COMP4038/G54SOD (Spring 2019)

Lecture 06

System Dynamics Modelling and Simulation + Hybrids

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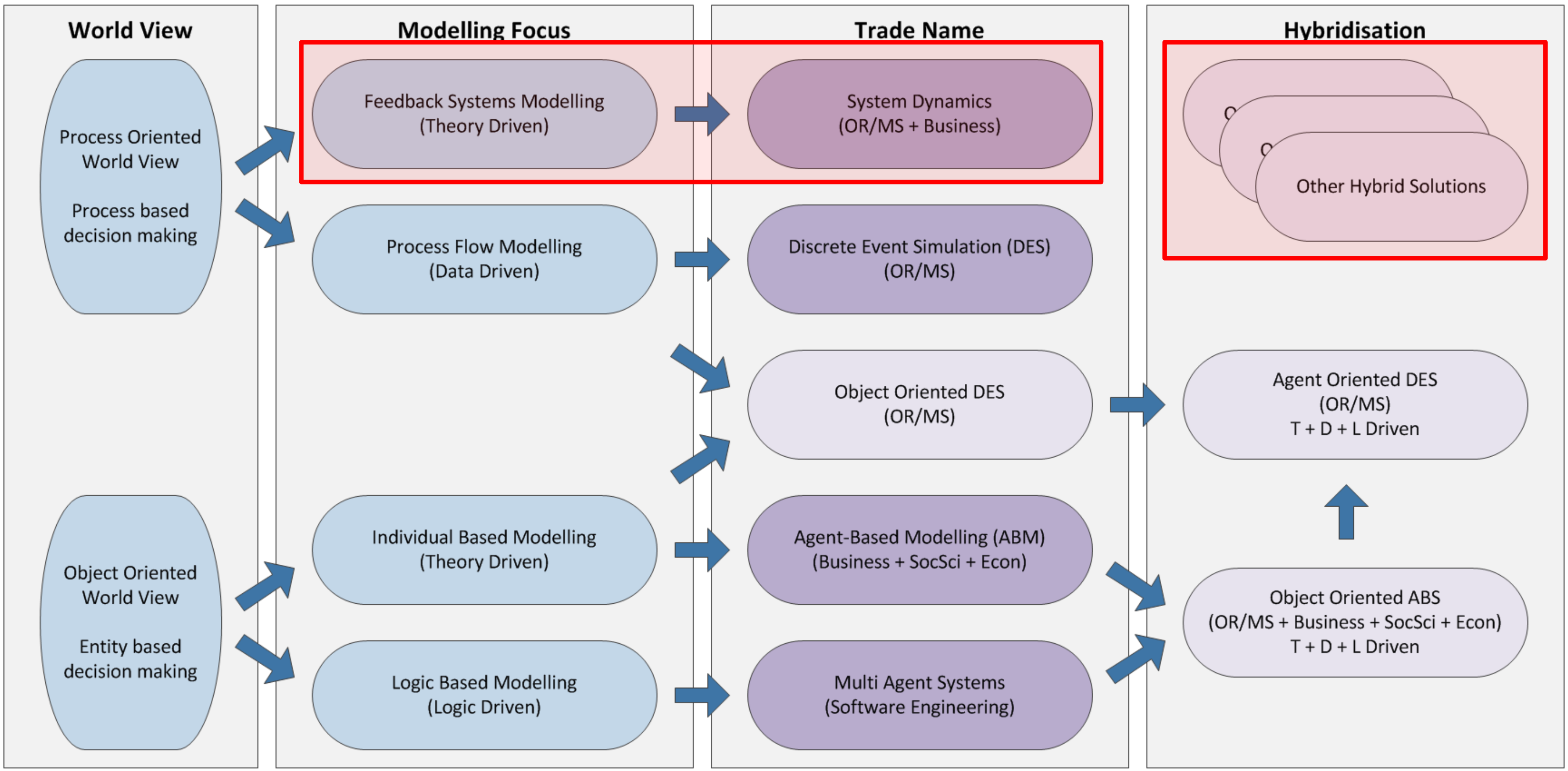
Content

- Introduction to Systems Thinking and System Dynamics
- System Dynamics Modelling and Simulation
- Hybrids
- Case Study: An Innovative Approach to Multi-Method Integrated Assessment Modelling of Global Climate Change

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

Introduction to Systems Thinking and System Dynamics

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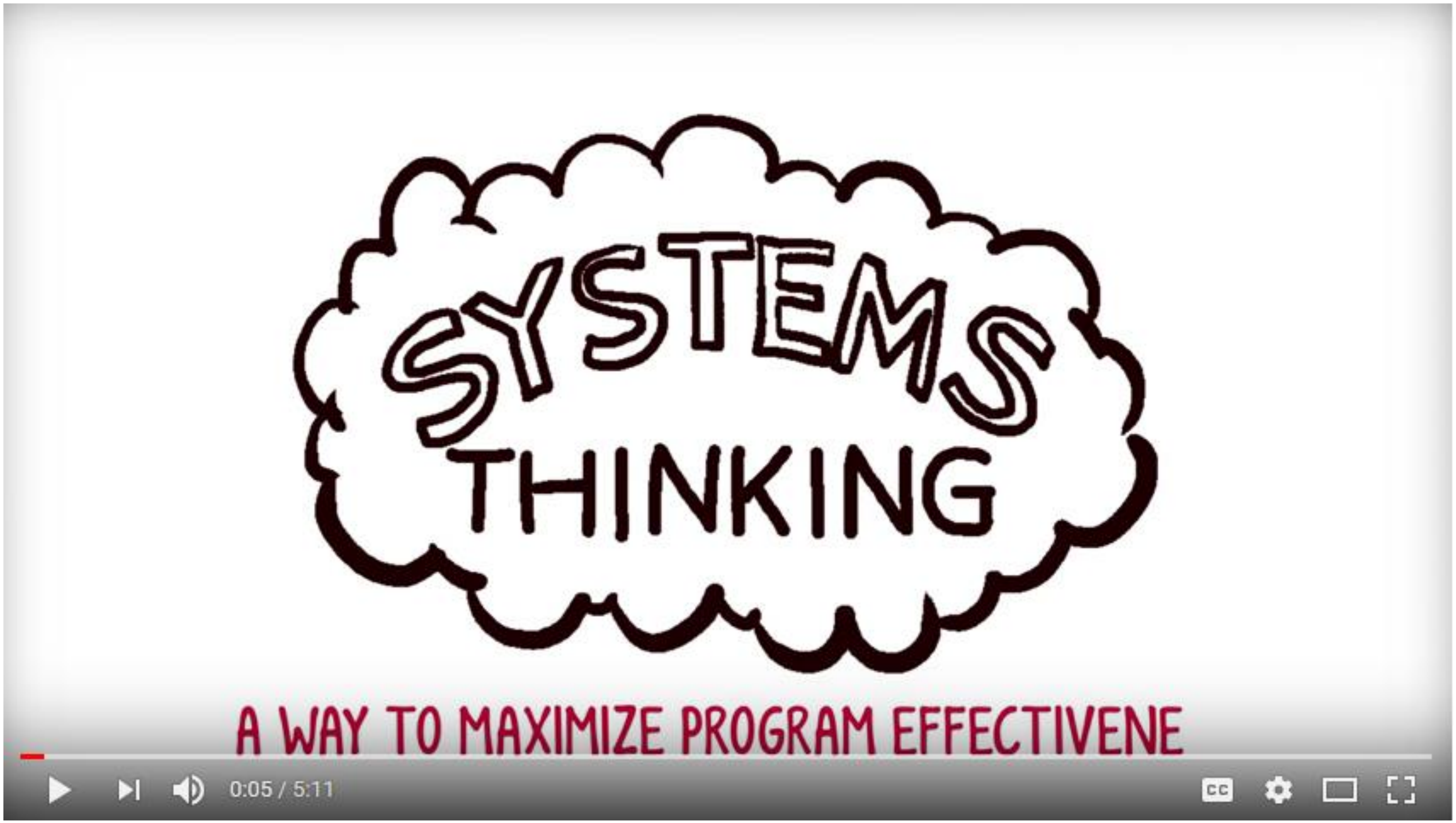
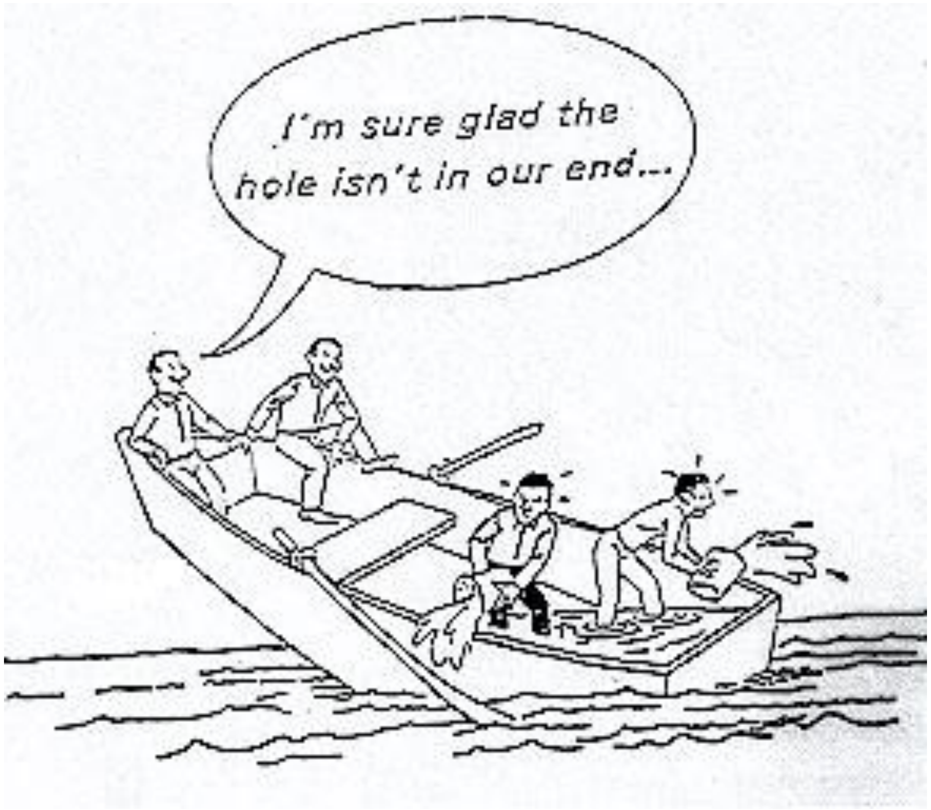
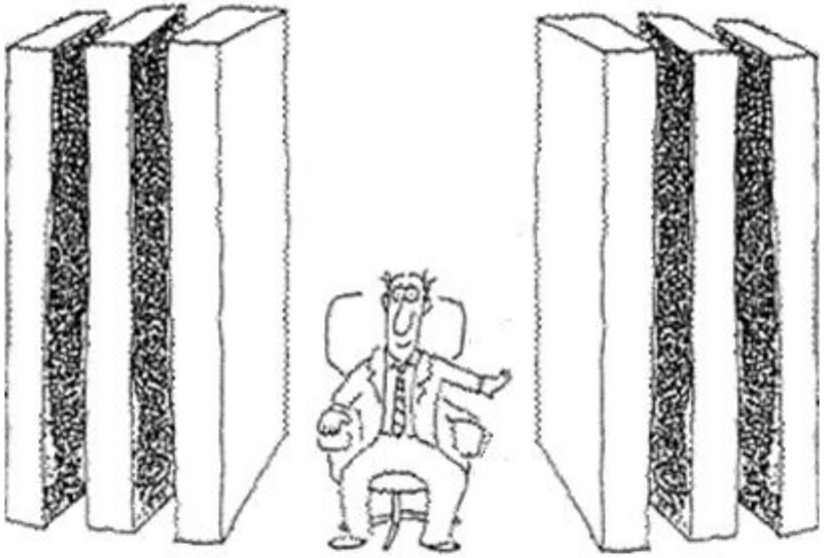
Systems Thinking



