Guided Study Program in System Dynamics

System Dynamics in Education Project
System Dynamics Group
MIT Sloan School of Management[1]

Solutions to Assignment #22
Wednesday, April 28, 1999

Reading Assignment:

Please refer to Road Maps 8: A Guide to Learning System Dynamics (D-4508-1) and read the following papers from Road Maps 8:

- *An Introduction to Sensitivity Analysis, by Lucia Breierova and Mark Choudhari (D-4526)*

Please read the following:

- Principles of Systems,[2] *by Jay W. Forrester, Section 2.5*

Please refer to Road Maps 6: A Guide to Learning System Dynamics (D-4506-4) and read the following paper from Road Maps 6:

- *Generic Structures in Oscillating Systems I, by Celeste Chung (D-4426-1)*

Please refer to Road Maps 8: A Guide to Learning System Dynamics (D-4508-1) and read the following papers from Road Maps 8:

- *Learning Through System Dynamics as Preparation for the 21st Century, by Jay W. Forrester (D-4434)*

Exercises:

1. An Introduction to Sensitivity Analysis

Please build the three models in Vensim PLE and perform all of the sensitivity tests described in this paper. In your assignment solutions document, include the Coffeehouse Model diagram and documented equations,[3] and do the following:

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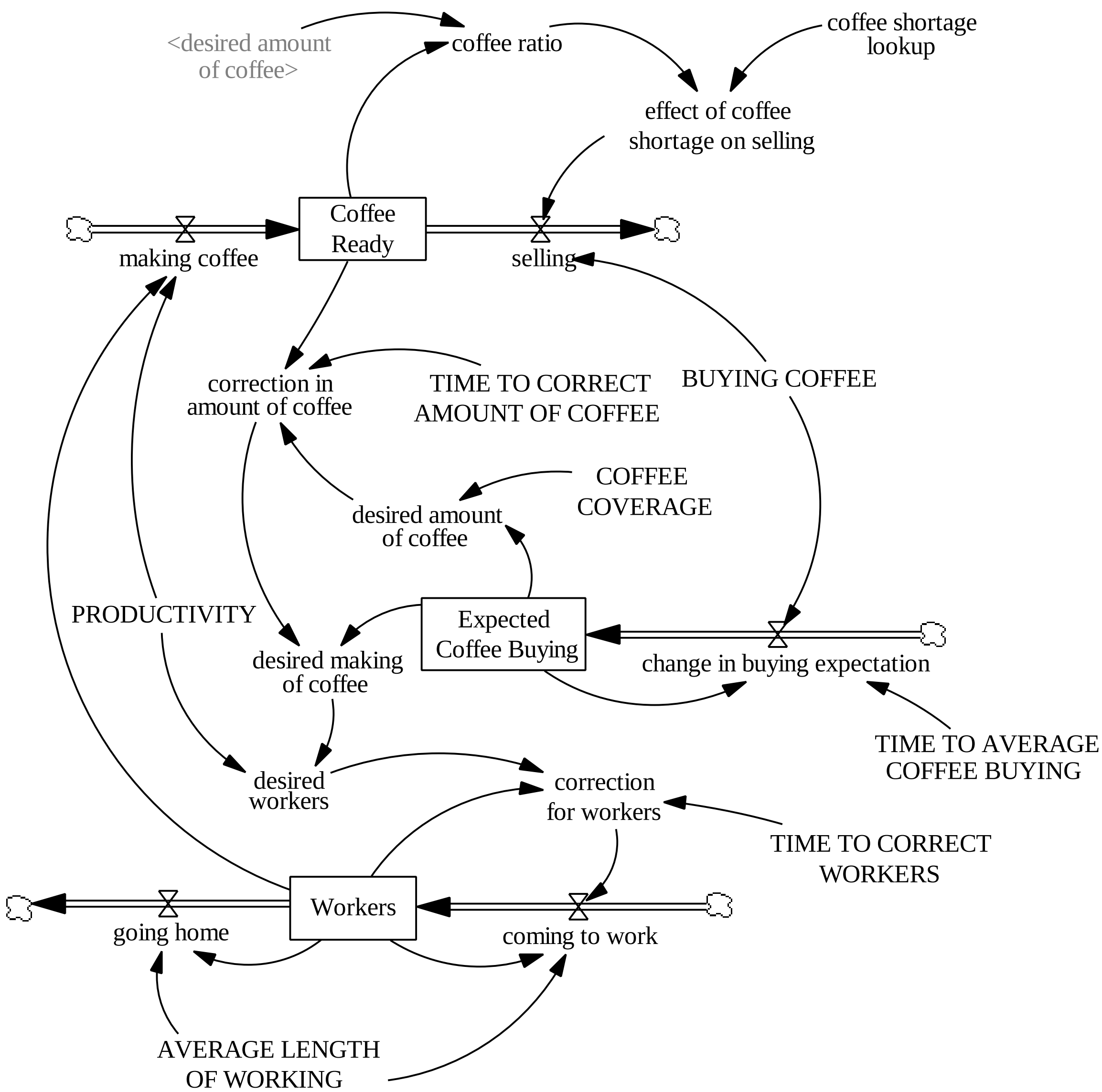
[2] Forrester, Jay W., 1968. *Principles of Systems*, (2nd. ed.). Waltham, MA: Pegasus Communications. 391 pp.
[3] The formulation of the “selling” rate equation as presented in the paper does not show good system dynamics modeling practice. Please use a formulation that does not use a MIN function. Instead, try using a lookup function.

Find a combination of realistic parameter values that minimizes the oscillations. List the parameter values and justify your choices by arguing that these values are realistic. Demonstrate and explain how this particular combination of parameter values dampens the system.

Model diagram:



Please note that the formulation of the “selling” rate equation as presented in the paper does not show good system dynamics modeling practice:

selling = MIN(BUYING COFFEE, Coffee Ready / Time Step)
Units: cups/Hour
The number of cups of coffee sold in the Coffeehouse every hour.

where

BUYING COFFEE = 20 + STEP(5,3)
Units: cups/Hour
The hourly demand for coffee.

To avoid using the MIN function and inserting the time step explicitly into the model, the equations should be formulated as follows:

Model equations:

AVERAGE LENGTH OF WORKING = 4
Units: Hour
The number of hours that a worker spends in the Coffeehouse.

BUYING COFFEE = 20 + STEP(5,3)
Units: cups/Hour
The hourly demand for coffee.

change in buying expectation = (BUYING COFFEE – Expected Coffee Buying) / TIME TO AVERAGE COFFEE BUYING
Units: (cups/Hour)/Hour
The rate at which the workers' expectation about demand for coffee change.

COFFEE COVERAGE = 2
Units: Hour
Coffee coverage determines the number of hours worth of coffee that Howard wants the workers to keep at the Coffeehouse at all times.

coffee ratio = Coffee Ready / desired amount of coffee
Units: dmnl
The ratio of the actual amount of coffee ready at the Coffeehouse to the desired amount of coffee.

Coffee Ready = INTEG (making coffee – selling, COFFEE COVERAGE * BUYING COFFEE)
Units: cups
The number of cups of coffee ready in the Coffeehouse.

coffee shortage lookup ([(0,0) - (1,1)], (0,0), (0.1,0.5), (0.2,0.8), (0.3,0.9), (0.4,0.98), (0.5,1), (0.6,1), (0.7,1), (0.8,1), (0.9,1), (1,1))
Units: dmnl
The effect of coffee shortage on the selling of coffee lookup function.

coming to work = correction for workers + Workers / AVERAGE LENGTH OF WORKING
Units: workers/Hour
The rate at which workers come to work.

correction for workers = (desired workers – Workers) / TIME TO CORRECT WORKERS
Units: workers/Hour
The number of workers who come to the Coffeehouse as a result of a difference between the desired and the actual number of workers.

correction in amount of coffee = (desired amount of coffee – Coffee Ready) / TIME TO CORRECT AMOUNT OF COFFEE
Units: cups/Hour
The number of cups of coffee that the workers prepare every hour as a result of a difference between the desired and actual amount of coffee.

desired amount of coffee = COFFEE COVERAGE * Expected Coffee Buying
Units: cups
The number of cups of coffee that the workers would like to have at the Coffeehouse. It is equal to the demand for coffee that they expect times the coffee coverage.

desired making of coffee = correction in amount of coffee + Expected Coffee Buying
Units: cups/Hour
The rate at which the workers would like to make coffee.

desired workers = desired making of coffee / PRODUCTIVITY
Units: workers
The number of workers that Howard wants to be working at the Coffeehouse.

effect of coffee shortage on selling = coffee shortage lookup (coffee ratio)
Units: dmnl
The effect of a shortage of coffee ready on the selling of coffee.

Expected Coffee Buying = INTEG (change in buying expectation, BUYING COFFEE)
Units: cups/Hour
The hourly demand for coffee that the workers expect.

going home = Workers / AVERAGE LENGTH OF WORKING
Units: workers/Hour
The rate at which the workers leave the Coffeehouse to go home and study.

making coffee = Workers * PRODUCTIVITY
Units: cups/Hour

The number of cups of coffee that the Coffeehouse workers prepare each hour. It is equal to the number of workers times their average productivity.

PRODUCTIVITY = 20
Units: (cups/workers)/Hour
The number of cups of coffee that a worker makes in an hour.

selling = BUYING COFFEE * effect of coffee shortage on selling
Units: cups/Hour
The number of cups of coffee sold in the Coffeehouse every hour.

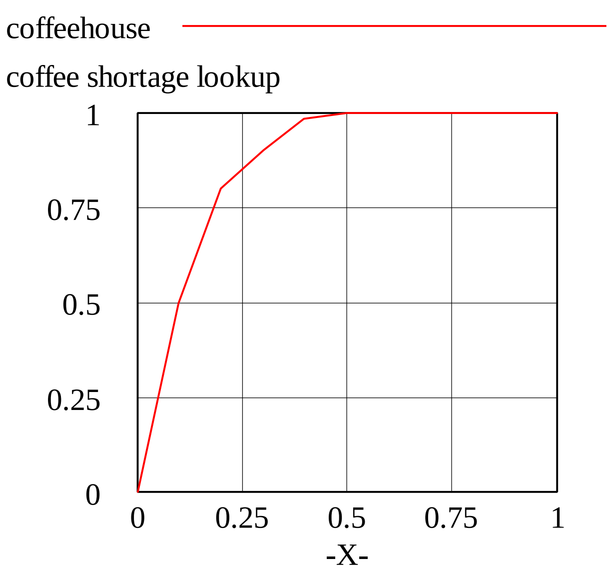
TIME TO AVERAGE COFFEE BUYING = 2
Units: Hour
The time it takes the workers to recognize a permanent change in demand for coffee from random fluctuations.

TIME TO CORRECT AMOUNT OF COFFEE = 1
Units: Hour
The time in which the workers attempt to correct a difference between the desired and the actual amount of coffee.

TIME TO CORRECT WORKERS = 3
Units: Hour
The time in which Howard wants to make more workers come to work.

Workers = INTEG (coming to work – going home, desired workers)
Units: workers
The number of workers currently working at the Coffeehouse.

<u>Graph of lookup function:</u>

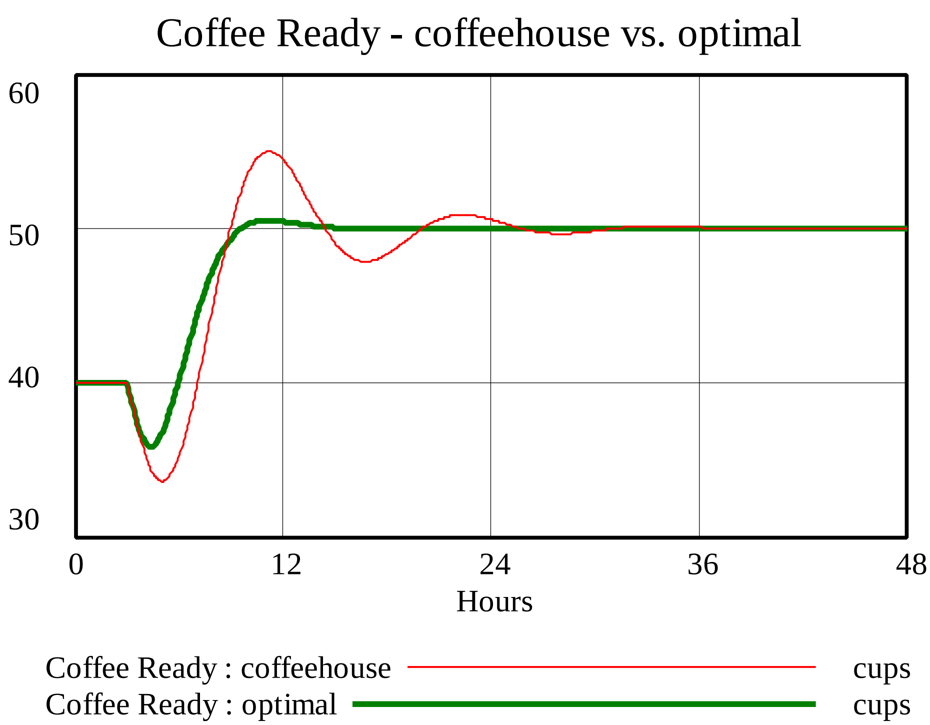


In order to minimize the oscillations, one should try to find realistic values for the parameters that control the amplitude of oscillations as well as the time it takes the system to reach equilibrium. Such parameter values are the time constants of the system. Other parameters, such as productivity or coffee coverage, affect the initial and equilibrium values of the stocks, but do not have significant effects on the amplitude of oscillations or the time to reach equilibrium.

Given the results presented in the paper, a sensible policy might try reducing the "TIME TO CORRECT WORKERS," increasing the "TIME TO CORRECT AMOUNT OF COFFEE," and reducing the "TIME TO AVERAGE COFFEE BUYING." For example, one might try the following values:

	"coffeehouse" simulation	"optimal" simulation
TIME TO CORRECT WORKERS	3 hours	1 hour
TIME TO CORRECT AMOUNT OF COFFEE	1 hour	2 hours
TIME TO AVERAGE COFFEE BUYING	2 hours	1 hour

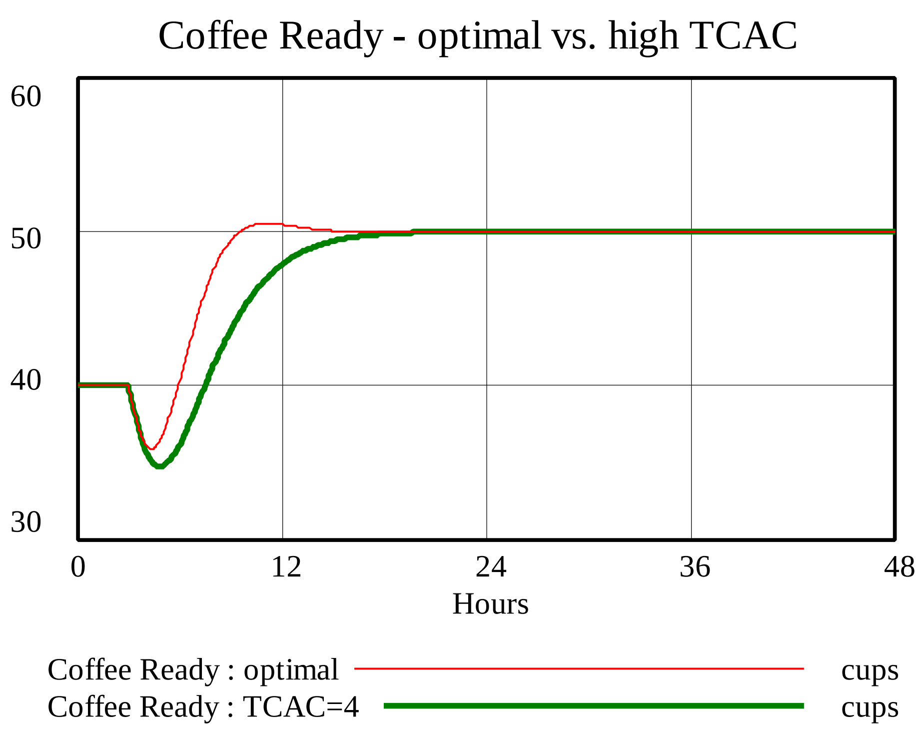
The model behavior comparing the two simulations is shown in the graph below:



As shown in the paper, reducing the "TIME TO CORRECT WORKERS" to very low values can eliminate the oscillations almost completely. Such low values, however, are quite unrealistic; therefore, a value of 1 hour was chosen for the "optimal" simulation.

