G54SOD (Spring 2018)

Lecture 05

System Dynamics Modelling and Simulation + Hybrids

Peer-Olaf Siebers

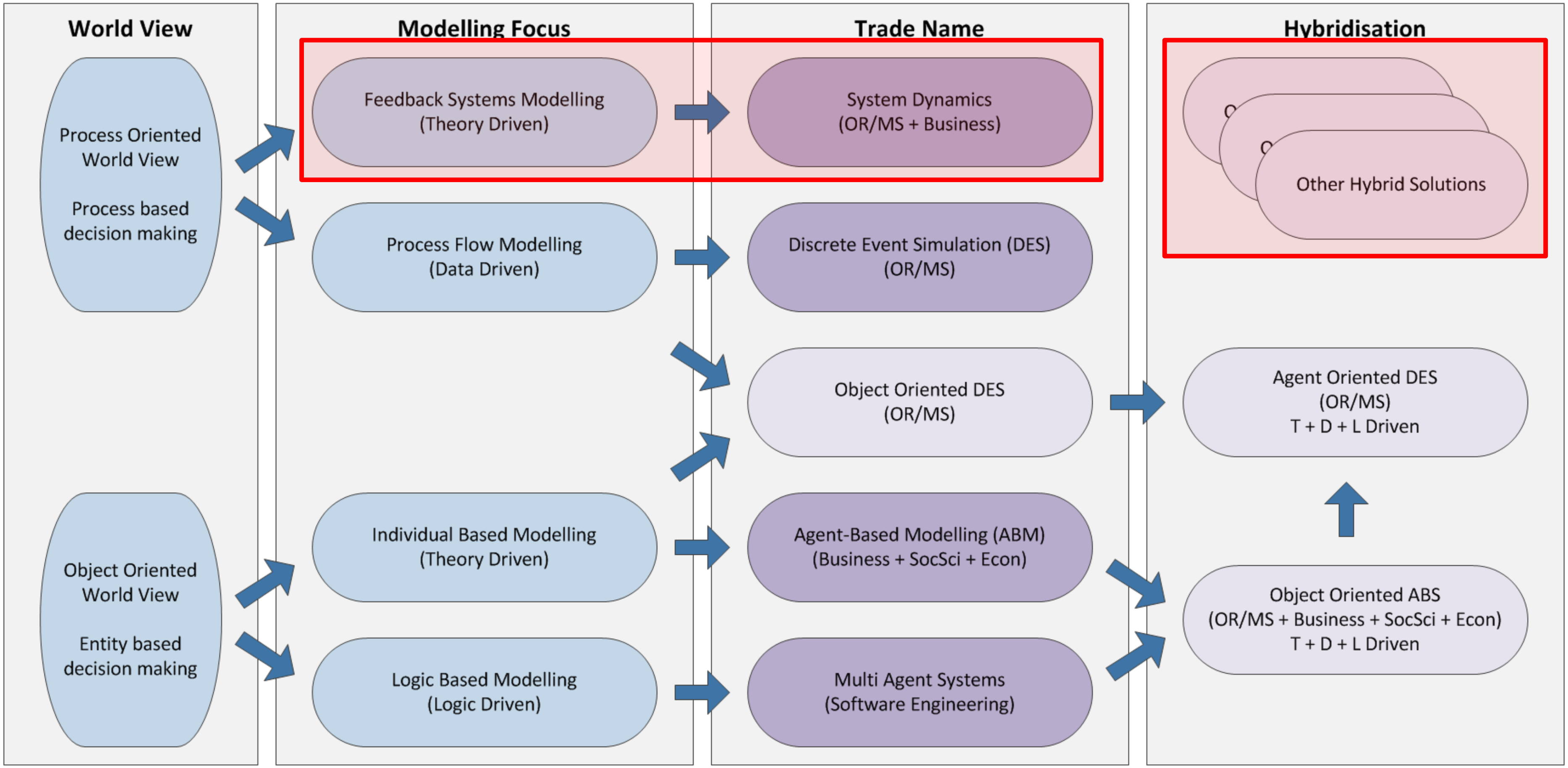
pos@cs.nott.ac.uk

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Motivation

- Understand the concepts of Systems Thinking and SD
- Gain insight into the design of SD models
  - Causal Loop Diagrams
  - Stock and Flow Diagrams
- Understand the "Math" behind the models
- Look at hybrids (SD+AB and AB+SD)

Simulation Modelling Framework

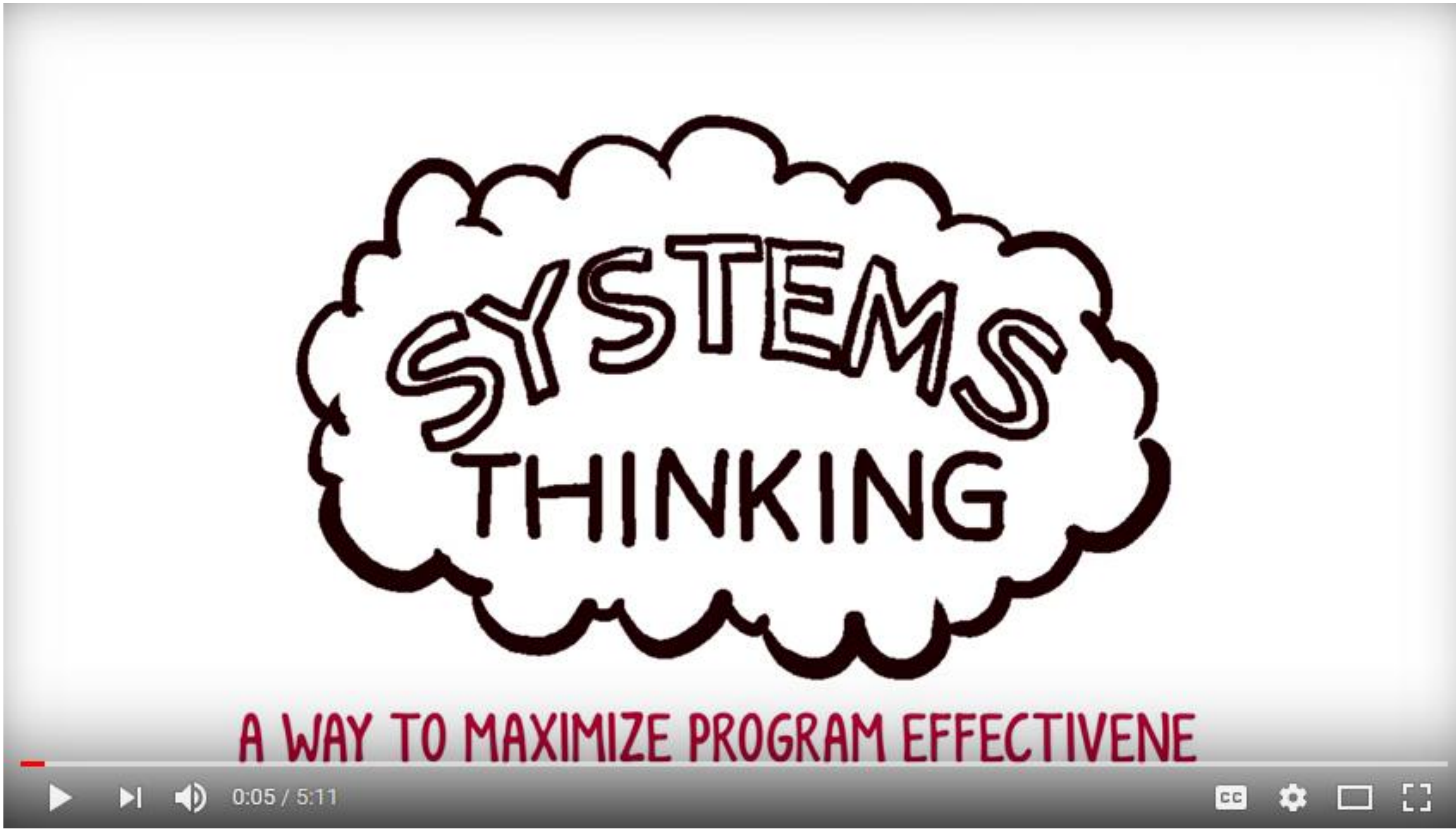


Theory Driven: Theories for model formulation; data for model validation
Data Driven: Data for model formulation (can be quantitative and qualitative); data for model validation
Logic Driven: Logic for model formulation; data for model validation

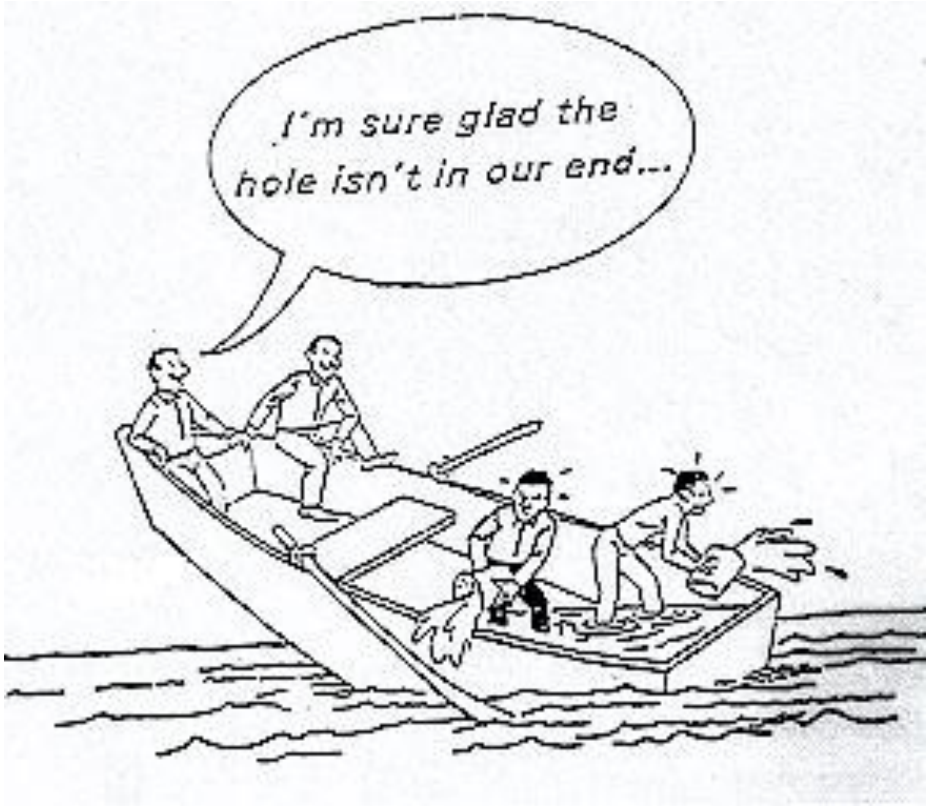
Systems Thinking
and System Dynamics

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

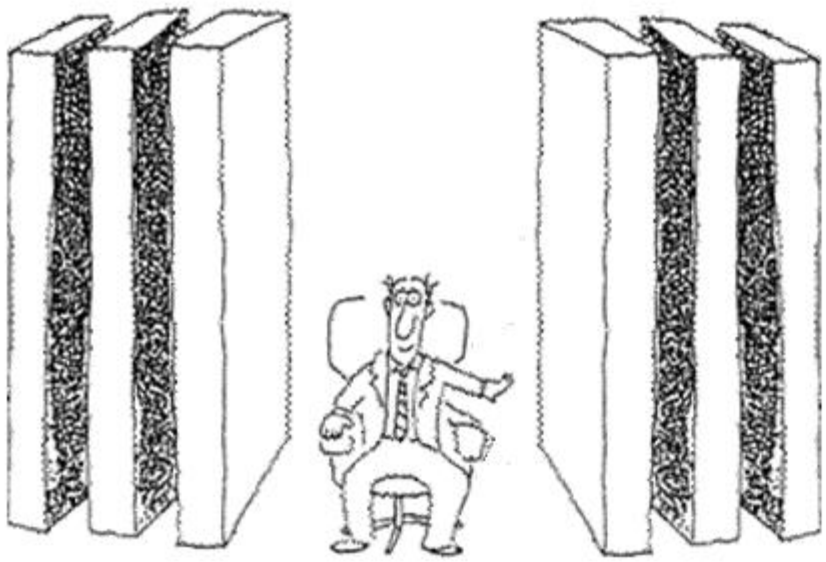
Systems Thinking



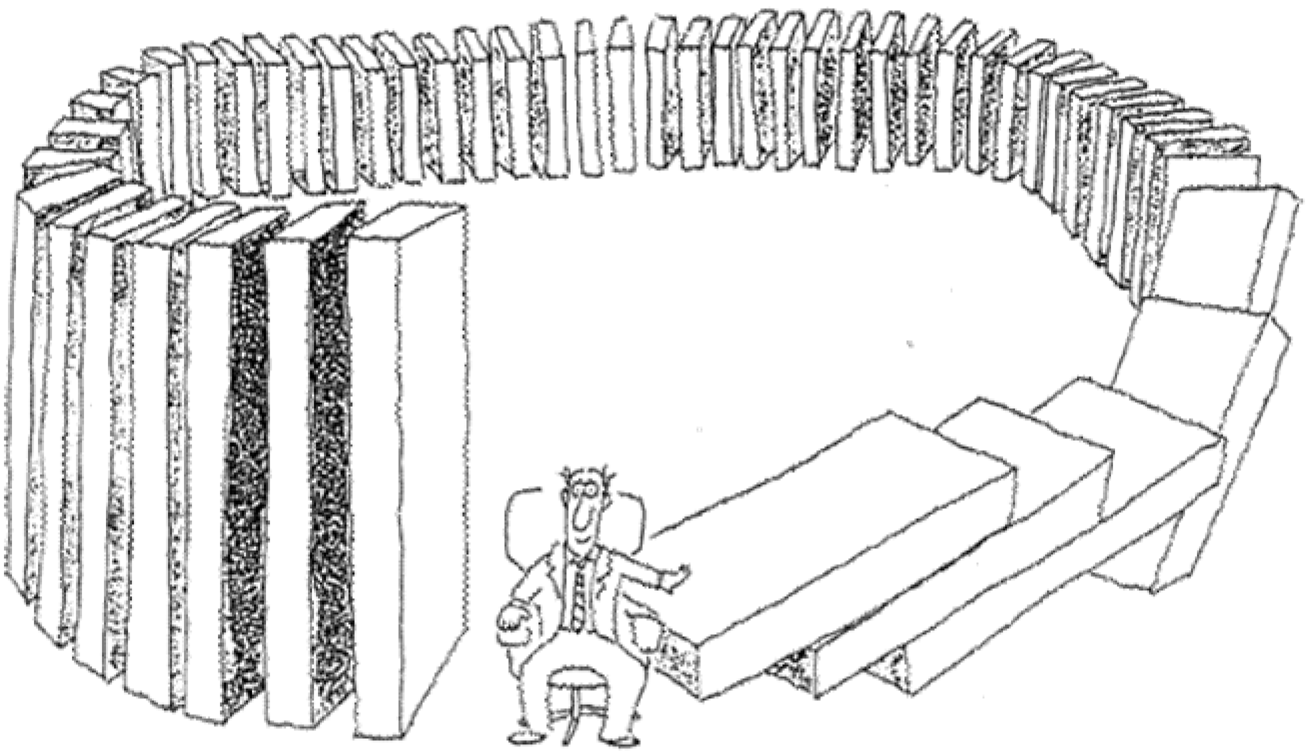
Systems Thinking



Systems Thinking



Systems Thinking



Systems Thinking / System Dynamics

- **Systems Thinking (ST):** The process of understanding how things influence one another within a whole. [Wikipedia]

- **System Dynamics (SD):** An approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. [Wikipedia]

System Dynamics
Modelling and Simulation

The University of Nottingham

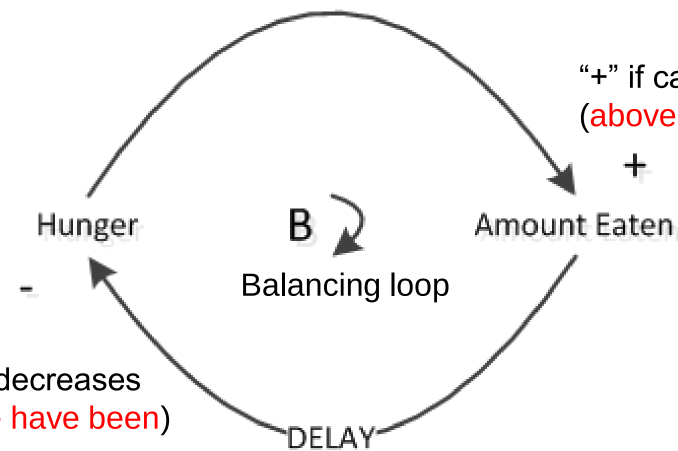
UNITED KINGDOM · CHINA · MALAYSIA

System Dynamics Modelling

- Model representations
  - Causal loop diagrams (qualitative)
  - Stock and Flow diagrams (quantitative)

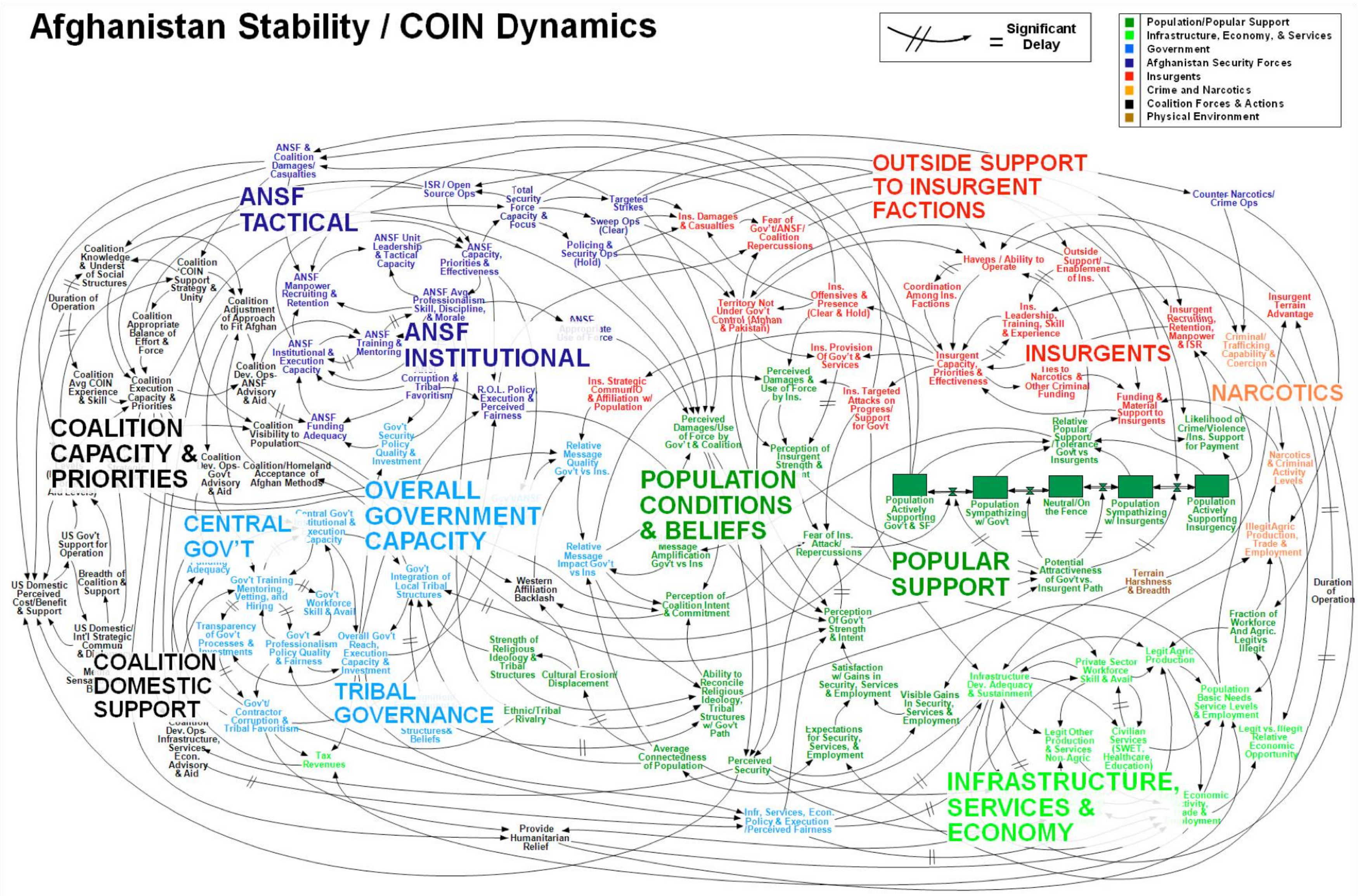
- Example: Simple causal loop diagram of food intake [Morecroft 2007]

