radical process reengineering is investigated.

Specifically, a change to the fundamental policy used to hire testers is considered. This requires a change in the basic process structure, as presented in Figure 1.1. The revised process structure, which is shown in Figure 1.4, is an attempt to more tightly couple the hiring rate to the anticipated need for testers. The listing for this model is given in the next subsection, and illustrative output is given in Figure 1.5.

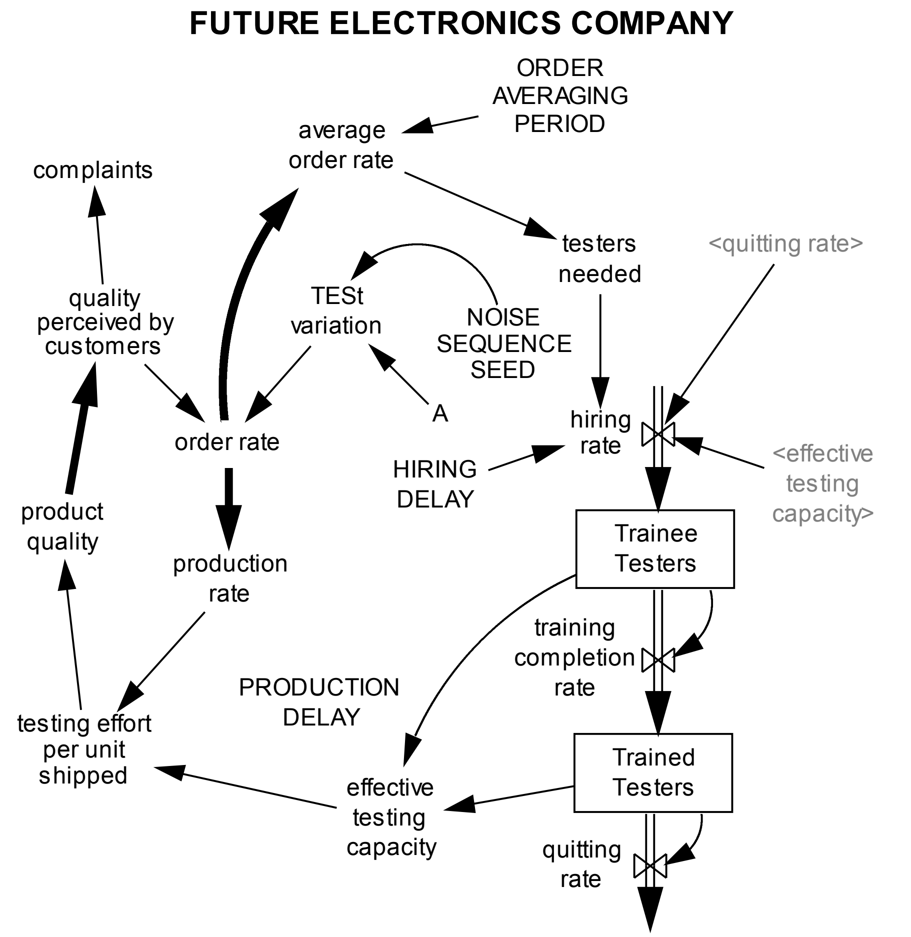


Figure 1.4 *Second model*

Second Model Listing

```
(01) A = 0
(02) average order rate = SMOOTH(order rate, ORDER AVERAGING PERIOD)
(03) complaints = (3 / quality perceived by customers) - 2
(04) effective testing capacity
          = Trained Testers - 0.5 * Trainee Testers
(05) FINAL TIME  = 120
(06) HIRING DELAY = 2
(07) hiring rate = MAX(0, quitting rate
  + (testers needed - effective testing capacity ) / HIRING DELAY)
(08) INITIAL TIME  = 0
(09) NOISE SEQUENCE SEED = 1013
(10) ORDER AVERAGING PERIOD = 2
(11) order rate = 10000 * quality perceived by customers
```