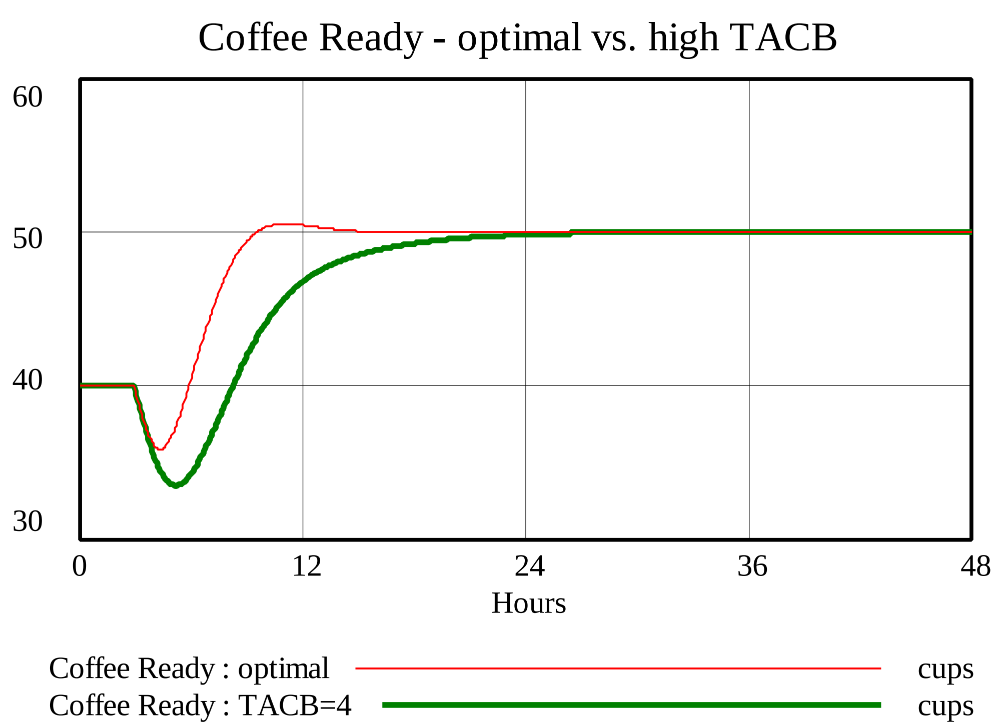
One could argue that because increasing the "TIME TO CORRECT AMOUNT OF COFFEE" reduces the instability of "Coffee Ready," the "optimal" simulation should use a much higher value of "TIME TO CORRECT AMOUNT OF COFFEE." Increasing the value of "TIME TO CORRECT AMOUNT OF COFFEE" decreases the overshoot of "Coffee Ready," but it also increases the initial decline of the stock. Therefore, when selecting a value for "TIME TO CORRECT AMOUNT OF COFFEE," there is always a trade-off between the initial decline of the stock and the subsequent overshoot. Also, a higher "TIME TO CORRECT AMOUNT OF COFFEE" increases the time to reach equilibrium. These results are shown in the following graph, comparing the "optimal" simulation to a simulation with "TIME TO CORRECT AMOUNT OF COFFEE" equal to 4 hours, as summarized in the table below:

	"optimal" simulation	"TCAC=4" simulation
TIME TO CORRECT WORKERS	1 hour	1 hour
TIME TO CORRECT AMOUNT OF COFFEE	2 hours	4 hours
TIME TO AVERAGE COFFEE BUYING	1 hour	1 hour



Reducing the "TIME TO AVERAGE COFFEE BUYING" decreases the initial decline of "Coffee Ready," but later increases the first overshoot of "Coffee Ready." Hence, in choosing a value for "TIME TO AVERAGE COFFEE BUYING," there is again a trade-off between the initial decrease and the subsequent overshoot of "Coffee Ready." Also, a higher "TIME TO AVERAGE COFFEE BUYING" increases the time to reach equilibrium. The following graph demonstrates these results, comparing the "optimal" simulation to a simulation with "TIME TO AVERAGE COFFEE BUYING" equal to 4 hours, as summarized in the table below:

	"optimal" simulation	"TACB=4" simulation
TIME TO CORRECT WORKERS	1 hour	1 hour
TIME TO CORRECT AMOUNT OF COFFEE	2 hours	2 hours
TIME TO AVERAGE COFFEE BUYING	1 hour	4 hours

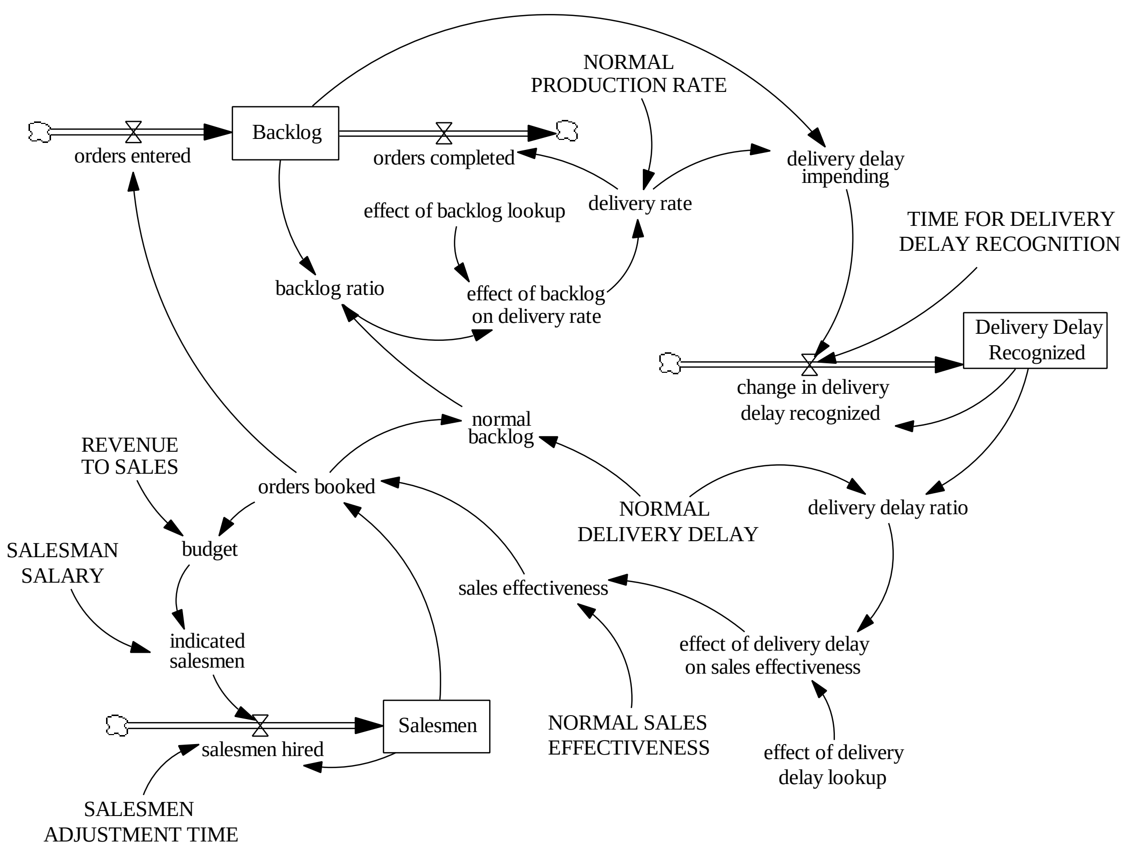


Hence, the decision of what is the "optimal" behavior depends on what a modeler is trying to accomplish: make the approach to equilibrium smoother and slower at the expense of a larger initial decline of "Coffee Ready," or make the approach to equilibrium faster, with a smaller initial decline, at the expense of some amount of overshoot of "Coffee Ready."

2. Principles of Systems: Section 2.5: Coupled Nonlinear Feedback Loops

This section builds and analyzes the market growth model introduced in assignment 7. As you read this section, please build the model as described in the book. Make sure to non-dimensionalize all of the table functions. You should pay particular attention to choosing appropriate reference or normal values. In your assignment solutions document, please include the model and a graph of the model behavior, as in Figure 2.5d. Work through all of the workbook exercises.

Model diagram:



Model equations:

Backlog = INTEG (orders entered - orders completed, 8000)

Units: unit

The backlog represents the net accumulation of orders entered minus orders completed.

backlog ratio = Backlog / normal backlog

Units: dmnl

The ratio of the present backlog to the normal backlog.

budget = orders booked * REVENUE TO SALES
Units: dollar/Month
The budget for salesmen's monthly salaries.

change in delivery delay recognized = (delivery delay impending – Delivery Delay Recognized) / TIME FOR DELIVERY DELAY RECOGNITION
Units: Month/Month
The rate of change in the recognized delivery delay.

delivery delay impending = Backlog / delivery rate
Units: Month
The actual delivery delay equals the size of the backlog divided by the delivery rate, giving the time necessary for the present delivery rate to work through the present backlog.

delivery delay ratio = Delivery Delay Recognized / NORMAL DELIVERY DELAY
Units: dmnl
The ratio of the recognized delivery delay to the normal delivery delay.

Delivery Delay Recognized = INTEG (change in delivery delay recognized, 2)
Units: Month
The recognized delivery delay is represented as a delayed version of delivery delay impending. It results from accumulating the changes described by change in delivery delay recognized.

delivery rate = NORMAL PRODUCTION RATE * effect of backlog on delivery rate
Units: unit/Month
The actual delivery rate equals the normal delivery rate times the effect of backlog on delivery rate.

effect of backlog lookup ([(0,0) - (1.25,1.1)], (0,0), (0.125,0.2564), (0.25,0.5128), (0.375,0.6923), (0.5,0.8205), (0.625,0.8974), (0.75,0.9487), (0.875,0.9744), (1,1), (1.125,1.021), (1.25,1.026))
Units: dmnl
The effect of backlog lookup function determines the relationship between backlog and delivery rate.

effect of backlog on delivery rate = effect of backlog lookup (backlog ratio)
Units: dmnl
The effect of backlog ratio on the delivery rate multiplier.

effect of delivery delay lookup ([(0,0) - (1.5,2)], (0,1.905), (0.125,1.905), (0.25,1.857), (0.375,1.762), (0.5,1.667), (0.625,1.524), (0.75,1.381), (0.875,1.19), (1,1), (1.125,0.857), (1.25,0.714), (1.375,0.571), (1.5,0.476))
Units: dmnl

The effect of delivery delay lookup function determines the relationship between the delivery delay and the sales effectiveness.

effect of delivery delay on sales effectiveness = effect of delivery delay lookup (delivery delay ratio)
Units: dmnl
The delivery delay affects the sales effectiveness in a negative way: the lower the delivery delay ratio, the higher the sales effectiveness.

indicated salesmen = budget / SALESMAN SALARY
Units: man
The number of salesmen who can be justified by the present rate at which new orders are being booked.

normal backlog = orders booked * NORMAL DELIVERY DELAY
Units: unit
The normal backlog equals the normal delivery delay multiplied by the orders booked each month.

NORMAL DELIVERY DELAY = 4
Units: Month
The normal delivery delay will result in the normal sales effectiveness.

NORMAL PRODUCTION RATE = 19500
Units: unit/Month
The normal production rate is the rate of production and delivery when backlog equals the normal backlog.

NORMAL SALES EFFECTIVENESS = 210
Units: (unit/man)/Month
The sales effectiveness is normal when the recognized delivery delay is equal to its normal value.

orders booked = Salesmen * sales effectiveness
Units: unit/Month
The number of units that the salesmen are able to sell every month.

orders completed = delivery rate
Units: unit/Month
The number of orders completed, which equals the rate of delivery of goods, depletes the backlog.

orders entered = orders booked
Units: unit/Month
The rate of orders entered equals the number of orders booked every month.

REVENUE TO SALES = 10
Units: dollar/unit
The number of dollars per unit that are allocated to selling cost.

sales effectiveness = NORMAL SALES EFFECTIVENESS * effect of delivery delay on sales effectiveness
Units: unit/(Month * man)
The actual sales effectiveness.

SALESMAN SALARY = 2000
Units: (dollar/man)/Month
The monthly salary of each salesman.

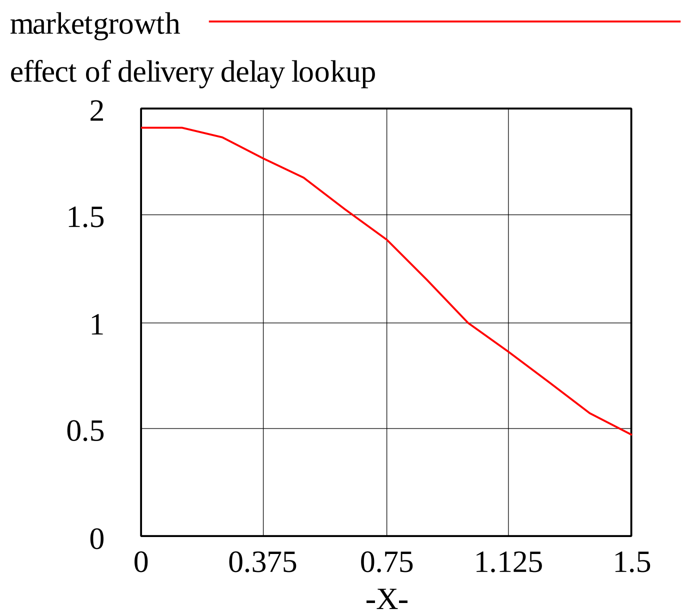
Salesmen = INTEG (salesmen hired, 10)
Units: man
The number of salesmen.

SALESMEN ADJUSTMENT TIME = 20
Units: Month
The adjustment time for changing the number of salesmen.

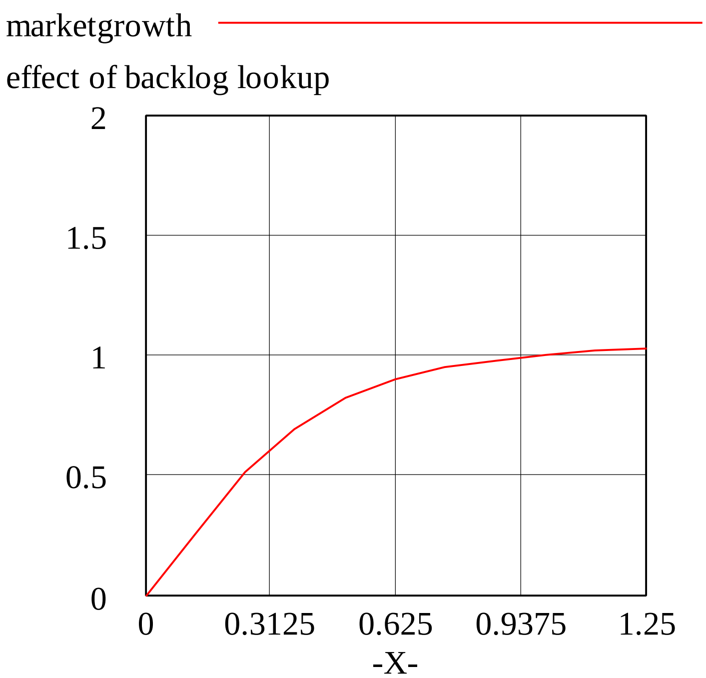
salesmen hired = (indicated salesmen – Salesmen) / SALESMEN ADJUSTMENT TIME
Units: man/Month
The number of salesmen hired each month adjusts the number of salesmen toward the indicated number.

TIME FOR DELIVERY DELAY RECOGNITION = 6
Units: Month
Time for delivery delay recognition represents the total of the time necessary for the salesmen to be informed of changes in delivery delay, the time for the customers to learn from the salesmen, and the time for the customers to plan changes in their suppliers.