“+” if cause increases ... effect increases
(above what it would otherwise have been)



“-” if cause increases ... effect decreases
(above what it would otherwise have been)

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA



For explanation see: http://msnbcmedia.msn.com/i/MSNBC/Components/Photo/_new/Afghanistan_Dynamic_Planning.pdf

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

System Dynamics Study Life Cycle

- Conceptualisation
  - Define purpose of the model
    - Focus on a problem and narrowing down the model's audience
  - Define model boundaries and identify key variables
    - Select components necessary to generate the behaviour of interest as set by the model purpose
  - Describe behaviour or draw the reference modes (hypothesised or based on historic data) of the key variables
    - Some of the most important variables are graphed over time; a modeller needs to think about which factors influence each other
  - Diagram the basic mechanisms (feedback loops) of the system
    - The basic mechanisms represent the smallest set of realistic cause-and-effect relations capable of generating the reference mode

System Dynamics Study Life Cycle

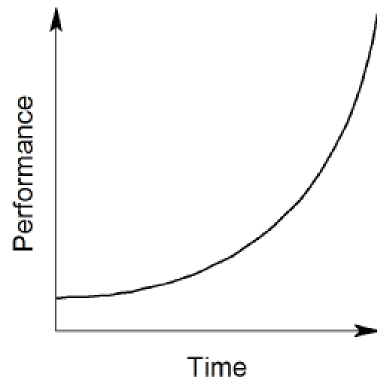
- Formulation
  - Convert diagrams to stock and flow equations
  - Estimate and select parameter values
  - Create the simulation model
- Testing
  - Test the dynamic hypothesis (the potential explanation of how structure is causing observed behaviour)
  - Test model behaviour and sensitivity to perturbations
- Implementation
  - Test model's responses to different policies
  - Translate study insight to an accessible form

System Dynamics Modelling

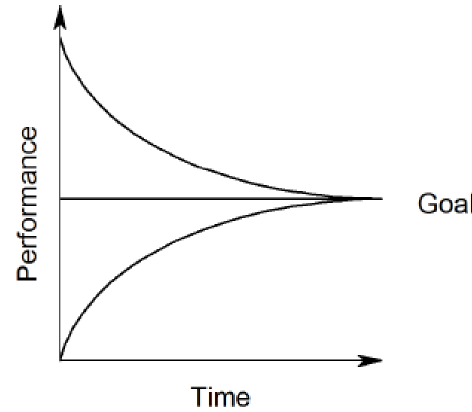
- Considering patterns of behaviour
  - Generalise from the specific events to consider patterns of behaviour that characterise the situation
  - Once we have identified a pattern of behaviour that is a problem, we can look for the system structure that is known to cause this pattern
  - By finding and modifying this system structure you have the possibility to permanently eliminate the problem pattern of behaviour

System Dynamics Modelling

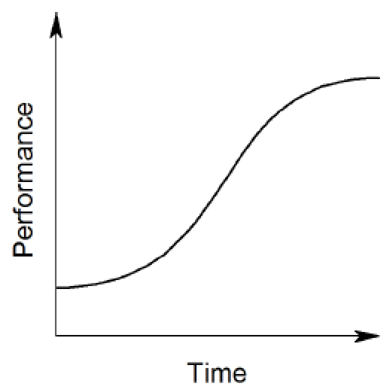
- Common patterns that show up either individually or combined



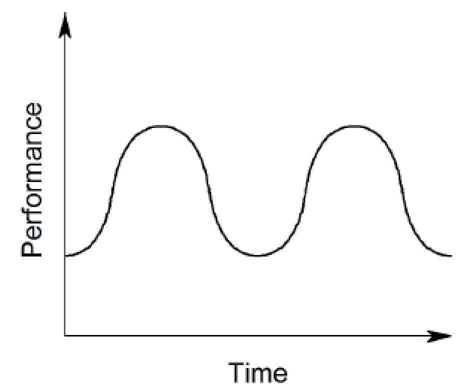
a. Exponential growth



b. Goal-seeking



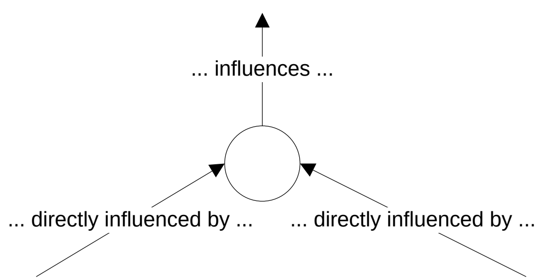
c. S-shaped

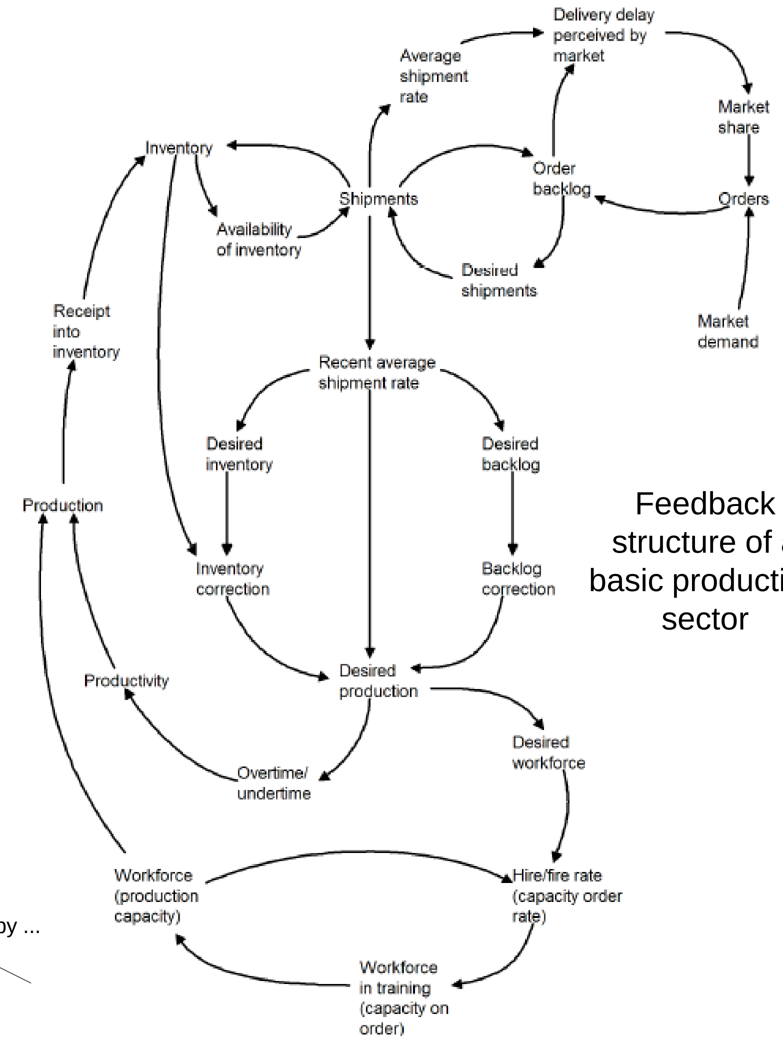


d. Oscillation

Feedback and Causal Loop Diagrams

- Notation for presenting system structures
  - Short descriptive phrases represent the elements which make up the sector.
  - Arrows represent causal influences between these elements

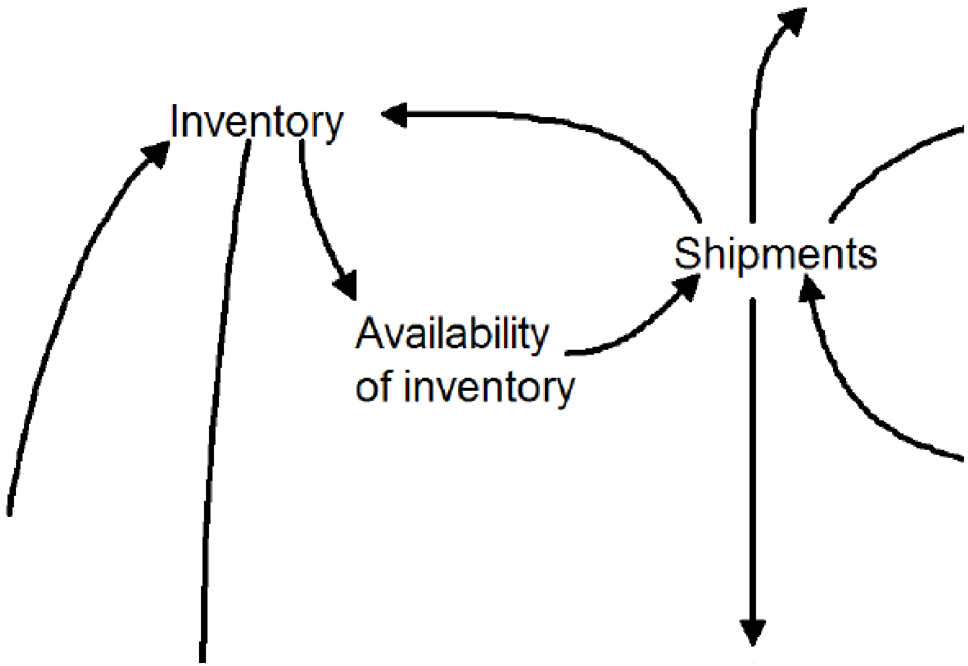




Feedback structure of a basic production sector

Feedback and Causal Loop Diagrams

- Feedback loop or causal loop: Element of a system indirectly influences itself



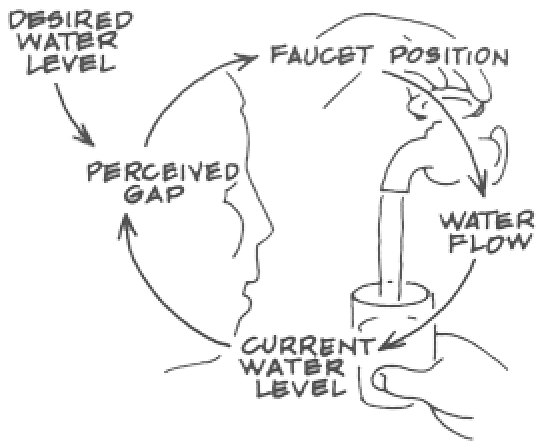
Feedback and Causal Loop Diagrams

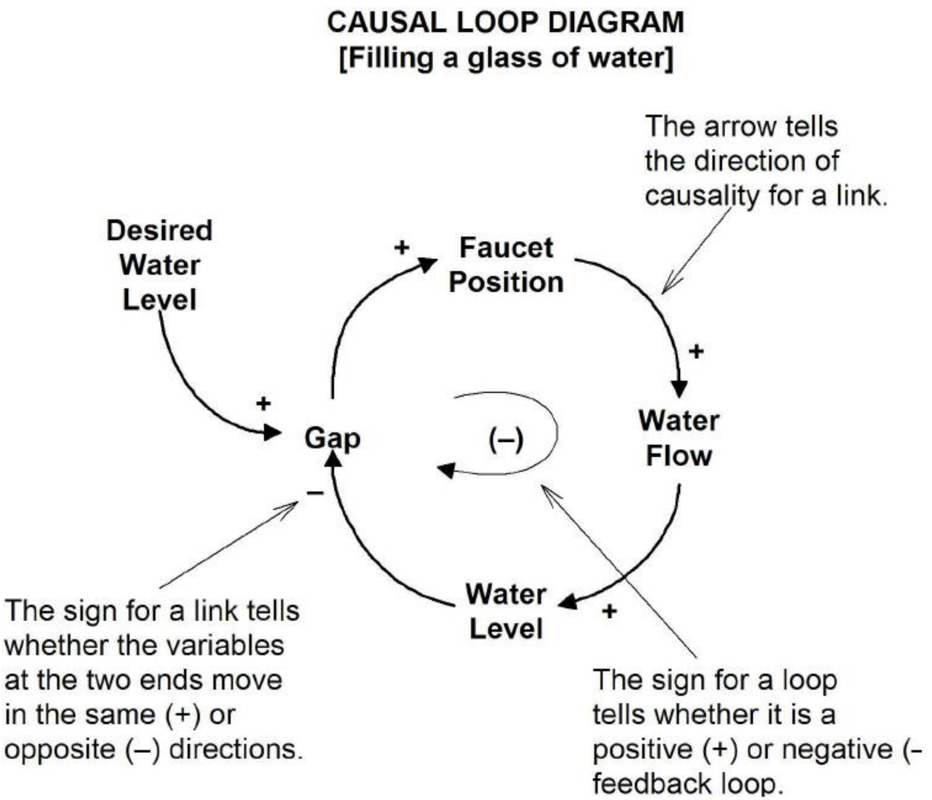
- Causal link impact direction
  - Causal link from element A to B is positive (+ or s) if either A adds to B or a change in A produces a change in B in the same direction
  - Causal link from element A to B is negative (- or o) if either A subtracts from B or a change in A produces a change in B in the opposite direction

- Feedback loop
  - A feedback loop is positive (+ or R) if it contains an even number of negative causal links
  - A feedback loop is negative (- or B) if it contains an uneven number of negative causal links

s=same; o=opposite; R=reinforcing; B=balancing

Feedback and Causal Loop Diagrams



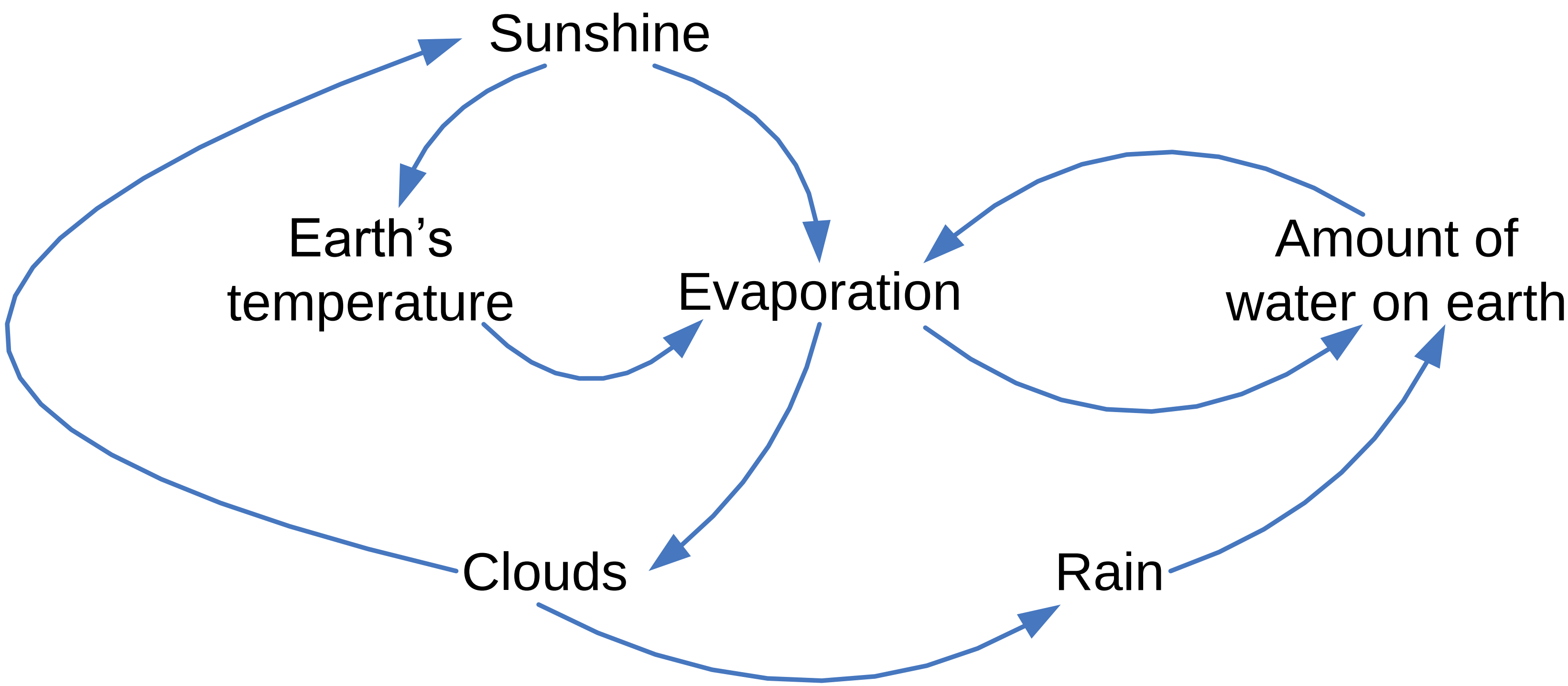


"+" if cause increases ... effect increases
(above what it would otherwise have been)

"-" if cause increases ... effect decreases
(above what it would otherwise have been)

