VENTANA systems, inc.

Vensim® Software

Linking systems thinking to powerful dynamic models

(Global) Model Analysis with Vensim

Tom Fiddaman
Ventana Systems, Inc.

Agenda

- **Introduction**
  - Why analyze?
  - Process
  - Habits
- **Speed-critique some global models**
  - World Dynamics
  - World3
  - Wonderland
  - DICE

Models & materials available at
http://vensim.com/vensim-video-library/

Why Analyze?

- **Better decisions**

- via -

- **Quicker and deeper understanding**
- **Responsible model use (knowledge of limitations)**
- **Faster model development (slow down to speed up)**

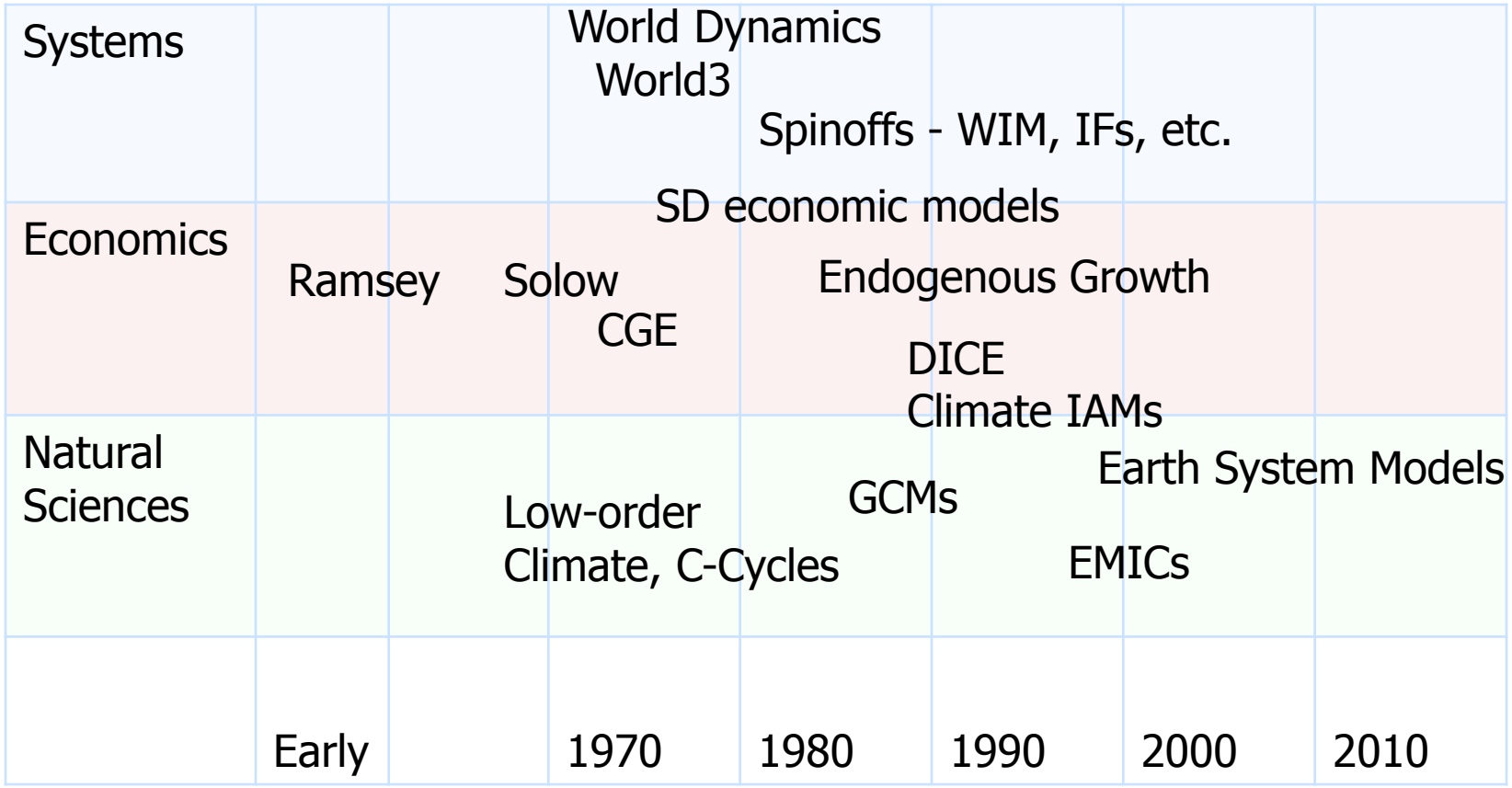
Process

- **Problem identification**
  - What questions is the model trying to answer? For whom?
- **Replication**
  - Can you reconstruct and run the model and experiments from archived sources?
- **Structure Inspection**
  - Evaluate fitness to purpose
  - Reveal structural flaws
  - Develop analytical insights
- **Behavior Testing**
  - Explore robustness and realism
  - Diagnose problem behaviors
  - Evaluate policy conclusions