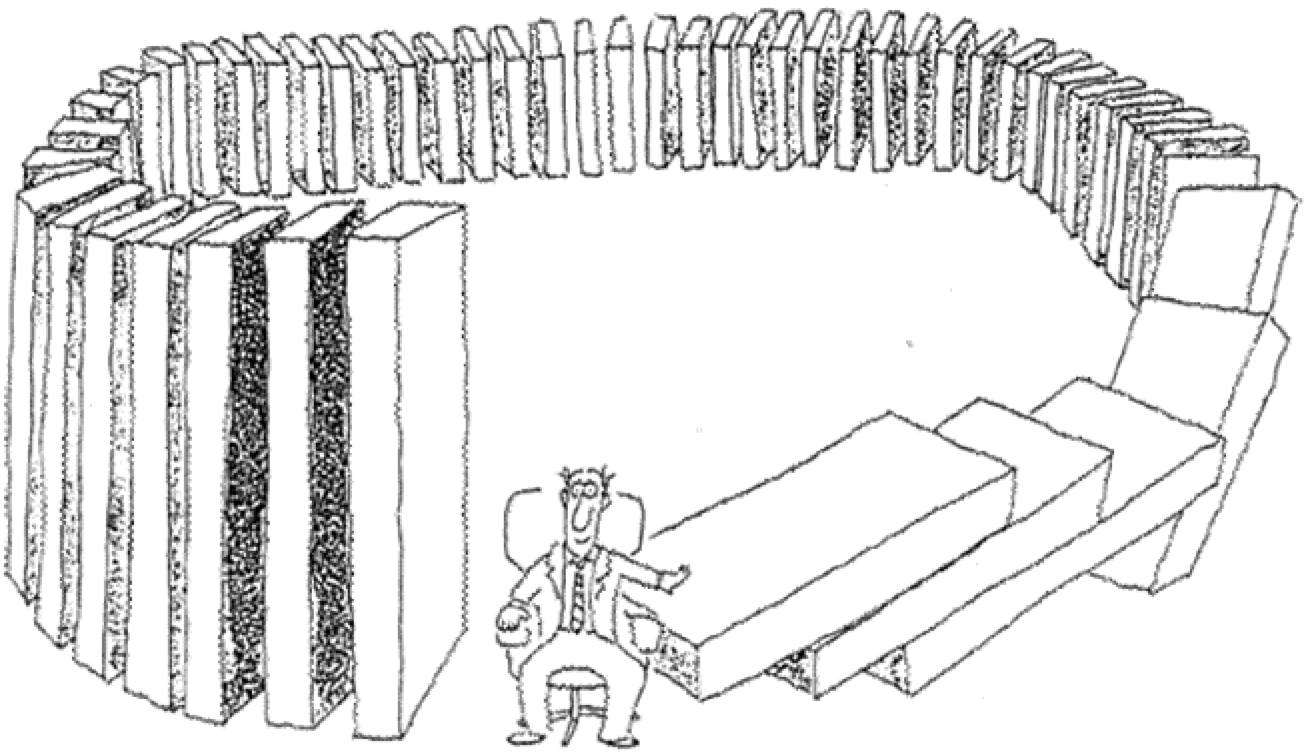
Systems Thinking



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

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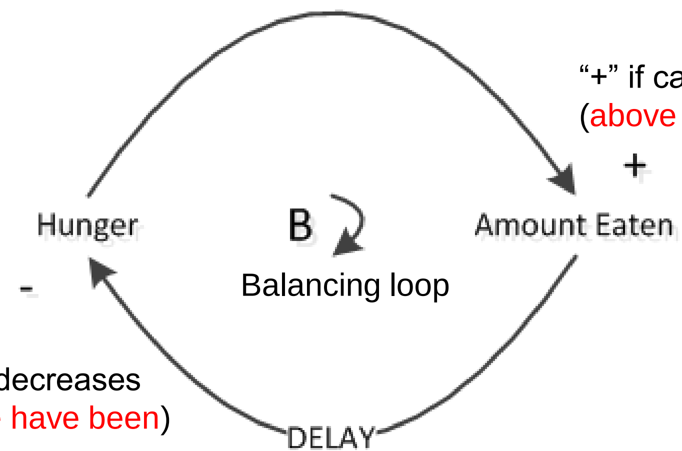
System Dynamics Modelling

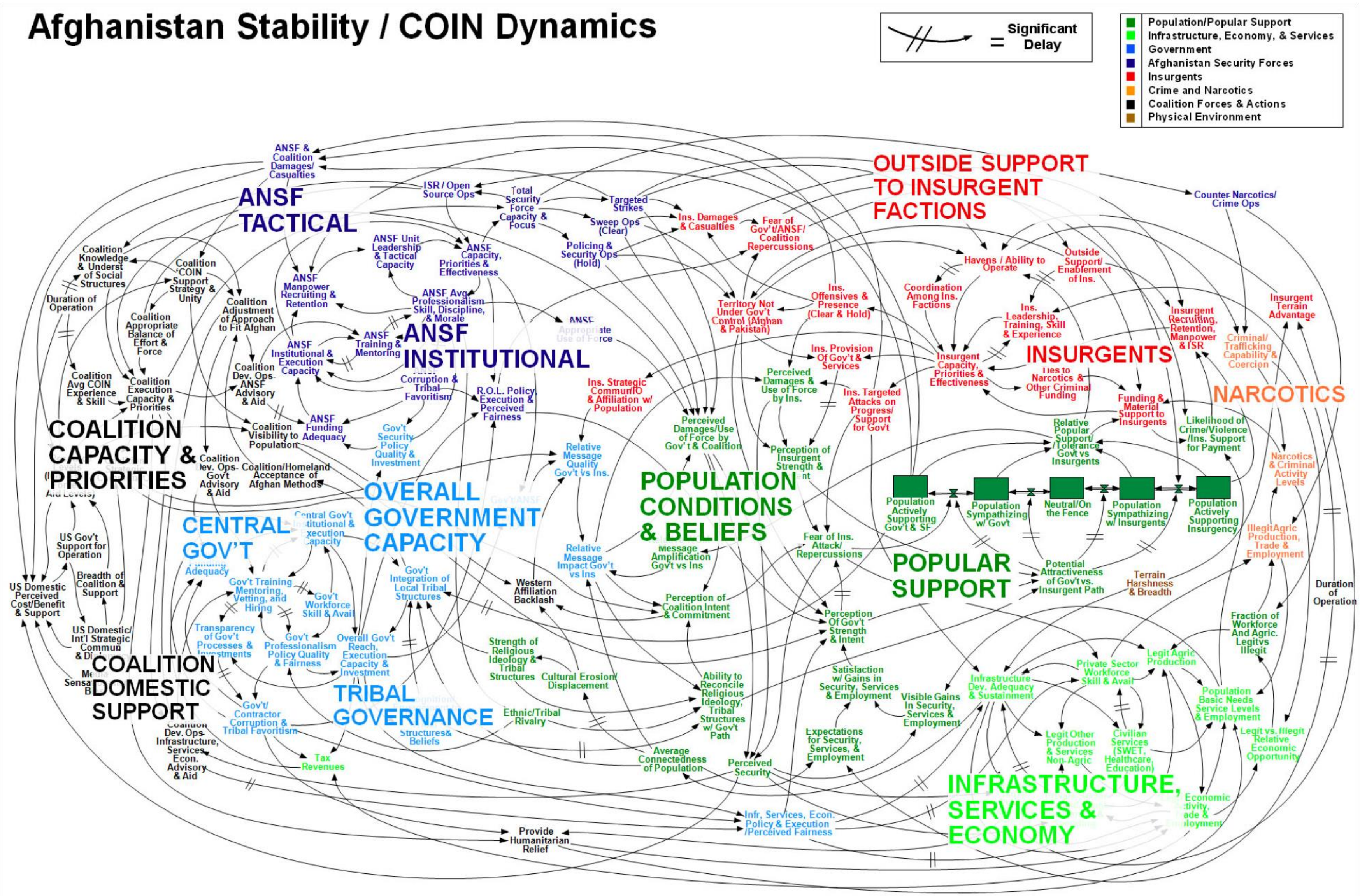
- Model representations
  - Causal loop diagrams (qualitative)
  - Stock and Flow diagrams (quantitative)

- 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)



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

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

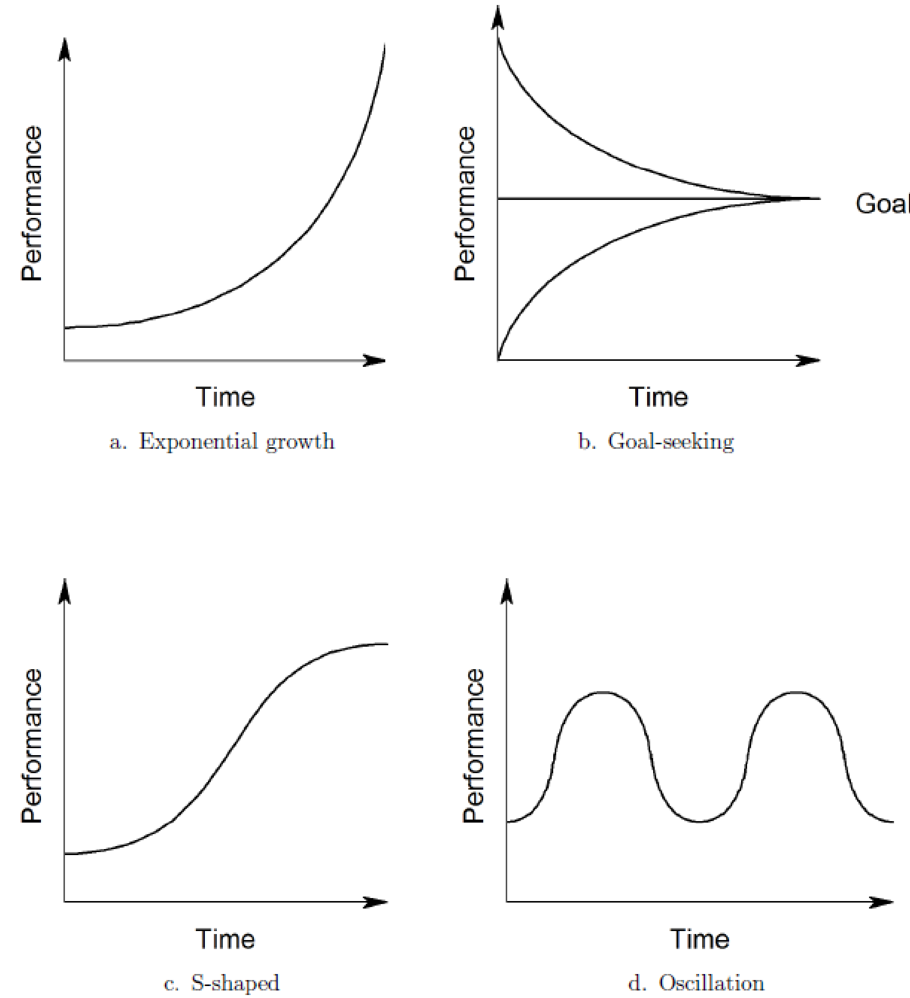
- Formulation
  - Convert diagrams to stock and flow equations
  - Estimate and select parameter values
  - Create the simulation model
- Testing
  - Test the dynamic hypothesis (the potential explanation of how structure is causing observed behaviour)
  - Test model behaviour and sensitivity to perturbations
- 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



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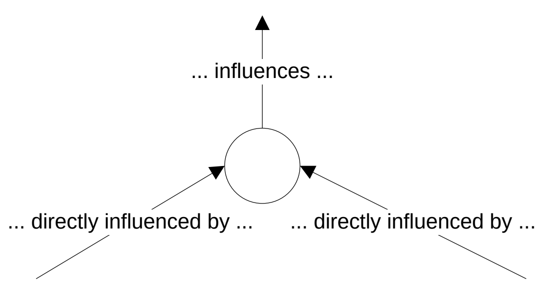
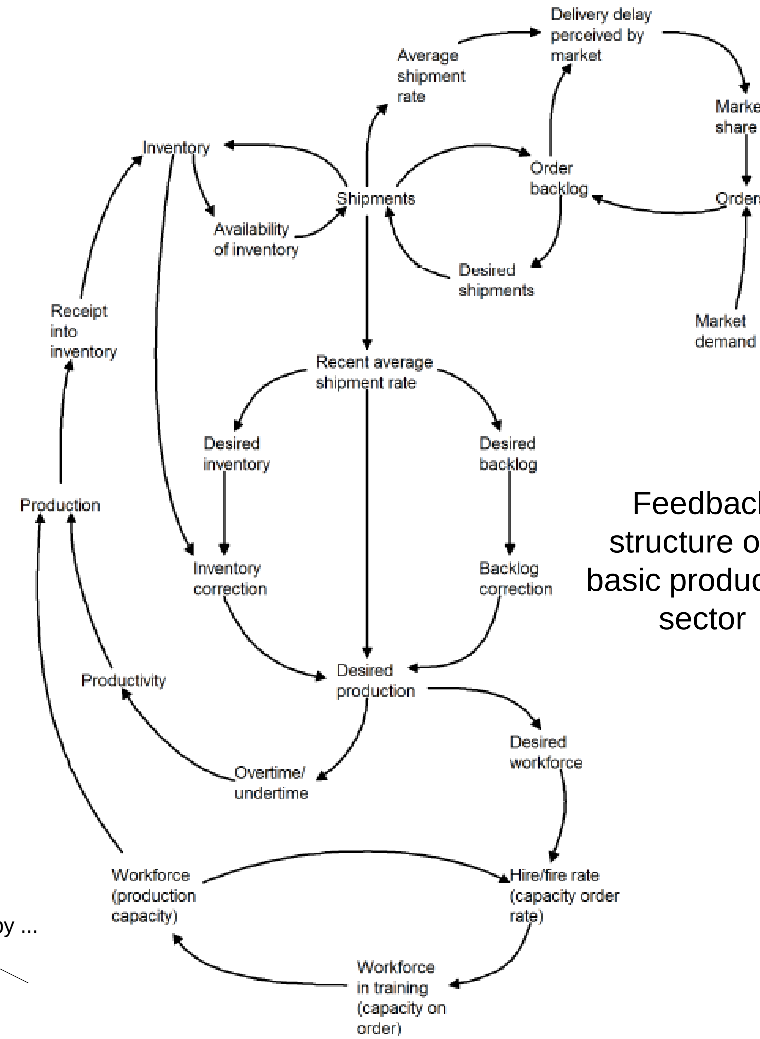
Feedback and Causal Loop Diagrams