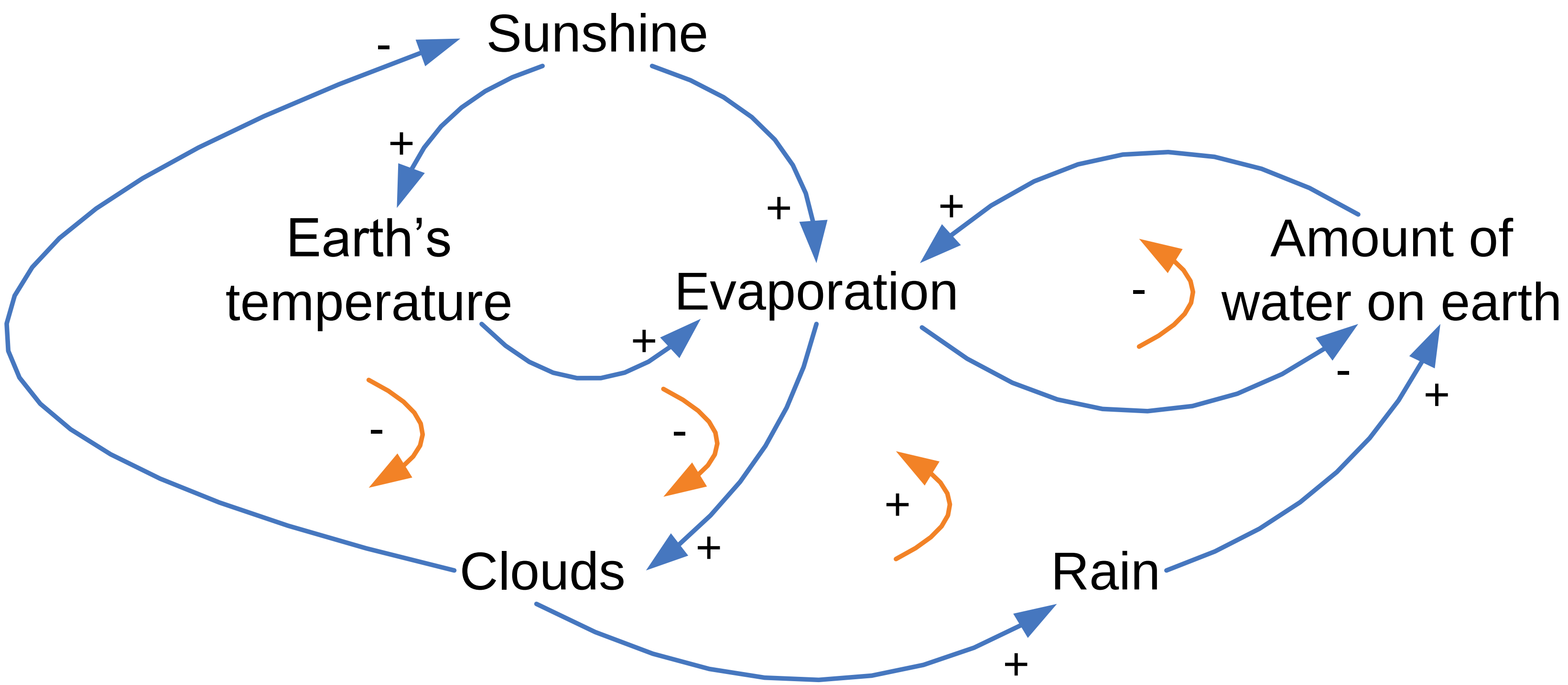
Feedback and Causal Loop Diagrams

- Self regulating biosphere



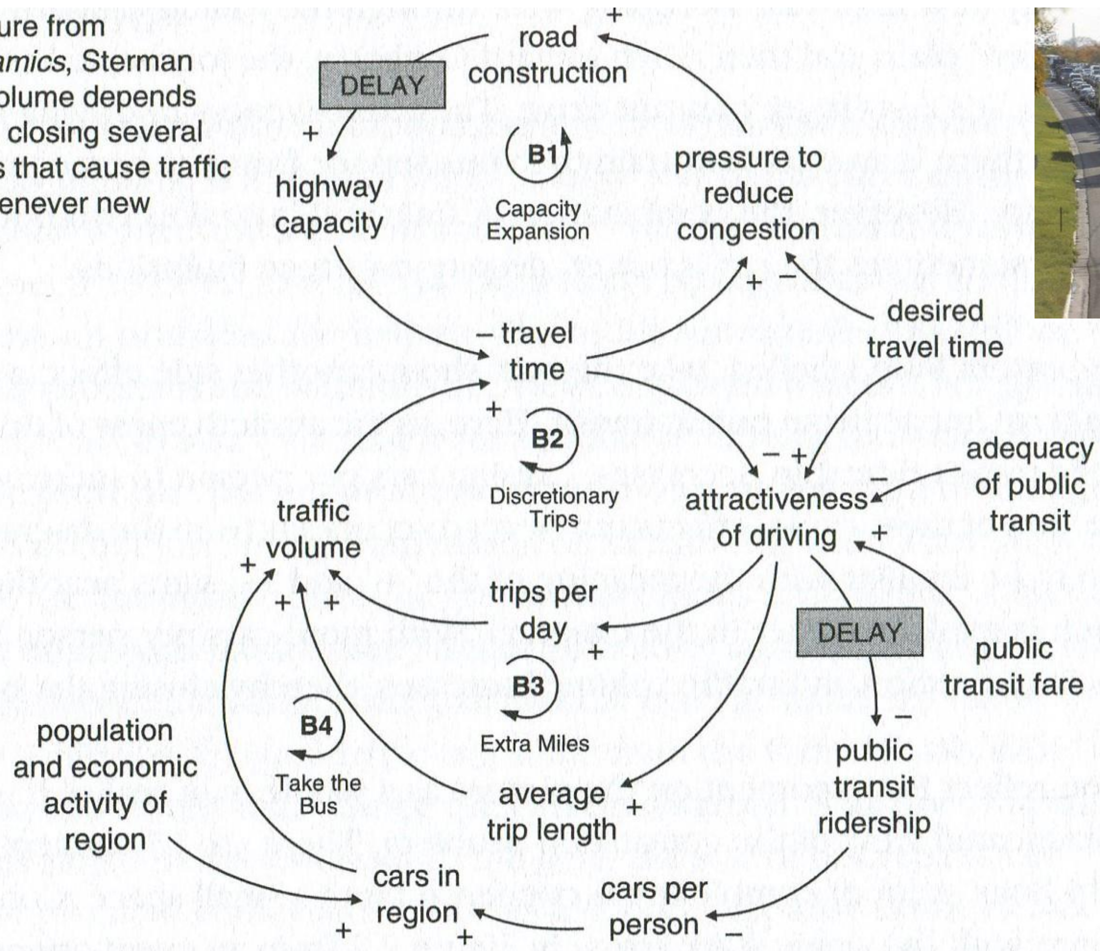
Feedback and Causal Loop Diagrams

- Self regulating biosphere



Example: Reduce Road Congestion

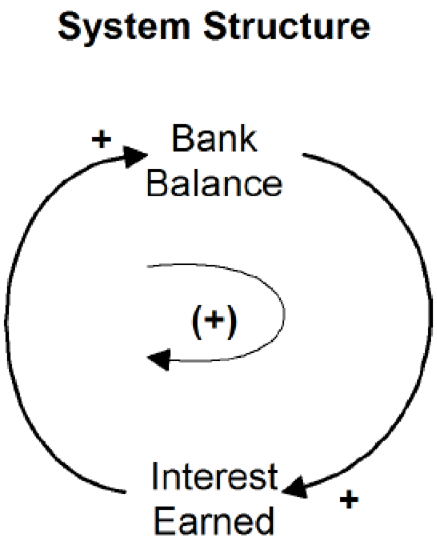
Based on a figure from *Business Dynamics*, Sterman 2000. Traffic volume depends on congestion, closing several feedback loops that cause traffic to increase whenever new roads are built.

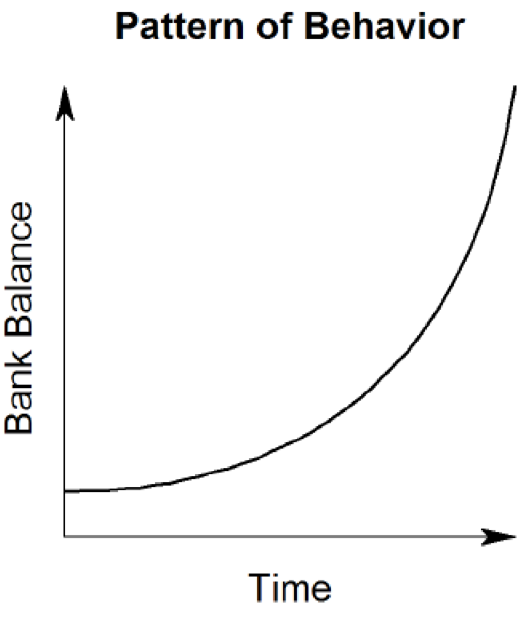


[Morecroft 2007]

System Structures and Patterns of Behaviour

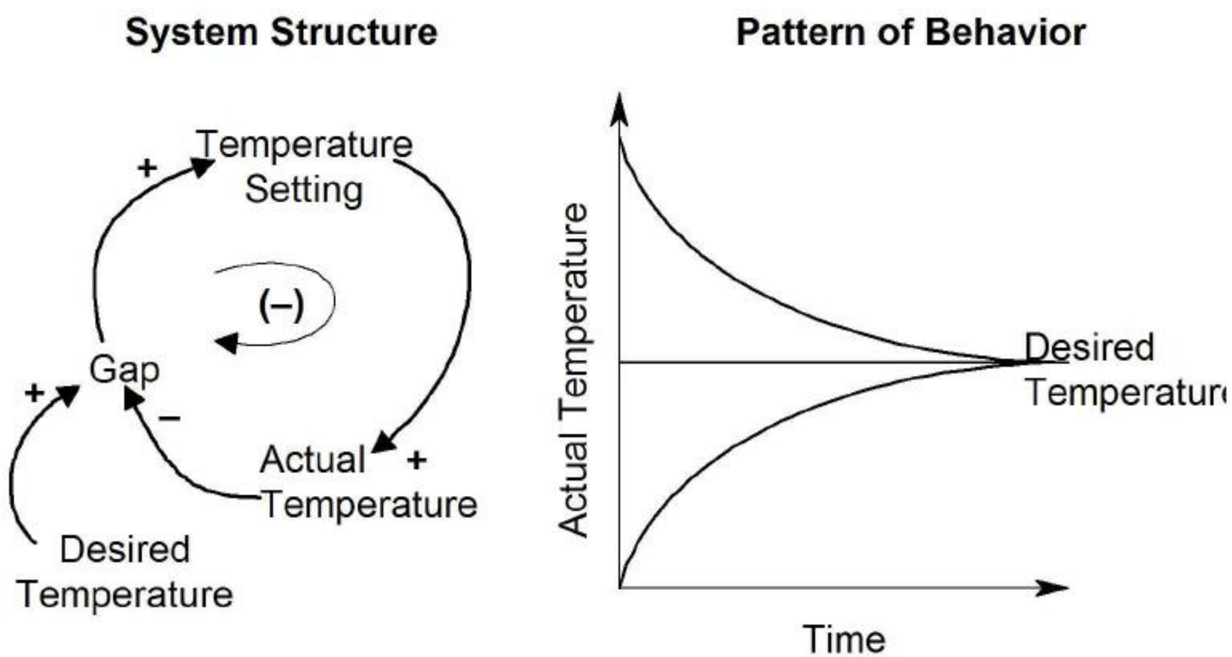
- Positive (reinforcing) feedback loop [e.g. growth of bank balance]





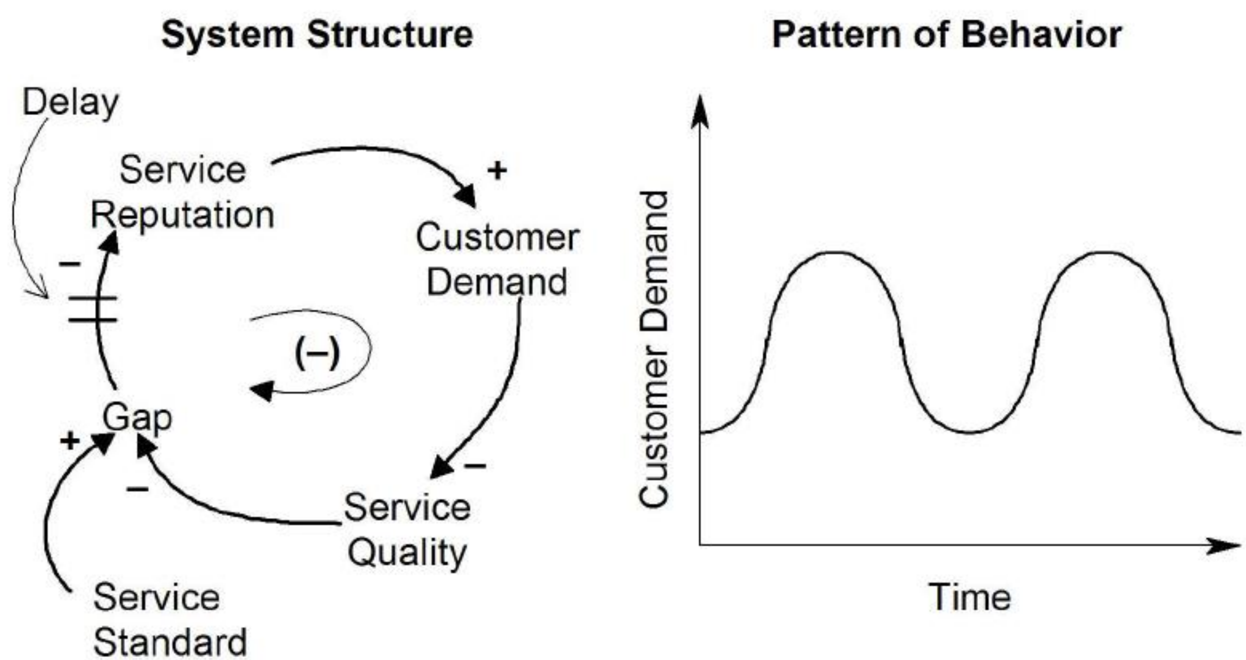
System Structures and Patterns of Behaviour

- Negative (balancing) feedback loop [e.g. electric blanket]



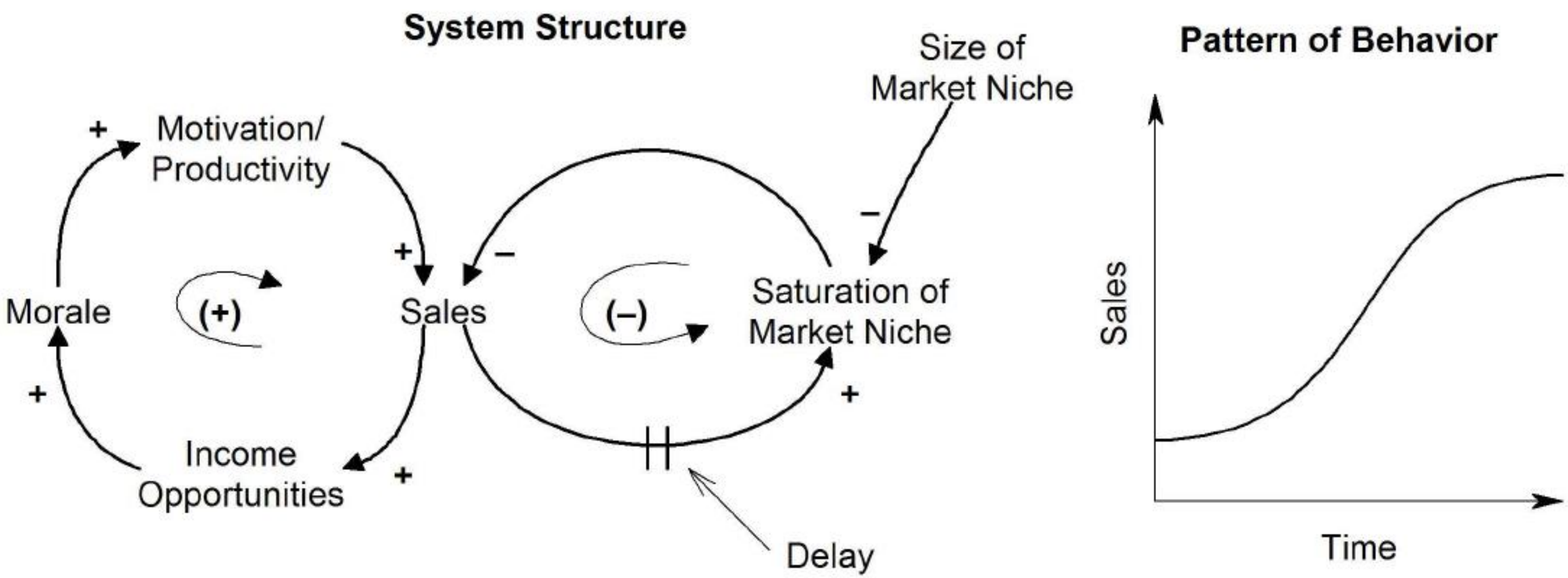
System Structures and Patterns of Behaviour

- Negative feedback loop with delay [e.g. service quality]



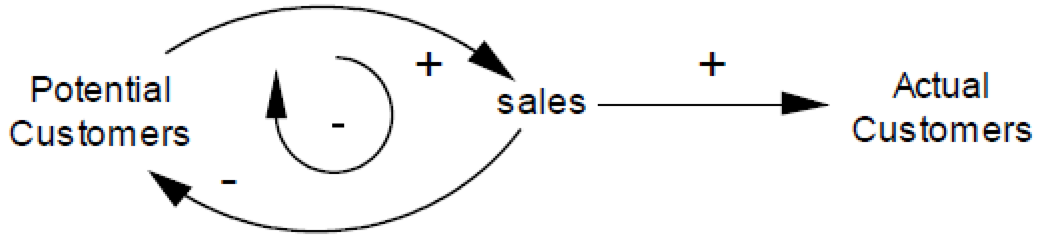
System Structures and Patterns of Behaviour

- Combination of positive and negative loop [e.g. sales growth]

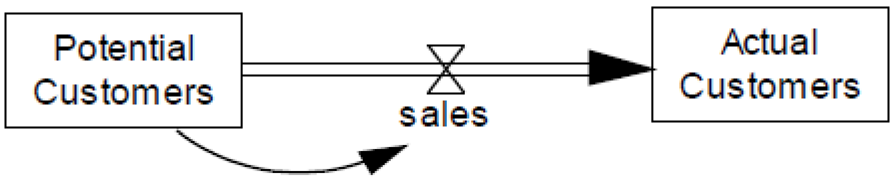


Stock and Flow Diagrams

- Example: Advertising for a durable good



a. Causal loop diagram



b. Stock and flow diagram

Stock and Flow Diagrams

- Stock and flow diagram:
  - Shows relationships among variables which have the potential to change over time (like causal loop diagrams)
  - Distinguishes between different types of variables (unlike causal loop diagrams)

- Basic notation:
  - Stock (level, accumulation, or state variable) {Symbol: Box}
    - Accumulation of "something" over time
    - Value of stock changes by accumulating or integrating flows
    - Physical entities which can accumulate and move around (e.g. materials, personnel, capital equipment, orders, stocks of money)

Stock and Flow Diagrams

- Basic notation (cont.)
  - Flow (rate, activity, movement) {Symbol: valve}
    - Flow or movement of the "something" from one stock to another
    - The value of a flow is dependent on the stocks in a system along with exogenous influences
  - Information {Symbol: curved arrow}
    - Between a stock and a flow: Indicates that information about a stock influences a flow

Stock and Flow Diagrams

- Additional notation
  - Auxiliary {Symbol: Circle}
    - Arise when the formulation of a stock's influence on a flow involves one or more intermediate calculations
    - Often useful in formulating complex flow equations
  - Source and Sink {Symbol: Cloud}
    - Source represents systems of stocks and flows outside the boundary of the model
    - Sink is where flows terminate outside the system

Stock and Flow Diagrams

- Growth of population through birth
  - Find the causal links and feedback loops