In order to non-dimensionalize the table functions, several changes had to be made to the model structure. First, one should choose a reasonable value for "NORMAL DELIVERY DELAY." This value was chosen to be 4 months, which is approximately equal to the equilibrium value of "Delivery Delay Recognized." Then, referring to Figure 2.5c from *Principles of Systems*, one should define a "NORMAL SALES EFFECTIVENESS" of 210 units/man-month. With these reference values, one can then create the following lookup function for the "effect of delivery delay on sales effectiveness," preserving the values from Figure 2.5c:

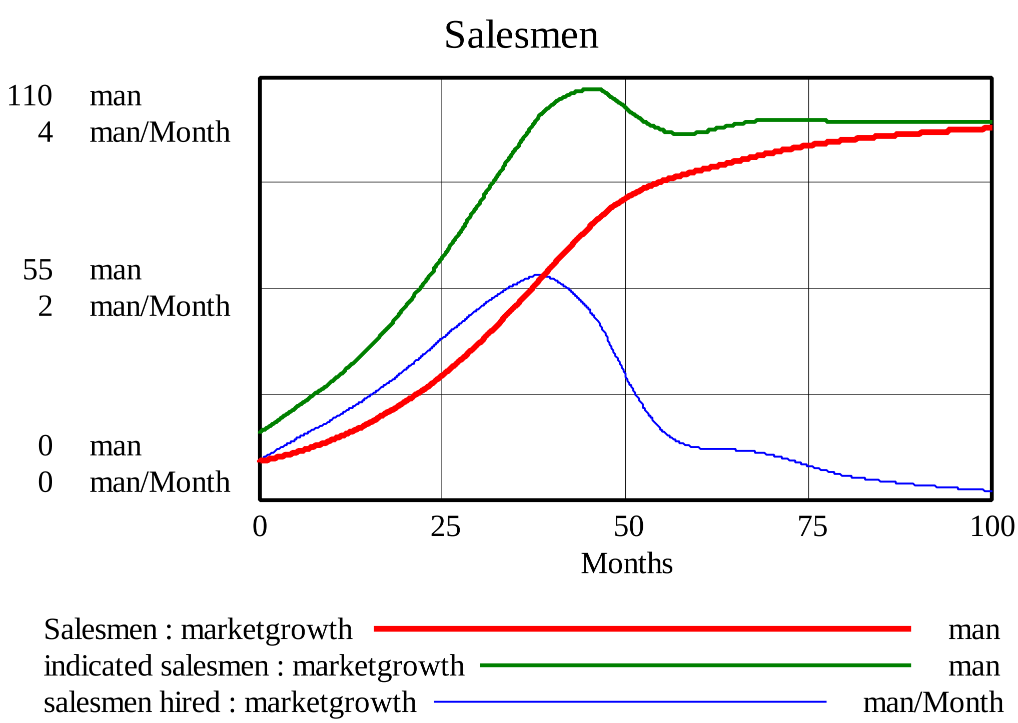


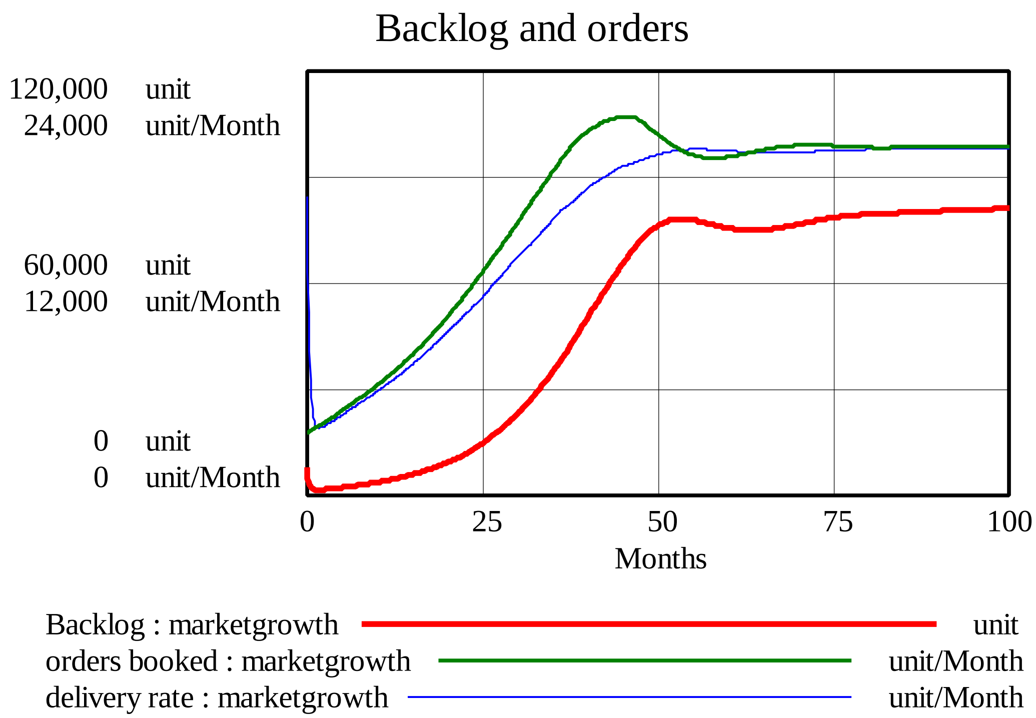
Non-dimensionalizing the table function for the “effect of backlog on delivery rate” is a little trickier. It is not correct to simply pick a reference value for backlog and then read off the corresponding reference value for the delivery rate from Figure 2.5b from *Principles of Systems*. For example, one might be tempted to define a “MAXIMUM BACKLOG” equal to 100,000 units, and then correspondingly define a “MAXIMUM DELIVERY RATE” equal to 20,000 units/month. There is, however, no reasonable concept for maximum backlog. Backlog could rise to unlimited values, and a maximum backlog would depend on the scale of operations. Similarly, one should not define a constant “NORMAL BACKLOG,” because a normal value of backlog changes with the scaling up of activity in the system, and probably depends on the “NORMAL DELIVERY DELAY.” Hence, one should rather define a variable “normal backlog,” equal to the “NORMAL DELIVERY DELAY” multiplied by the number of “orders booked” each month. With a variable “normal backlog,” however, it becomes difficult to redefine the values for the “effect of backlog on delivery rate” lookup function. When the system is in equilibrium, “orders booked” are approximately 20,000 units per month, which results in a “normal backlog” of 80,000 units, with “NORMAL DELIVERY DELAY” equal to 4 months. Referring to Figure 2.5b, one can see that a “Backlog” of 80,000 units corresponds to a “delivery rate” of 19,500 units/month. Therefore, one can then define a “NORMAL PRODUCTION RATE” of 19,500 units/month. With these reference values, the following lookup function can be created, preserving the values from Figure 2.5b:

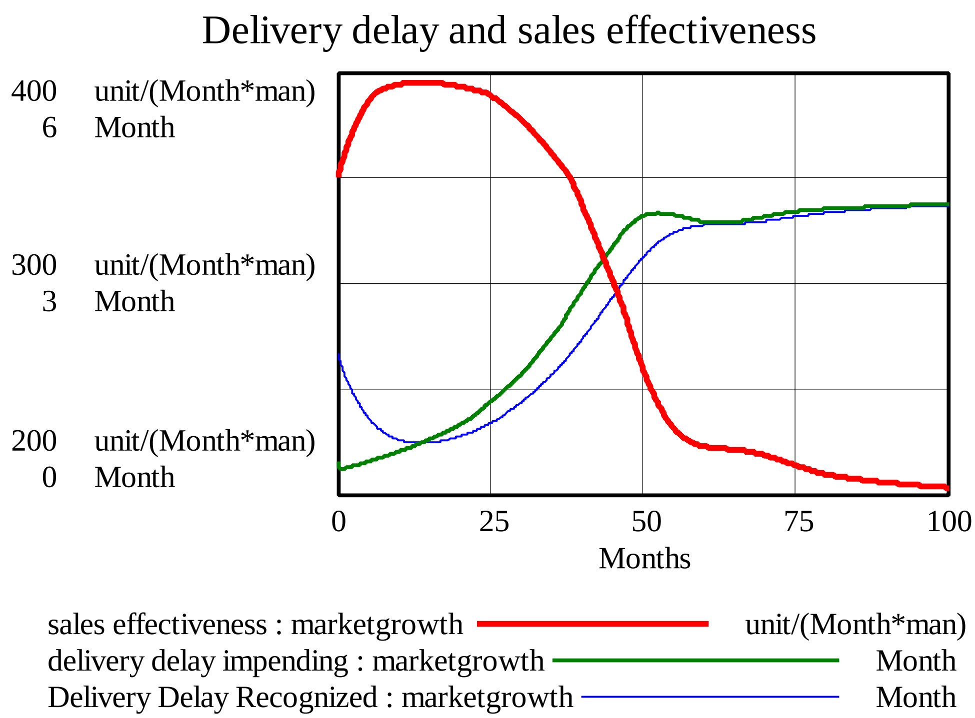


Model behavior:

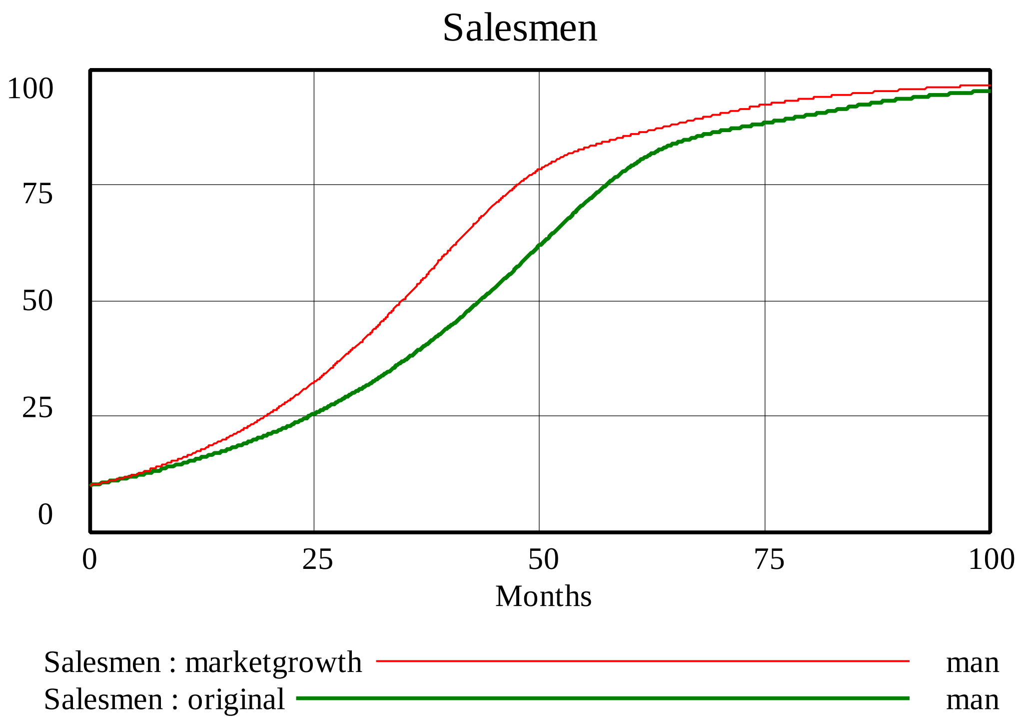
The modified model produces the following behavior:

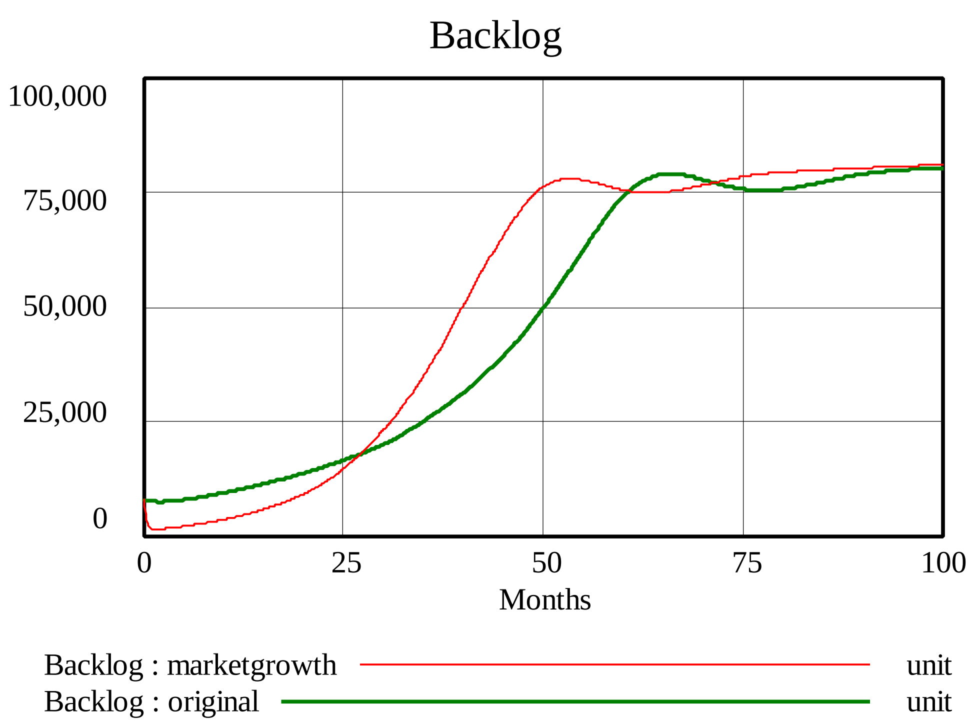


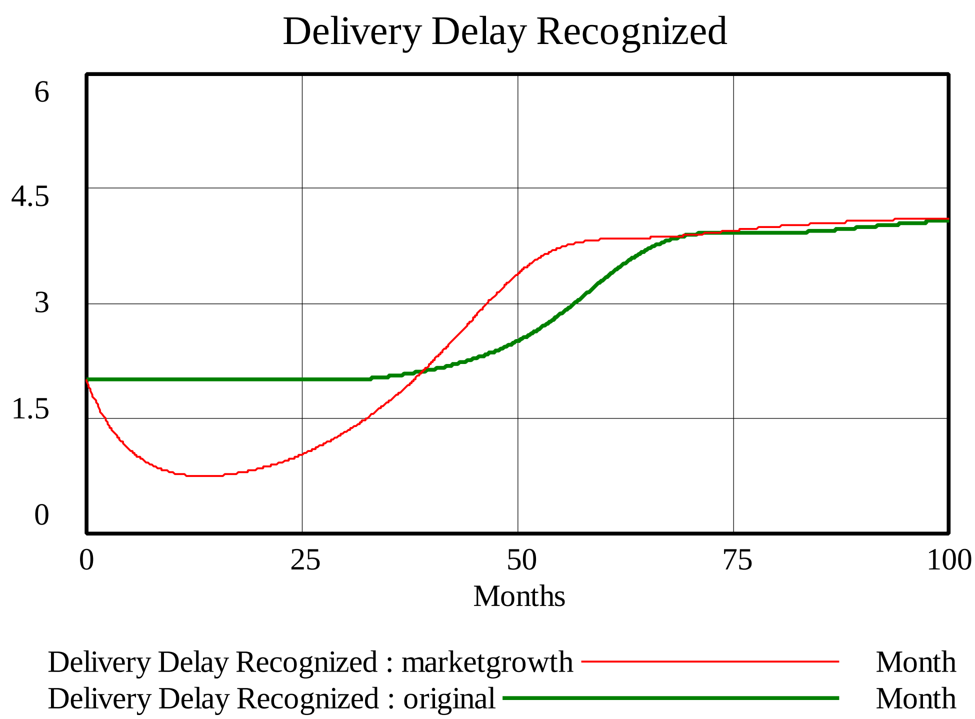




The modified model generates behavior that is similar to the behavior of the original model, but the initial behavior differs. The initial growth in the system is faster because "Delivery Delay Recognized" is much lower than the "NORMAL DELIVERY DELAY," so "sales effectiveness" can initially rise to higher values. The following graphs compare the behavior of the levels in the modified model ("marketgrowth" simulation run) and in the original model ("original" simulation run):