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

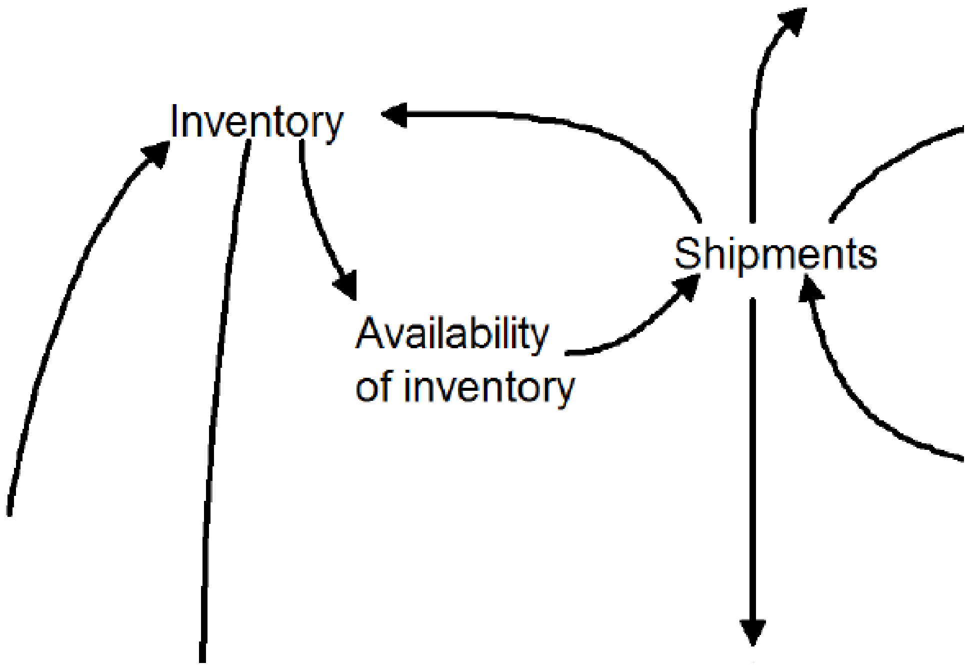




Feedback structure of a basic production sector

Feedback and Causal Loop Diagrams

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



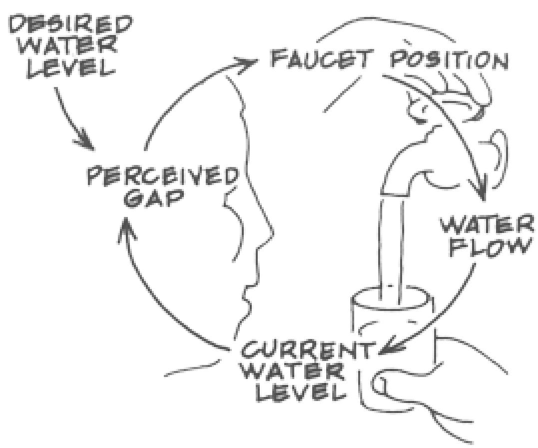
Feedback and Causal Loop Diagrams

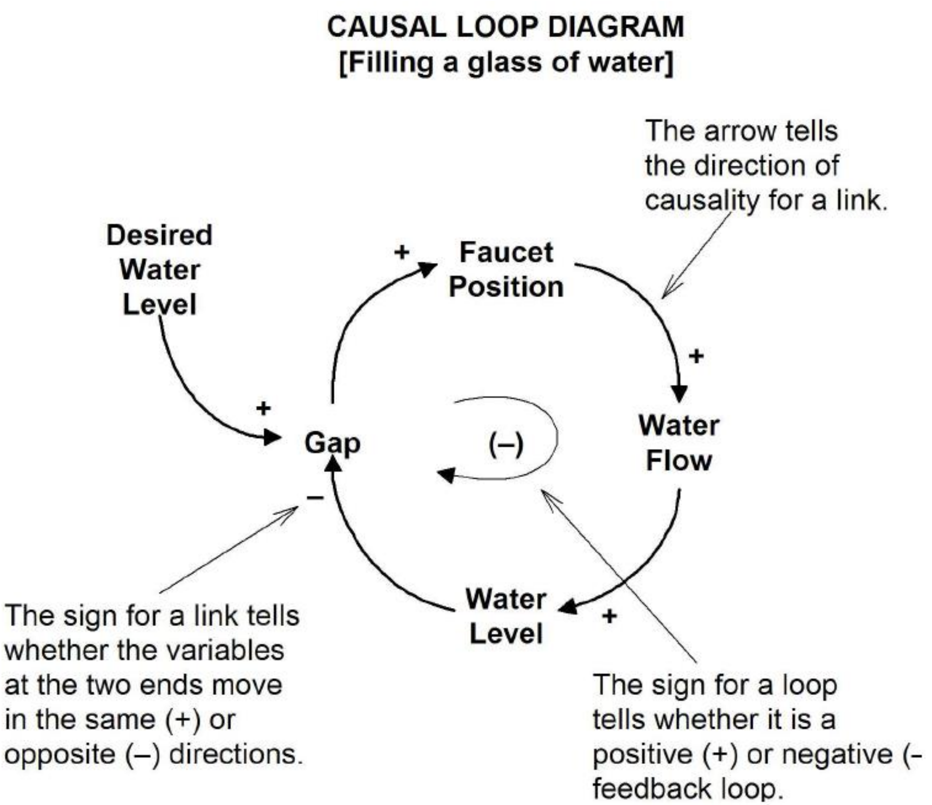
- Causal link impact direction
  - Causal link from element A to B is positive (+ or s) if either A adds to B or a change in A produces a change in B in the same direction
  - Causal link from element A to B is negative (- or o) if either A subtracts from B or a change in A produces a change in B in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



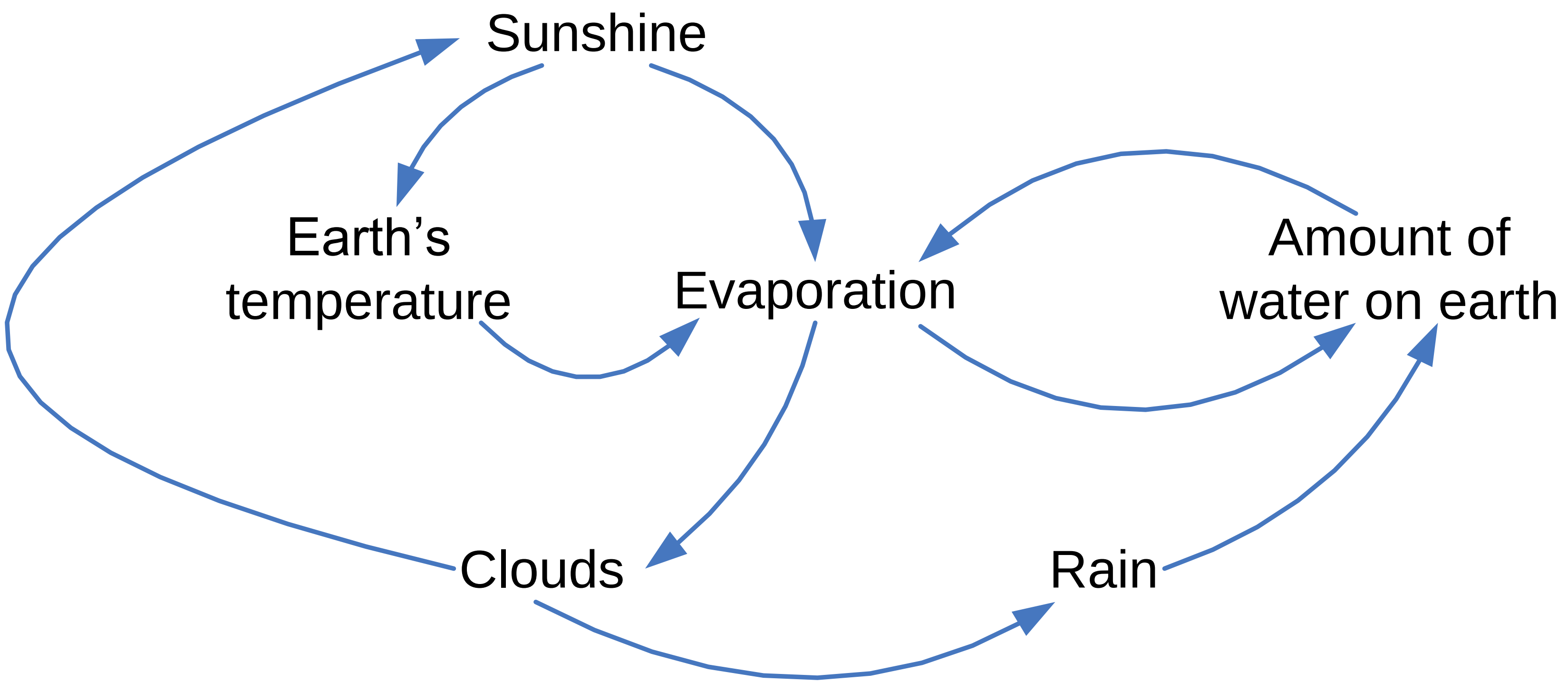


"+" if cause increases ... effect increases
(above what it would otherwise have been)