Births

Children

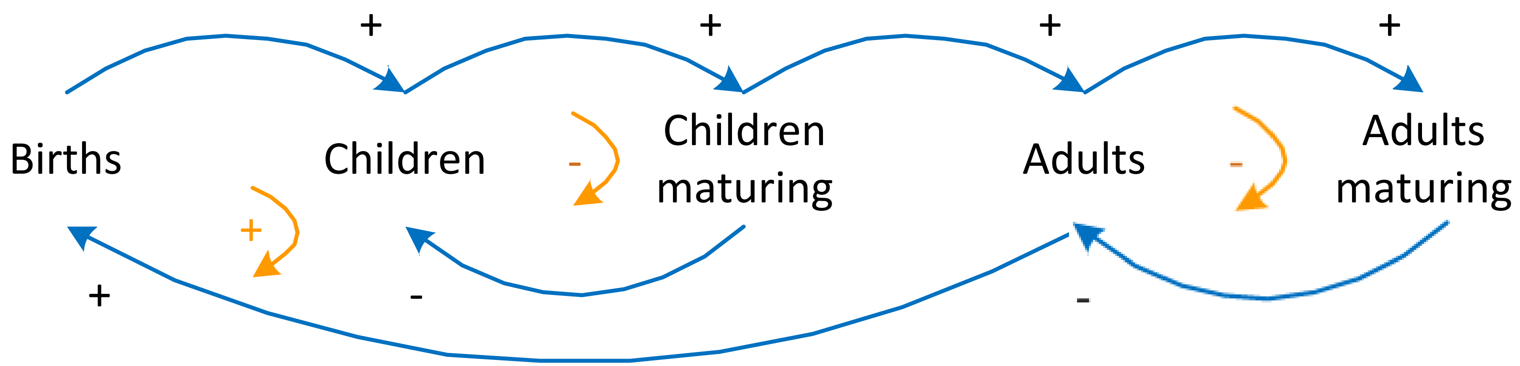
Children maturing

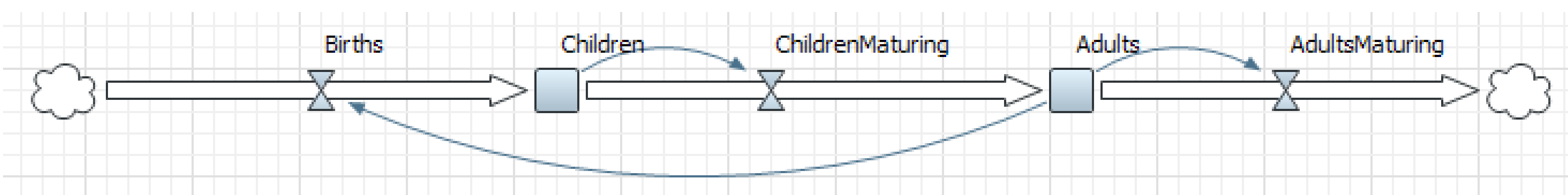
Adults

Adults maturing

Stock and Flow Diagrams

- Growth of population through birth



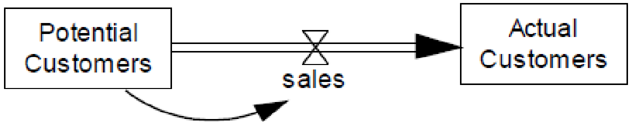


System Dynamics Simulation

- Computation behind the System Dynamics simulation
  - Time slicing
    - At each time point ...
      - Compute new stock levels at time point
      - Compute new flow rates after the stocks have been updated (flow rate held constant over dt)
      - Move clock forward to next time point
  - The software must apply numerical methods to solve the integrations
    - Integration errors

System Dynamics Simulation

- Back to the advertising example ...
  - Can our stock and flow diagram below help us answering the question: How will the number of potential customers vary with time?



b. Stock and flow diagram

  - No! We need to consider the quantitative features of the process
    - Initial number of potential and actual customers
    - Specific way in which sales flow depends on potential customers

System Dynamics Simulation

- Simplifying assumptions
  - Aggregate approach is sufficient
  - Flows within processes are continuous
  - Flows do not have a random component
- Analogy: Plumbing system
  - Stocks are tanks full of liquid
  - Flows are pumps that control the flow between the tanks
- To completely specify the process model
  - Initial value of each stock + equation for each flow

System Dynamics Simulation

- Number of potential customers at any time t

$$\text{Potential Customers}(t) = 1,000,000 - \int_0^t \text{sales}(\tau)\, d\tau.$$

- Number of actual customers at any time t

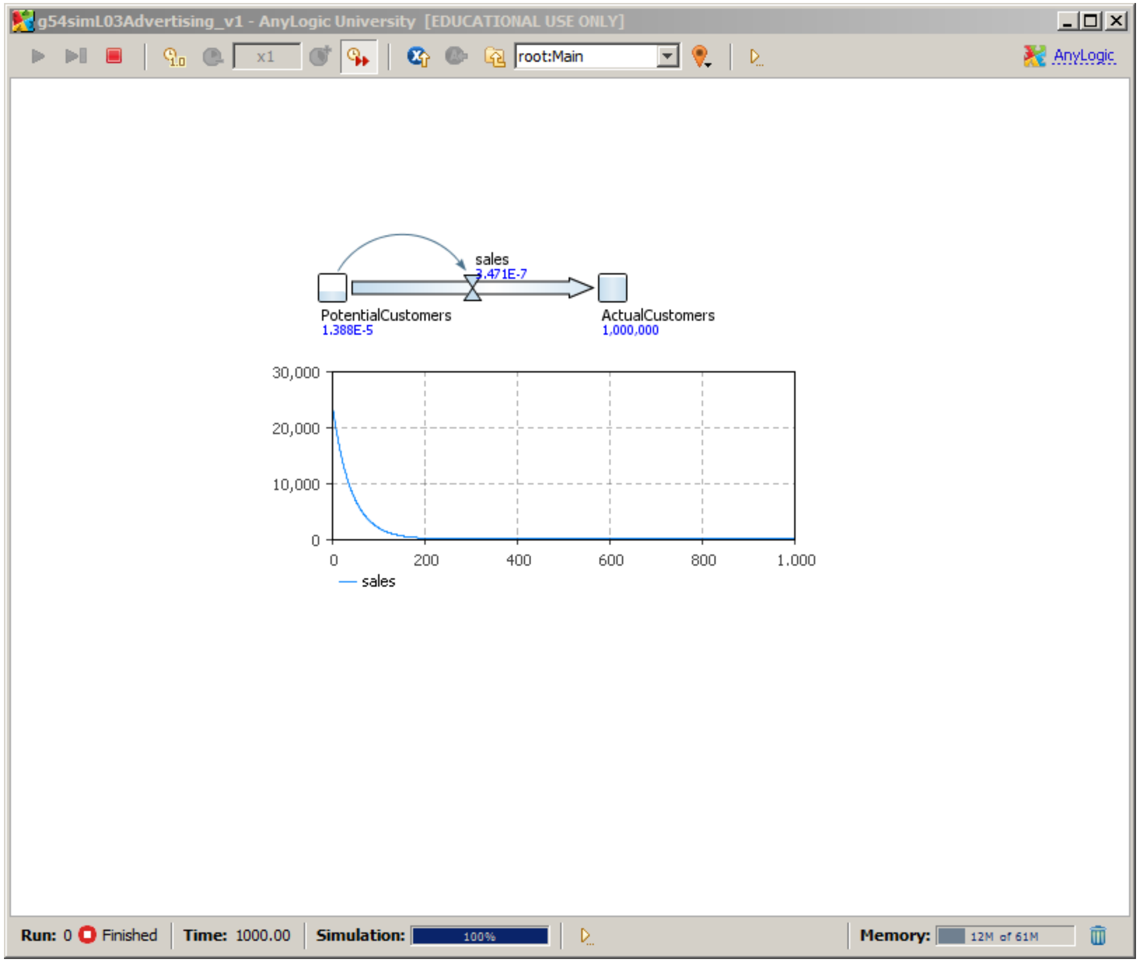
$$\text{Actual Customers} = \int_0^t \text{sales}(\tau)\, d\tau.$$

- Many possible flow equations! It is up to the modeller to choose a realistic one

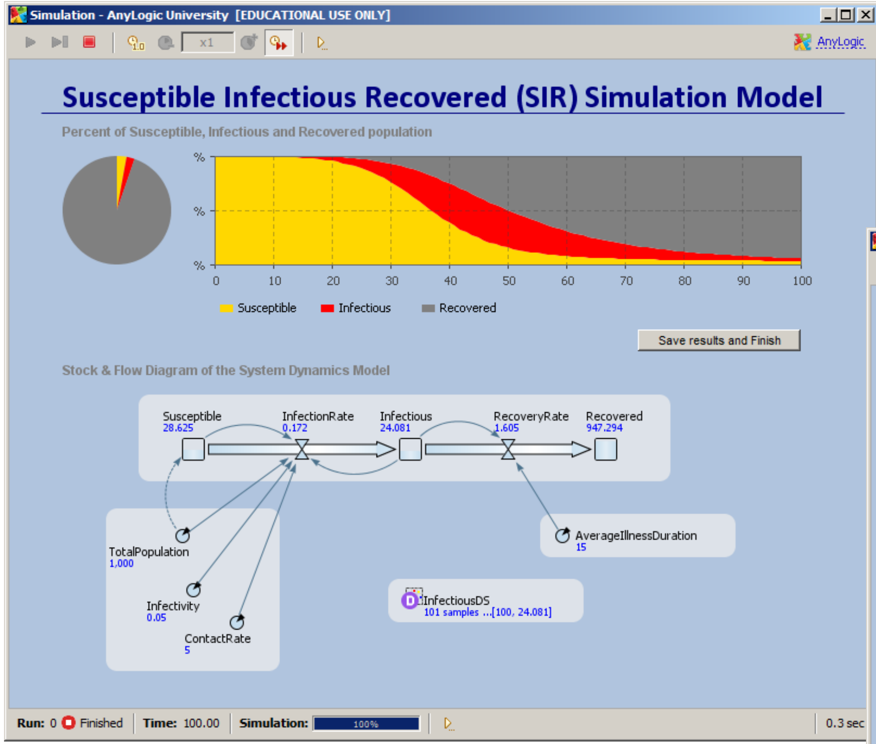
$$\text{sales}(t) = 0.025 \times \text{Potential Customers}(t)\text{rs}(t) > 0$$

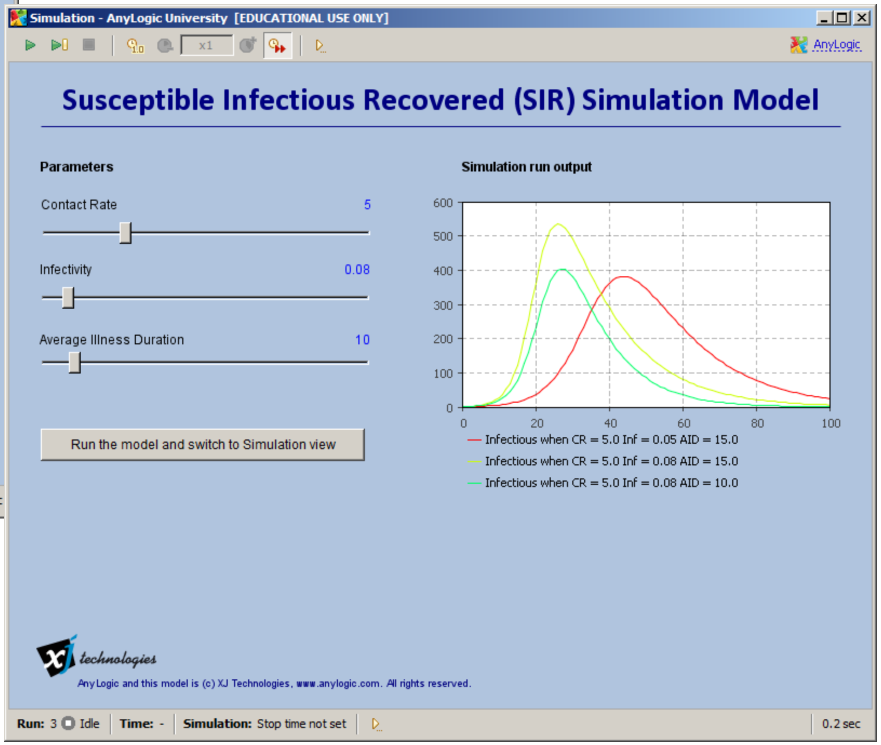
$$0, \qquad \text{otherwise}$$

System Dynamics Simulation

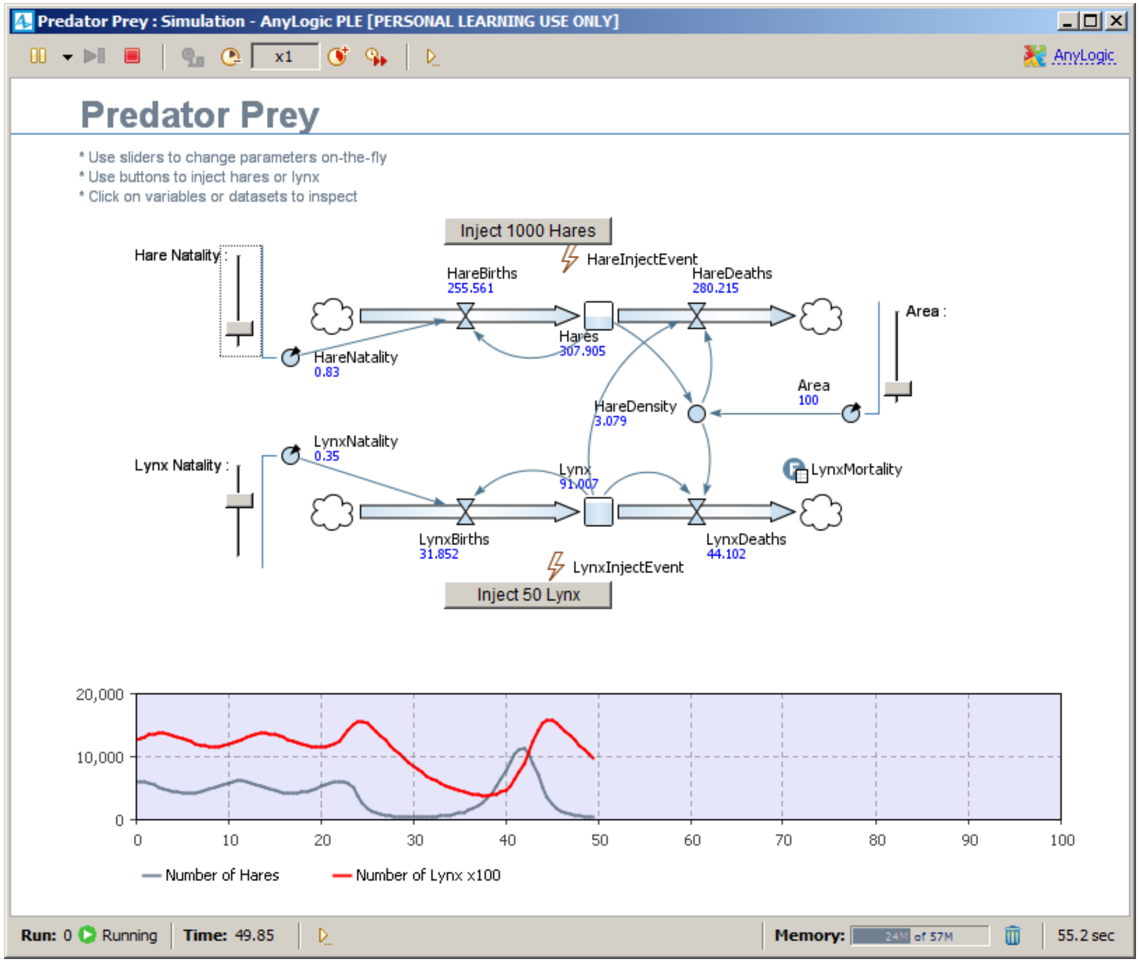


System Dynamics Simulation





System Dynamics Simulation

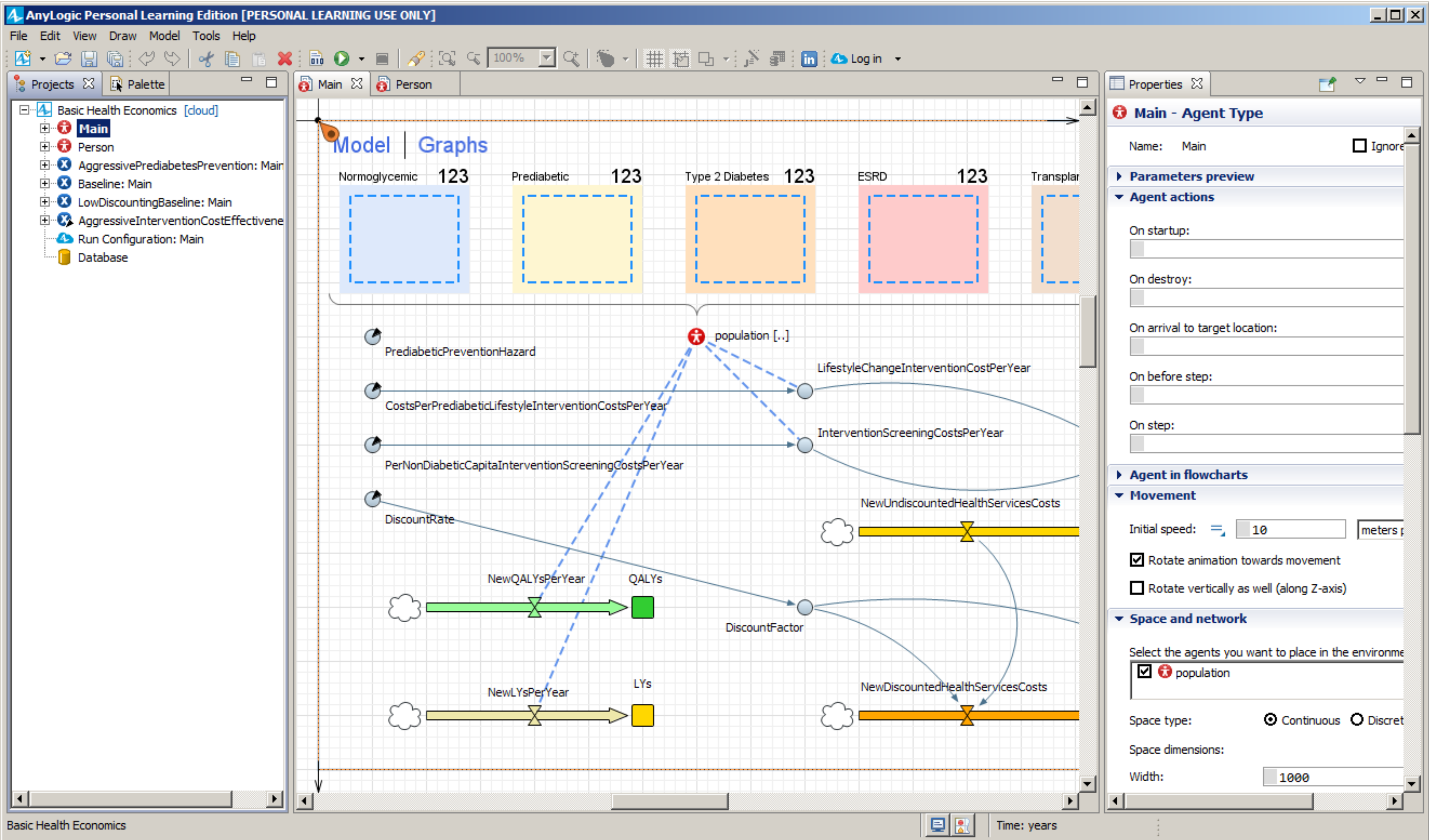


Hybrids

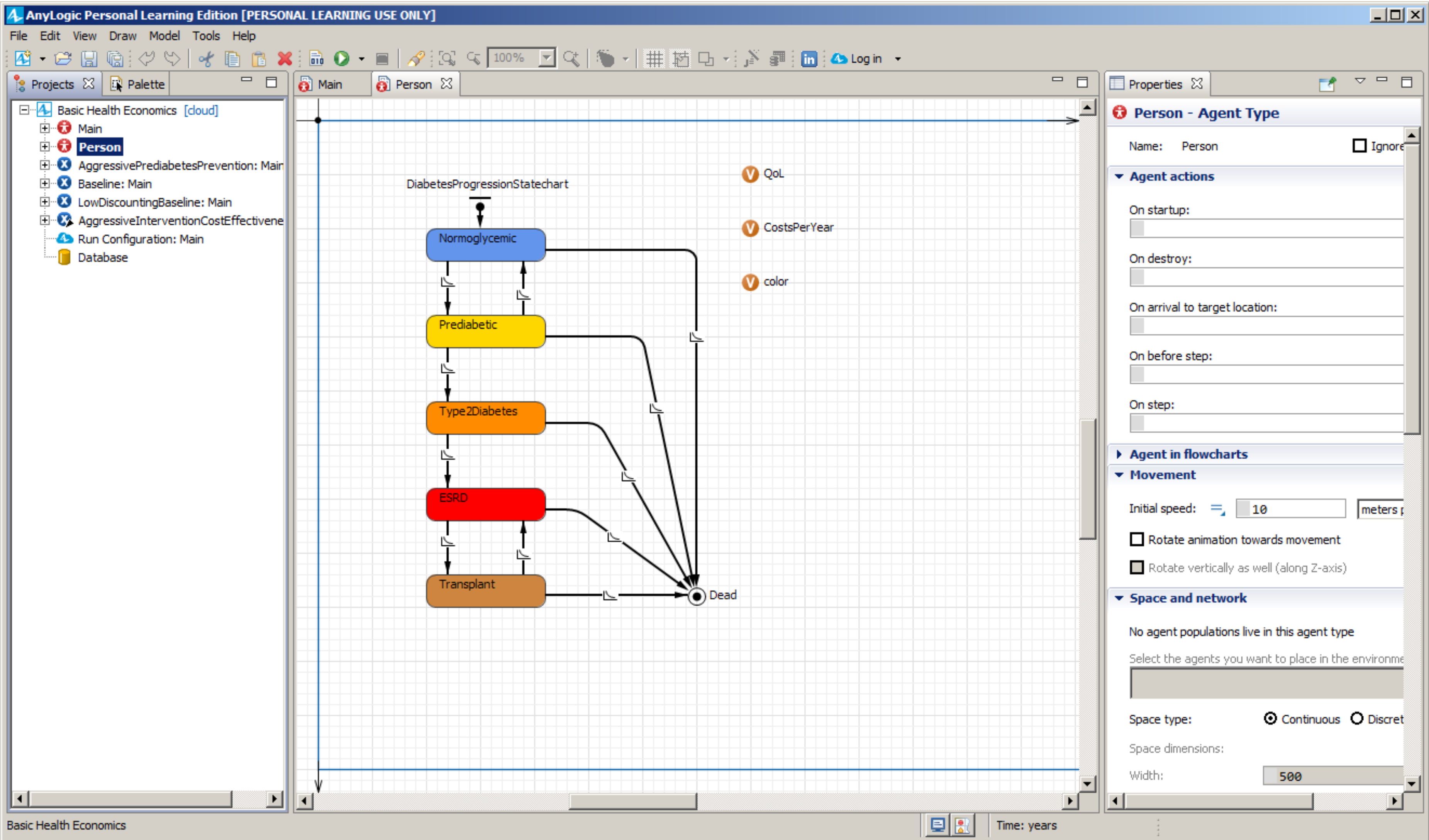
Hybrid Architectures

- Agents in an SD environment
  - e.g. population in a city infrastructure
    - Agents' decisions depend on the values of the SD variables and, in turn, the agents affect the SD variables
- SD inside agents
  - e.g. consumer's individual decision making
    - Dynamics of consumer decision making is modelled using SD approach