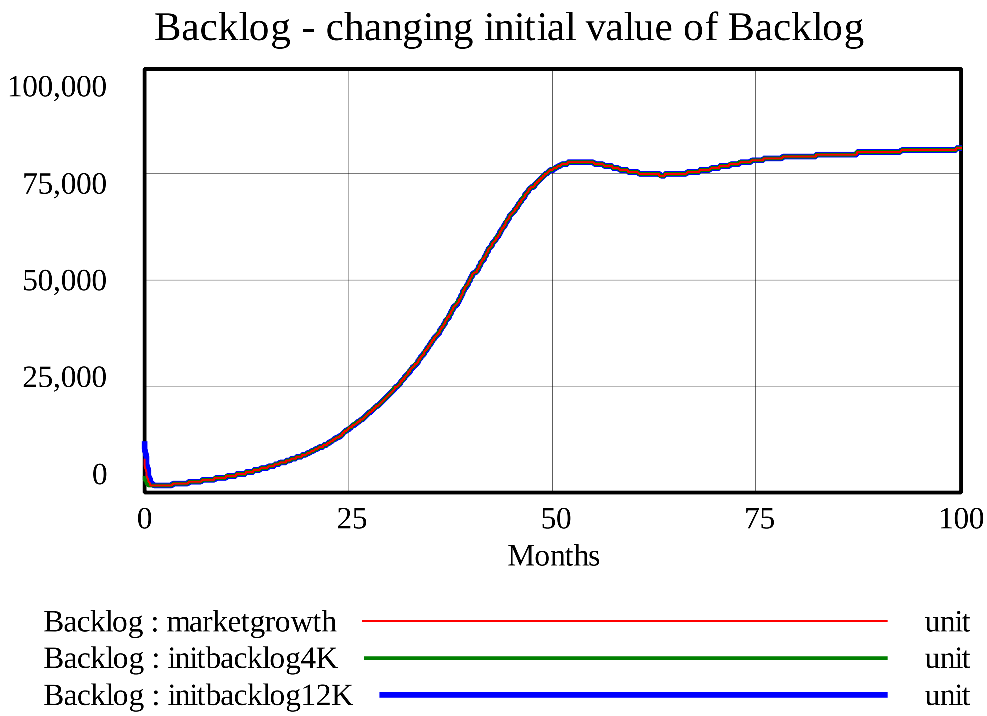


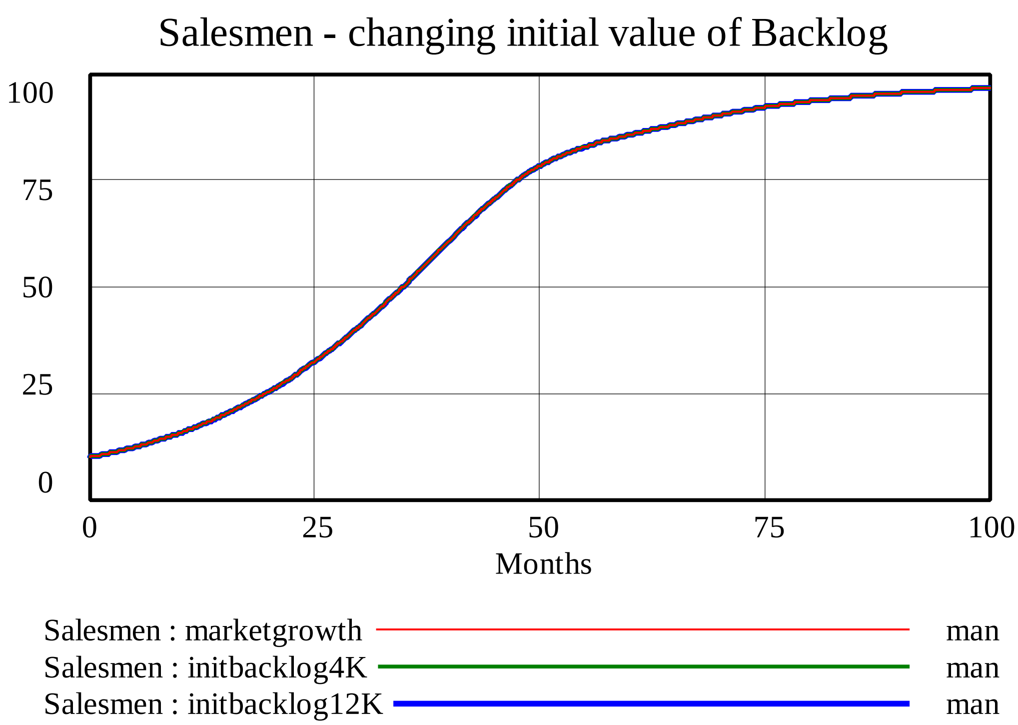
<u>3. Independent Exercise</u>

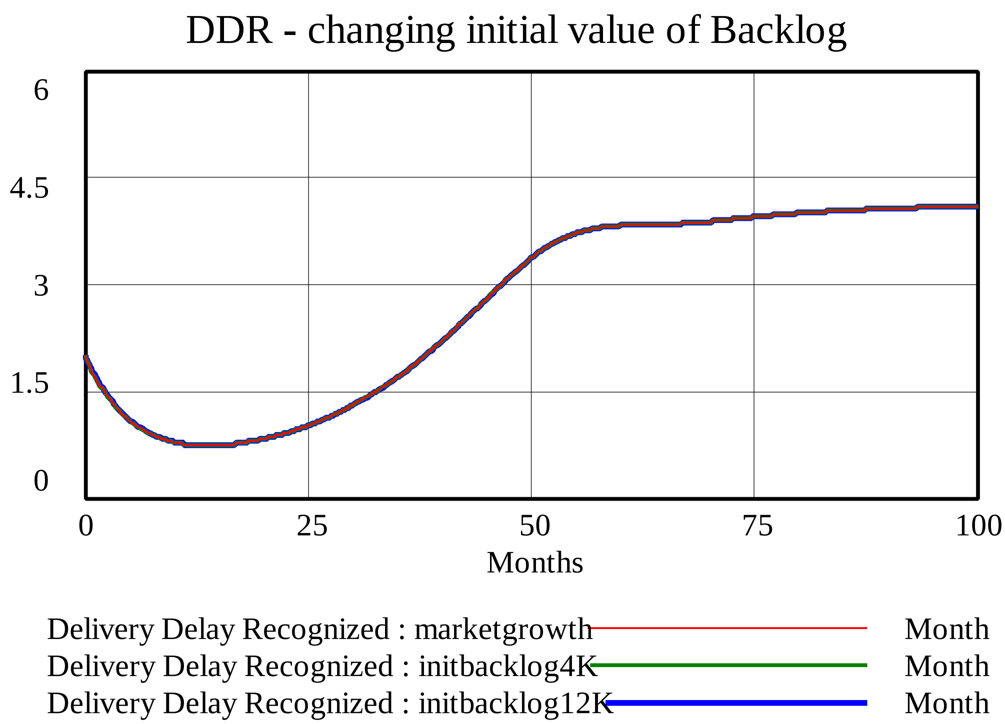
A. Using the methods described in An Introduction to Sensitivity Analysis, perform sensitivity analysis on the market growth model built in Exercise 2. Demonstrate and explain how increases and decreases in each parameter value affect the behavior of the model.

In all the sensitivity tests that follow, we will look at the changes in behavior of the three stocks in the system: "Backlog," "Salesmen," and "Delivery Delay Recognized" (DDR).

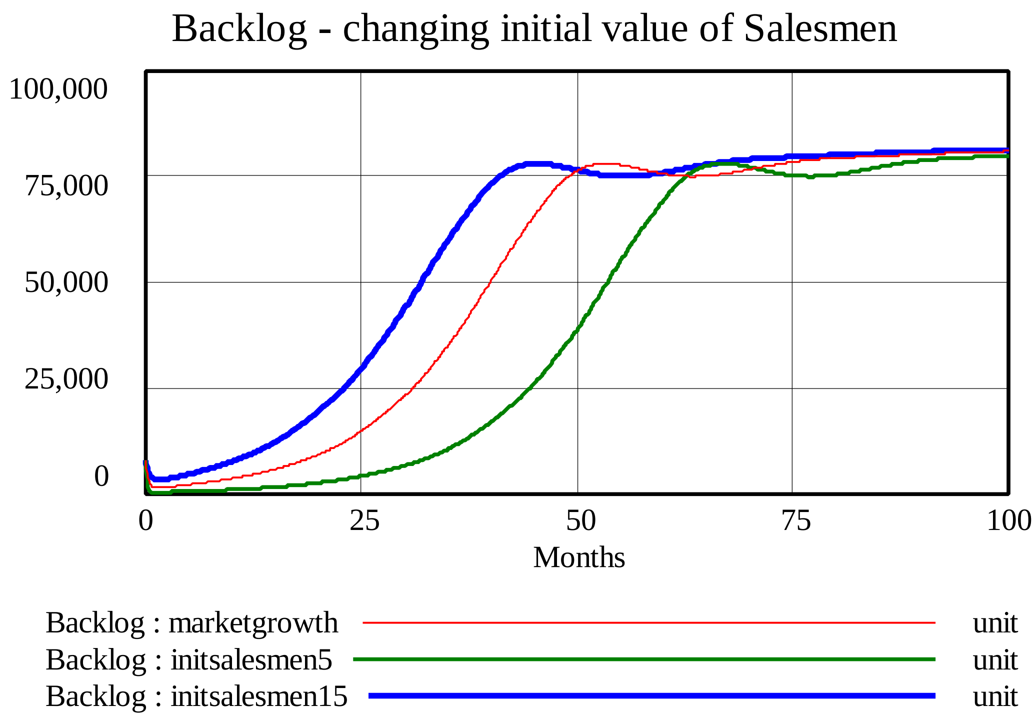
First, let us examine the sensitivity of behavior to changes in the initial value of "Backlog." From studying the *"Introduction to Sensitivity Analysis"* paper, one would expect the effect of such changes to be very small. Indeed, this expectation is confirmed by the following graphs with initial values of "Backlog" equal to 4000 (initbacklog4K), 8000 (marketgrowth), and 12000 (initbacklog12K) units:

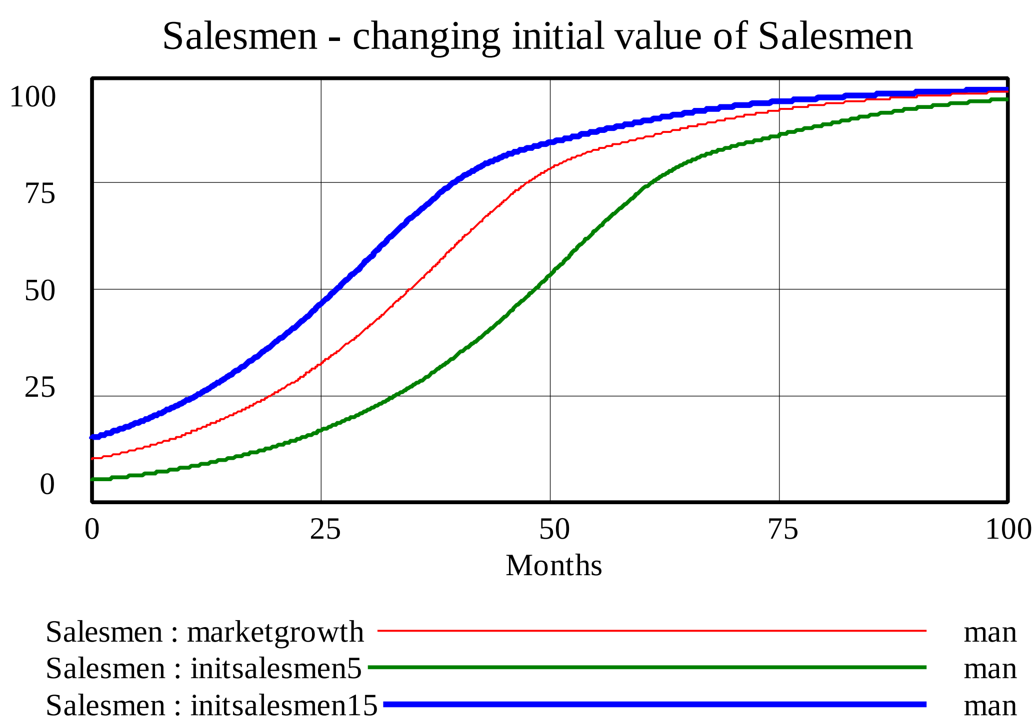

Backlog - changing initial value of Backlog
100,000
75,000
50,000
25,000
0
0
25
50
75
100
Months
Backlog : marketgrowth
unit
Backlog : initbacklog4K
unit
Backlog : initbacklog12K
unit

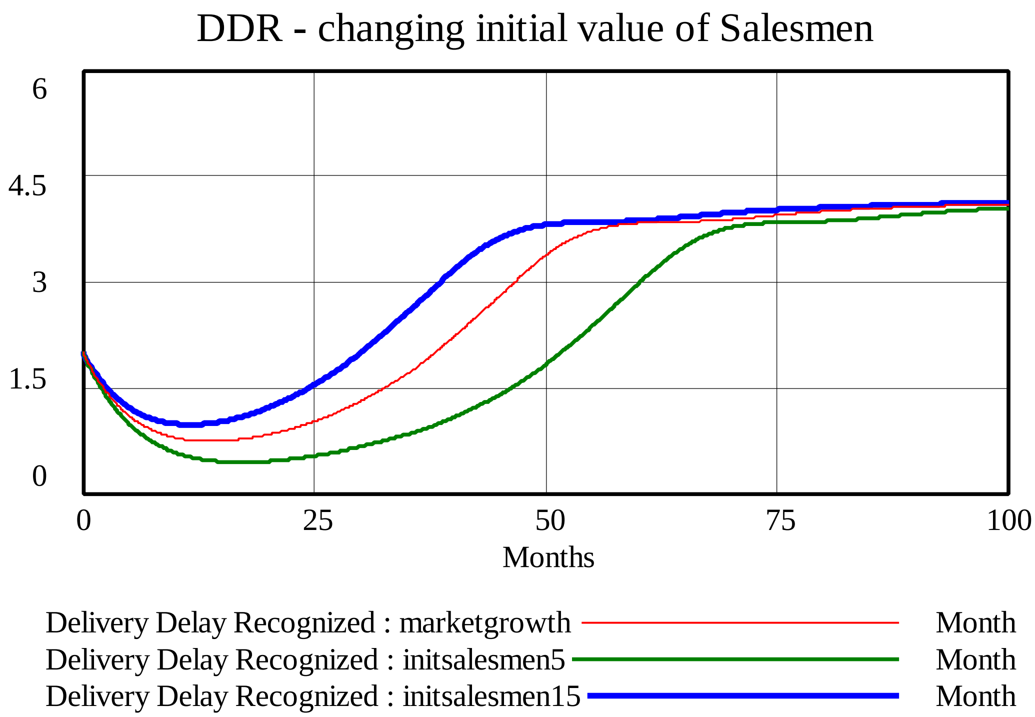

Salesmen - changing initial value of Backlog
100
75
50
25
0
0
25
50
75
100
Months
Salesmen : marketgrowth
man
Salesmen : initbacklog4K
man
Salesmen : initbacklog12K
man



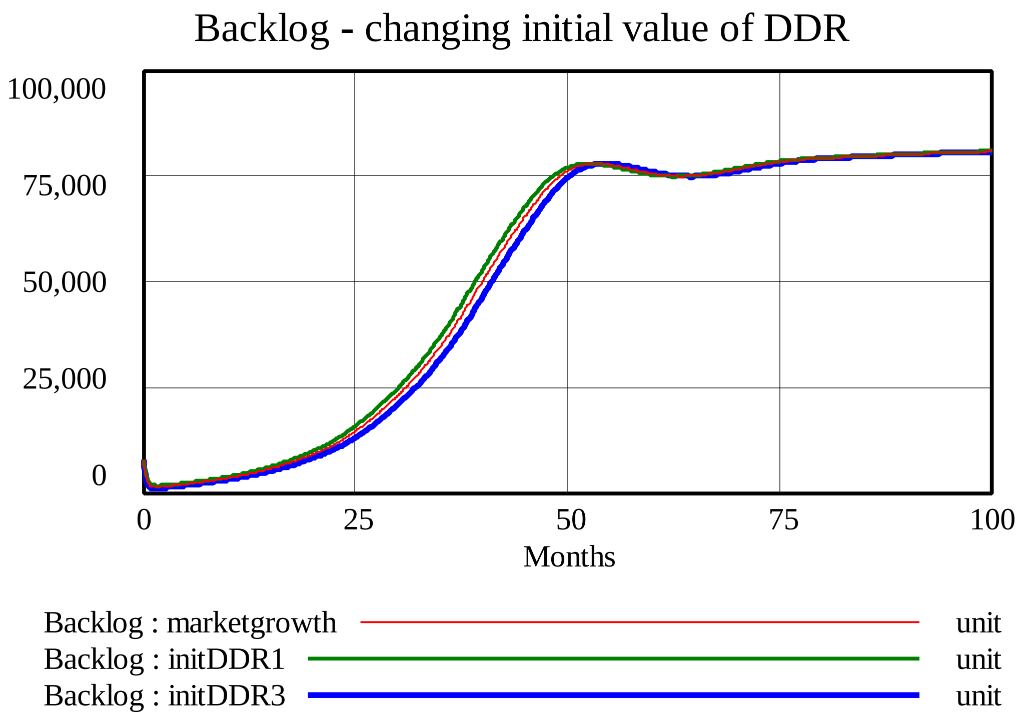
Similarly, one would expect changes in the initial value of “Salesmen” to have only a small effect on system behavior. Higher initial values of “Salesmen,” however, should lead to more rapid initial growth and a faster approach to equilibrium. Again, the expectation is confirmed by the following graphs with initial values of “Salesmen” equal to 5 (initsalesmen5), 10 (marketgrowth), and 15 (initsalesmen15) men:

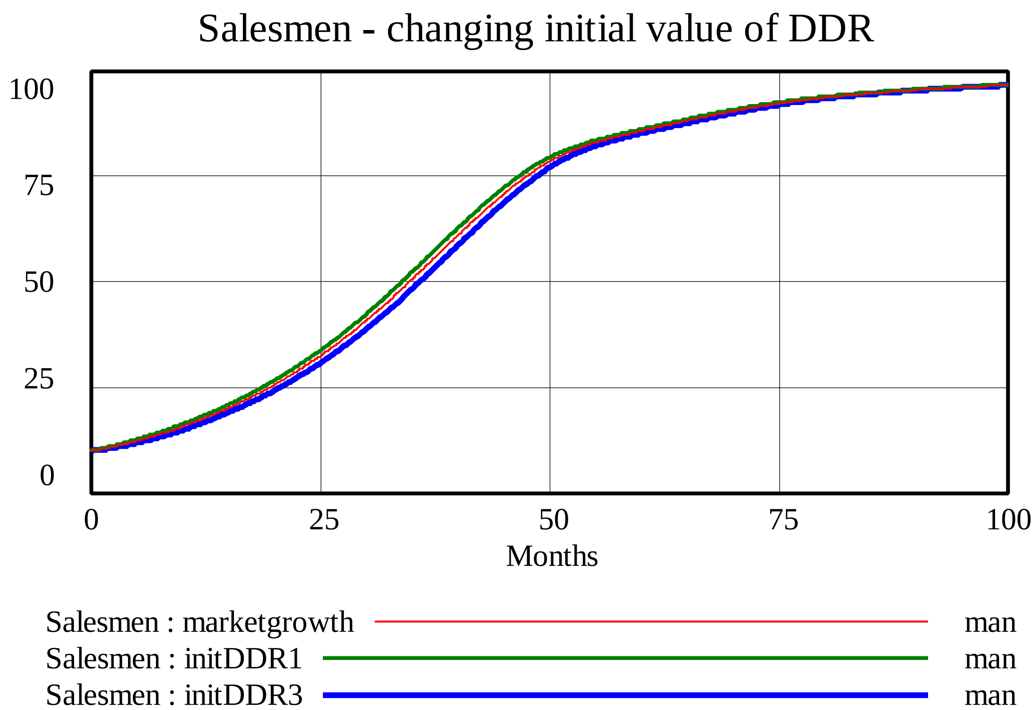

Backlog - changing initial value of Salesmen
100,000
75,000
50,000
25,000
0
0
25
50
75
100
Months
Backlog : marketgrowth unit
Backlog : initsalesmen5 unit
Backlog : initsalesmen15 unit

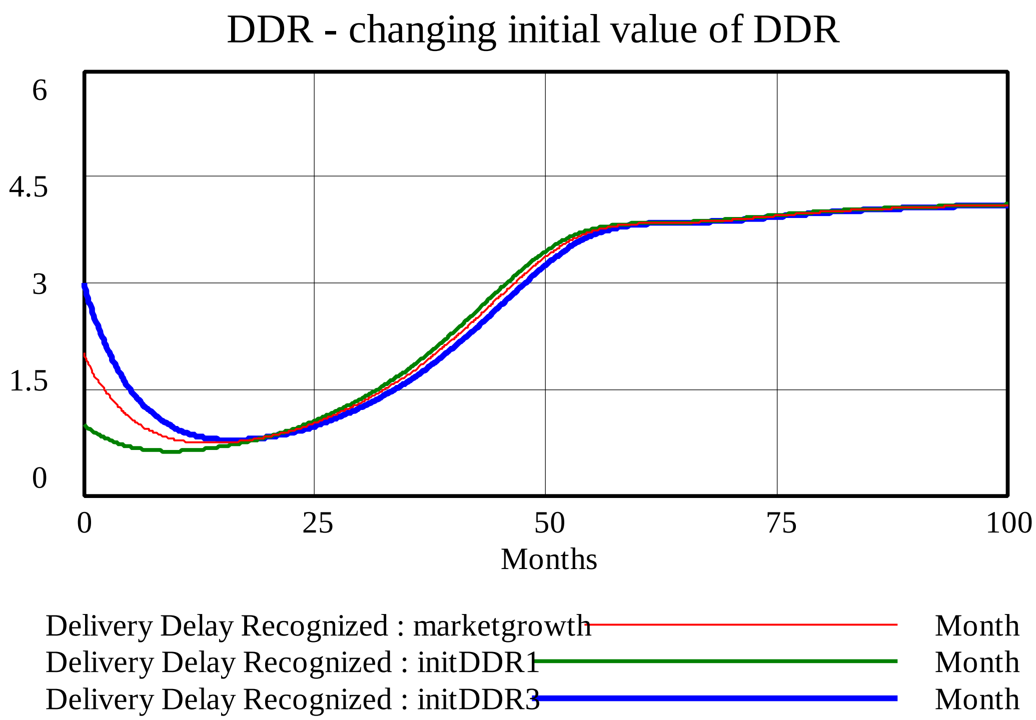

Salesmen - changing initial value of Salesmen
100
75
50
25
0
0
25
50
75
100
Months
Salesmen : marketgrowth man
Salesmen : initsalesmen5 man
Salesmen : initsalesmen15 man



One would also expect that changes in the initial value of "Delivery Delay Recognized" would have only a limited effect on system behavior. The following graphs again confirm this expectation, with the initial value of "Delivery Delay Recognized" equal to 1 (initDDR1), 2 (marketgrowth), and 3 (initDDR3) months:

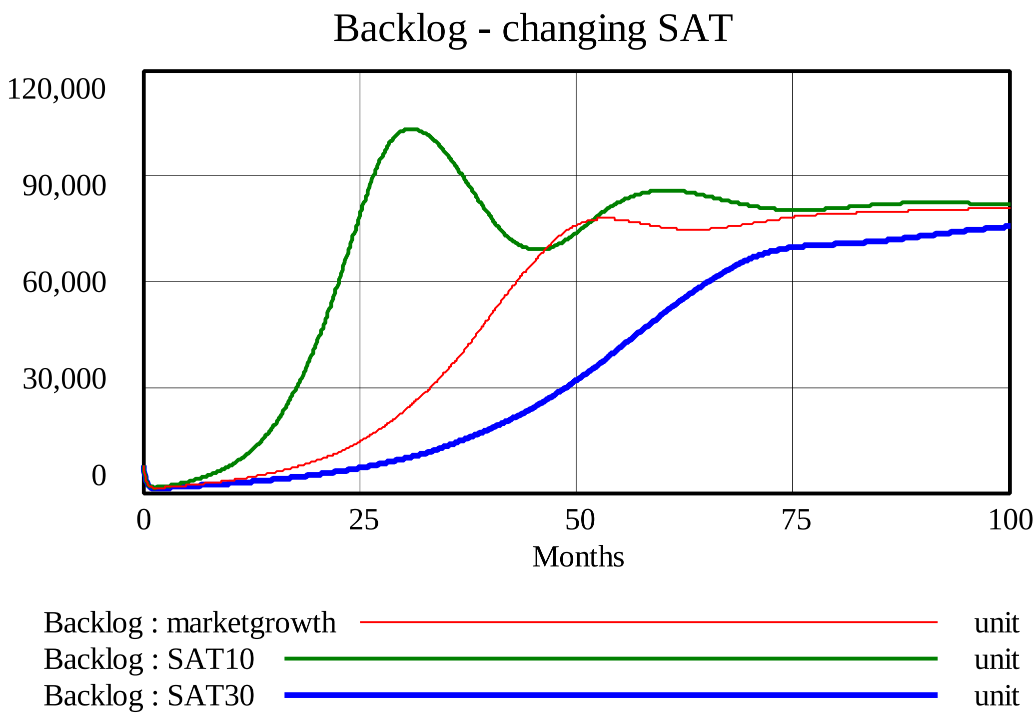

Backlog - changing initial value of DDR
100,000
75,000
50,000
25,000
0
0
25
50
75
100
Months
Backlog : marketgrowth
unit
Backlog : initDDR1
unit
Backlog : initDDR3
unit

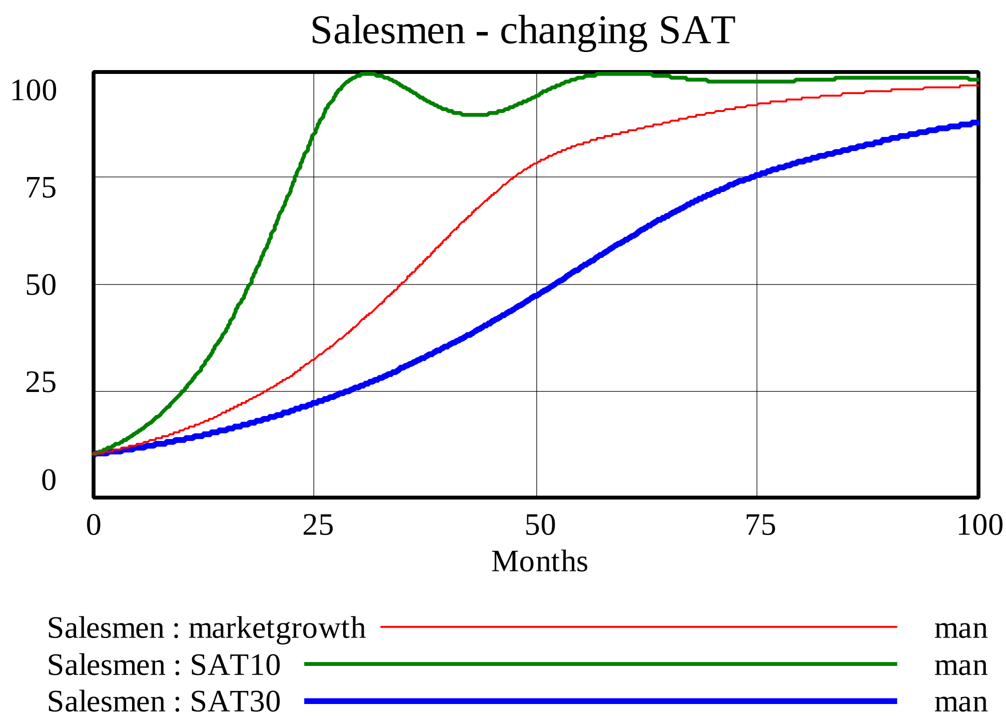

Salesmen - changing initial value of DDR
100
75
50
25
0
0
25
50
75
100
Months
Salesmen : marketgrowth
man
Salesmen : initDDR1
man
Salesmen : initDDR3
man

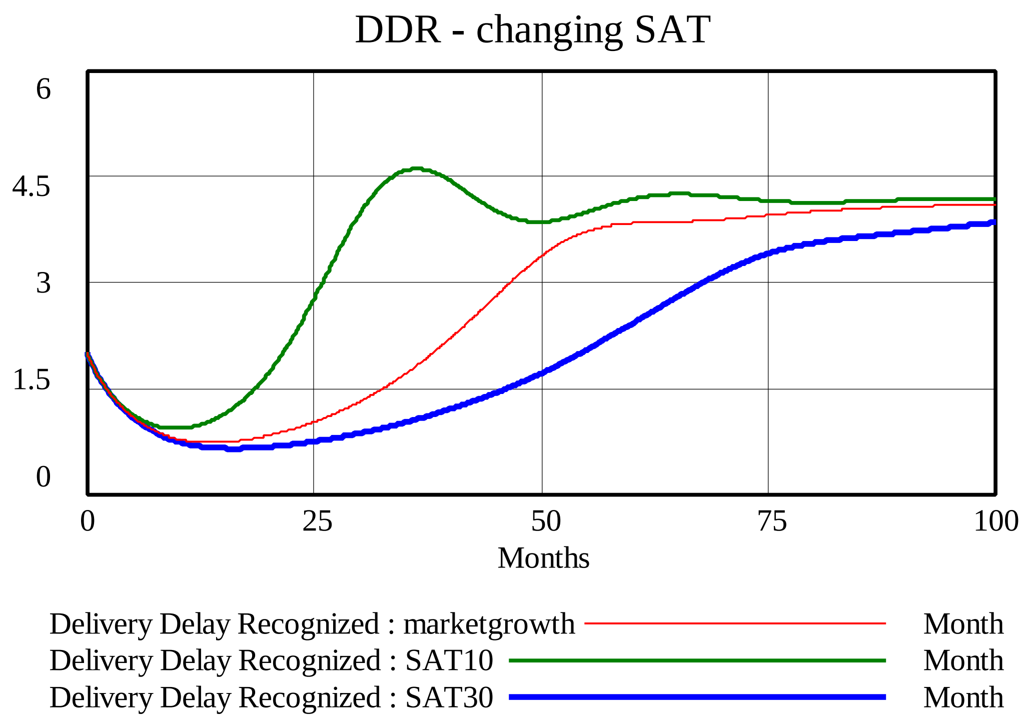


Now, we will look at the changes in behavior that result from changing parameter values.

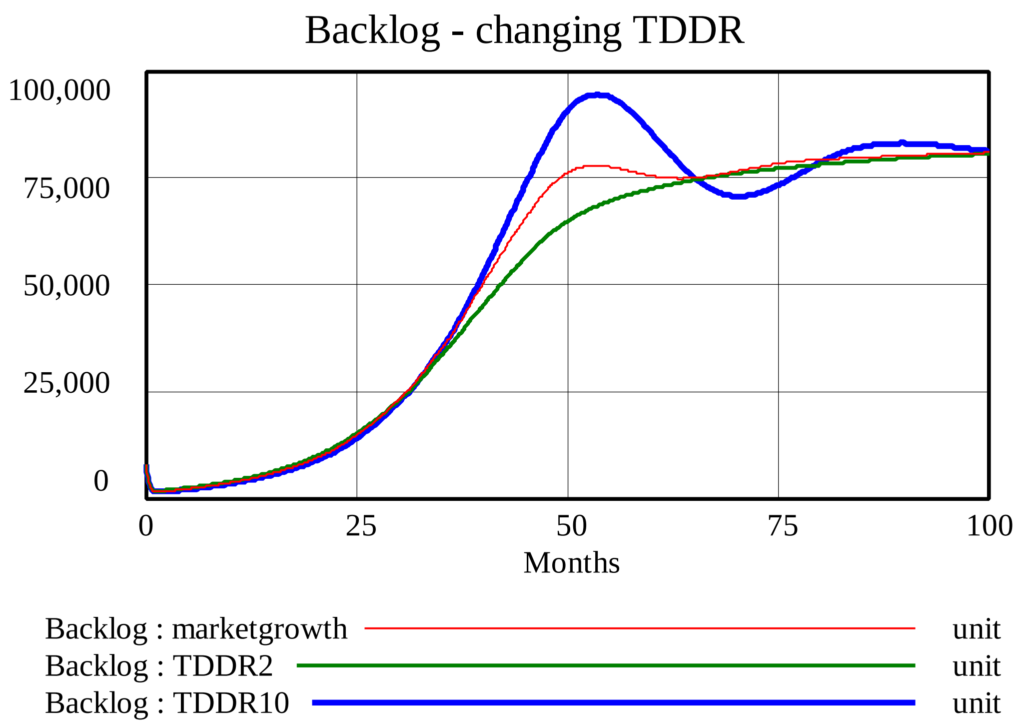
First, let's examine the effect of changes in the "SALESMEN ADJUSTMENT TIME." This time constant controls how fast the rate of "salesmen hired" adjusts the number of "Salesmen" to the number of "indicated salesmen," and hence affects the speed of approach to equilibrium. A higher value of "SALESMEN ADJUSTMENT TIME" should therefore result in a longer time to reach unchanged equilibrium values for all system levels. On the other hand, when the "SALESMEN ADJUSTMENT TIME" is longer, the amplitude of oscillations should be damped. A lower value of "SALESMEN ADJUSTMENT TIME" would then reduce the time to reach equilibrium and increase the amplitude of oscillations. These expectations are confirmed by the following graphs that show the model behavior with "SALESMEN ADJUSTMENT TIME" equal to 10 (SAT10), 20 (marketgrowth), and 30 (SAT30) months:

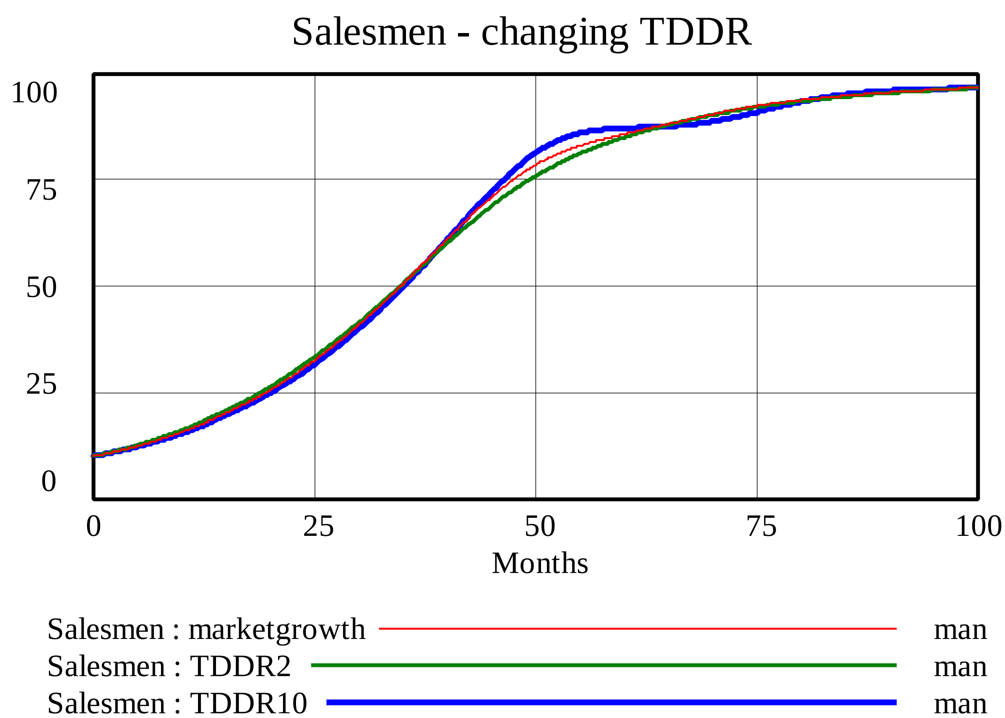

Backlog - changing SAT
120,000
90,000
60,000
30,000
0
0
25
50
75
100
Months
Backlog : marketgrowth
unit
Backlog : SAT10
unit
Backlog : SAT30
unit

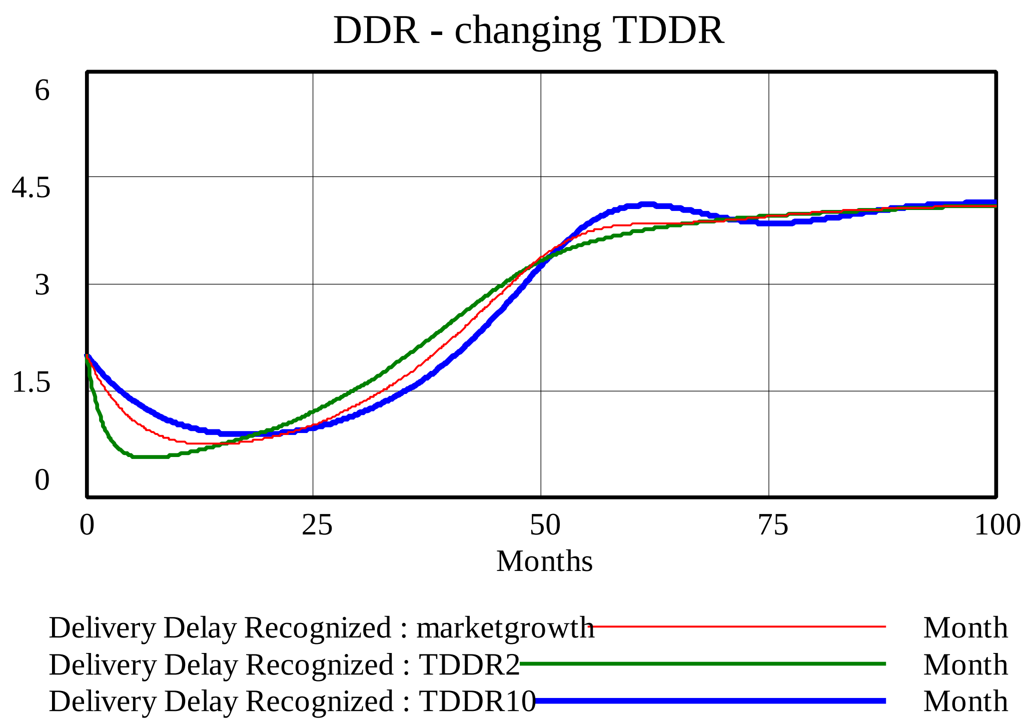

Salesmen - changing SAT
100
75
50
25
0
0
25
50
75
100
Months
Salesmen : marketgrowth
man
Salesmen : SAT10
man
Salesmen : SAT30
man



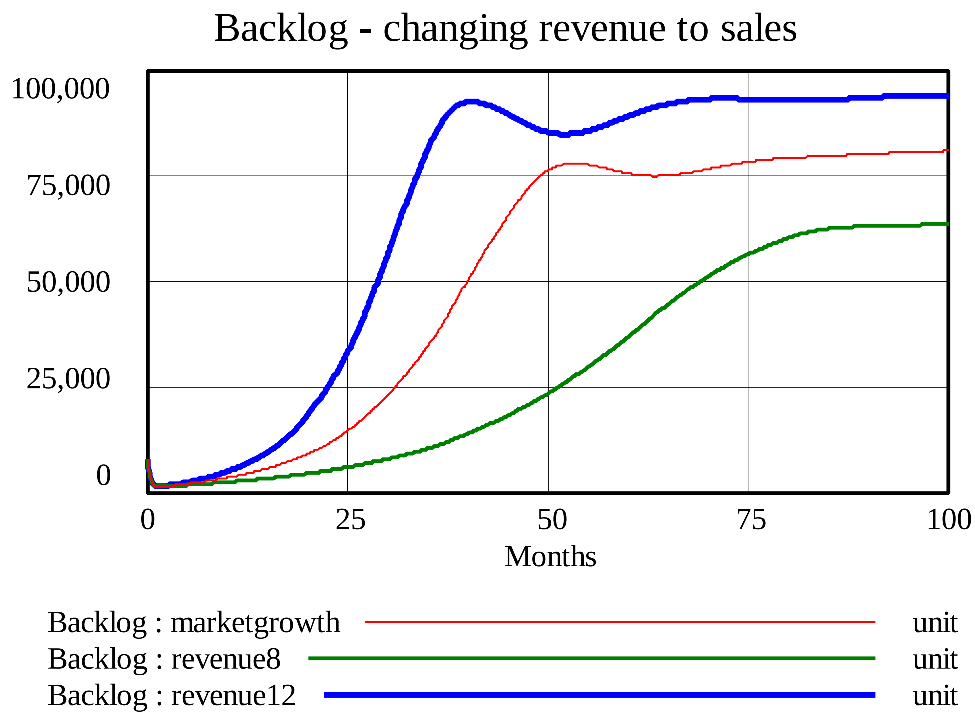
The time constant "TIME FOR DELIVERY DELAY RECOGNITION" determines the difference between the "delivery delay impending" and the "Delivery Delay Recognized." The difference between the actual and recognized state of the system is the source of the damped oscillation. The greater the difference, the higher the magnitude of oscillations, and the longer the time to reach equilibrium. Hence, the higher the value of "TIME FOR DELIVERY DELAY RECOGNITION," the slower the approach of "Delivery Delay Recognized" to its goal, "delivery delay impending," which results in stronger oscillations that take a longer time to be damped towards equilibrium. A lower value of "TIME FOR DELIVERY DELAY RECOGNITION" should therefore dampen the oscillations and make the system approach equilibrium faster. The following graphs confirm these expectations, showing the system behavior with "TIME FOR DELIVERY DELAY RECOGNITION" equal to 2 (TDDR2), 6 (marketgrowth), and 10 (TDDR10) months:

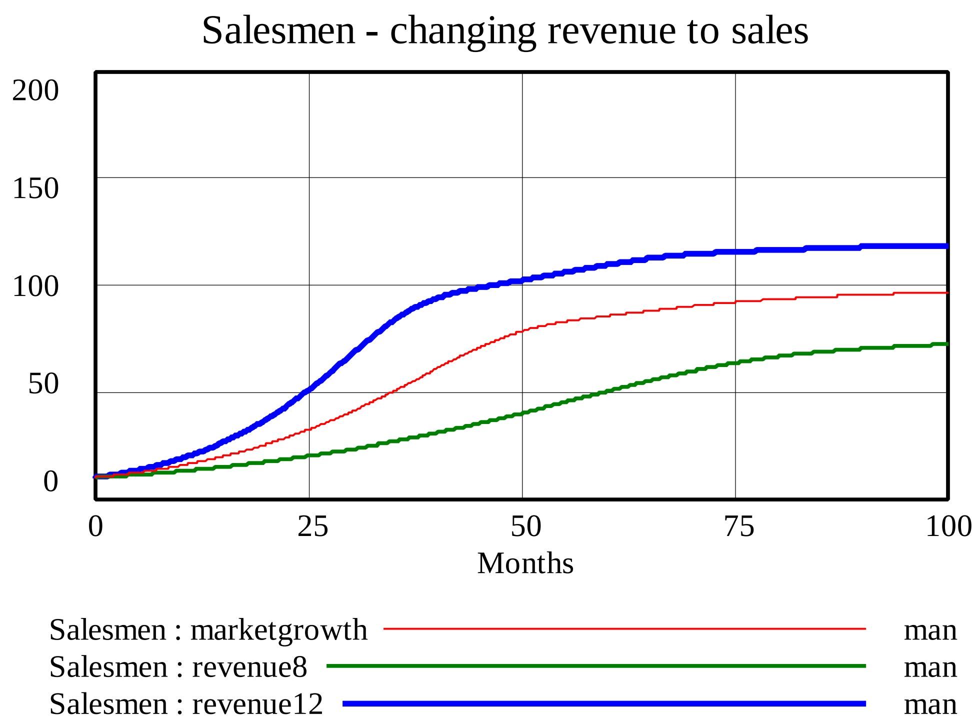

Backlog - changing TDDR
100,000
75,000
50,000
25,000
0
0
25
50
75
100
Months
Backlog : marketgrowth
unit
Backlog : TDDR2
unit
Backlog : TDDR10
unit

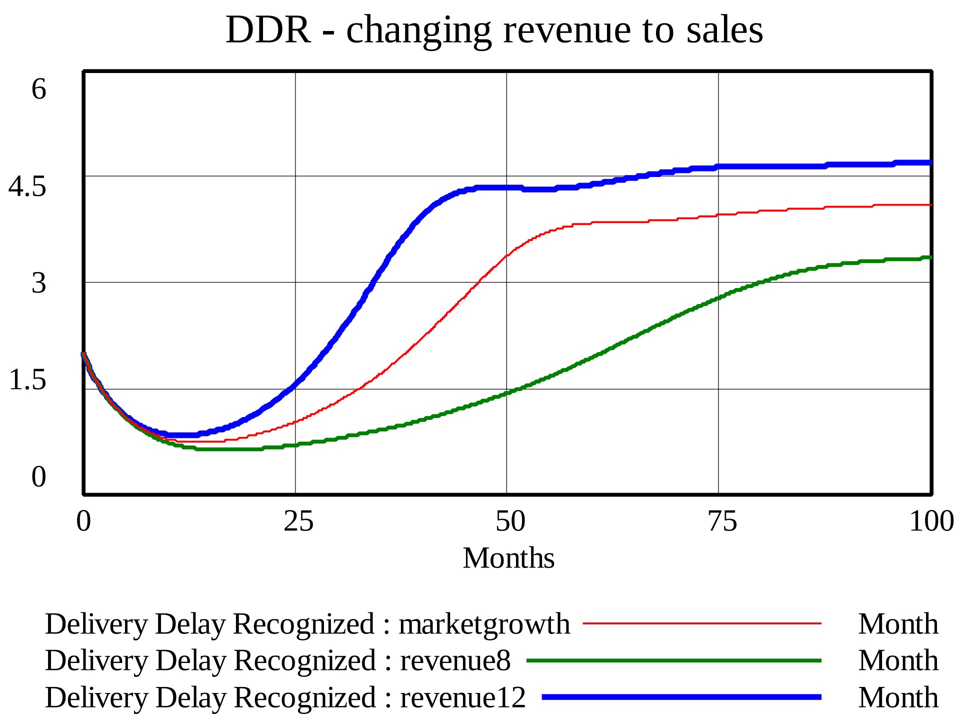

Salesmen - changing TDDR
100
75
50
25
0
0
25
50
75
100
Months
Salesmen : marketgrowth
man
Salesmen : TDDR2
man
Salesmen : TDDR10
man



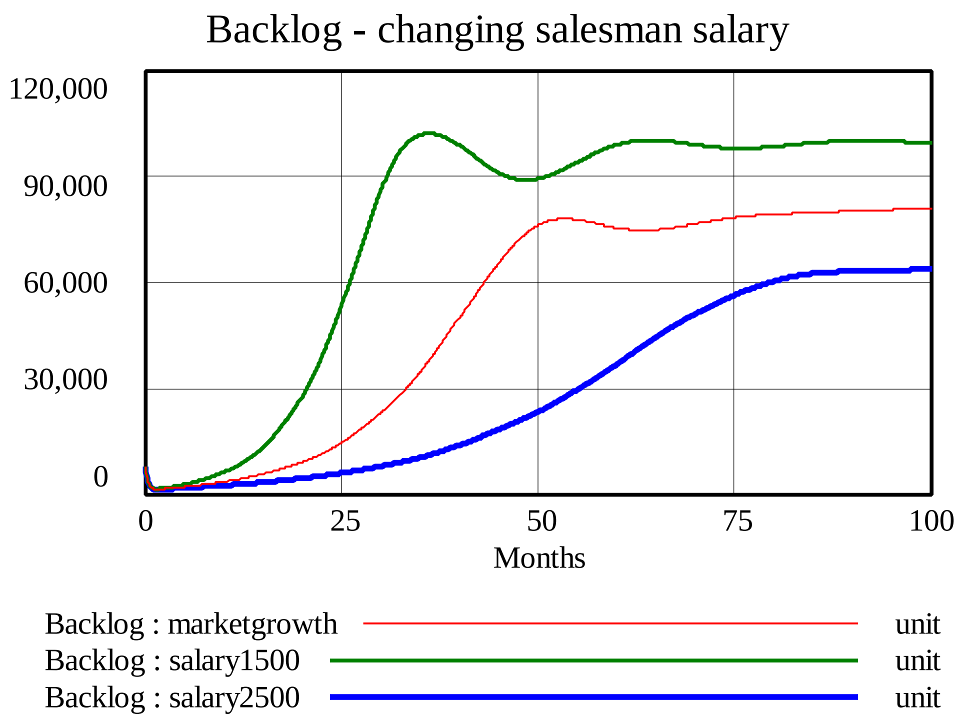
The "REVENUE TO SALES" parameter determines how much money is allocated towards the sales budget for each order booked. A higher value of "REVENUE TO SALES" means the ability to hire more new salesmen, which results in faster growth and increased instability of the system, measured by higher amplitude of oscillations. In addition, a higher amount allocated to the sales budget should result in higher equilibrium values of all system levels. Reducing "REVENUE TO SALES" should have the opposite effect on system behavior: the company will be able to afford fewer "Salesmen," resulting in slower growth but increased system stability, accompanied by lower equilibrium values of "Backlog" and "Delivery Delay Recognized." The following graphs confirm these expectations, showing the system behavior with "REVENUE TO SALES" equal to 8 (revenue8), 10 (marketgrowth), and 12 (revenue12) dollars per unit:

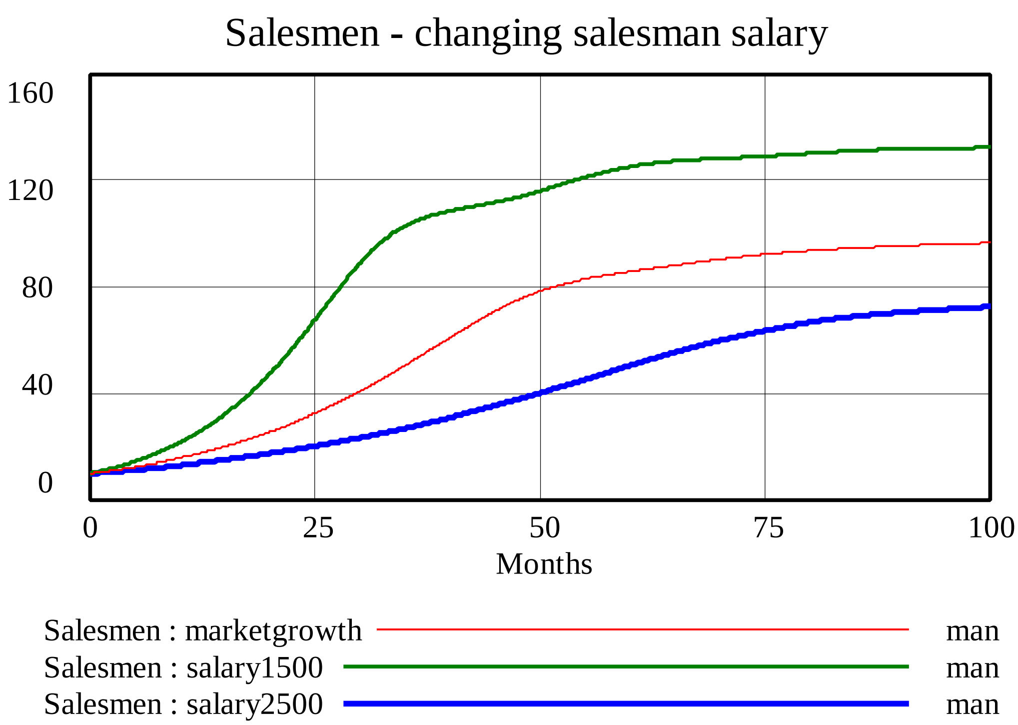

Backlog - changing revenue to sales
100,000
75,000
50,000
25,000
0
0
25
50
75
100
Months
Backlog : marketgrowth unit
Backlog : revenue8 unit
Backlog : revenue12 unit

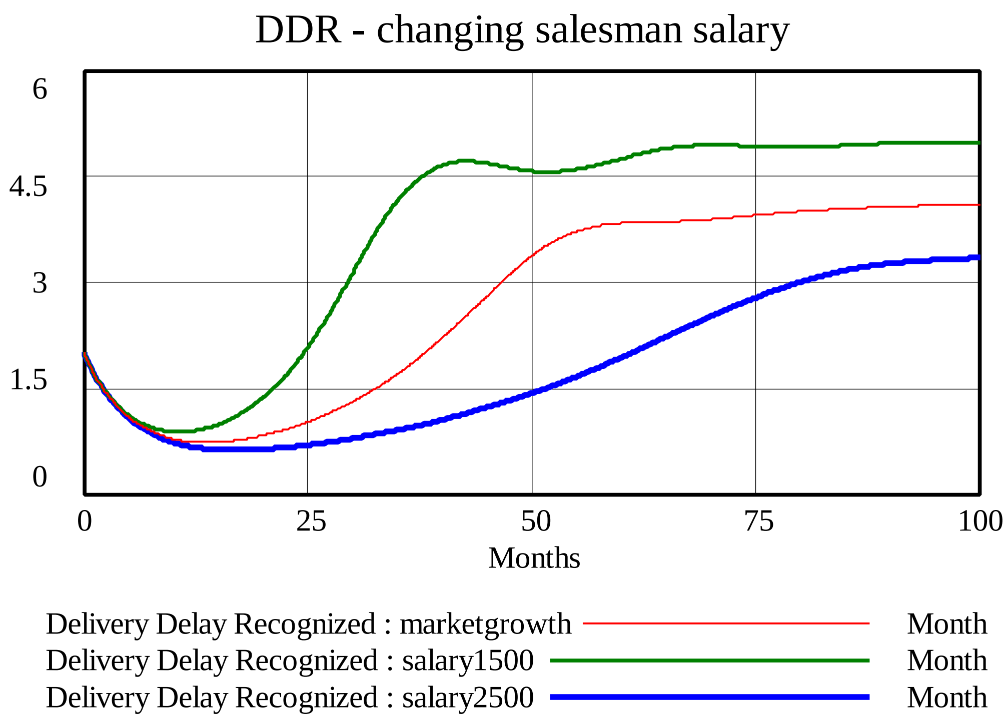

Salesmen - changing revenue to sales
200
150
100
50
0
0
25
50
75
100
Months
Salesmen : marketgrowth man
Salesmen : revenue8 man
Salesmen : revenue12 man



The "SALESMAN SALARY" parameter determines how many "Salesmen" the company can afford to have given a fixed budget. A higher value of "SALESMAN SALARY" therefore means that the company is able to higher fewer new "Salesmen," thus slowing the growth and increasing system stability. Also, an increase in "SALESMAN SALARY" reduces the equilibrium values of "Backlog," "Salesmen," and " Delivery Delay Recognized." These results are confirmed by the following graphs that show the system behavior with "SALESMAN SALARY" equal to 1500 (salary1500), 2000 (marketgrowth), and 2500 (salary2500) dollars:


Backlog - changing salesman salary
120,000
90,000
60,000
30,000
0
0
25
50
75
100
Months
Backlog : marketgrowth unit
Backlog : salary1500 unit
Backlog : salary2500 unit


Salesmen - changing salesman salary
160
120
80
40
0
0
25
50
75
100
Months
Salesmen : marketgrowth man
Salesmen : salary1500 man
Salesmen : salary2500 man



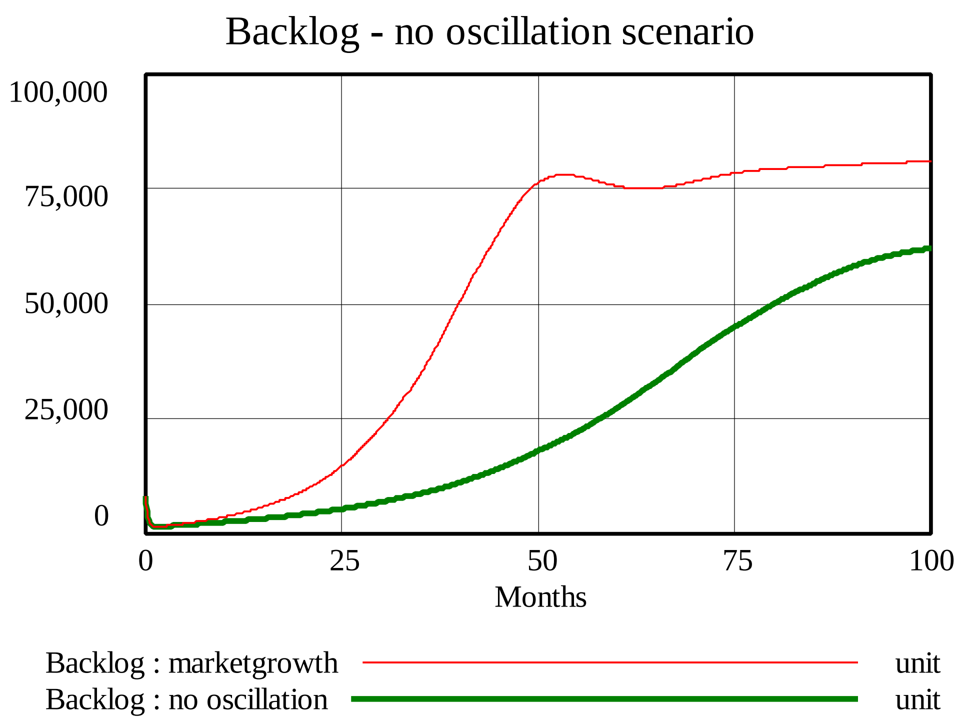
B. Find a combination of realistic parameter values that minimizes the oscillations. List the parameter values and justify your choices by arguing that these values are realistic. Demonstrate and explain how this particular combination of parameter values dampens the system.

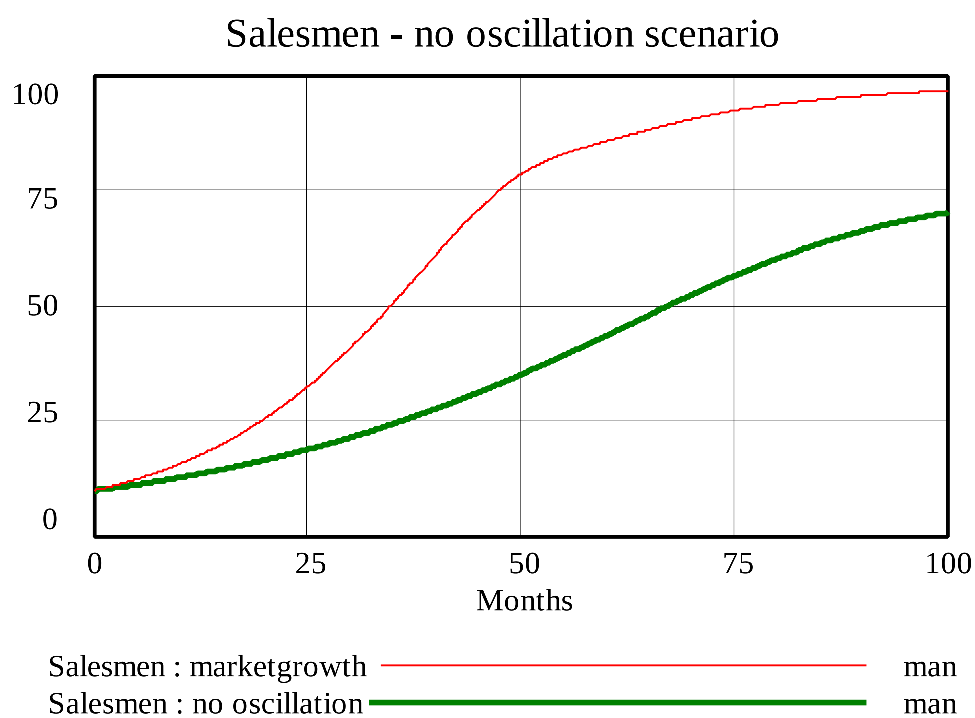
The sensitivity analysis from part A showed that in order to minimize the oscillations of the system, one should increase the adjustment time for hiring salesmen and decrease the time it takes to recognize the delivery delay, while making sure that these changes are realistic. The company could, for example, reduce the "TIME FOR DELIVERY DELAY RECOGNITION" to about 4 months by improving communication with salesmen and customers. The company also decides how fast the number of salesmen should be adjusted to the indicated number, and thus increasing the "SALESMEN ADJUSTMENT TIME" to, for example, 24 months should be possible. In addition, the company can also control the parameters that are related to the sales budget, "REVENUE TO SALES" and "SALESMAN SALARY." Allocating a lower amount towards the sales budget, for example $9 per unit sold, while increasing the salary of salesmen to $2200 will slow down the growth and thus stabilize the system. Many companies, however, may rather have some instability than slower growth.

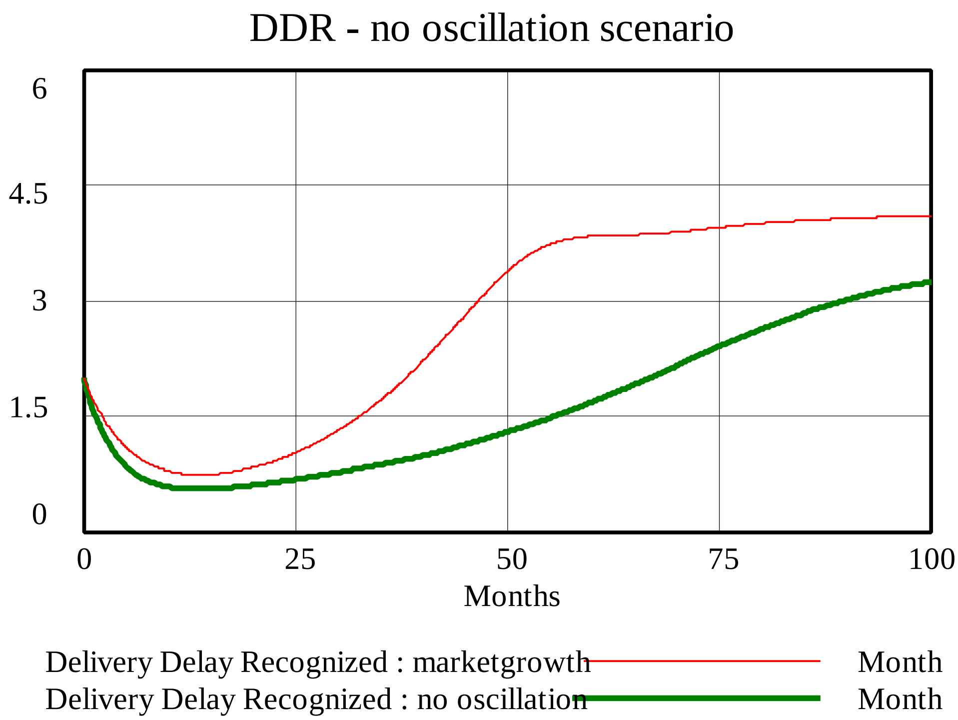
The following graphs show the behavior of the system levels for the original "marketgrowth" run compared to the "no oscillation" run. In the "no oscillation" simulation, the following values were used:

TIME FOR DELIVERY DELAY RECOGNITION = 4 months

SALESMEN ADJUSTMENT TIME = 24 months
REVENUE TO SALES = 9 dollars/unit
SALESMAN SALARY = 2200 (dollars/man)/month







In the "no oscillation" simulation, growth is slower and oscillations are avoided. The equilibrium values for all levels are lower and are reached more smoothly, after a longer time. For many companies, however, more rapid growth would outrank the small amount of overshoot in judging which policy and behavior is more desirable.

4. Learning through System Dynamics as Preparation for the 21st Century:

Please read this vision paper and answer the following questions:

A. Prof. Forrester listed the objectives of a SD education as developing personal skills, shaping an outlook and personality to fit the 21st century, and understanding the nature of systems in which we work and live. Which objective is most important to you? Has system dynamics helped you meet that objective?

To me, the most important objective of a system dynamics education is to understand the nature of systems in which we work and live. I deeply believe that knowledge about us is very valuable. I always believed that we create our own problems, and that we are the ones who can solve them. Somebody said: "The best way to forecast the future is to create it." But, often we are not aware of what we are creating. We tend to concentrate on short-term situations and on short-term goals. At the same time, we are not aware that cause and effect are often not closely related in time or space.

Creating system dynamics models, conducting experiments, and making mistakes (which is the most important) certainly can help us in attaining this objective. One of the models from assignments that I find most rewarding is the eroding-goals model from Assignment 9. I could see how this works on my own example, because I tried to develop a habit of riding a bike twice a week. At first I set my goal too high (three times a week), then decreased it in order to be satisfied. However, the bad thing was that I usually decreased the goal too much (once a week). It took me two years to develop a habit of riding a bike twice a week. This model illustrates what I found most rewarding about system dynamics. For me, the greatest things about system dynamics models are that you have to think about how a system works when developing a model, you can make lots of mistakes in the process, and you can finally experiment with it. The best of all is that system structures are transferable. If one understands how the running goal erodes, he or she will be able to understand how other goals in the personal or public sphere decline. In other words, knowledge is transferable from systems that are not at first sight connected.

B. High leverage policies can often be wrongly applied. Think of an example and explain how the policy could affect the system and what happens if it is wrongly applied.