Learning Habits

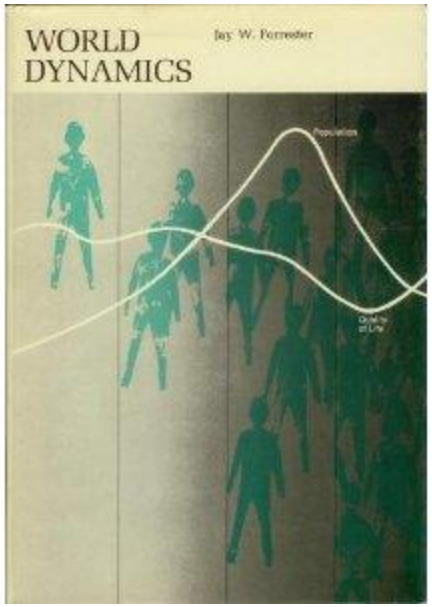
- **Scientific method**
  - Use controls – vary one thing at a time
  - Confirm/reject hypotheses with appropriate tests
- **Learn from surprise**
  - Develop and record expectations before running experiments
  - Follow up on puzzling outcomes
- **Relate behavior to structure**
- **Look at every variable in the model at some point**
- **Think about the structural Big Picture**
- **Keep a lab notebook to record deficiencies and insights**
- **Share**

A crude history of global models



World Dynamics

- **Jay W. Forrester, 1971**



Model Inspection

- **Browse through the model to familiarize yourself with its structure.**
  - How many feedback loops can you identify?
  - What are the key decisions?
  - What are the key stocks and flows? Do they contain physical quantities or information?
  - What common structures (or Molecules) are used?
  - Can you spot any potential problem areas?
- **Check the units of the model. Are there any errors?**

Base Run Behavior

- **Make a "Base" run with no parameter changes, and explore the behavior.**
  - Are any runtime warnings generated? What do they indicate? (Be sure Tools>Options>Settings has warnings set to "Display")
- **What does the model do?**
  - What behavior modes does the model exhibit? Exponential growth or decay? Overshoot? Oscillation?
  - What variables change the most? The least?
- **What variables, stock-flow structures, or feedback loops are responsible for the behavior you see?**
- **Is the behavior driven by external disturbances, or is it due to inherent tendencies of the model?**

Simulation Method

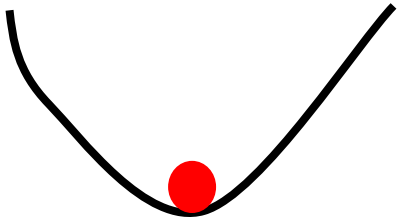
- **Run the model with a new name, using a TIME STEP half the initial value (i.e. 0.125 years).**
  - Is there a change in behavior?
- **What happens as you increase the TIME STEP (for example, 2 years)? Is this realistic?**
- **What does this say about the time constant for pollution?**

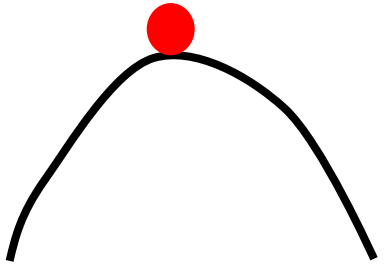
Pollution Equilibrium

- **In Synthesim, right-click to override Pollution Generation with a constant, using the default range [0,4e10]**
  - What happens?
- **Temporarily isolate pollution from population/capital issues by overriding Population with a constant (but hold the thought)**
- **Smoothly vary Pollution Generation from about 5 billion upwards (right arrow key while the slider is active is handy for this)**
  - What happens above about 14 billion?
- **Stop & Restart your simulation**
- **As another way of looking at this, override Pollution with a ramp from 0 to 200 billion (=200e9 or 2e11)**