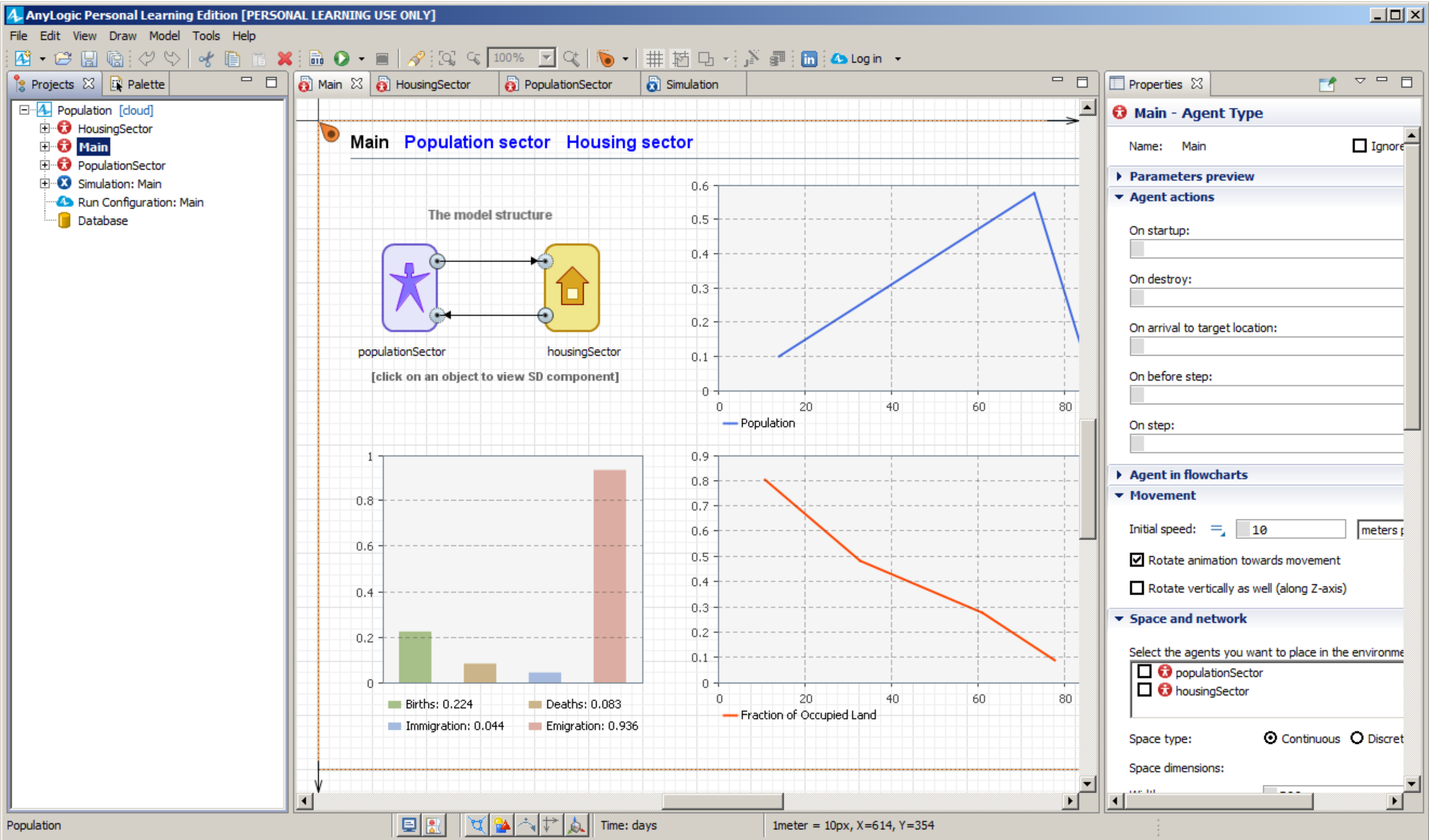
Agents in an SD Environment



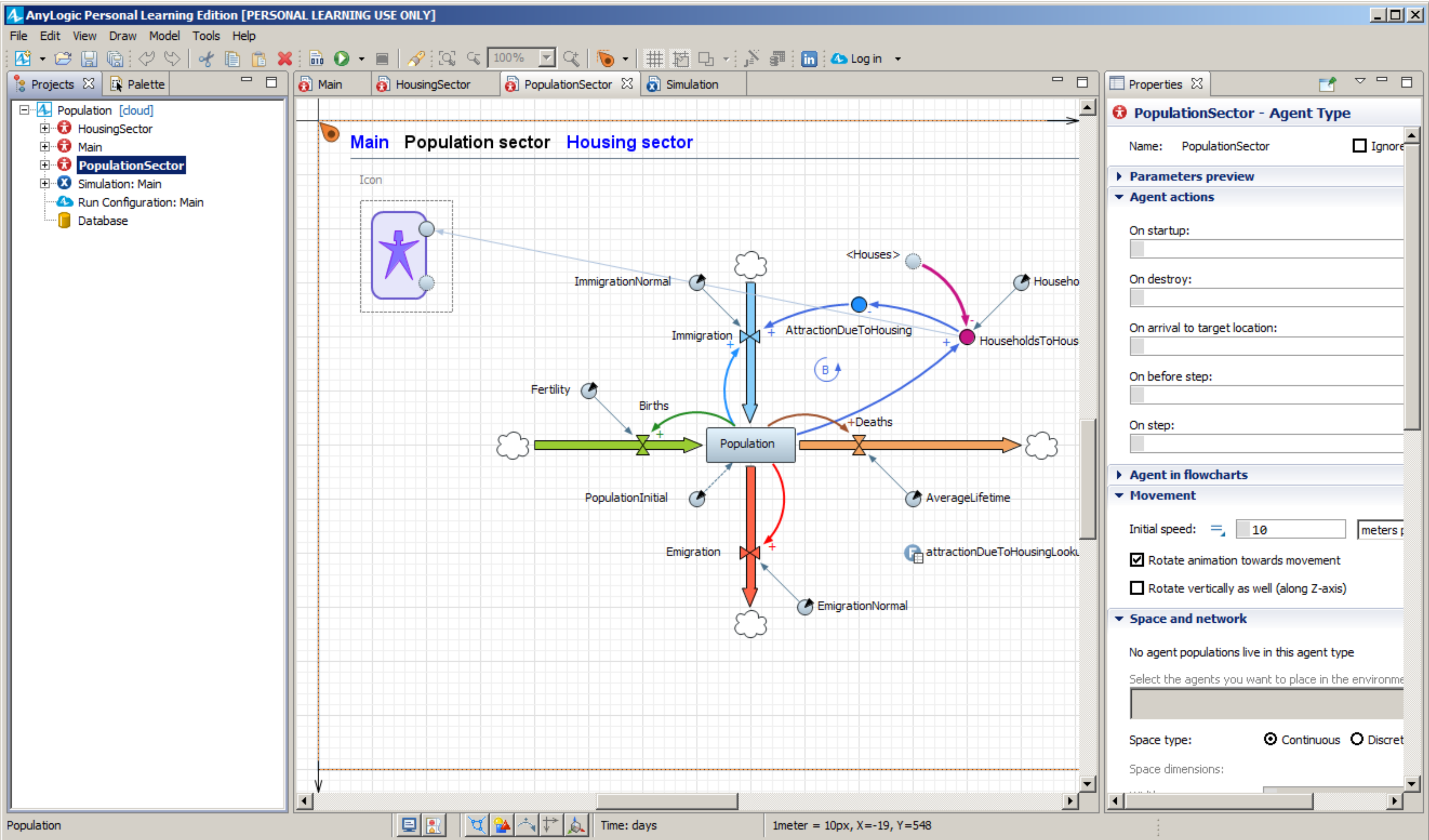
Agents in an SD Environment



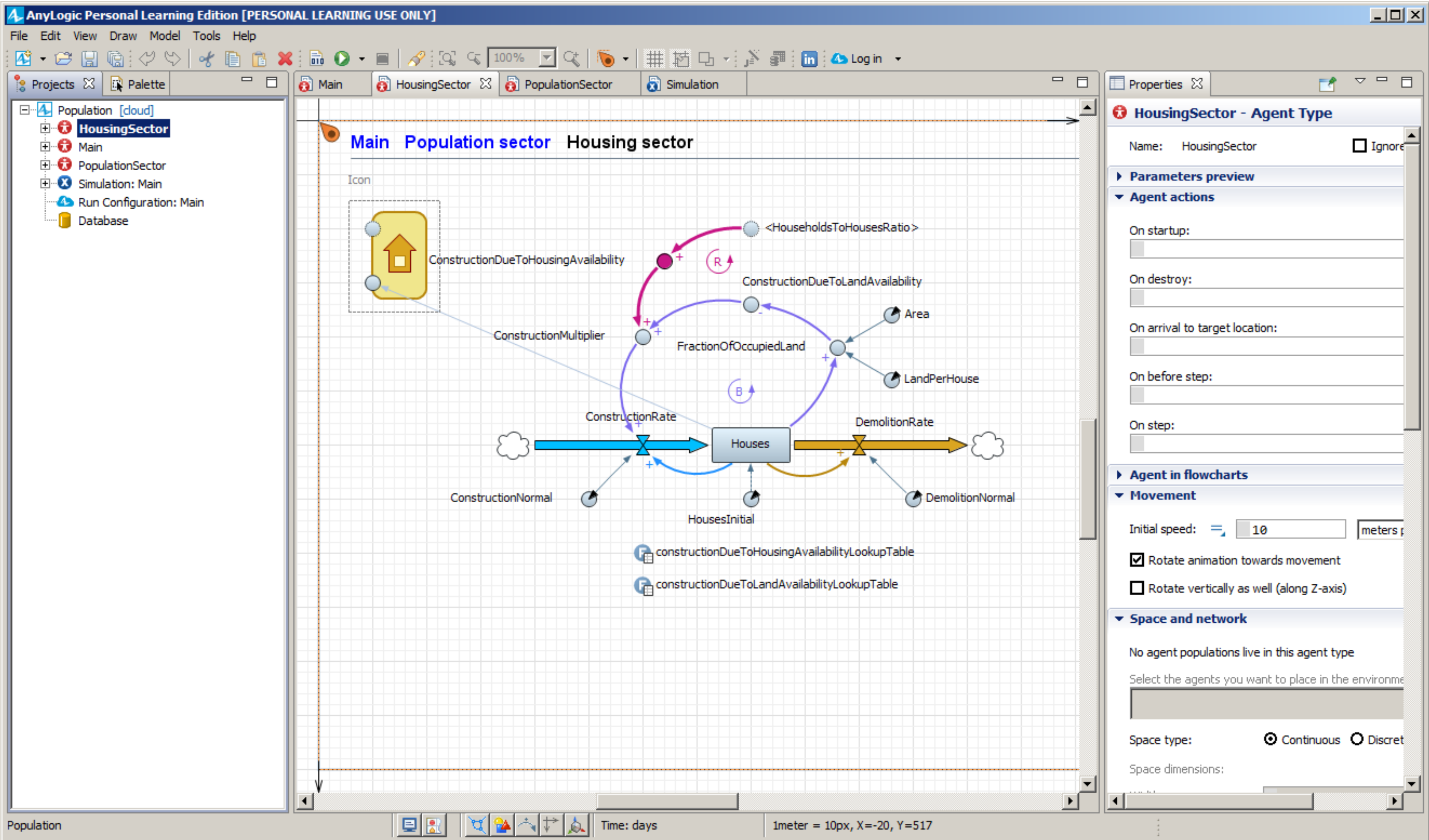
SD Inside Agents



SD Inside Agents



SD Inside Agents



Using a Hybrid Approach on Climate Assessment Modelling

Zhi En (2015)

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

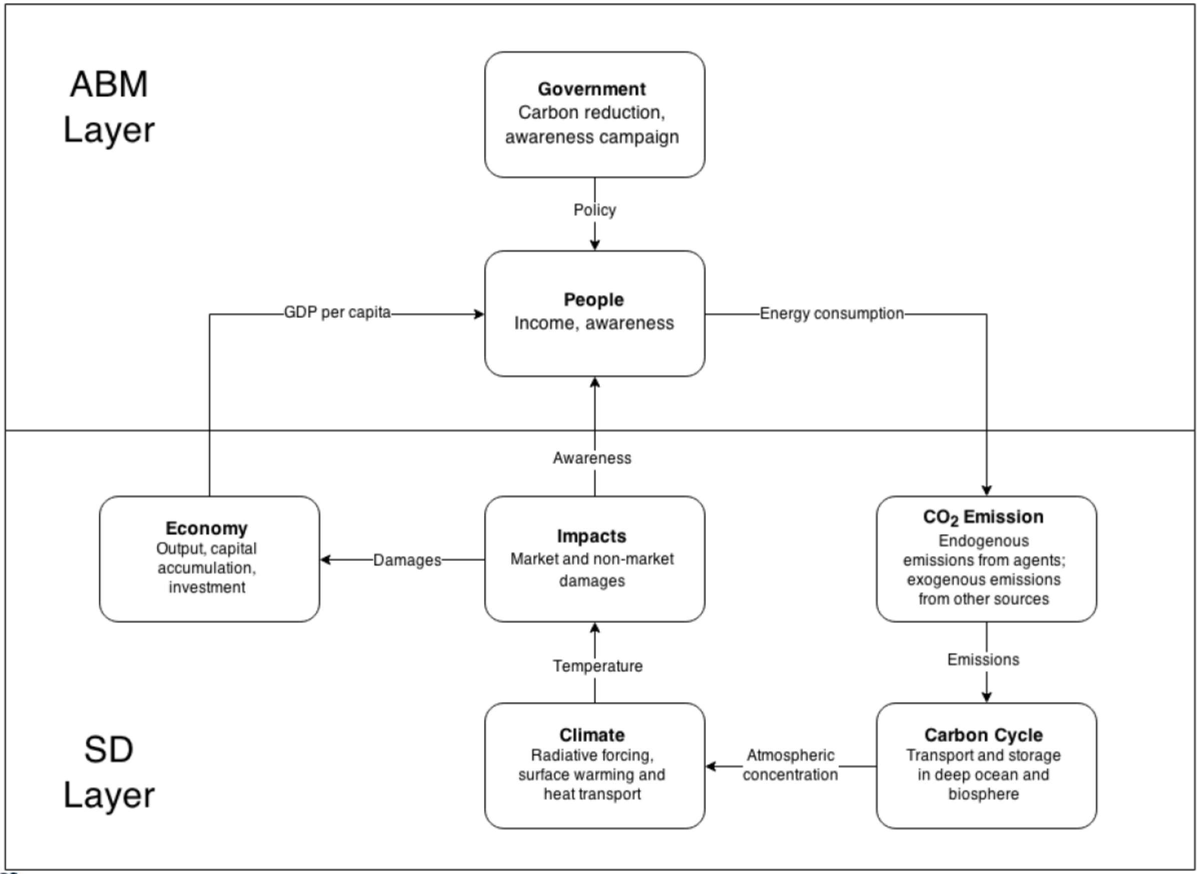
Problem

Modeling and simulation has played an increasingly significant role in exploratory researches and informing policy decisions on climate change mitigation subjects

- Current approach:
  - Integrated assessment models using System Dynamics Simulation (SDS)
- Issues with current approach:
  - Rigid structure and aggregated perspective of SDS tend to undermine the importance of low-level details
    - No consideration of a heterogeneous population
  - Lack of scalability in current assessment models
    - Geographical impact distribution of climate change is uneven by nature