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

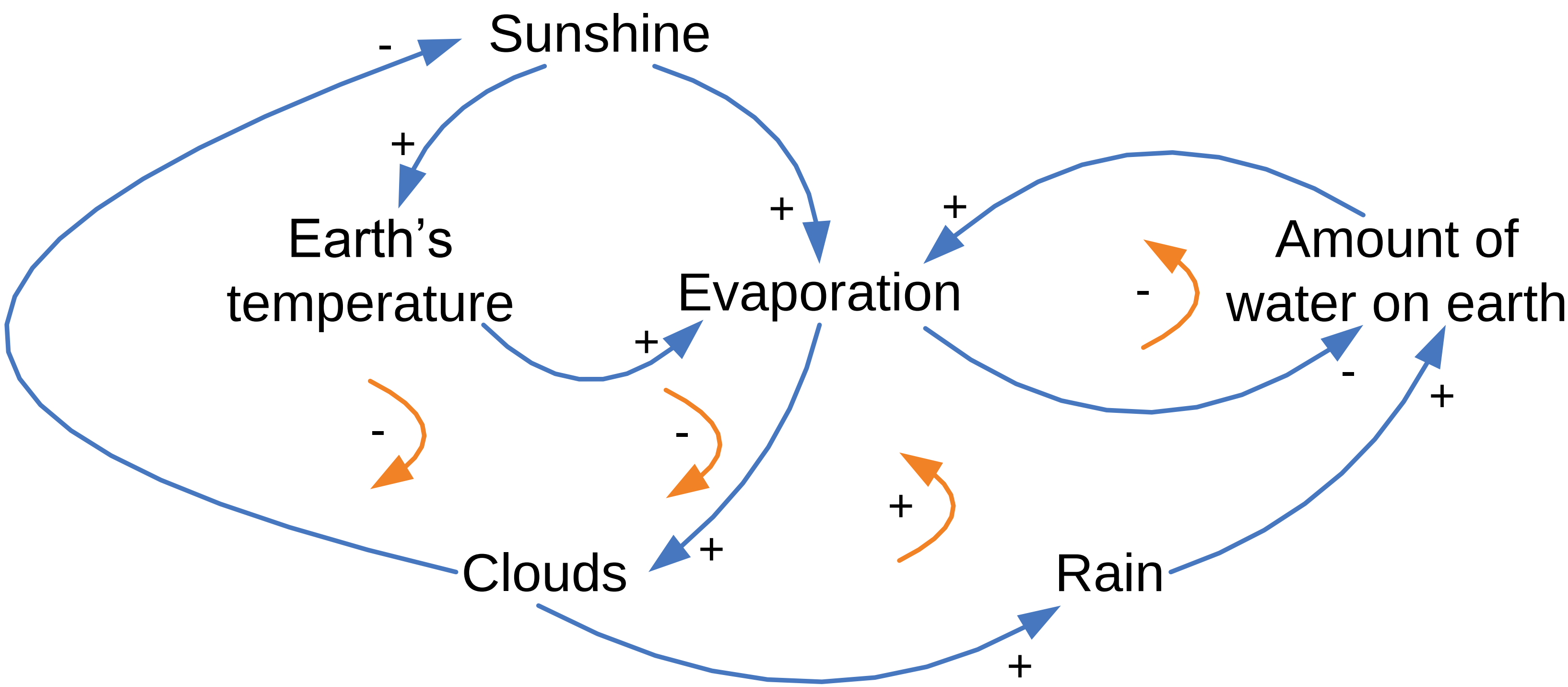
Feedback and Causal Loop Diagrams

- Self regulating biosphere



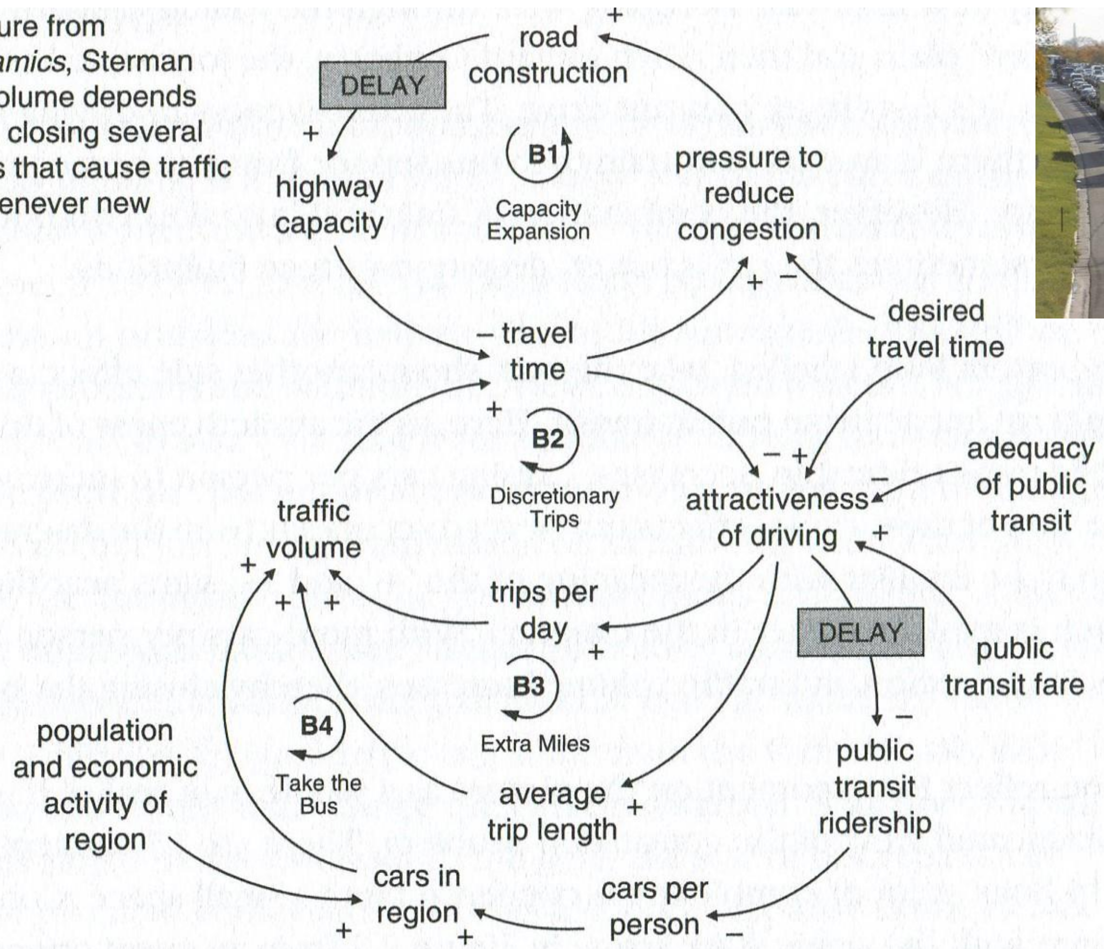
Feedback and Causal Loop Diagrams

- Self regulating biosphere



Example: Reduce Road Congestion

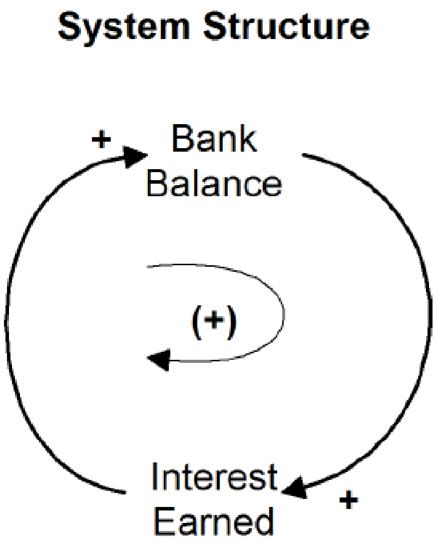
Based on a figure from *Business Dynamics*, Sterman 2000. Traffic volume depends on congestion, closing several feedback loops that cause traffic to increase whenever new roads are built.

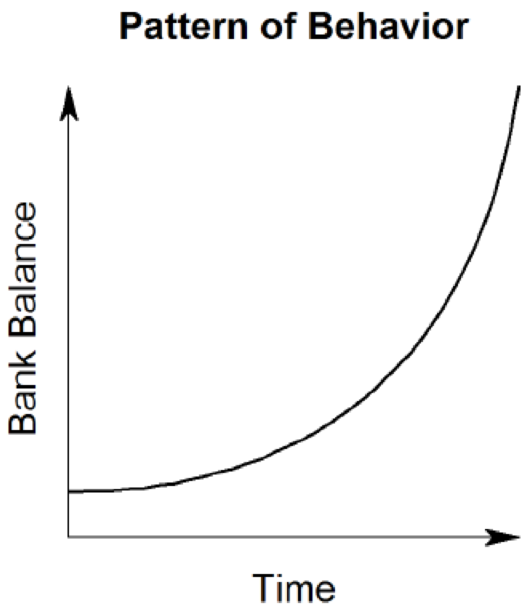


[Morecroft 2007]

System Structures and Patterns of Behaviour

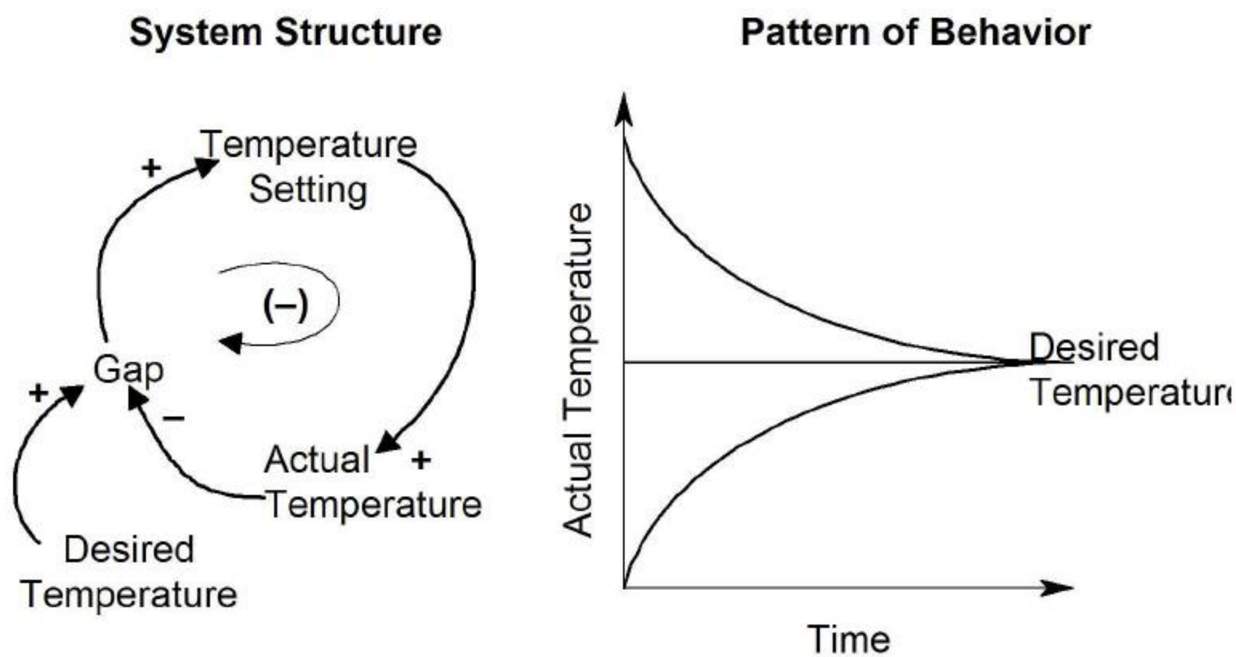
- Positive (reinforcing) feedback loop [e.g. growth of bank balance]





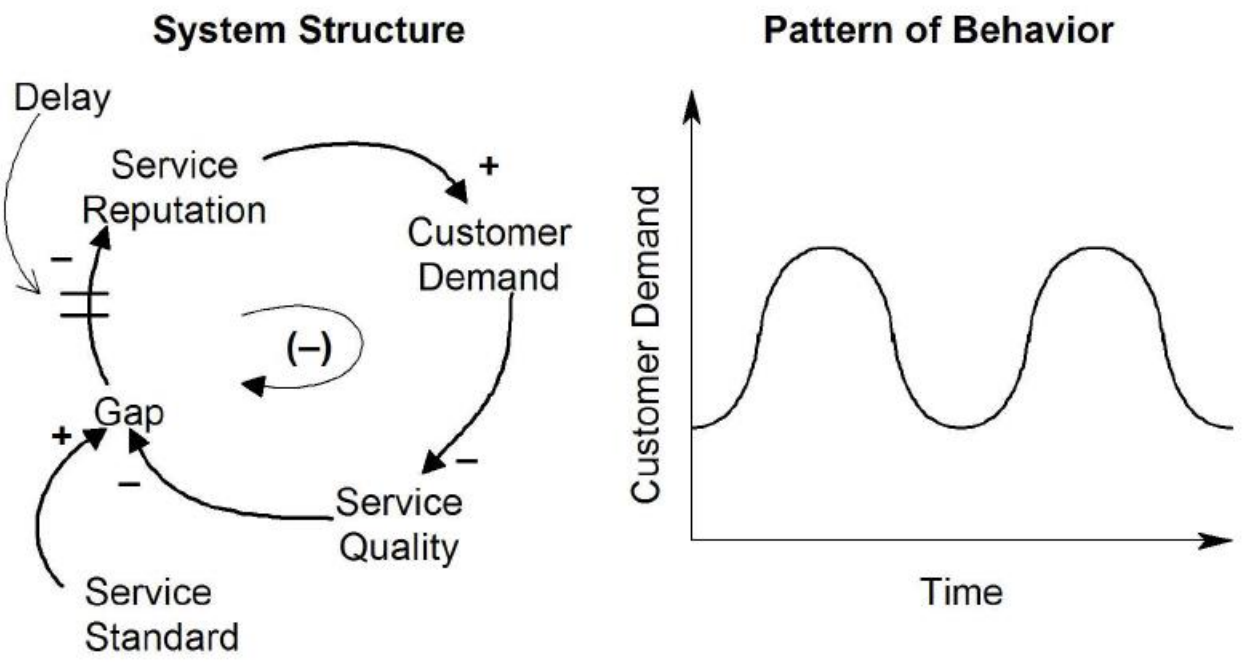
System Structures and Patterns of Behaviour

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



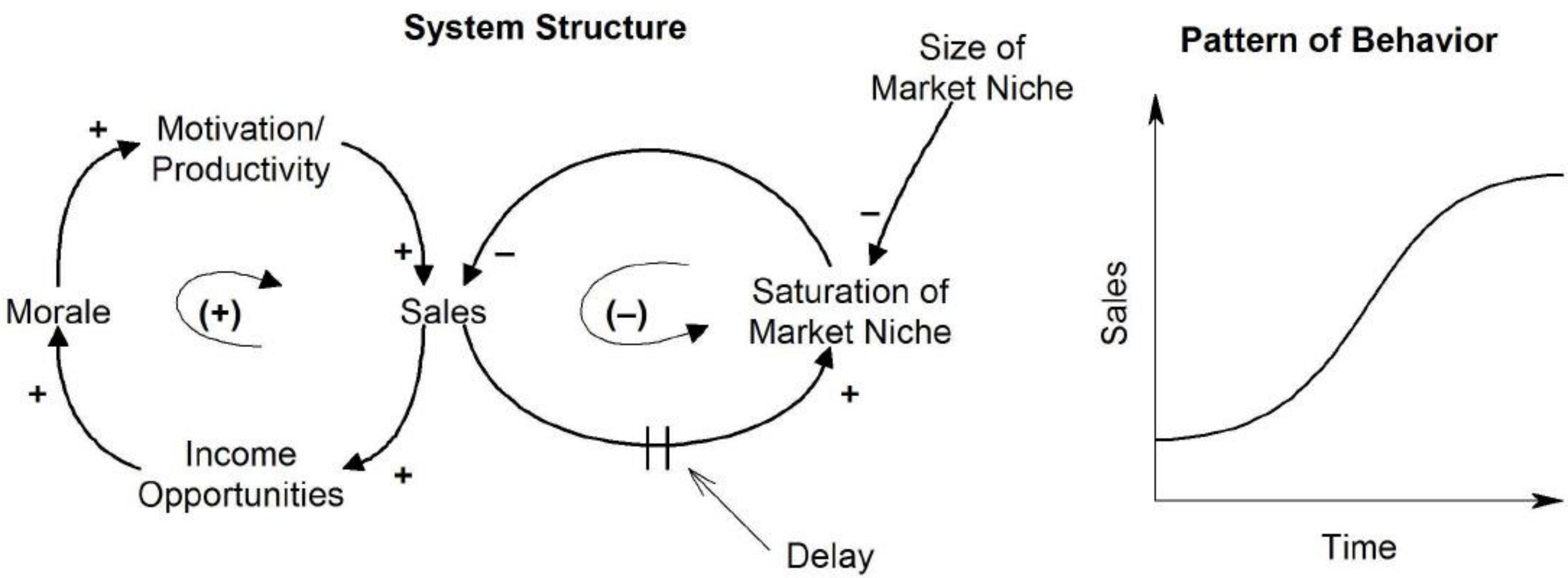
System Structures and Patterns of Behaviour

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



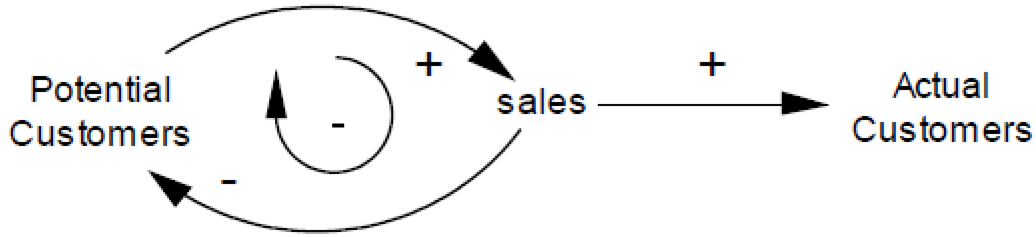
System Structures and Patterns of Behaviour