Global Equilibrium

- **Is the model initially in equilibrium?**
- **Does it achieve an equilibrium state after some time?**
  - Try extending the time horizon (FINAL TIME) to see what happens
- **Can you identify an equilibrium state?**
  - Is it interesting, or somehow trivial?
  - Is it stable, i.e. does the model return to equilibrium after a small disturbance?
  - Do you think there are others?
- **For each stock, what would have to be true for equilibrium to be achieved?**





Putting the model in equilibrium

- **Option 1: manual experimentation**
  - See Equilibrium view in the model for a control panel
- **Option 2: seek analytic solutions**
- **Option 3: numerical - automate with optimizer**
  - Create a payoff that penalizes net changes in stocks
  - Create a control file that sets initial stocks
  - Run over a short time horizon
  - Optimize to minimize the payoff
  - Use random multistart to explore multiple possibilities
  - (Beyond today's scope)

Feedback Elimination

- **Starting from a new run, override Pollution with a constant, near the initial value (<1e9)**
  - What does this modification to the model mean in terms of the real system?
  - How does the behavior change?

- **At the same time, hold Natural Resources constant**
- **Now what happens to population and capital?**

- **Try holding just Natural Resources constant**
  - Extending FINAL TIME by a few hundred years helps to see what's happening

Feedback Elimination
Oscillation with constant Natural Resources

Continuing with constant Natural Resources,

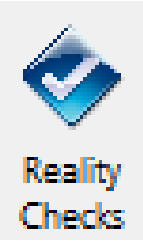
- **What kind of oscillation is this? How could you tell?**
- **Does the level of resources matter?**
- **Are there parameters or lookups that influence the amplitude, period, phase, etc.?**
- **Can you determine the structure essential to the oscillation?**
  - Does the Capital Agriculture Fraction stock need to participate?
- **What happens to the response to various lookups over the cycle?**
  - You can flatten the shape of a lookup on the fly to eliminate its feedback effect

Decisions, Decisions

- **Start a new Synthesim run**
- **Right-click to override Pollution Generation with a constant, using the default range [0,4e10] and setting it to the middle (2e10=20B)**
- **What is happening to Material Standard of Living and variables that it affects?**

A Reality Check

- **On the Capital & Quality of Life view, take a look at TI no capital**
  - This is a test input that steps capital to 0 in 1950; presumably this should shut down the economy, such that there is no output or investment
- **Look at RC no investment**
  - This is a constraint that tests whether there is in fact 0 investment



- **Use the Reality Check button to run this test**
  - Hit the Test All button
  - Examine the runtime messages and any graphs that pop up

Modeling Decisions

- **Explicit stocks and flows**
- **Desired and actual states distinguished**
- **Only information actually available to decisionmakers is used**
- **Policy structure for achieving the desired states in the system corresponds with practice**
- **Model is robust under extreme conditions**

P. Senge, 1978

Measurement Without Data

- **William Nordhaus (1973) "World Dynamics: Measurement without Data"** ***Economic Journal*** **83:332.**
- **J.W. Forrester, Gilbert Low & Nathanial Mass (1974) "The Debate on** ***World Dynamics*****: A Response to Nordhaus"** ***Policy Sciences*** **5 pp. 169-190.**

- **(These are included in the model folder.)**

Nordhaus' Objection

- See **net pop growth rate** while holding **crowding=1, pollution ratio=1** & **Population-Material_Std** graph