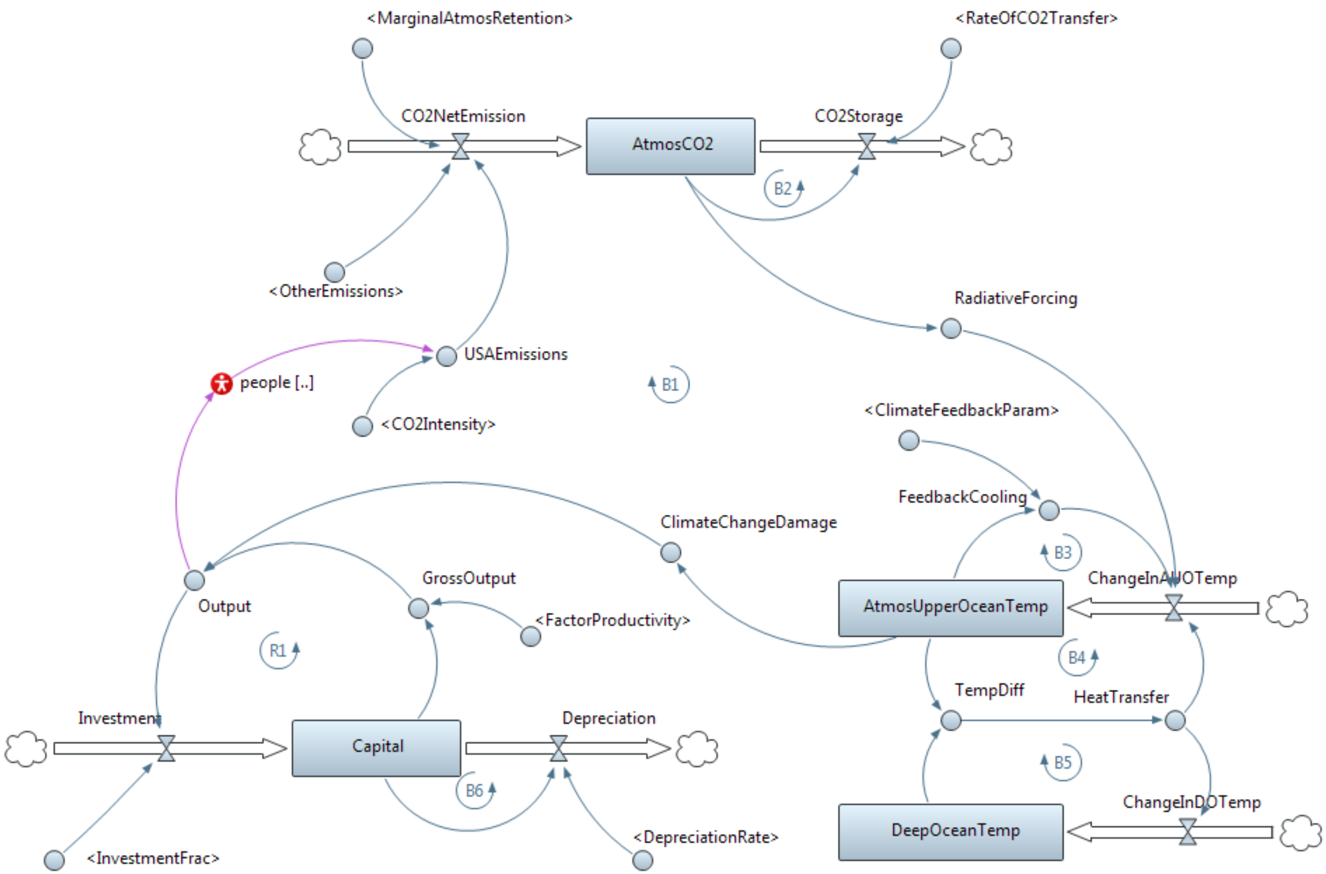
Conceptual Model

- Sector Boundary Map (showing feedback structure)



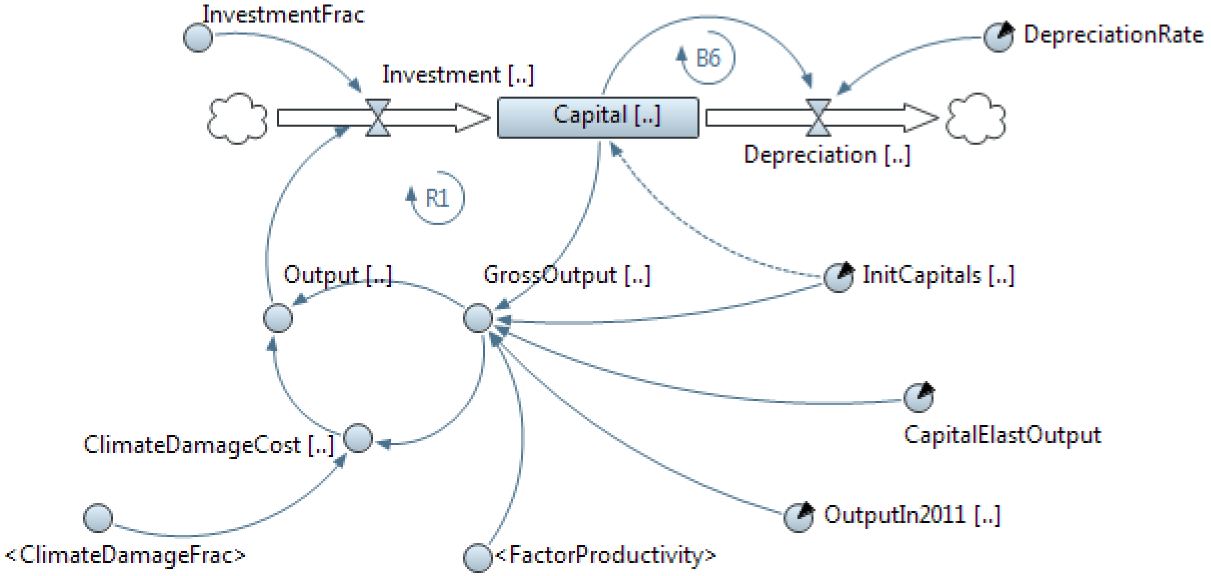
Climate-Economy Modelling

- We used the DICE model (Nordhaus 1992) as a basis



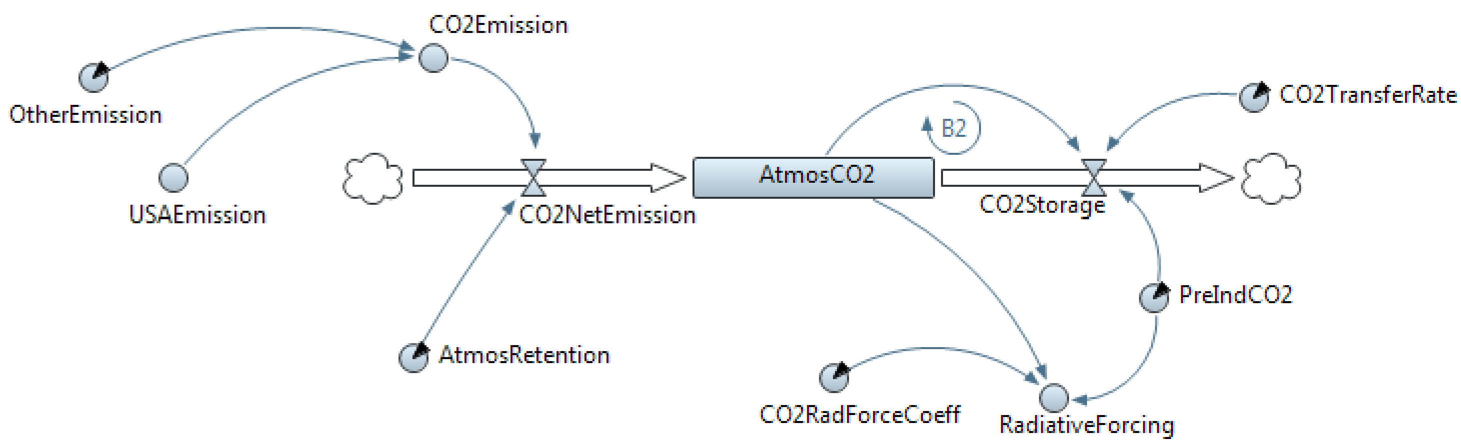
Climate-Economy Modelling

- Economy Subsystem
  - NB: Stock of population from the original DICE model has been omitted as 1) the population is represented by the number of agents rather than a stock aggregate and 2) the population growth is not modeled in HCAM



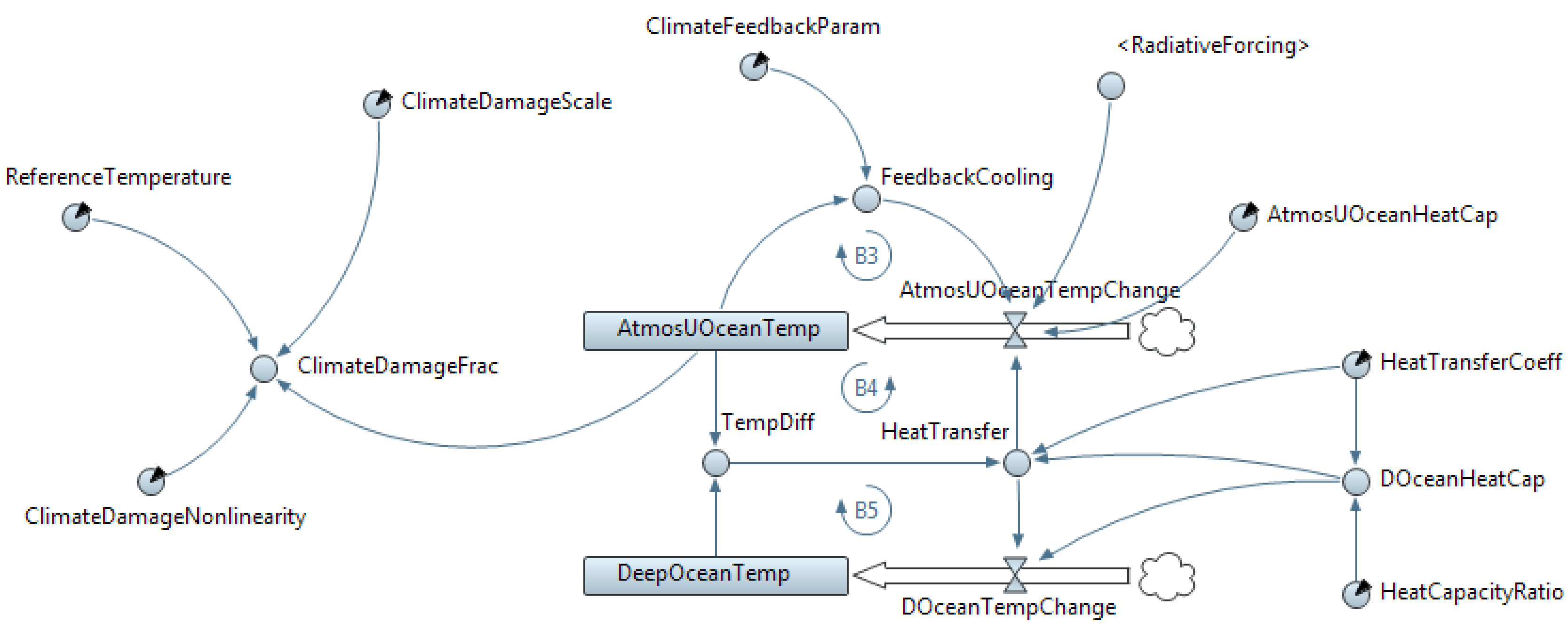
Climate-Economy Modelling

- Carbon Cycle



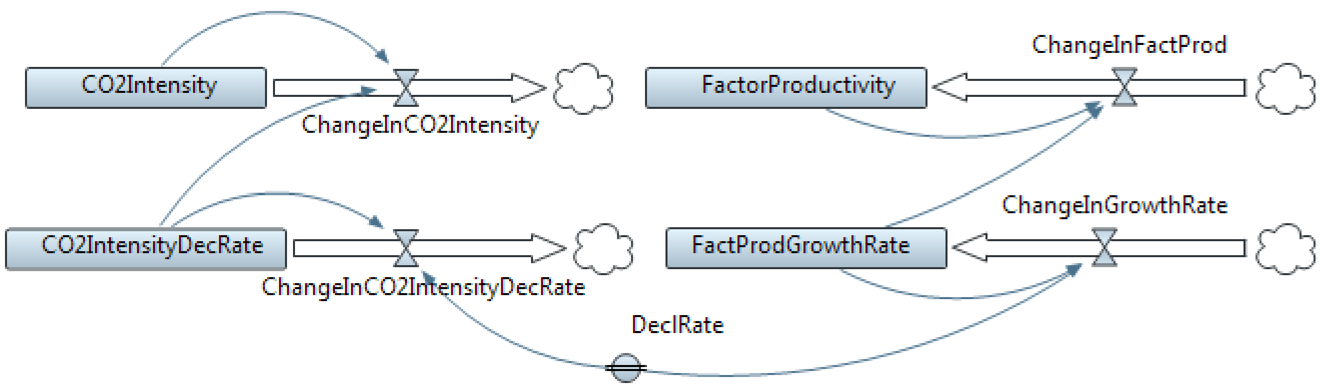
Climate-Economy Modelling

- Climate Subsystem



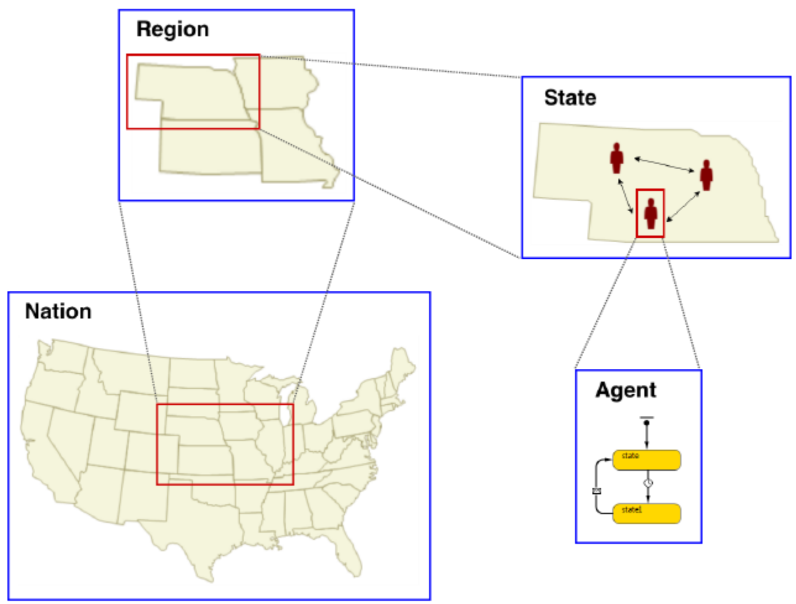
Climate-Economy Modelling

- Exogenous Drivers
  - NB: Second order feedback structures of two exogenous factors that have been introduced previously: CO2 Intensity and Factor Productivity. CO2 Intensity determines the emissions level of individuals based on their incomes while Factor Productivity represents the level of technological sophistication that drives the economy.



Population Modelling

- Aggregation levels
  - The social structure of human population in HCAM can be partitioned into social units of ascending aggregation levels
    - individual ⊂ state ⊂ region ⊂ nation



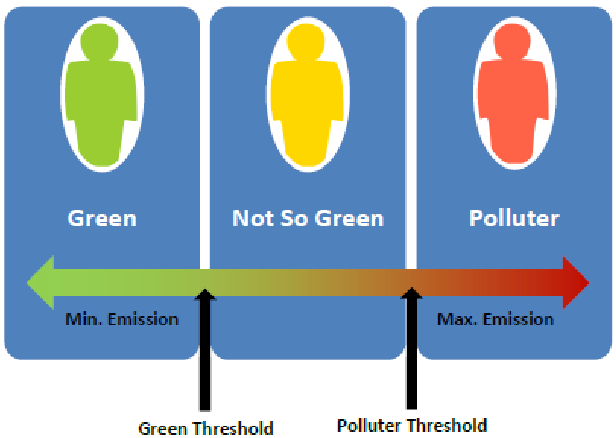
Population Modelling

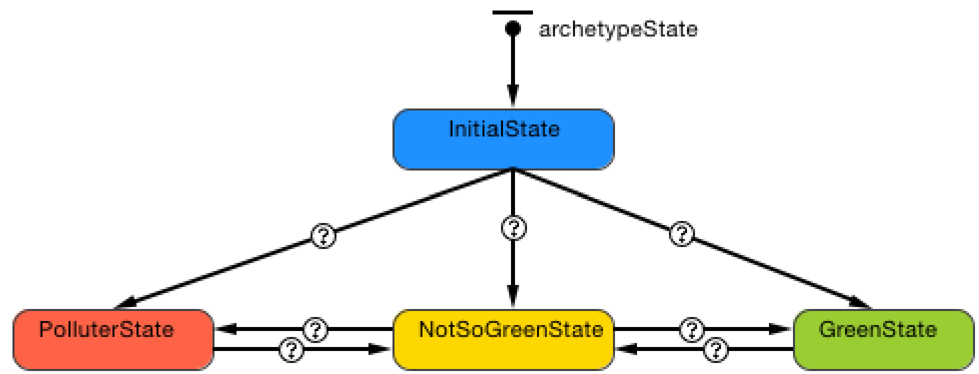
- Agent types
  - InfluenceAction class is a data model of the influencing actions initiated by campaigns and word-of-mouth; it encapsulates the parameters of an influencing action and is transmitted to the receiving agent like a network packet

Agent Type	Role
Main	National climate policies
Region	Regional climate policies
State	State-level administration
Person	Emissions and networking
InfluenceAction	Influence-passing data model

Population Modelling

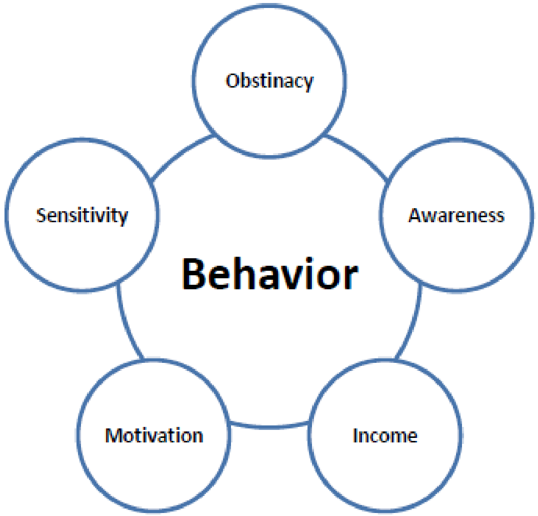
- Person agent archetypes and states

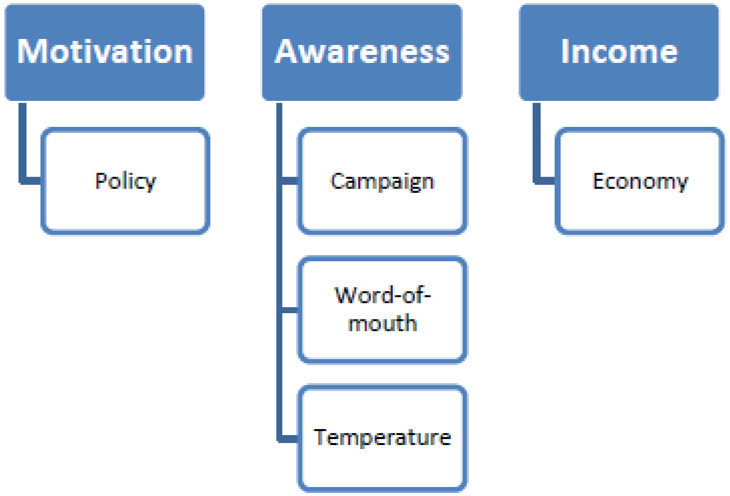




Population Modelling

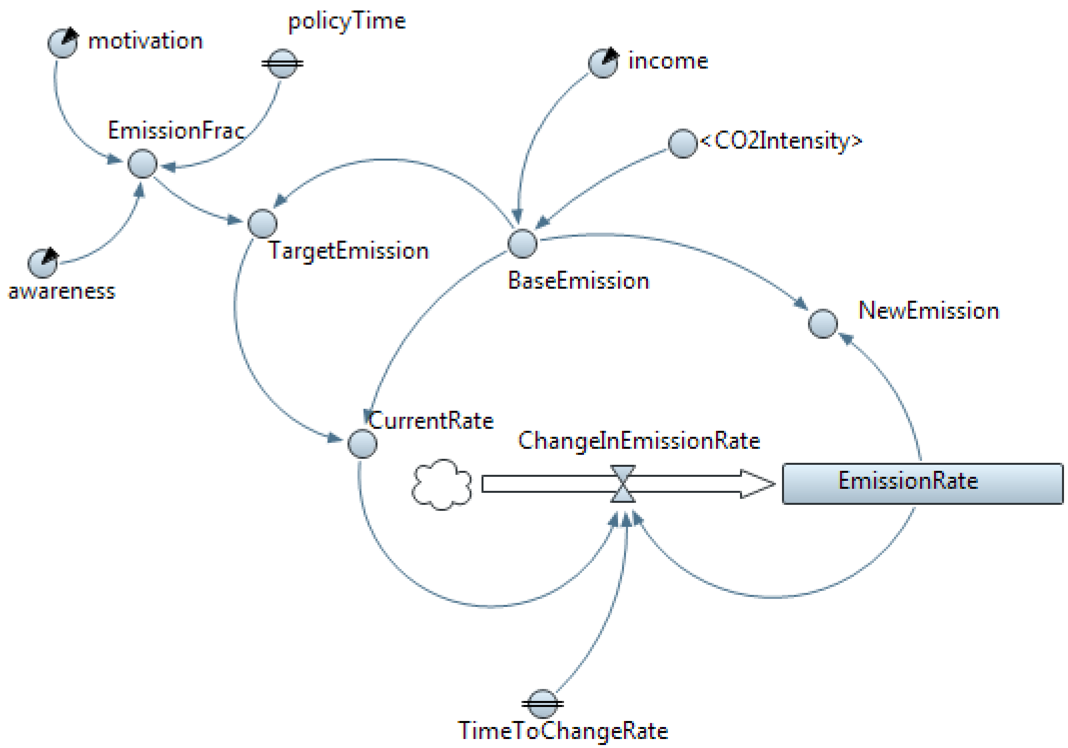
- Person agent mental model and external influences
  - Mental attributes
    - Obstinacy, awareness, motivation and sensitivity
  - Welfare attributes
    - Income