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

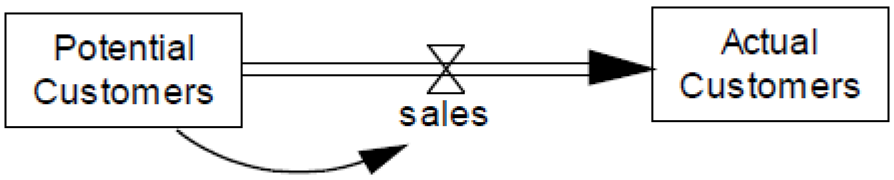


Stock and Flow Diagrams

- 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

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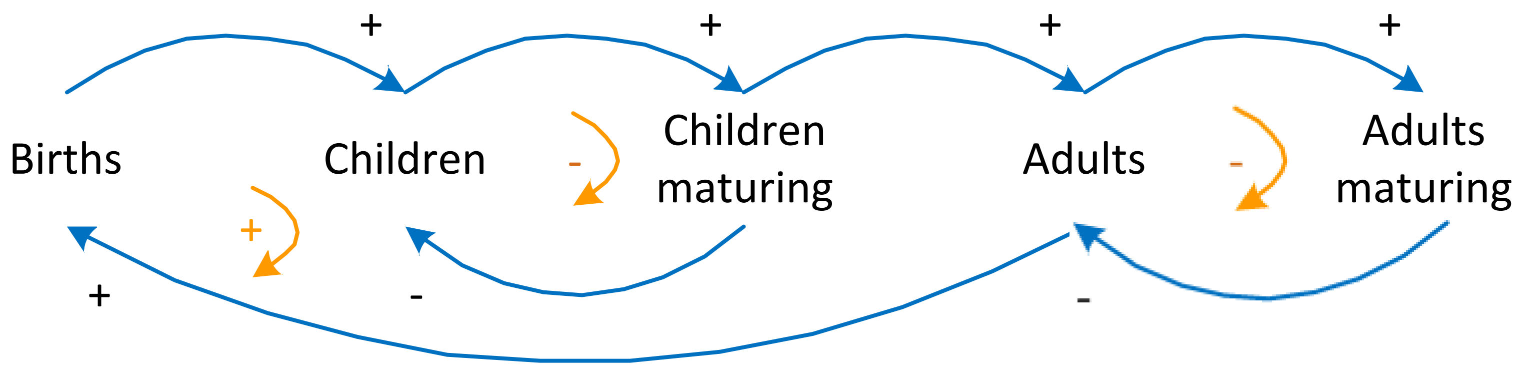
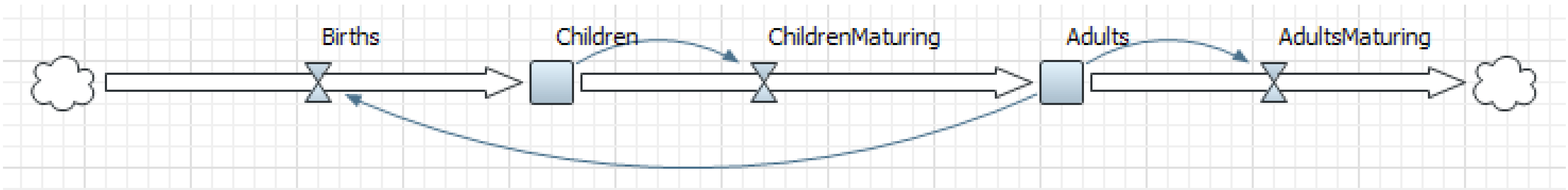
Stock and Flow Diagrams

- Growth of population through birth



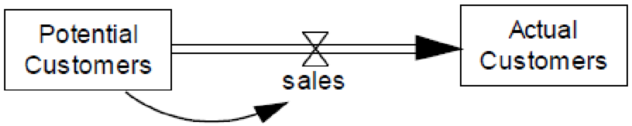


System Dynamics Simulation

- 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

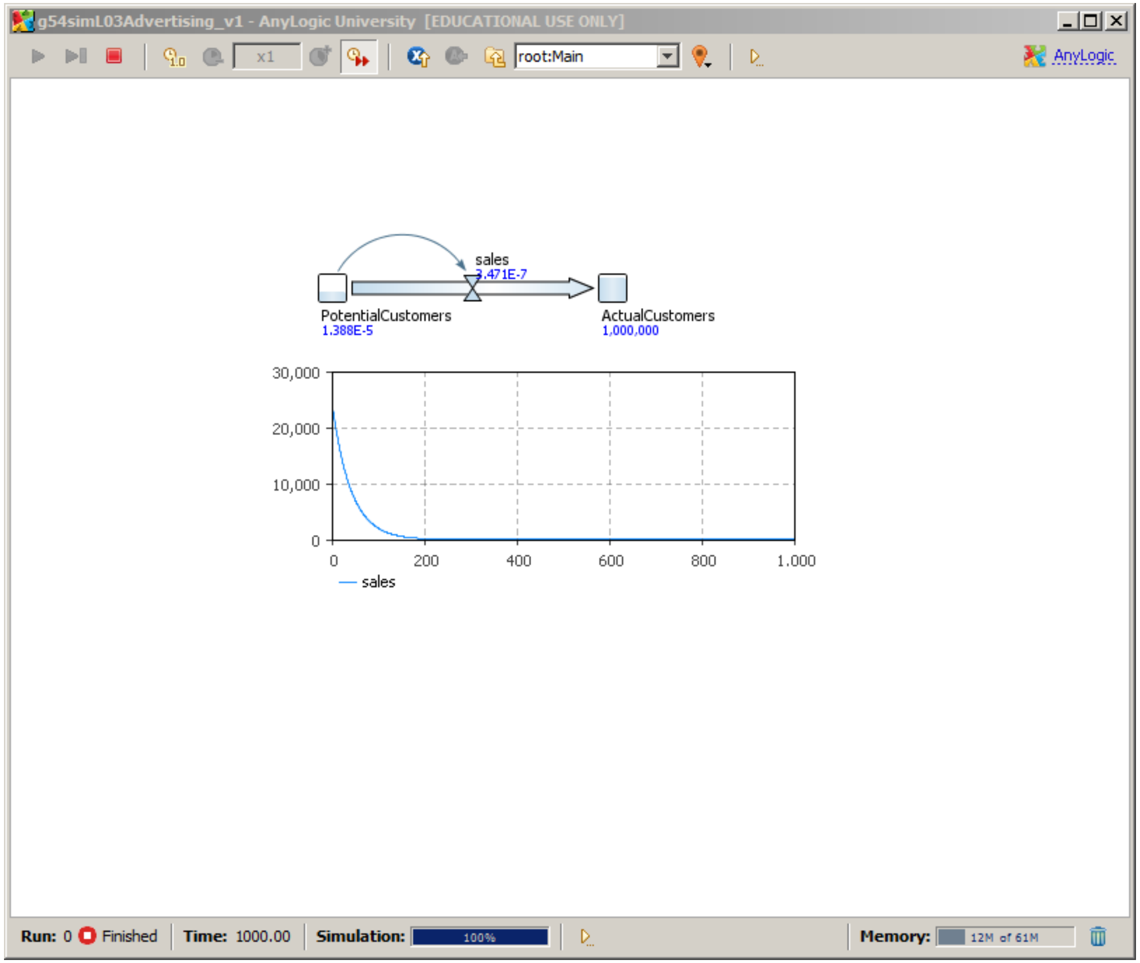
$$\text{Actual Customers} = \int_0^t \text{sales}(\tau)\, d\tau.$$

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

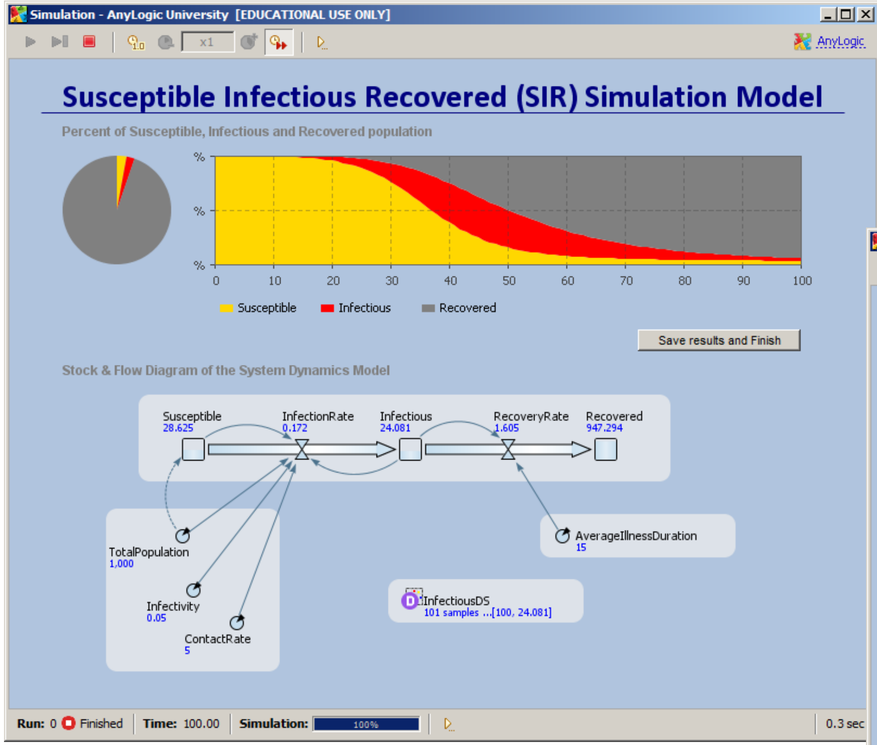
$$\text{sales}(t) = 0.025 \times \text{Potential Customers}(t)\text{rs}(t) > 0$$