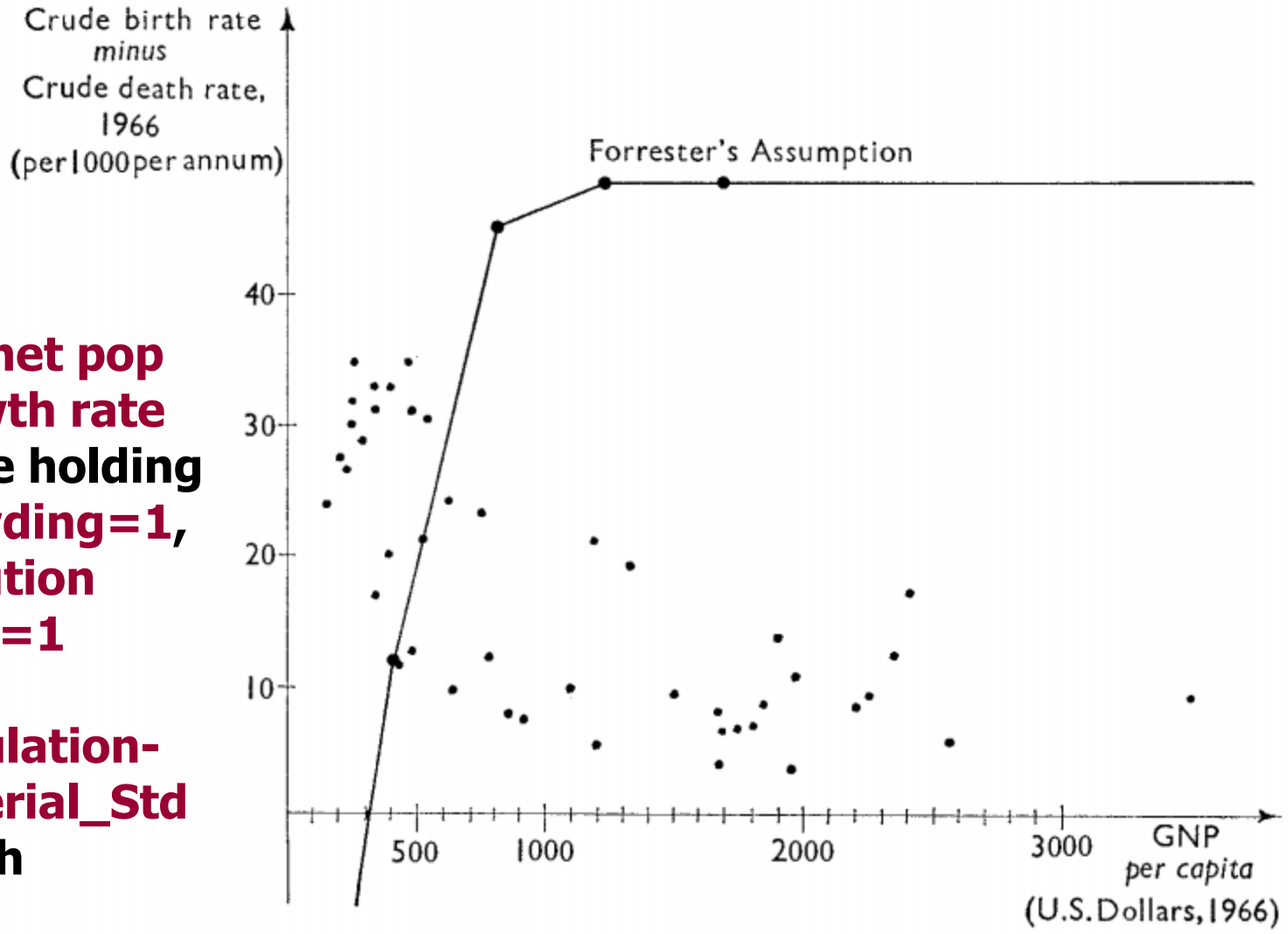
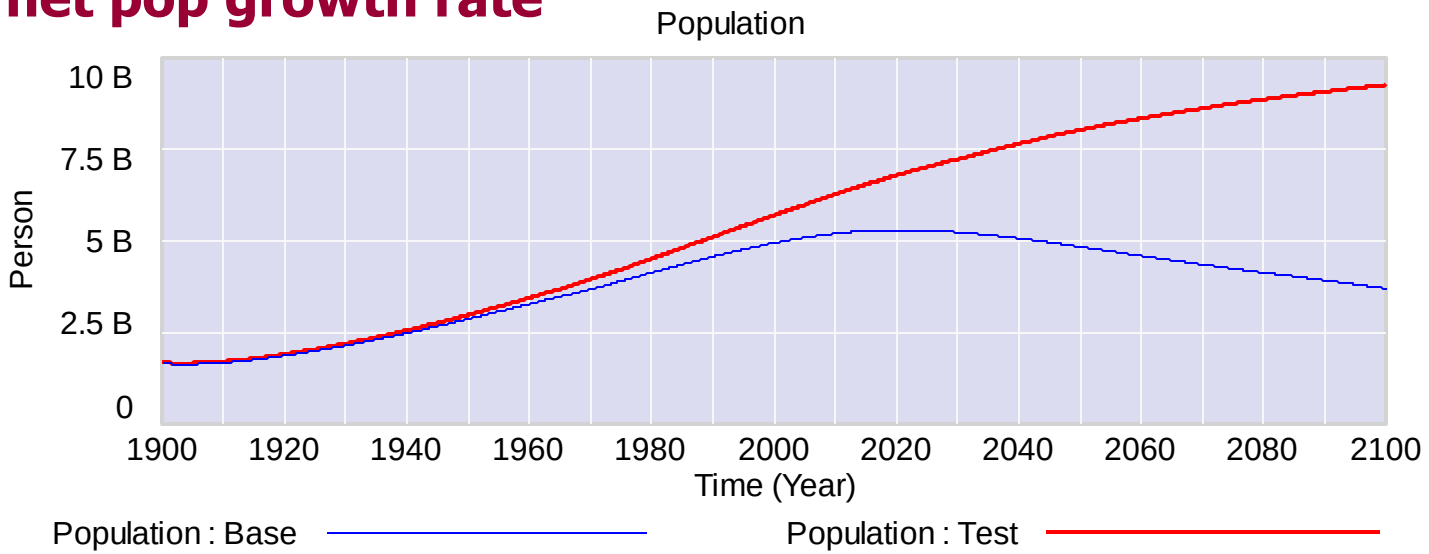