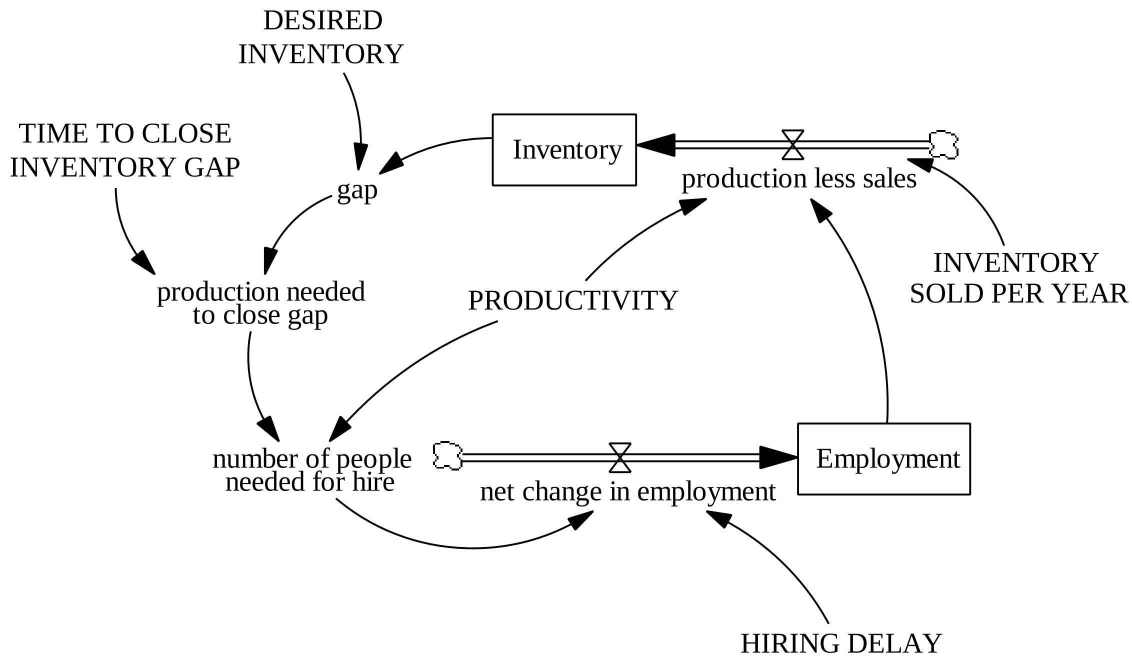
One example of a high leverage policy might be the following situation related to upcoming elections in Indonesia. It was recently suggested by some high-level officials that the elections might have to be postponed by a few months because the country was not fully prepared to carry them out. The purpose of the current policy is to hold elections to create a legitimate government that will have better public support and thus be better able to govern. On the surface, if we ignore the possible political motivations, the policy of delay might appear reasonable: in fact, the nation is not fully ready for elections, people are not registered, ballots may not be ready etc. Thus, a delay could lead to better election conditions.
However, the probable situation that would occur if the elections were postponed would be a country even less able to hold elections. Unrest, already coming to the surface in several areas would break out in many more areas and rumors that certain parties were behind the delay (so they could take advantage of the situation) would grow rapidly. Instability would increase drastically and the probability of fair elections, which is now reasonable, would decrease.

<u>5. Generic Structures in Oscillating Systems</u>

Figure 8 on page 15 shows oscillating behavior of "Employment" and "Inventory." From your understanding of the model, and from what you have learned through the exercises on oscillating systems, please answer the following questions.

A. Build the employment instability model in Vensim PLE. In your assignment solutions document, include the model diagram and documented equations.

<u>Model diagram:</u>



<u>Model equations:</u>

DESIRED INVENTORY = 20000
Units: widgets
The desired inventory, which is also equal to one year worth of sales.

Employment = INTEG (net change in employment, 200)
Units: people
Number of employees.

gap = DESIRED INVENTORY – Inventory
Units: widgets
The difference between desired inventory and current inventory.

HIRING DELAY = 0.25
Units: year
The time required to hire and train new employees to work to full productivity.

Inventory = INTEG (production less sales, 25000)
Units: widgets
The number of widgets in the inventory.

net change in employment = number of people needed for hire / HIRING DELAY
Units: people/year
The rate at which the number of employees changes.

number of people needed for hire = production needed to close gap / PRODUCTIVITY
Units: people
The number of people needed for hire is the desired production needed to close the inventory gap divided by the productivity.

production less sales = Employment * PRODUCTIVITY – INVENTORY SOLD PER YEAR
Units: widgets/year
The change in inventory per year.

production needed to close gap = gap / TIME TO CLOSE INVENTORY GAP
Units: widgets/year
The production of widgets needed to close the inventory gap is the number of widgets needed divided by the time desired to close the inventory gap.

PRODUCTIVITY = 100
Units: widgets/people/year
The number of widgets a person can produce per year.

SALES PER YEAR = 20000
Units: widgets/year
Number of widgets sold every year.

TIME TO CLOSE INVENTORY GAP = 0.5
Units: year
The desired time within which the plant manager would like the inventory discrepancy to be fixed.

Notice that the model has the same basic structure as the model used in Exercise 2 of assignment 20. That is, the model contains only one loop within which are two level equations. There is no cross loop from either level back to any part of the system. Hence, as discussed in assignment 20, if this system contains an initial imbalance, it will oscillate continuously without the oscillation growing or diminishing.

B. What changes can you make to the model to change the amplitude of the oscillations? Verify your hypotheses by implementing the changes using the model you built in part A. In your assignment solutions document, include graphs of the model behavior that support your hypotheses.

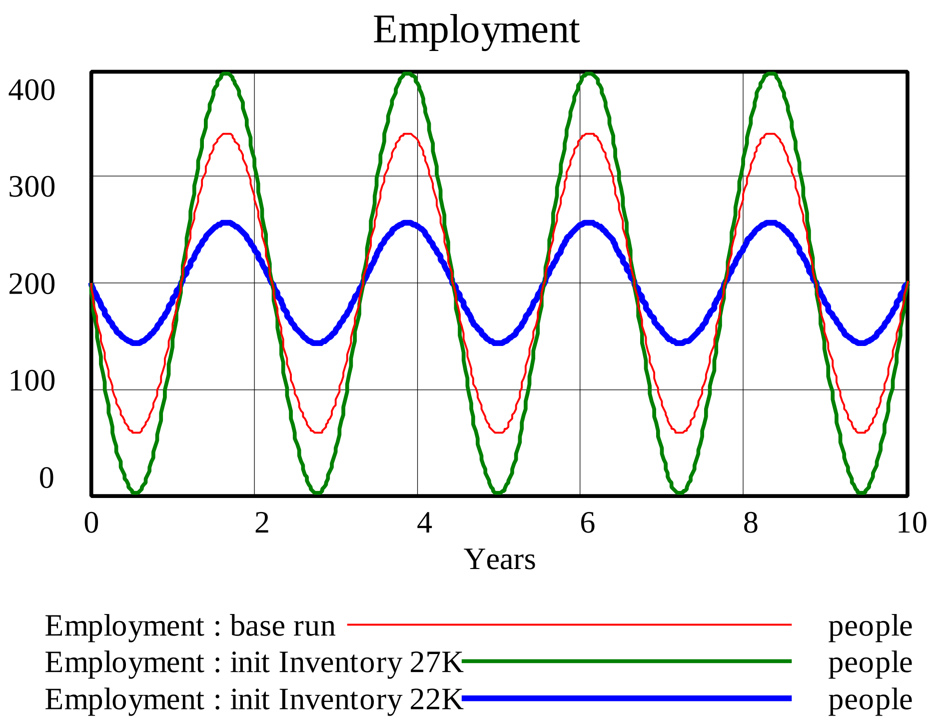
As explained in assignment 20, in a system consisting of a single loop with two levels, the amplitude of oscillation depends on an initial imbalance in the system. As the system corrects that imbalance, an oscillation is initiated, which is then sustained forever. The amplitude is dependent on the degree of imbalance. When the two levels have initial values that represent system equilibrium, there will be no oscillation.

Hence, for a given system with a particular set of parameters, the only way to affect the amplitude of oscillation is to alter the initial values of the levels.

The inventory-employment system as given starts out with 25,000 widgets in the "Inventory" and 200 employees. The company's sales are fixed at 20,000 widgets per year. Because the "PRODUCTIVITY" per employee is 100 widgets per year, the system has exactly the right number of employees to supply the sales. The initial "Inventory," however, is 25,000 widgets while the "DESIRED INVENTORY" is 20,000 widgets, representing an initial imbalance that leads to sustained oscillation.

Employment hiring and firing decisions are made in an effort to seek the right number of employees to maintain a "DESIRED INVENTORY." Meanwhile, production is determined by the number of employees multiplied by each employee's annual "PRODUCTIVITY." The two stocks drive each other and are constantly compensating for any gap, positive or negative, between "Inventory" and "DESIRED INVENTORY." The amplitude is entirely dependent on the nature of the initial imbalance in the system.

The following figure shows the effects of changing the initial value of "Inventory." An increase in the initial value of "Inventory" leads to an increase in the amplitude of oscillation because there is now a greater imbalance in the initial conditions (remember that in the original scenario, the initial value of "Inventory" was greater than the "DESIRED INVENTORY"). A decrease in the initial value of "Inventory" leads to a decrease in the amplitude of oscillation because there is a smaller imbalance in the initial conditions. The figure below shows the model behavior with initial value of "Inventory" equal to 25,000 widgets (base run), 22,000 widgets (init Inventory 22K), and 27,000 widgets (init Inventory 27K):

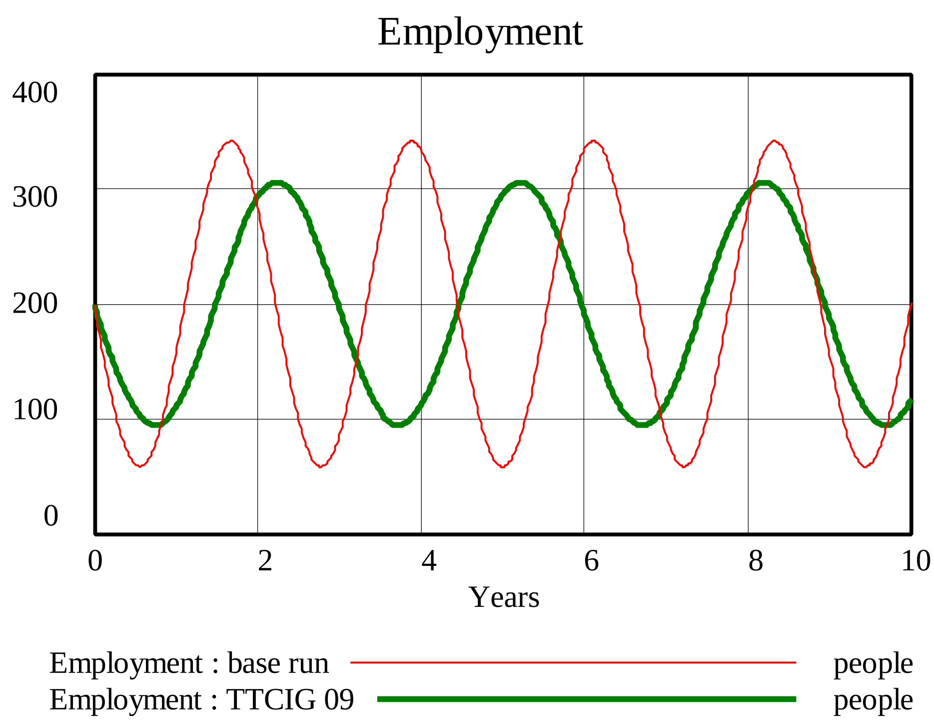


The reader may have observed in this model that the amplitude of oscillation can apparently be caused to change by changing various parameters in the model. However, such is not a valid test because changing a parameter represents a change in the system itself. Only a change in initial conditions will change the amplitude of oscillation within a specific two-level, single-loop system. When one changes parameters in this simple model and observes a change in amplitude, the change in amplitude arises because the new parameters result in a new degree of disequilibrium. Some parameter changes (such as desired inventory) can change the equilibrium of the system so that the initial values of levels are either closer to or farther from the new system equilibrium. Other parameter changes can accentuate the initial disequilibrium, such as an increase in productivity in this model, which causes an initial increase in the already excessive initial inventory.

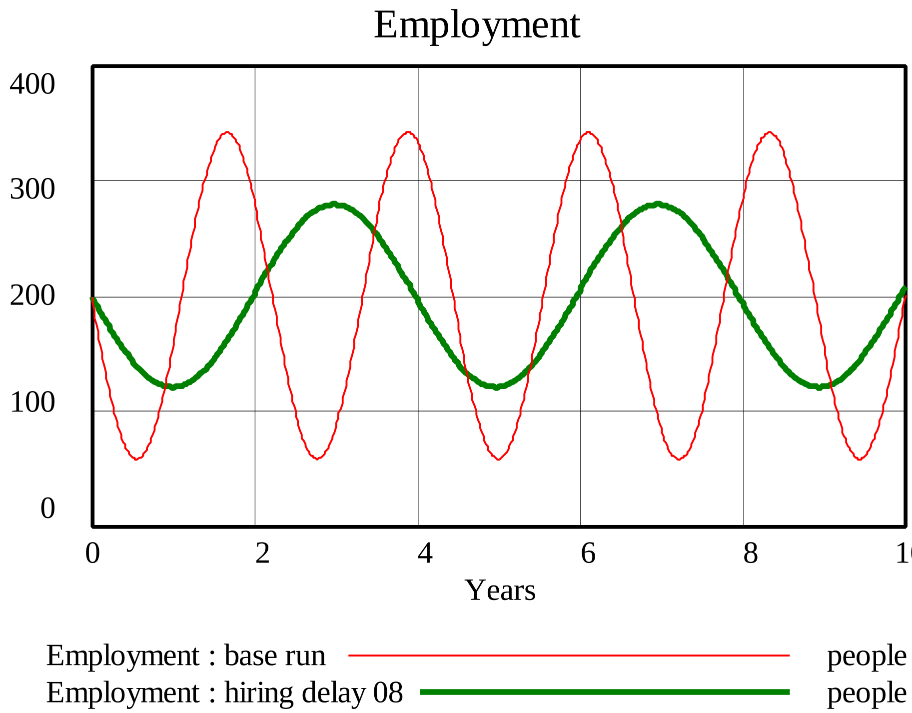
C. What changes can you make to the system and model to change the period of the oscillations (the period is the time that passes between two consecutive peaks)? Verify your hypotheses by implementing the changes using the model you built in part A. In your assignment solutions document, include graphs of the model behavior that support your hypotheses.

The period of the oscillation will change with any parameter that changes the gain around the loop. Remember that the "speed" at which a stock grows or falls depends on the constant associated with its flow. Therefore, if the delay is long, it will take more time for the stock to approach its desired value. Thus, the period increases. However, you will notice that changing the value of "PRODUCTIVITY" does not change the period of oscillations in this model. It turns out that "PRODUCTIVITY" appears in the model twice: it is multiplied with "Employment" once and divided by "production needed to close gap" once. As a result, the effect of altering the value of "PRODUCTIVITY" on the model behavior is canceled out.

As an example of a parameter change that alters the period, the following graph shows the behavior of "Employment" with different values for "TIME TO CLOSE INVENTORY GAP." In the original model, "TIME TO CLOSE INVENTORY GAP" was set to 0.5 years. In the modified simulation, that value was raised to 0.9 years. As the time constant increases, the period increases as well:



Similarly, altering other parameters can change the period of oscillation. The graph below shows an increase in "HIRING DELAY" from 0.25 years to 0.8 years, resulting in a longer period of oscillation:



The above graphs show that increasing time constants in the system increases the period (reduces the frequency) of oscillations. Many companies, in their attempt to control inventory fluctuations, decide to "react faster," decreasing the time constants, and end up having even greater instability than before.

D. Is it possible for "Employment" and "Inventory" to oscillate at different frequencies (the frequency of an oscillation is the inverse of its period)? Why or why not?

No, it is impossible for the two stocks to ever oscillate at different frequencies within this model, just like in the model used in Exercise 2 of assignment 20. Each stock drives the other's flow, thus sustaining the oscillating behavior. When the flow to one stock peaks, the flow to the other stock is zero. If the two stocks were to oscillate at different frequencies, we would not see the sustained oscillating behavior that this structure produces. In order for two stocks in the same system to oscillate at different frequencies, the system must be of higher-order (that is, contain more stocks).

The results from this exercise confirm the analysis from Exercise 2 of assignment 20 and the exercises on oscillations from previous assignments. The amplitude of oscillation is determined by the initial imbalance in the system, that is, by the imbalance between the initial and desired values of the levels. Recall that in Exercise 2 of assignment 20, changing the initial value of "Stock" or "Stock 2" resulted in a change in amplitude, without affecting the period. The period of oscillation is determined by system parameters that change the gain around the loop. Again, recall that changing the "stock 2 multiplier" in Exercise 2 of assignment 20 resulted in a change in period.