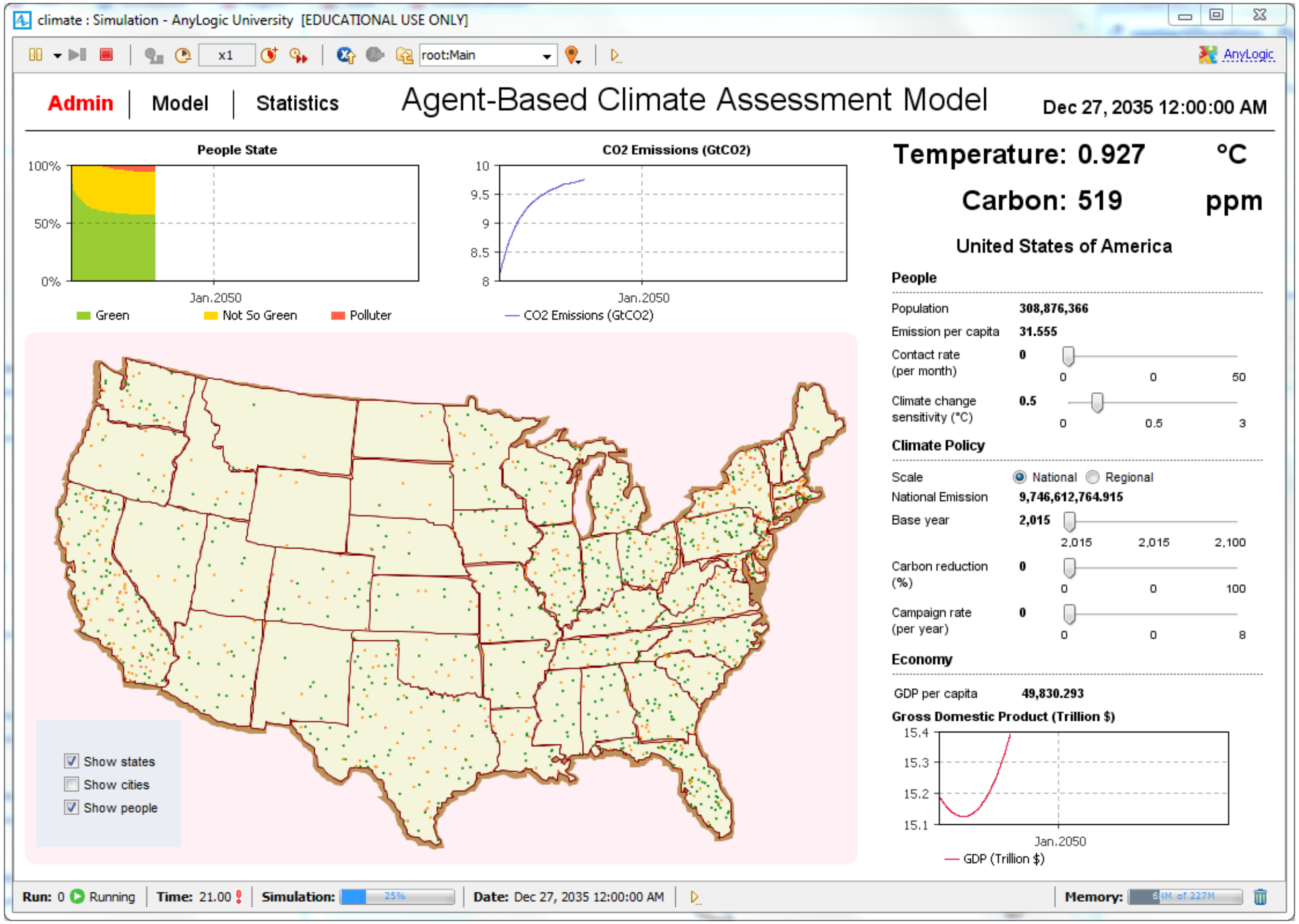
Population Modelling

- Person agent primary behavioural model
  - Using the following SD model inside each agent