FIG. 2. Assumed and Cross Section Population Growth, 1966.

Forrester et al. Rejoinder

- **Omitting full feedback is a mistake**
- **With all feedbacks but no pollution/resource constraints, the model makes a demographic transition as expected**
- **To test, override Pollution=0 and Natural Resources=900B (900e9), and observe Population and net pop growth rate**



Sensitivity Analysis

- **Experiment with different parameter and lookup changes in the model.**
  - Which feedback loops does the parameter change affect?
  - What influence does the parameter have? Does it change a loop's goal? Does it change the delay around a loop?
  - What characteristics of the output change? Are there slight numerical changes, or qualitative behavior changes?
  - Do the effects of Initial values of the stocks differ from other parameters?

Automating Sensitivity Analysis

- **Use the Sim Control button**  **or Model>Simulate… to bring up the Simulation Control dialog**
- **On the Advanced tab, set the Payoff to QualityOfLife.vpd.**
  - This sets Quality of Life as an objective to maximize
  - Note that the payoff is integrated over time, but here there is no discounting or population weighting, so this is a rough experiment
- **Set the Optimization Control file to AllConstants.voc**
  - This directs Vensim to vary all parameters in the model by +/- 10%
- **Hit the Optimize button**
- **Sorted results are in <runname>_sortsens.tab**

Model Inspection

Model Inspection

- **Basic Assumptions**
  - Scope
  - Simulation Method
  - Perspective
- **Variables**
- **Physics**
- **Functional forms**
- **Special cases**

Model Scope

- **Purpose**
  - Point prediction
  - Behavior pattern prediction
- **Boundary**
- **Time Horizon**
- **Aggregation**

Simulation Method

- **Continuous vs. discrete time or discrete event**
- **Continuous value vs. integer or discrete**
- **Equilibrium/simultaneous vs. disequilibrium**
- **Deterministic vs. stochastic**

Perspective

- **Behavior**
  - Bounded rationality
  - Optimization
  - Evolutionary learning
- **Feedback**
  - Causality vs. correlation
  - Sparse vs. rich

Variables

- **Operational correspondence with real system**
  - One variable <-> one concept
- **Names**
  - Non - normative
  - Nouns for stocks
  - "…ing," "… Rate," etc. for flows
  - Clear direction for positive and negative
  - No double negatives

"Physics"

- **Conservation of stocks and flows of material quantities**
  - Challenge sources & sinks
- **Physical stocks always >= 0**
  - Flows realistically constrained
- **Conformance to other physical laws (thermodynamics, gravity, ...)**
- **Units balance**
  - Flow Units = Stock Units / Time
  - Dimensional analysis

Functional Forms & Lookup tables

- Domain and range
- (Non)linearity
- Continuity
- Monotonicity
- Normalization
- Anchor points
- Reference lines
- Implicit time constants

Functional Forms - Special Cases

- Discrete Logic (IF THEN ELSE, binary switches)
- Discrete Events
- Simultaneity
- Noise
- Delays
- Exogenous inputs
- Data