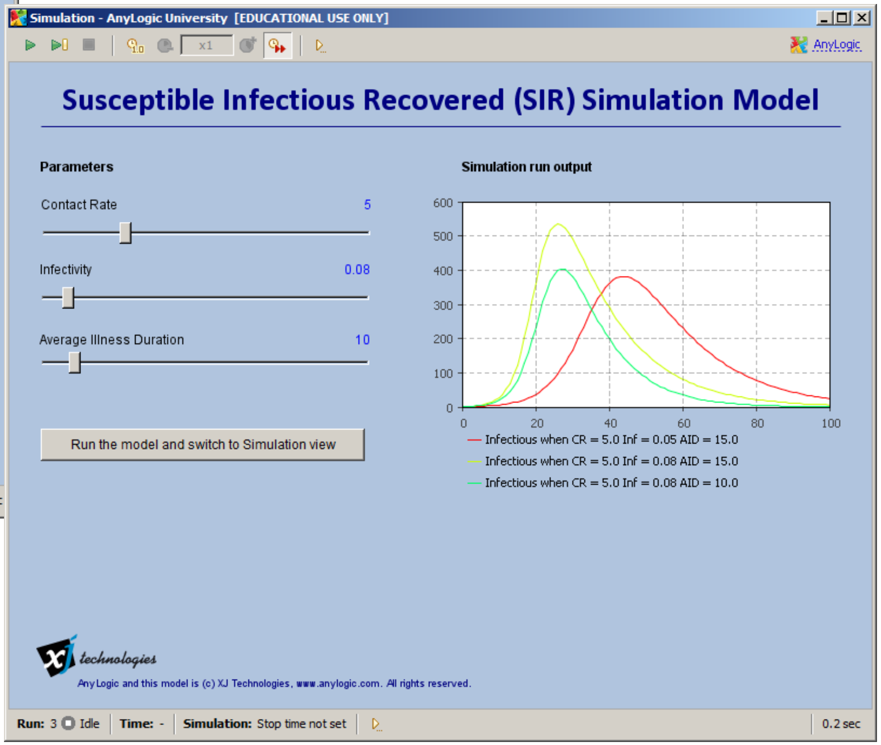
$$\{ 0, \qquad \text{otherwise}$$

System Dynamics Simulation

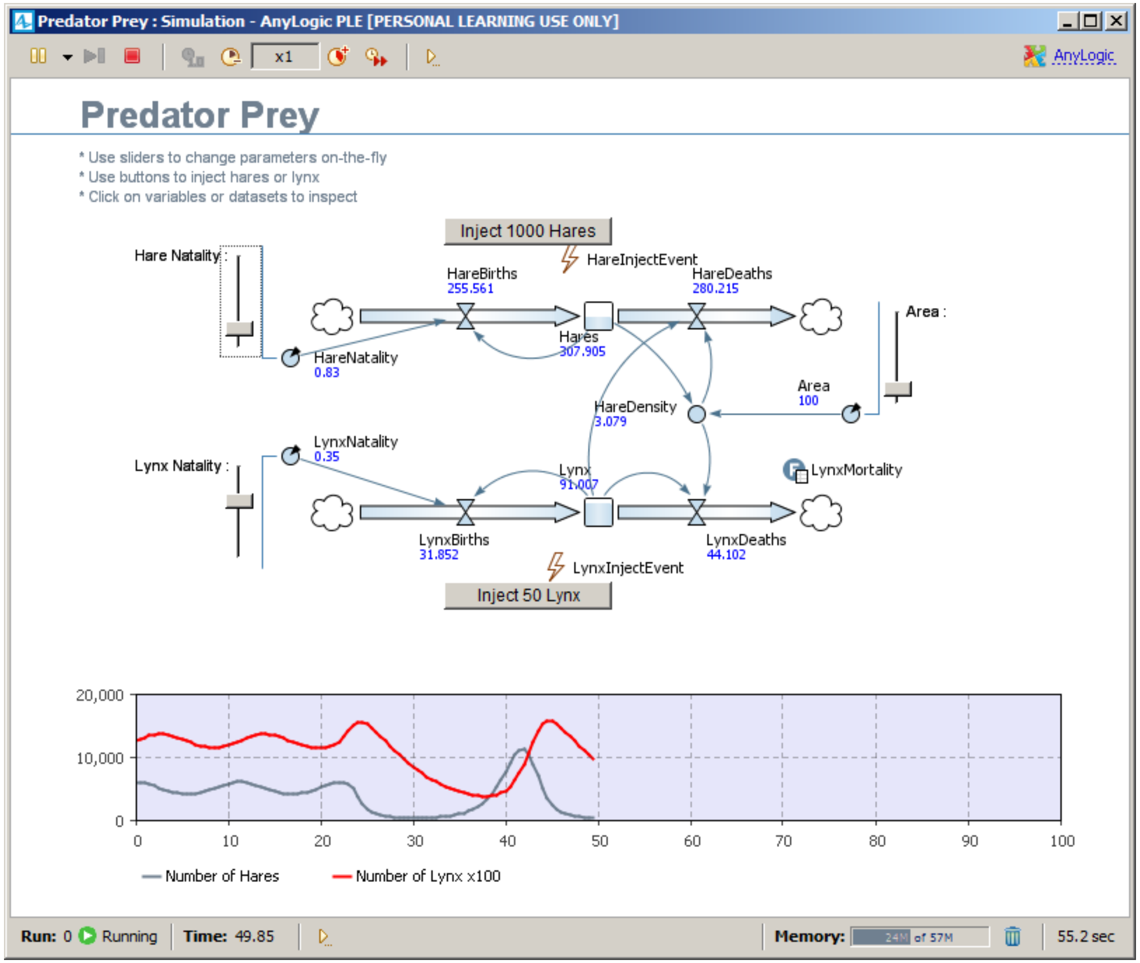


System Dynamics Simulation

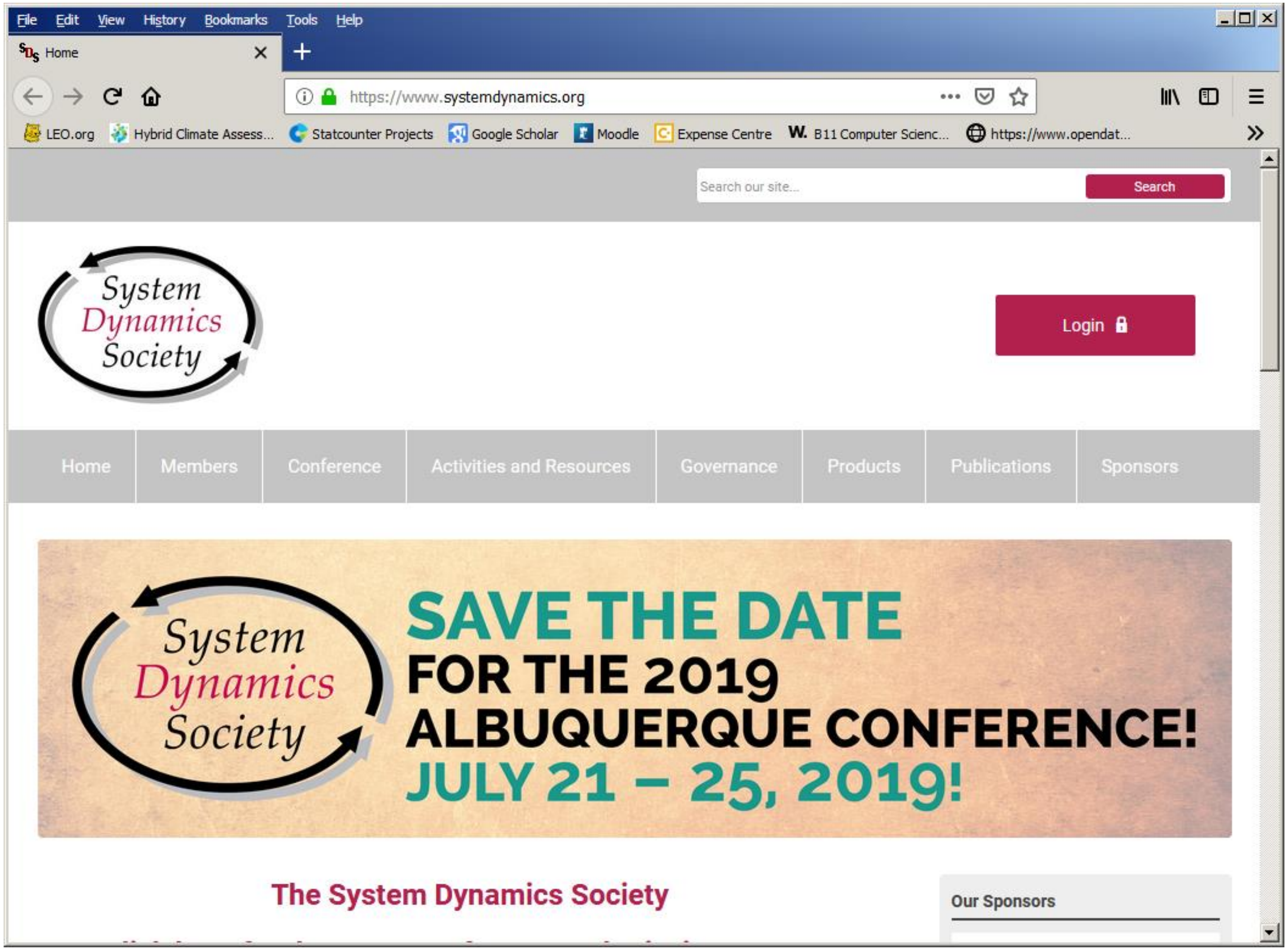




System Dynamics Simulation



System Dynamics Society



Hybrids

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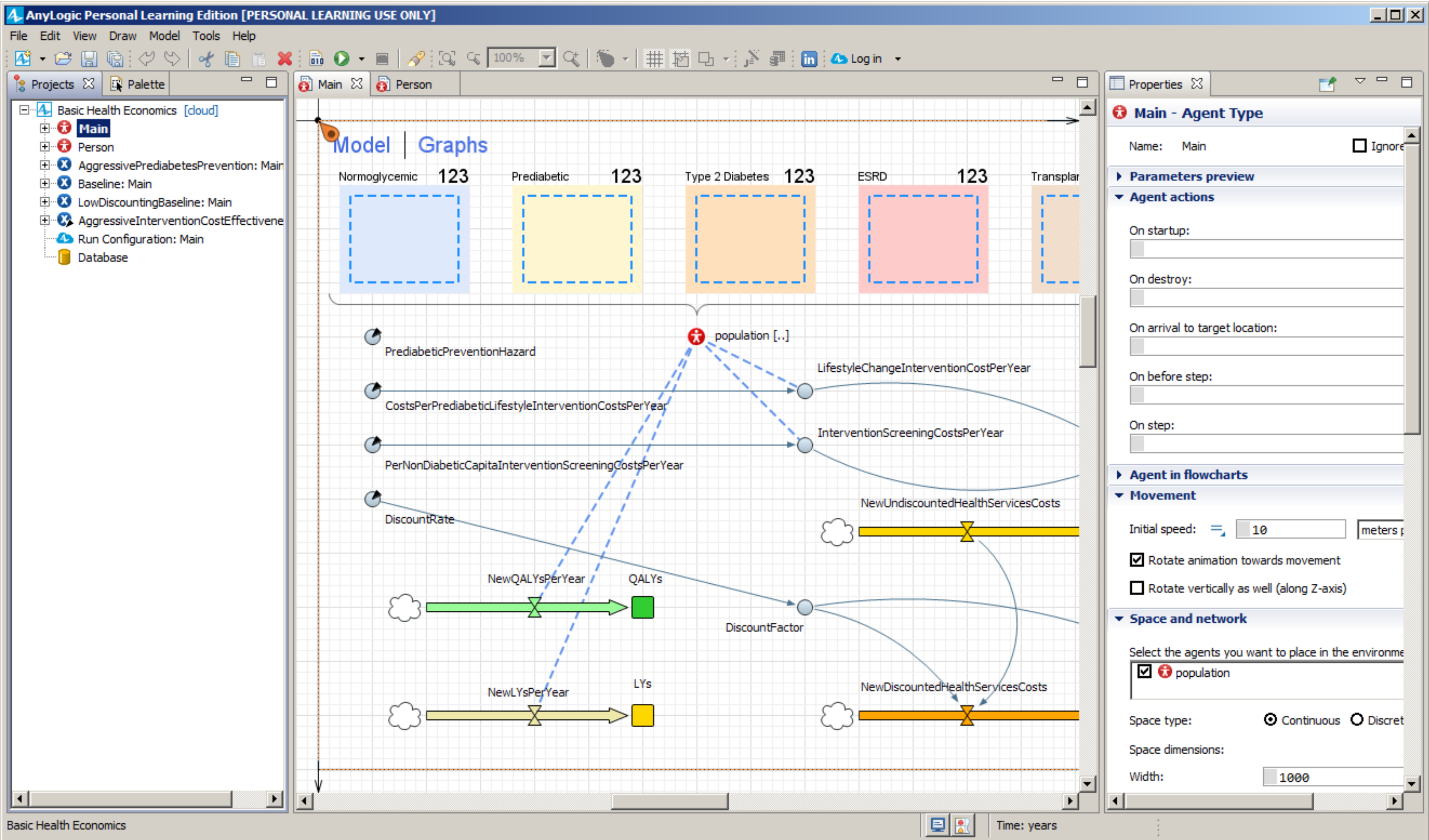
Hybrid Architectures

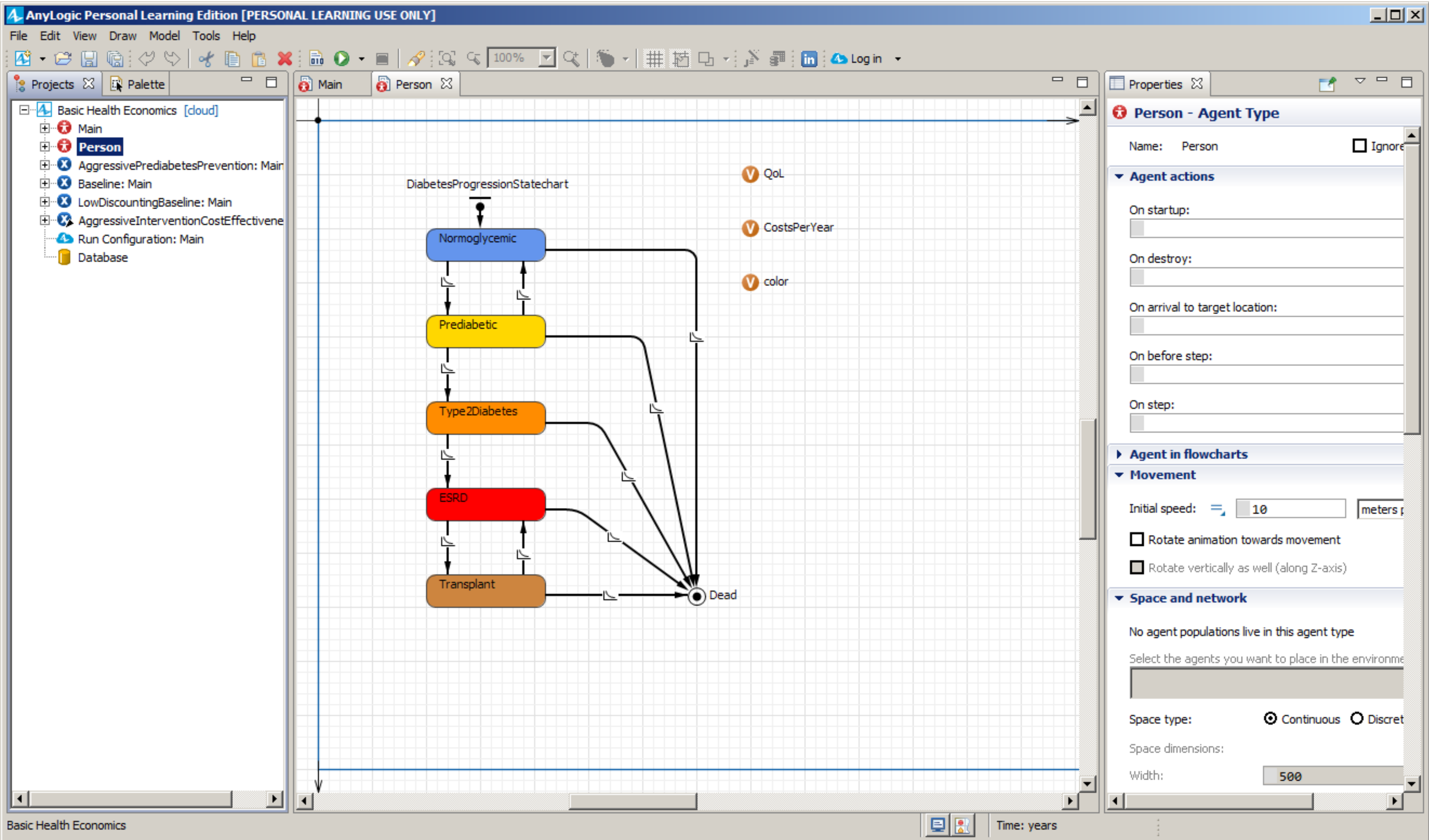
- Agents in an SD environment
  - e.g. population in a city infrastructure
    - Agents' decisions depend on the values of the SD variables and, in turn, the agents affect the SD variables