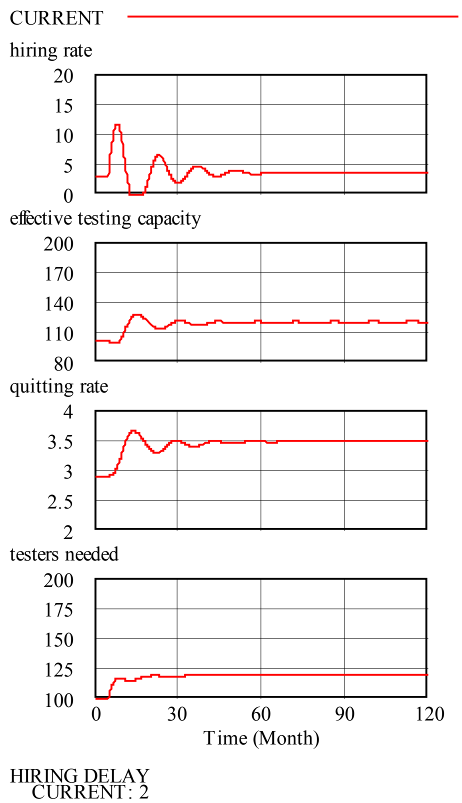


Figure 1.5 *Second model output*

```
        * ( 1 + TESt variation)
(12) product quality
        = IF THEN ELSE(testing effort per unit shipped < 0.01,
           100 * testing effort per unit shipped,
           1 + 10 * (testing effort per unit shipped - 0.01))
(13) PRODUCTION DELAY = 3
(14) production rate
        = DELAY FIXED(order rate, PRODUCTION DELAY, order rate)
(15) quality perceived by customers
        = SMOOTHI(product quality, 6, 1)
(16) quitting rate = Trained Testers / 36
(17) SAVEPER  = TIME STEP
(18) TESt variation = STEP(0.2, 5) * ((1 - A) + A
                     * (RANDOM UNIFORM(-0.5, 0.5, NOISE SEQUENCE SEED))
(19) testers needed = 0.01 * average order rate
(20) testing effort per unit shipped
        = effective testing capacity / production rate
(21) TIME STEP  = 0.125
(22) Trained Testers
        = INTEG(+training completion rate-quitting rate,
            100 * 24 / 23)
```

```
(23) Trainee Testers
         = INTEG(hiring rate-training completion rate,
             (3/36) * (100 * 24 / 23))
(24) training completion rate = Trainee Testers / 3
```

1.5 Questions for Second Model

14) Describe qualitatively how the second model shown in Figure 1.4 differs from the first model shown in Figure 1.1 and why the revised process might be expected to reduce the oscillations in the hiring rate for testers.
15) Draw a causal loop diagram for the second model. This diagram should include all the variables shown in Figure 1.4.
16) Figure 1.5 shows that the process reengineering substantially reduces, but does not totally eliminate, the oscillations that were seen in the first model. Explain what in the system structure is causing the oscillations shown in Figure 1.5 and why the rate of oscillation is faster than it was in the first model.
17) Investigate the impact of reducing the delays (PRODUCTION DELAY, ORDER AVERAGING PERIOD, and HIRING DELAY) in order to more quickly respond to changes in product quality. Specifically, determine and discuss the impact of cutting each of these delays in half, one at a time.
18) While this may seem counterintuitive, investigate the impact of becoming *less* responsive to changes in order rate. Specifically, investigate the impact of increasing the HIRING DELAY. (Hint: This actually reduces the oscillations.)
19) Briefly describe the operations management implications of the change in process structure from Figure 1.1 to Figure 1.4. Specifically discuss changes in cross-functional aspects of operations management that are implied by the change in process structure. Also briefly discuss potential difficulties in implementing this process reengineering. (Hint: Note that this change requires modifying the information links between the human resources/hiring function and other functions within Future Electronics Company.)

1.6 Reference

W. E. Jarmain (ed.), *Problems in Industrial Dynamics*, The MIT Press, Cambridge, Massachusetts, 1963.