Testing

Testing

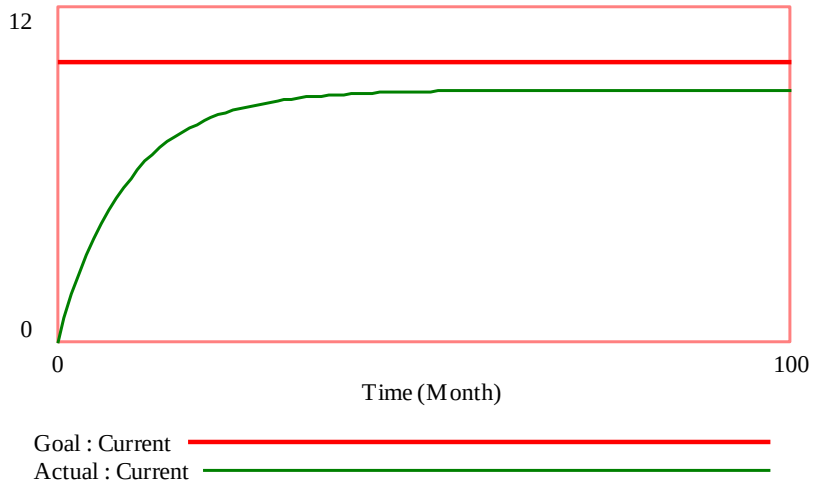
- **Behavior modes and performance**
- **Response to input changes**
- **Sensitivity to simulation technique**
- **Equilibrium**
- **Extreme conditions**
- **Reality Check**
- **Response to parametric and feedback changes**

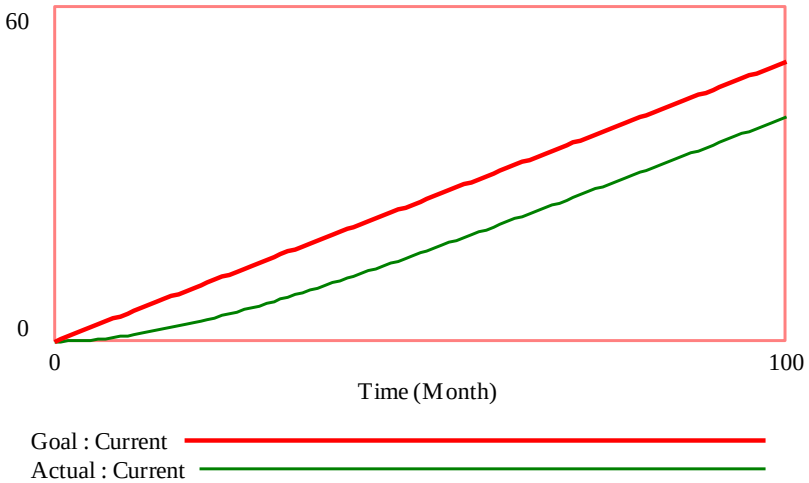
Behavior Modes

- Growth
- Decay
- S-shaped growth
- Overshoot
- Overshoot and collapse
- Oscillation
- Limit cycle
- Chaos

Performance Metrics for Steady State

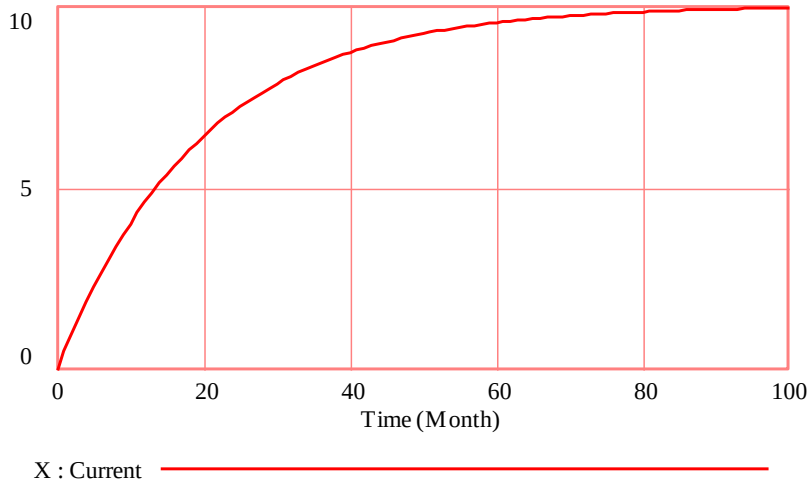
- **Mean value**
- **Equilibrium value**
- **Steady-state error**
- **Velocity error**