- SD inside agents
  - e.g. consumer's individual decision making
    - Dynamics of consumer decision making is modelled using SD approach

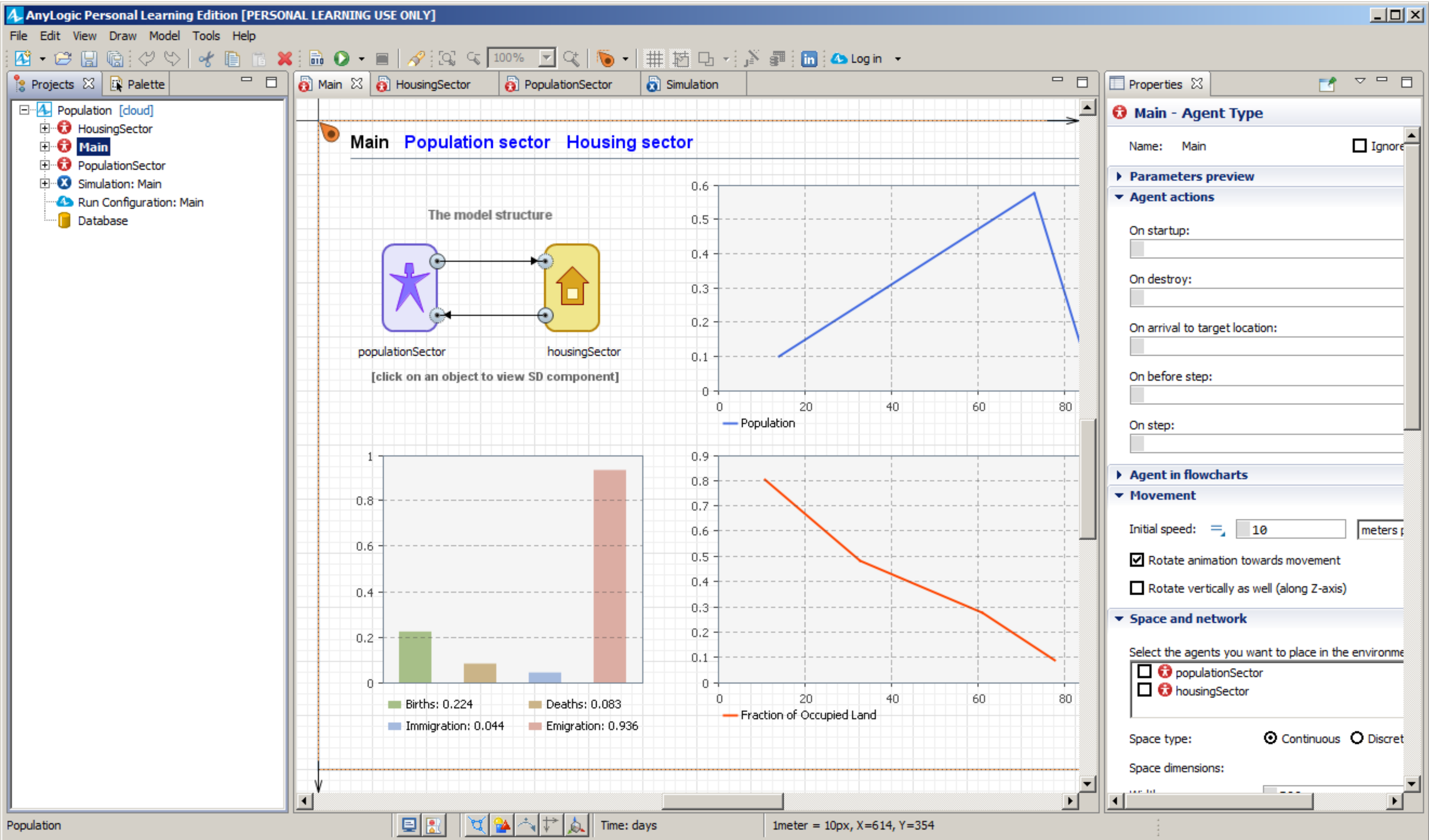
Agents in an SD Environment



Agents in an SD Environment



SD Inside Agents



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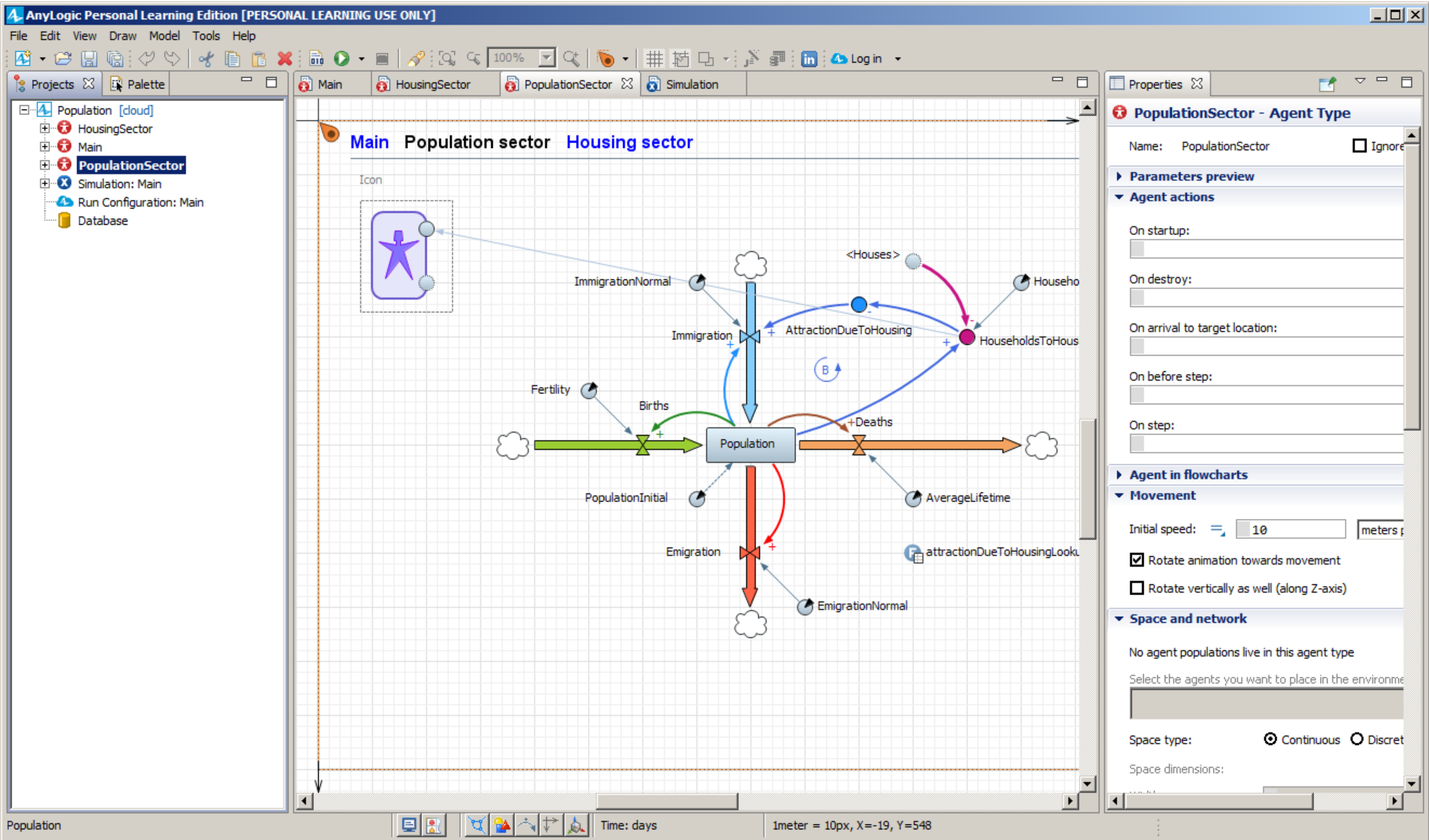
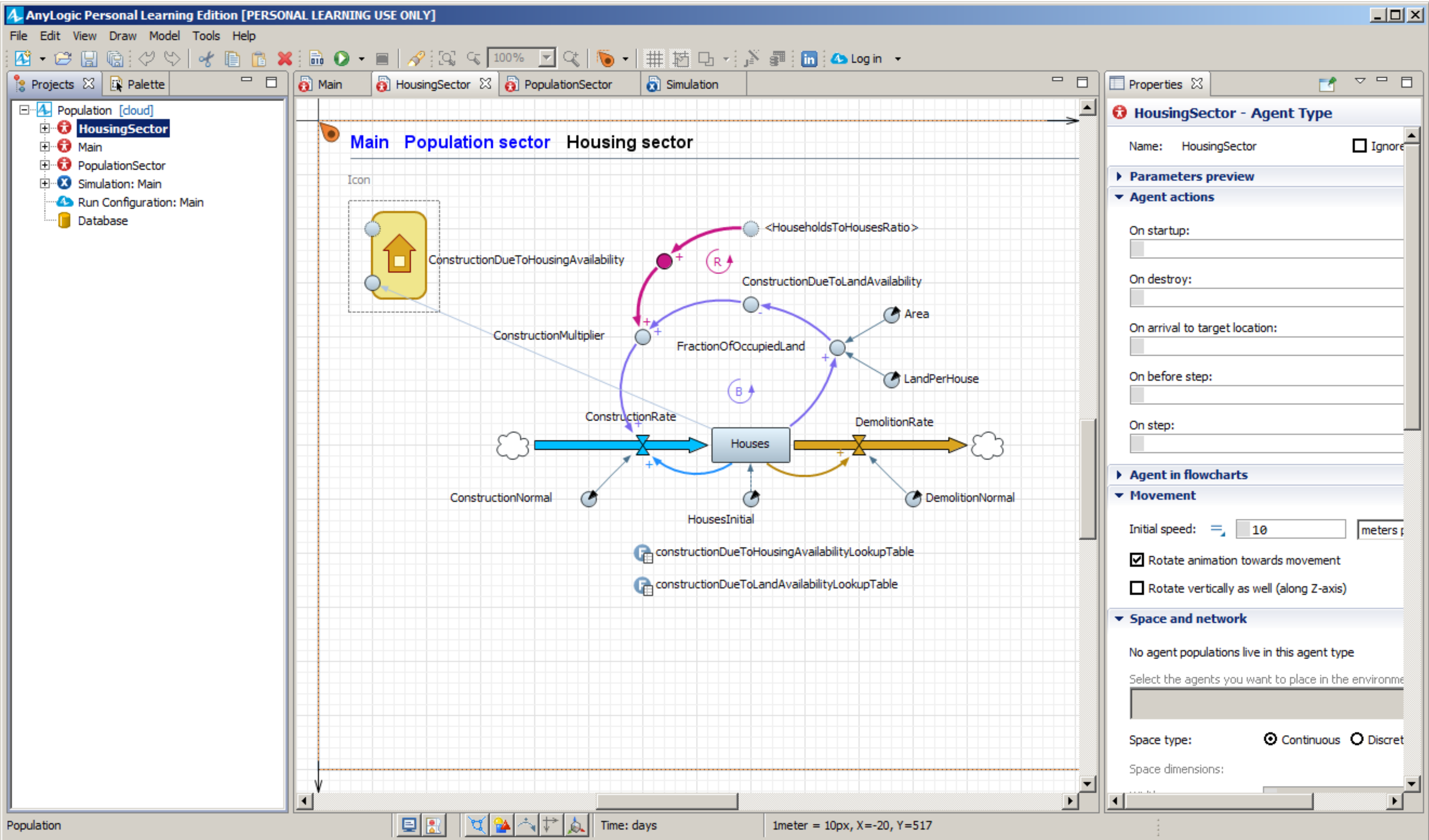
SD Inside Agents



SD Inside Agents



An Innovative Approach to Multi-Method Integrated Assessment Modelling of Global Climate Change

Siebers et al (under review)

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The Context

- Modelling and simulation play an increasingly significant role in **exploratory studies for informing policy makers** on climate change mitigation strategies

- There is considerable research being done in creating **Integrated Assessment Models** (IAMs), which focus on examining the human impacts on climate change

The Problem

- IAMs are often created as **steady state optimisation models**, holding **aggregate views** on variables, and hence are unable to capture a finer level of details of the underlying system components

- This presents a problem as the **risks and impacts** associated with climate change are **unevenly distributed**, geographically and demographically.

Alternatives

- An **alternative approach** that allows modelling populations as a collection of individual and unevenly distributed entities is **Agent-Based Modelling** (ABM) but simulating huge numbers of individual entities can quickly become an issue, as it **requires large amounts of computational resources**.

What about taking the best of both worlds and come up with a hybrid approach that overcomes the limitations of the individual approaches?