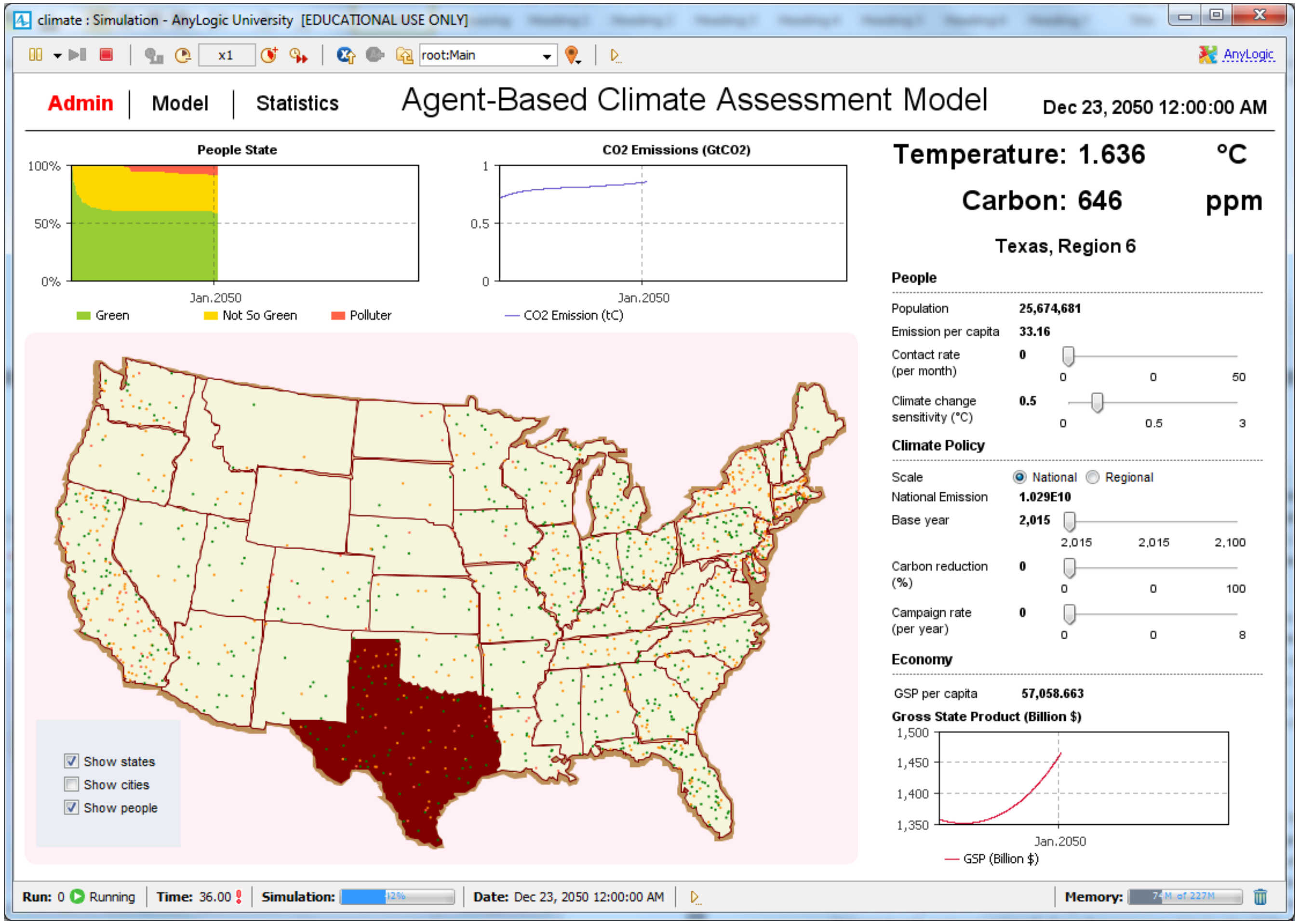
Implementation

GUI: Admin / Nation



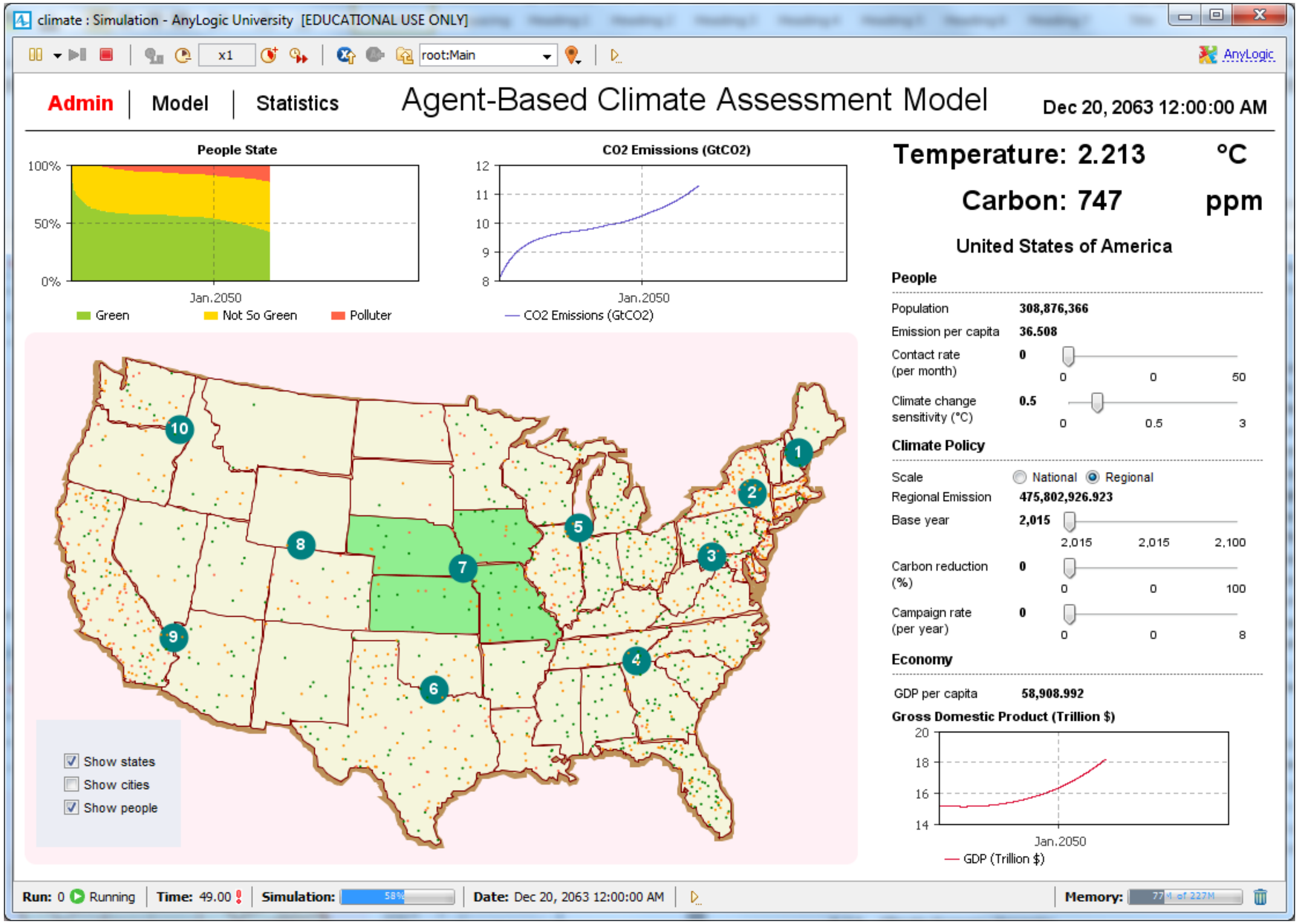
Implementation

GUI: Admin / State



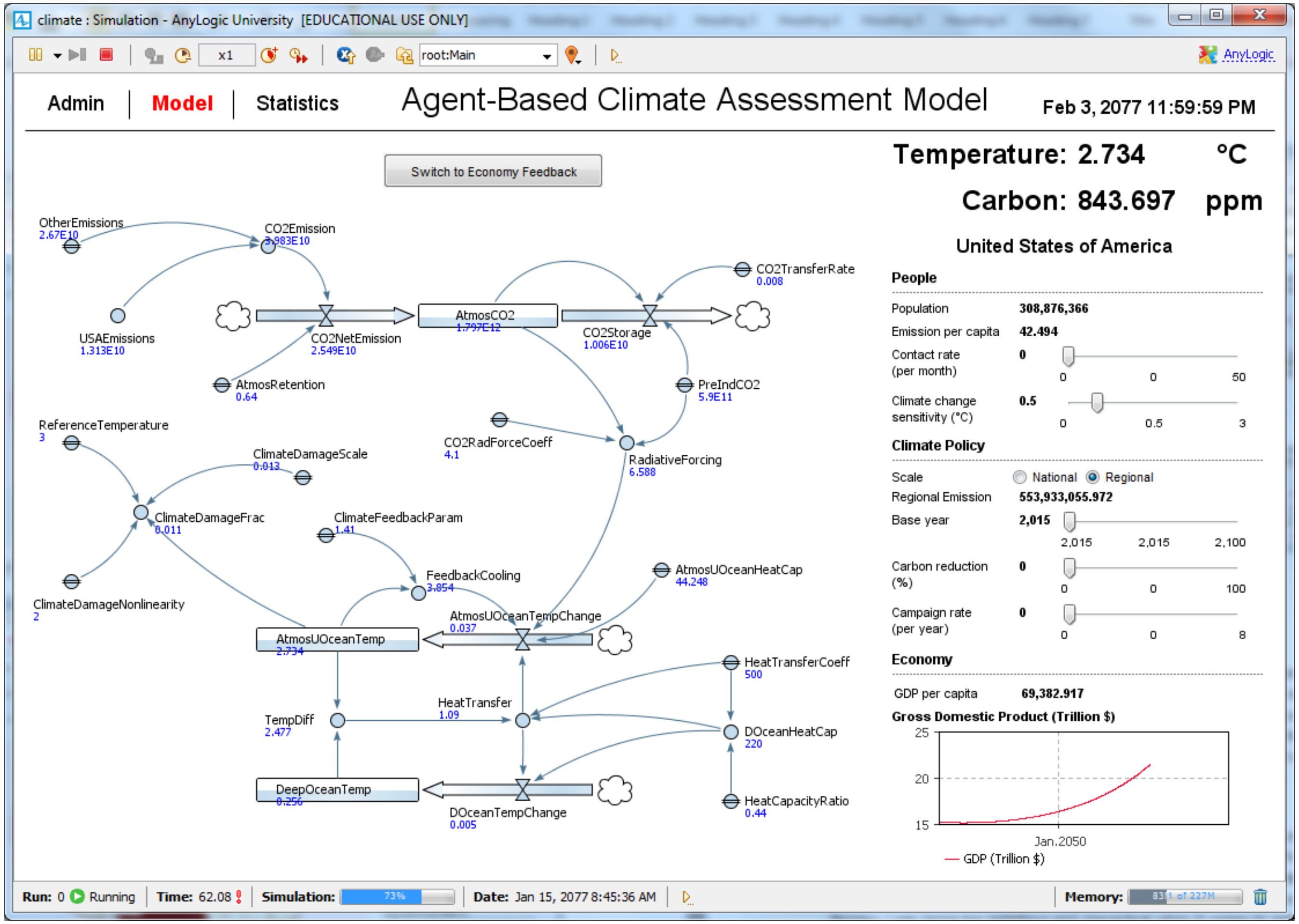
Implementation

GUI: Admin / Region



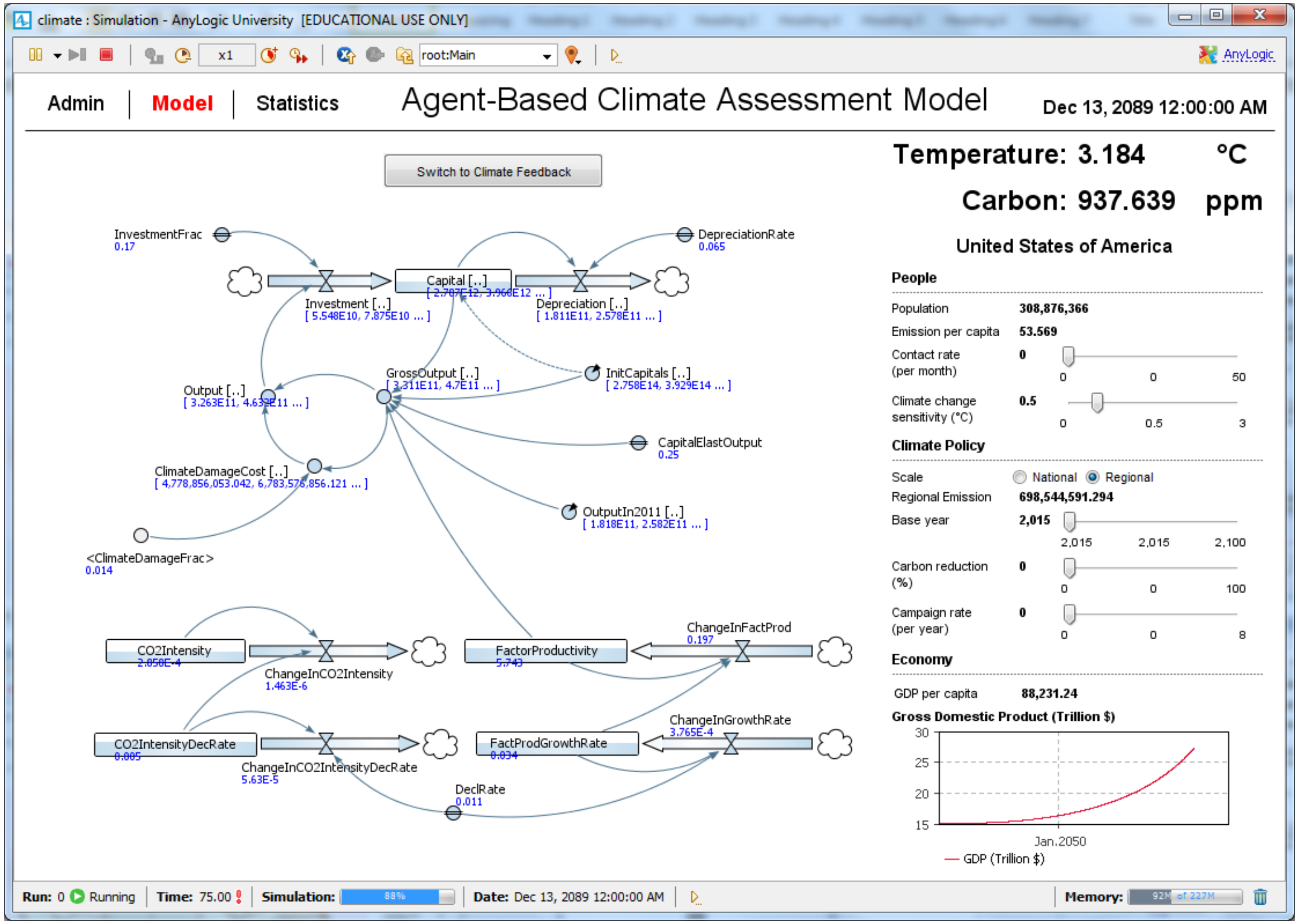
Implementation

GUI: Model / Climate



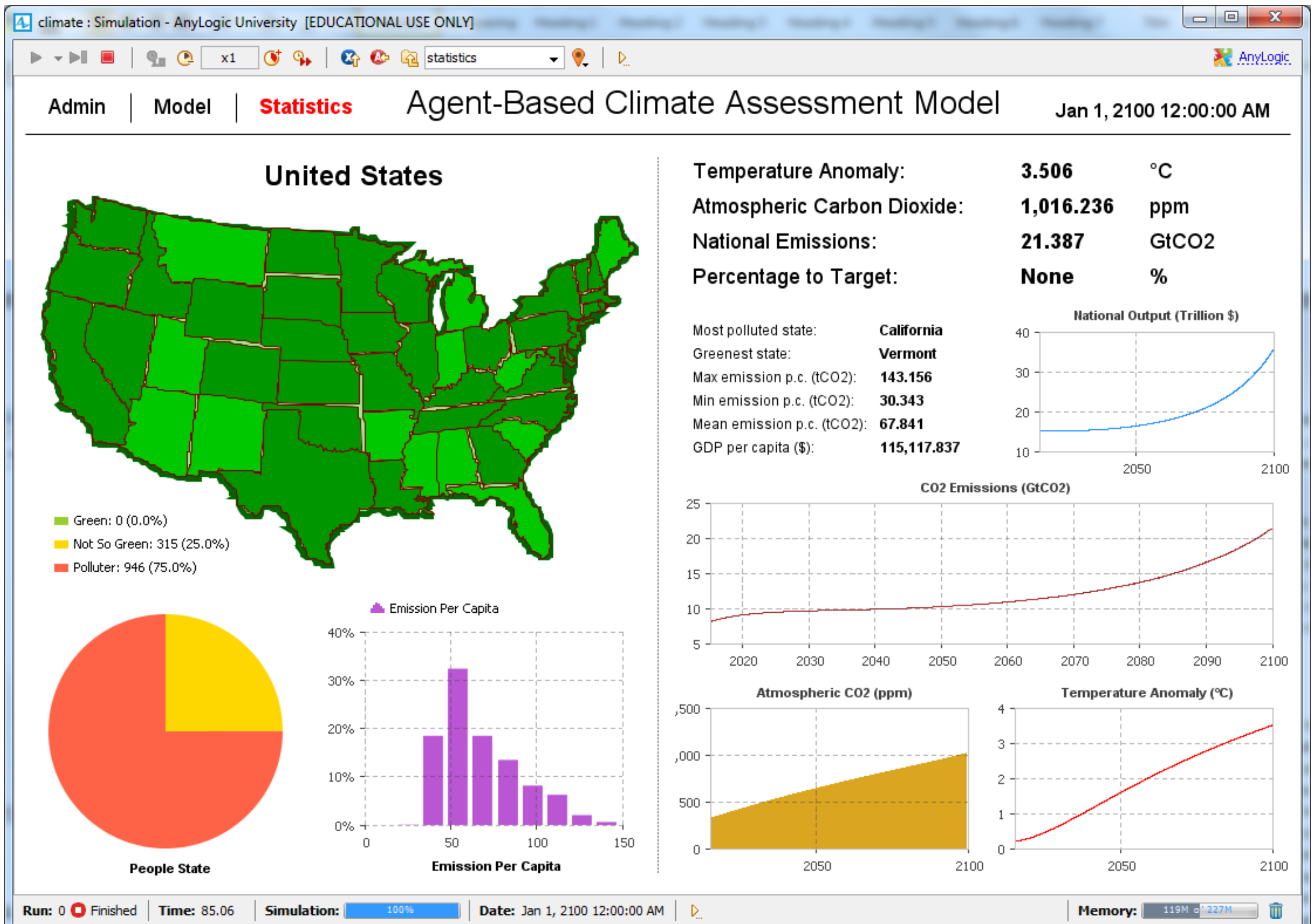
Implementation

GUI: Model / Economy



Implementation

GUI: Model / Statistics

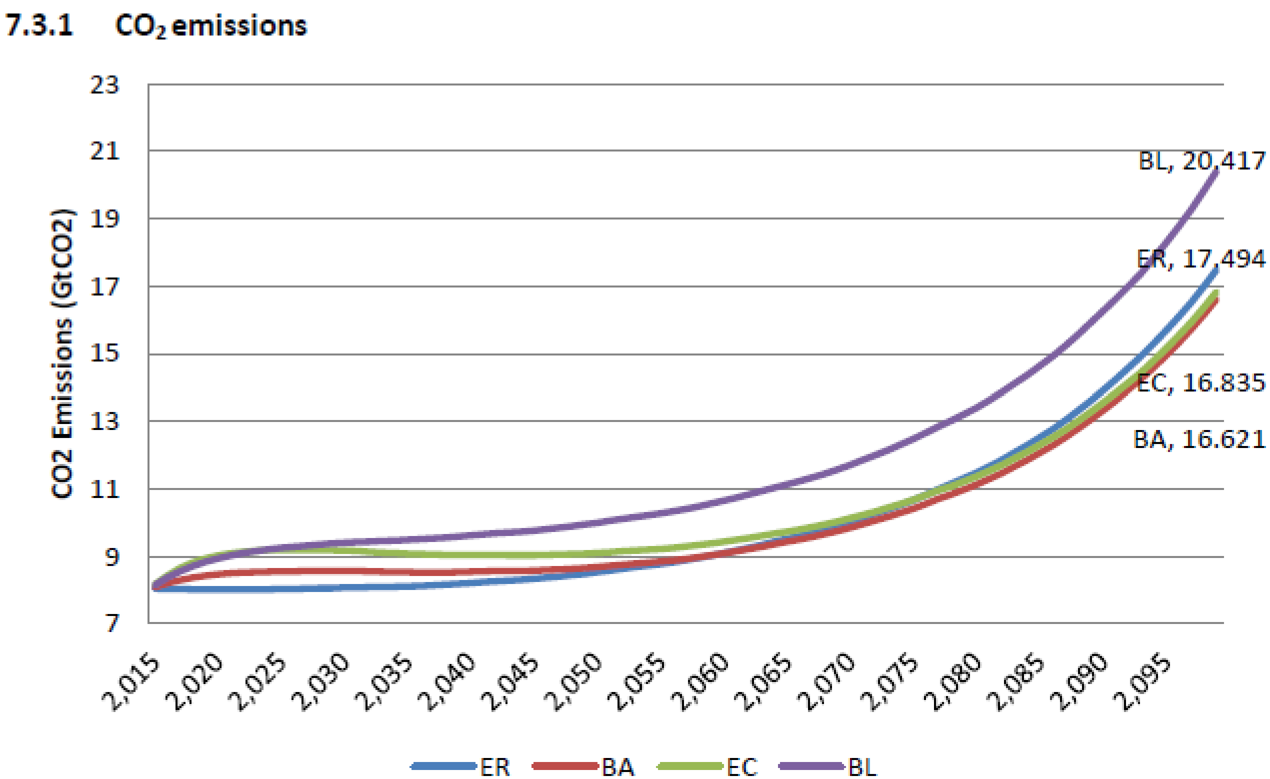


Experimentation

- Question: Given a constant amount of capital allocated for the climate mitigation sector, what is/are the most effective policy(s) that the federal US government can invest the funds in to leverage the available resources?
  - Baseline scenario: no mitigation actions
  - Balanced scenario: evenly-split spending
    - Carbon reduction target of 17% based on target set by Obama
  - Extreme campaign: all funding is spent on organizing campaigns
  - Extreme reduction: all funding is invested in carbon abatement

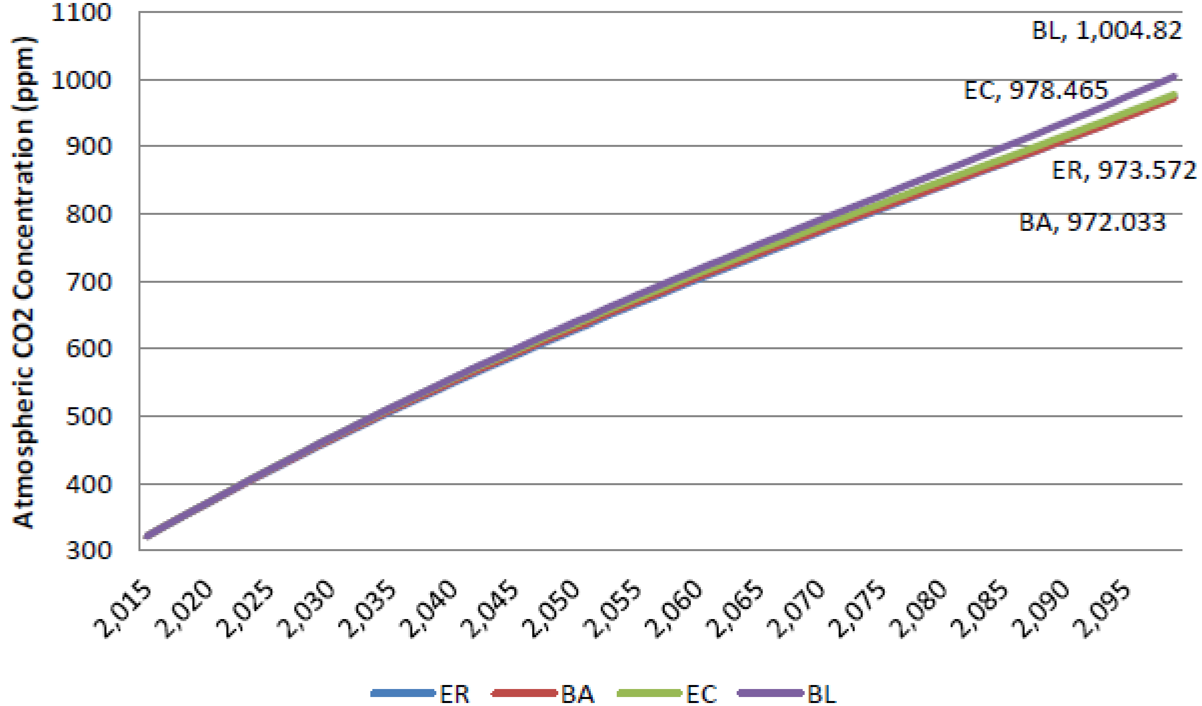
Policy \ Scenario	BL	BA	EC	ER
Carbon Reduction (%)	0	17	0	34
Campaign (per year)	0	4	8	0

Experimentation



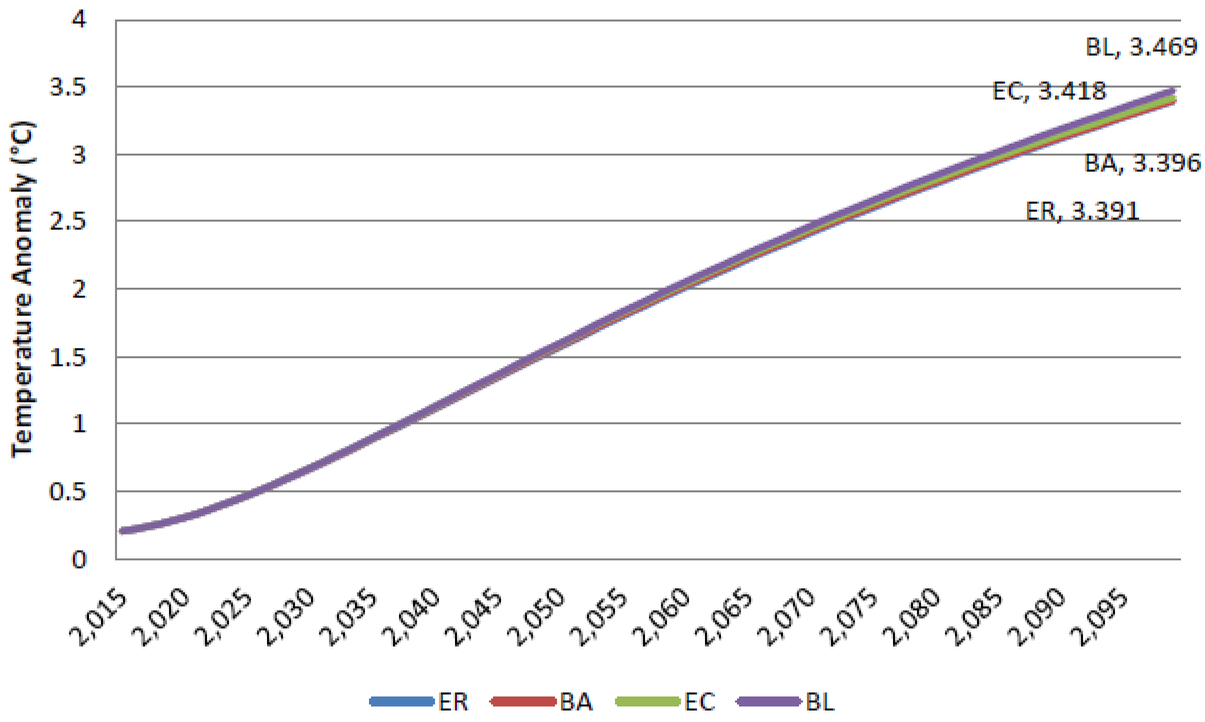
Experimentation

7.3.2 Atmospheric CO_2

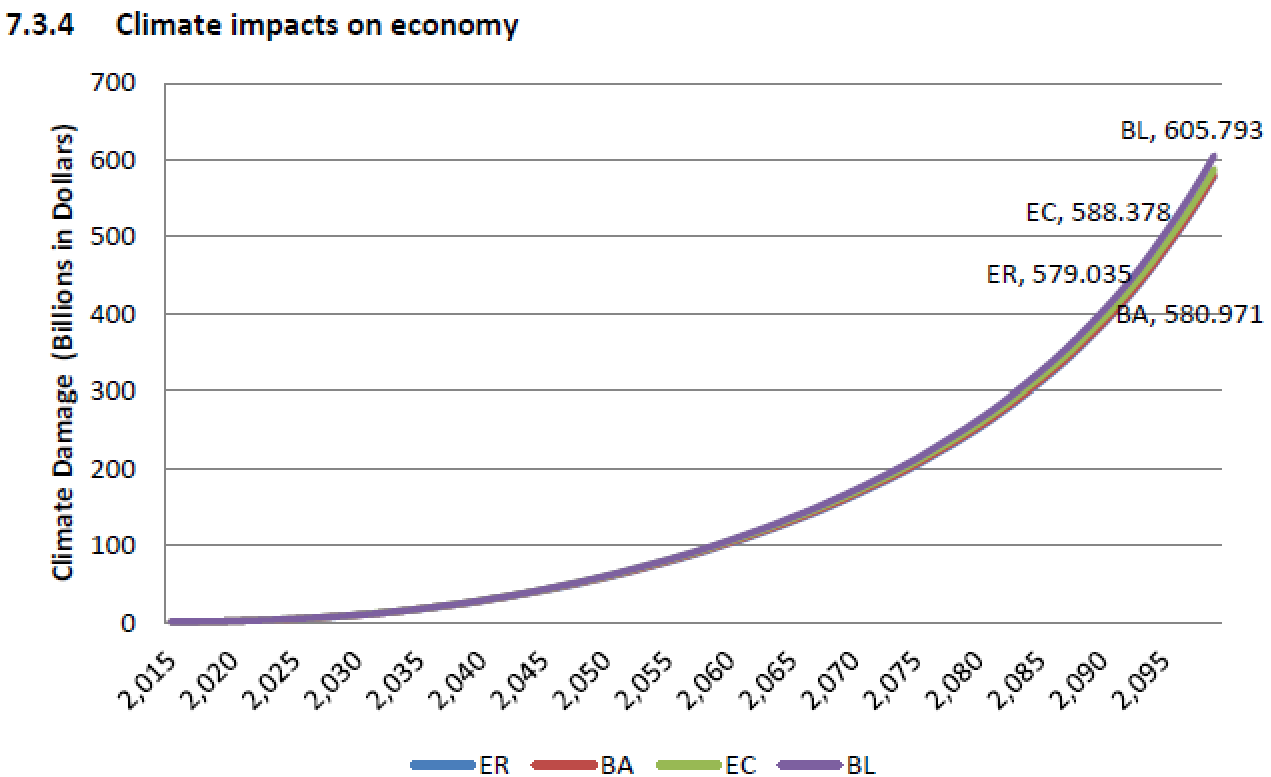


Experimentation

7.3.3 Temperature anomaly



Experimentation



Further Reading & Acknowledgement

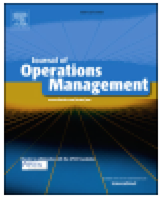
Journal of Operations Management 39-40 (2015) 1–5

ELSEVIER

Contents lists available at ScienceDirect

Journal of Operations Management

journal homepage: www.elsevier.com/locate/jom



Editorial

System dynamics perspectives and modeling opportunities for research in operations management

CrossMark

1. Introduction

It is an exciting time to work in operations management. Advances in theory and methods, including behavioral operations, dynamic modeling, experimental methods, and field studies provide new insights into challenging operational contexts. Yet the world of operations continues to change rapidly, creating new and difficult challenges for scholars. Increasingly, operations management requires theory, models and empirical methods to address the cross-functional, interdisciplinary character of modern operational systems and the complex nonlinear dynamics these systems generate.

The OM research community has a long tradition of dynamic modeling, going back at least to the pioneering work of Forrester (1958) and Holt et al. (1960). These innovators recognized that even core processes in organizations, such as production and supply chains, are dynamic systems. approach to dynamic modeling any management system, indeed, any dynamic system, along with the conceptual and software tools to develop, test, and improve behavioral, dynamic models of human systems, and implement the recommendations arising from them. Soon after the publication of *Industrial Dynamics*, these concepts were applied to a variety of contexts, first in management, and soon after to ecological, urban, and societal problems, among others. By the late 1960s the breadth of the field led to a name change, from industrial dynamics to system dynamics (SD), and the growth of a vibrant field of study, taught around the world (see e.g. http://systemdynamics.org).

There are many conceptual overlaps and synergies between OM/OR and SD; these can be traced to the origins and stated goals of both fields (see Lane, 1997; and Größler et al., 2008). Here we focus on the methodological elements of SD that are most distinctive and relevant to the OM community.

Questions / Comments

Acknowledgement

- Acknowledgement:
  - Slides are based on Kirkwood (1998), Fishwick (2011) and Zhi En (2015)

References

- Fishwick P (2011) CAP4800/5805 Computer Simulation: System Dynamics Lecture Slides (http://www.cise.ufl.edu/~fishwick/cap4800/sd1.ppt)
- Kirkwood CW (1998) System Dynamics Methods: A Quick Introduction (http://www.public.asu.edu/~kirkwood/sysdyn/SDIntro/SDIntro.htm)
- Morecroft JD (2007) Strategic Modelling and Business Dynamics. Wiley, Chichester, UK.
- Nordhaus WD (1992) The'DICE'Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming. Cowles Foundation for Research in Economics, Yale University.
- Proceedings of the International System Dynamics Conference (1983-2012) (http://conference.systemdynamics.org/past_conference/)
- Sterman JD (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw Hill, Boston, USA.
- VenSim User's Guide (http://www.vensim.com/ffiles/VensimUsersGuide.zip)
- Zhi En L (2015) Using a Hybrid Approach on Climate Assessment Modeling. BSc CompSci+AI Dissertation, Nottingham University, UK.