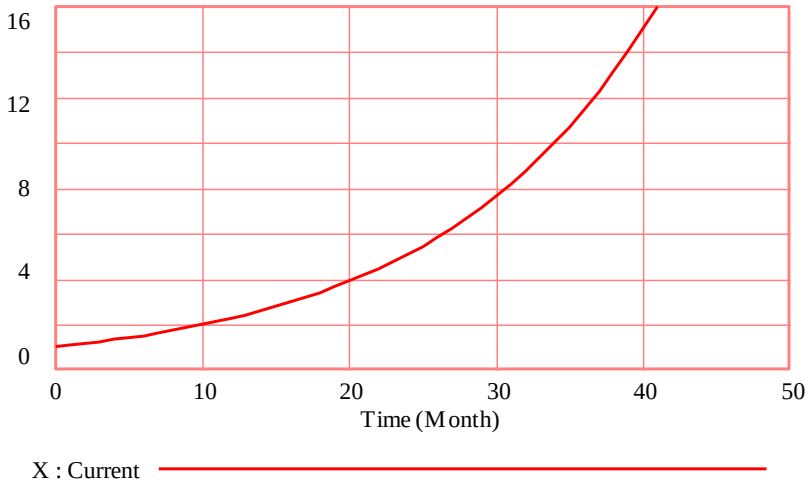




Performance Metrics for Growth and Decay

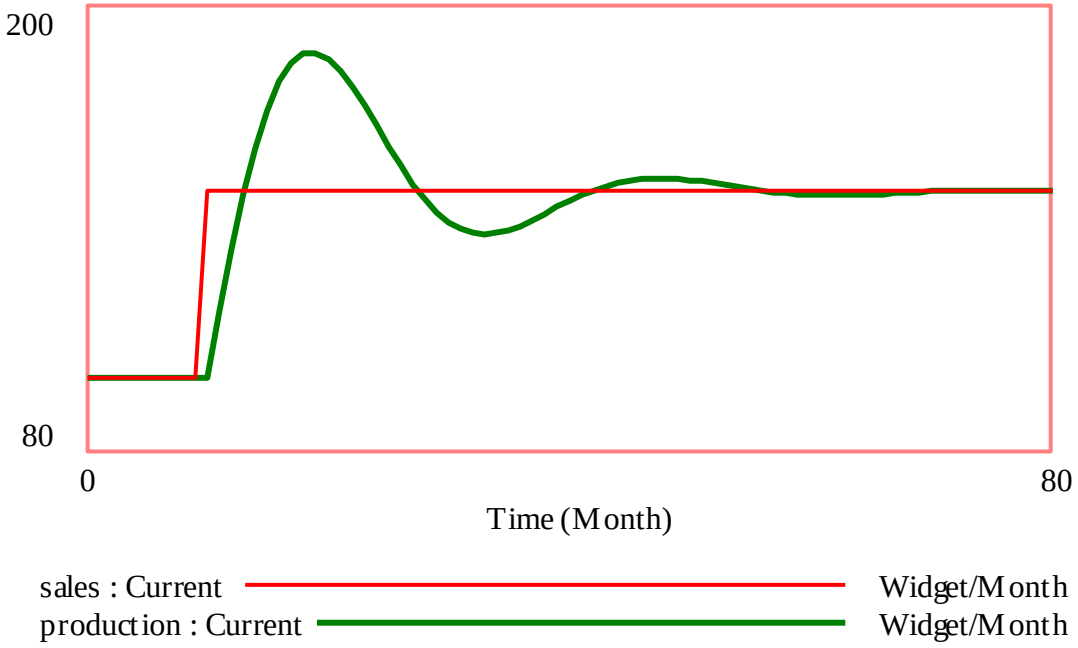
- **Time constant**
- **Half-life**
- **Growth rate**
- **Doubling time**





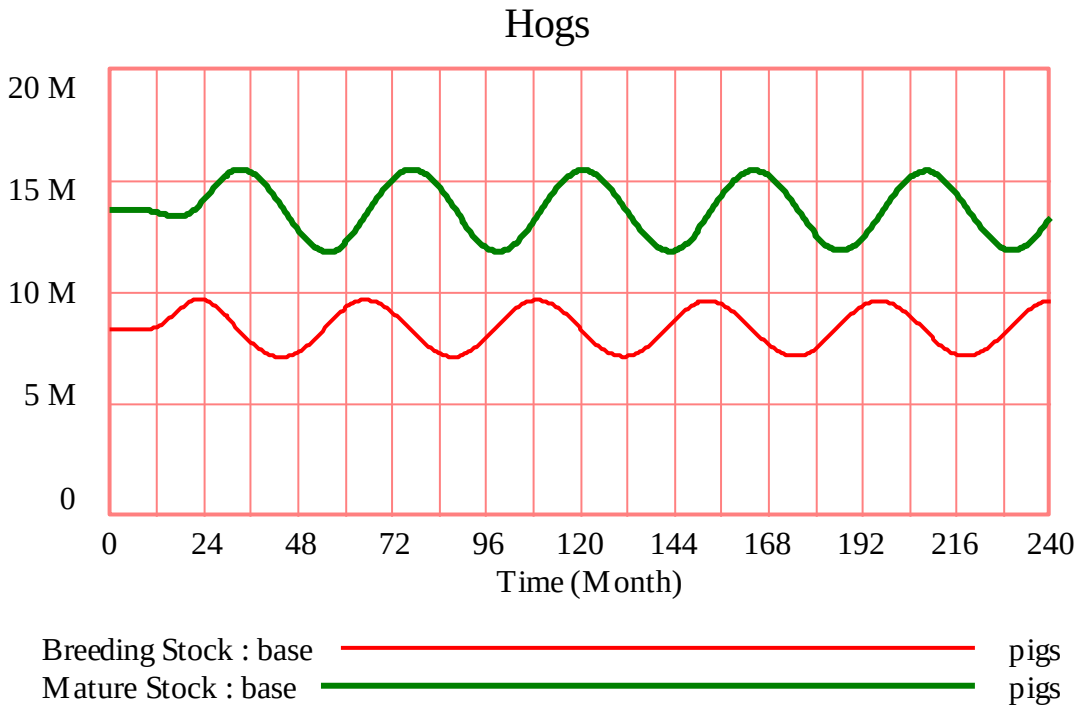
Performance Metrics for Overshoot

- **Rise time**
- **Maximum overshoot**
- **Time to peak**
- **Settling time**
- **Amplification**



Performance Metrics for Oscillation

- **Amplitude**
- **Period**
- **Phase lag**



Equilibrium and Stability

Equilibrium

- **Inflows + Outflows = 0**
- **Initial conditions**
- **Long horizon**
- **Stability**
  - stable
  - unstable
  - metastable
- **Vs. steady state**

Simulation Method

- **Time step**
  - Shorter than 1/2 to 1/4 of shortest time constant (delay)
  - Halve until behavior is unchanging
- **Integration method**
  - Test alternatives
  - Euler for models with discrete events
  - RK4 for models with oscillation

Active Testing

Generating Surprises

- **Test for asymmetric responses to positive and negative disturbances**
- **Test small and large amplitude inputs**
- **Test policies at multiple points in system**
- **Test multiple patterns of behavior**

Dynamic Test Inputs

- **Purpose**
  - Reveal inherent behavior
  - Create extreme conditions
- **Examples**
  - Pulse
  - Step
  - Ramp
  - Exponential growth
  - Noise

Extreme Conditions

- **Purpose**
  - Reveal weaknesses
  - Generate insight
- **Methods**
  - Remove contents of stock with PULSE
  - Cut off inflows or outflows
  - Artificially force variables to 0 or ~infinity

Reality Check

- **Purpose**
  - Automate model quality checks
- **Format**
  - Test input
    - :THE CONDITION: Staff = 0
  - Constraint (expected consequence)
    - :IMPLIES: Production = 0

Structure Testing

Partial Model Testing

- **Purpose**
  - Divide and conquer
  - Develop understanding of subsystems
  - Test response of subsystems to driving data
- **Methods**
  - Cut & paste structures into a new model
  - Use data variables or test inputs to drive behavior

Feedback Elimination

- **Purpose**
  - Identify feedback loops that are causing behavior
- **Methods**
  - Sever flow connections
  - Replace variables with constants or test inputs
  - Insert 0*… or (…)^0 in equations
  - Flatten lookups

Sensitivity Analysis

Examples of Sensitivity

- **Numerical**
  - Numerical values change, but behavior is qualitatively the same
- **Behavior mode**
  - Shift from s-shaped growth to oscillation
- **Policy**
  - Policy conclusions change
- **Chaotic**
  - Small initial deviations grow exponentially
- **Insensitive**
  - Pendulum always comes to rest at bottom

Parameter Sensitivity Analysis

- **Purpose**
  - Link behavior to feedback loop structure
  - Identify leverage points
  - Search for equilibria
- **Methods**
  - Vary parameters and initial conditions
  - Stretch and shift lookup table shapes

Policy Evaluation

- **Purpose**
  - Develop effective policies
  - Identify conditions for effectiveness
  - Identify weaknesses in formulation of existing policies
- **Tools**
  - Sensitivity Analysis
  - Optimization
  - Gaming