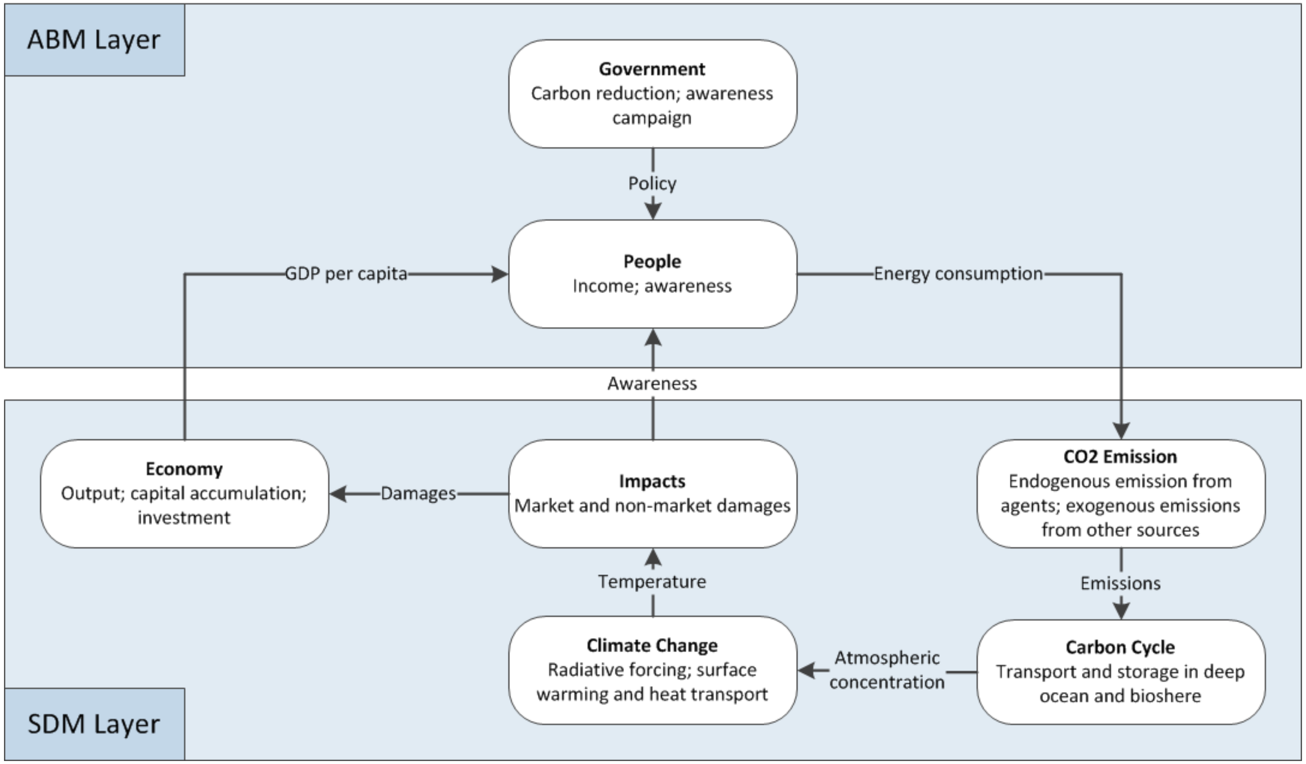
HCAM: Our Hybrid Approach

- We represent the **physical and economic environments** we use parts of a well-established **System Dynamics** (SD) interpretation of a well-established IAM called DICE (Nordhaus 1992)

- Social units and the **population** are embedded into this SD model in form of a hierarchical agent-based model.
  - At the top end we represents social units (nation; region; state) and at the bottom end we represent the population as a collection of **Collective Person Agent** (CPA) units
  - These CPA units are endowed with an **internal SD model** to track their collective psychological state, which influences their decision making

Conceptual Modelling

- Sector Boundary Map (showing feedback structure)



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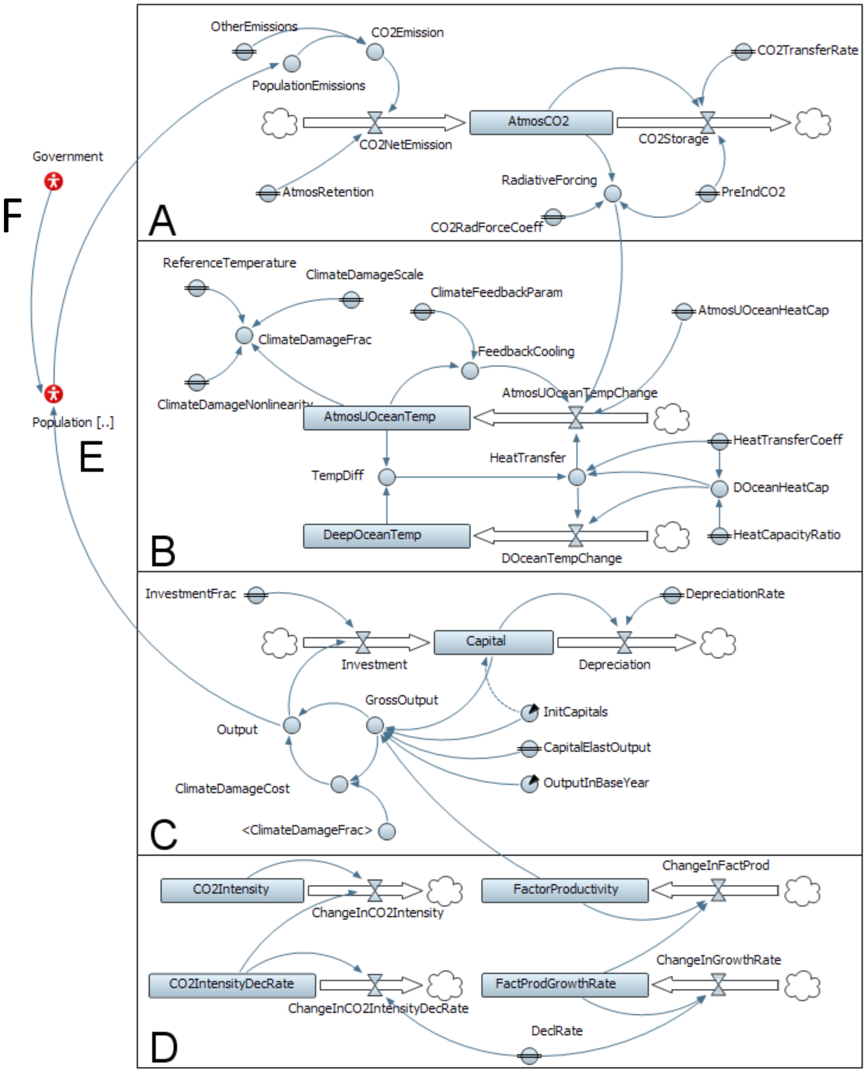
Conceptual Modelling

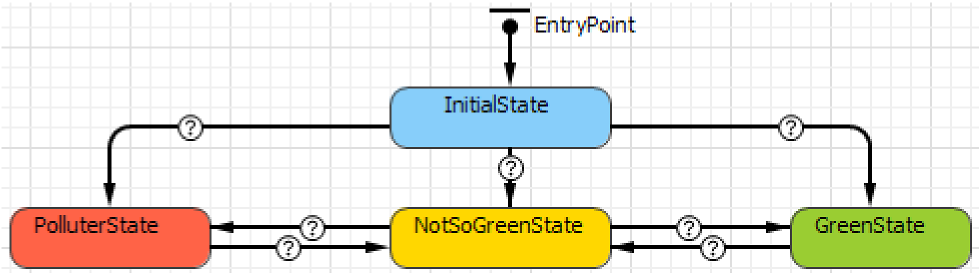
- Base Model
  - A = Carbon Cycle
  - B = Climate Subsystem
  - C = Economy Subsystem
  - D = Exogenous Drivers
  - E = Population
  - F = Government (Policy Makers)



Conceptual Modelling

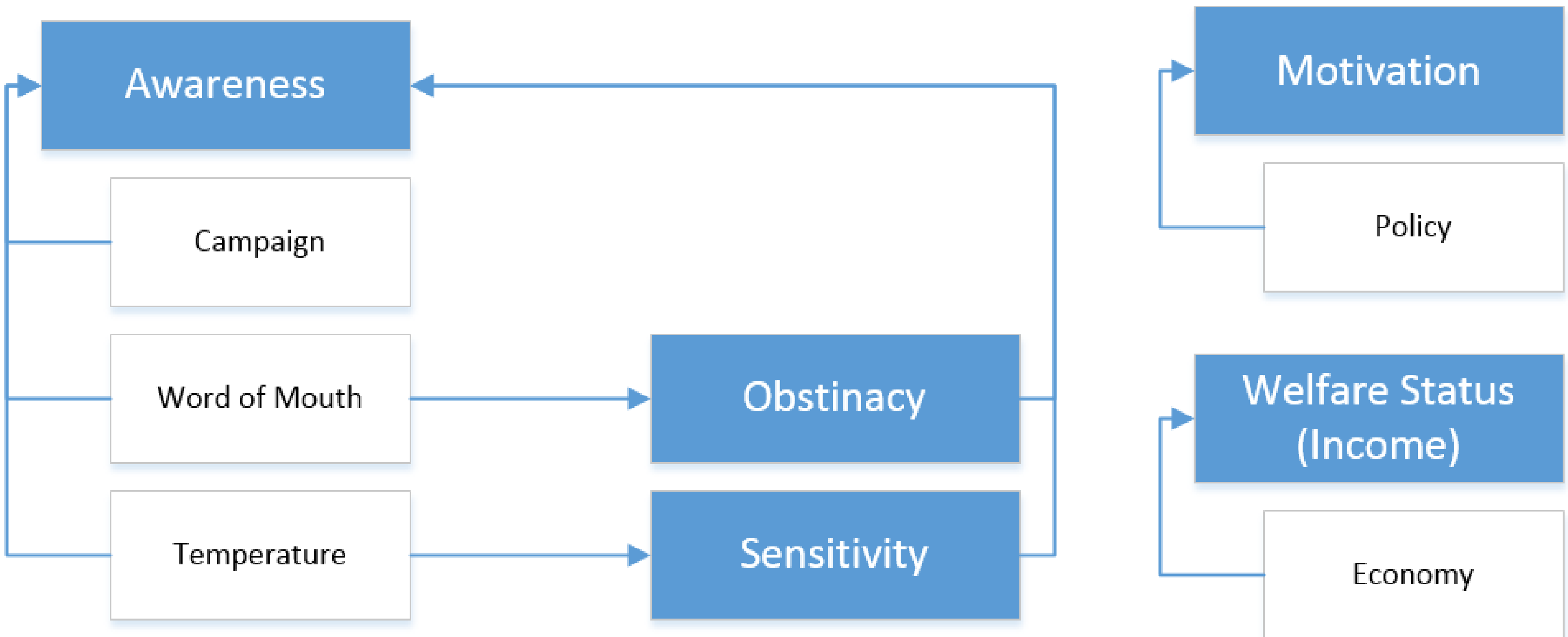
- Collective Person Agents (CPAs)
  - Capturing large populations through scaling (e.g. 1:250,000)
  - Activities of CPAs
    - Consume energy; produce emissions; network with other CPAs

- Classifications of CPAs
  - They are classified into different stereotypes, based on their emission levels; these range from "green" to "polluter"



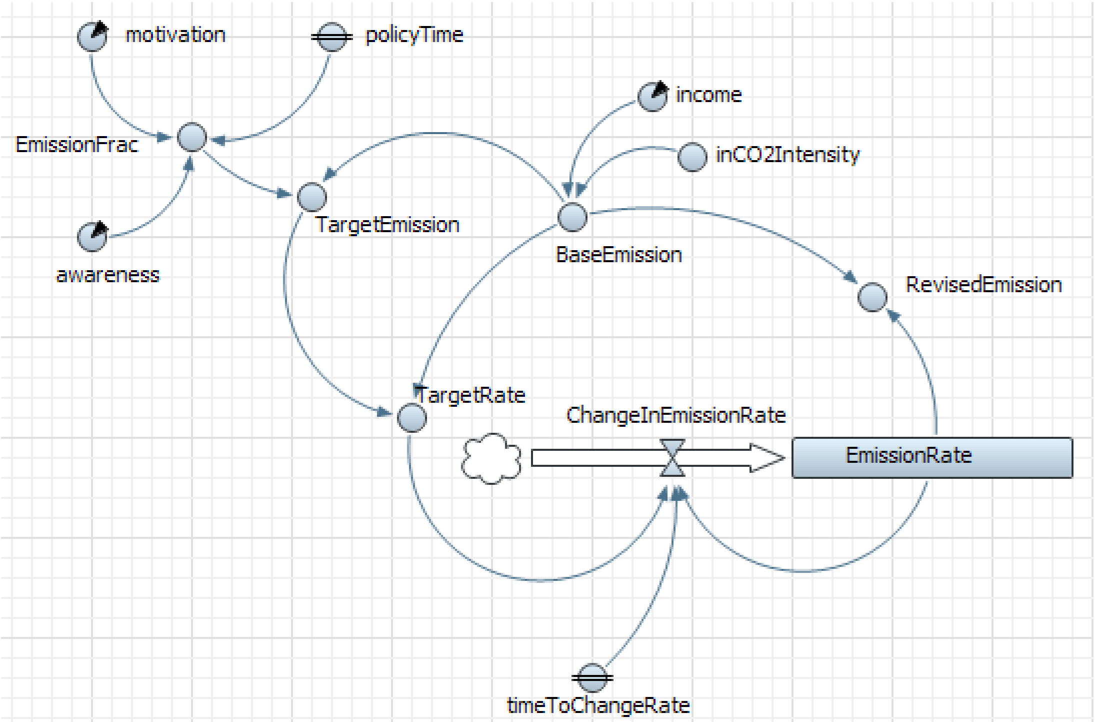
Conceptual Modelling

- Mental model of CPAs
  - Blue boxes: Mental model attributes
  - White boxes: External influences



Conceptual Modelling

- Behaviour model of CPAs
  - Emission rate SD model inside the CPAs



Conceptual Modelling

- Multi-level modelling of social structures
  - CPA ⊂ State ⊂ Region ⊂ Nation

- Networking
  - All CPAs are equipped with networking modules, enabling them to communicate with each other by passing time-stamped InfluenceAction objects to each other

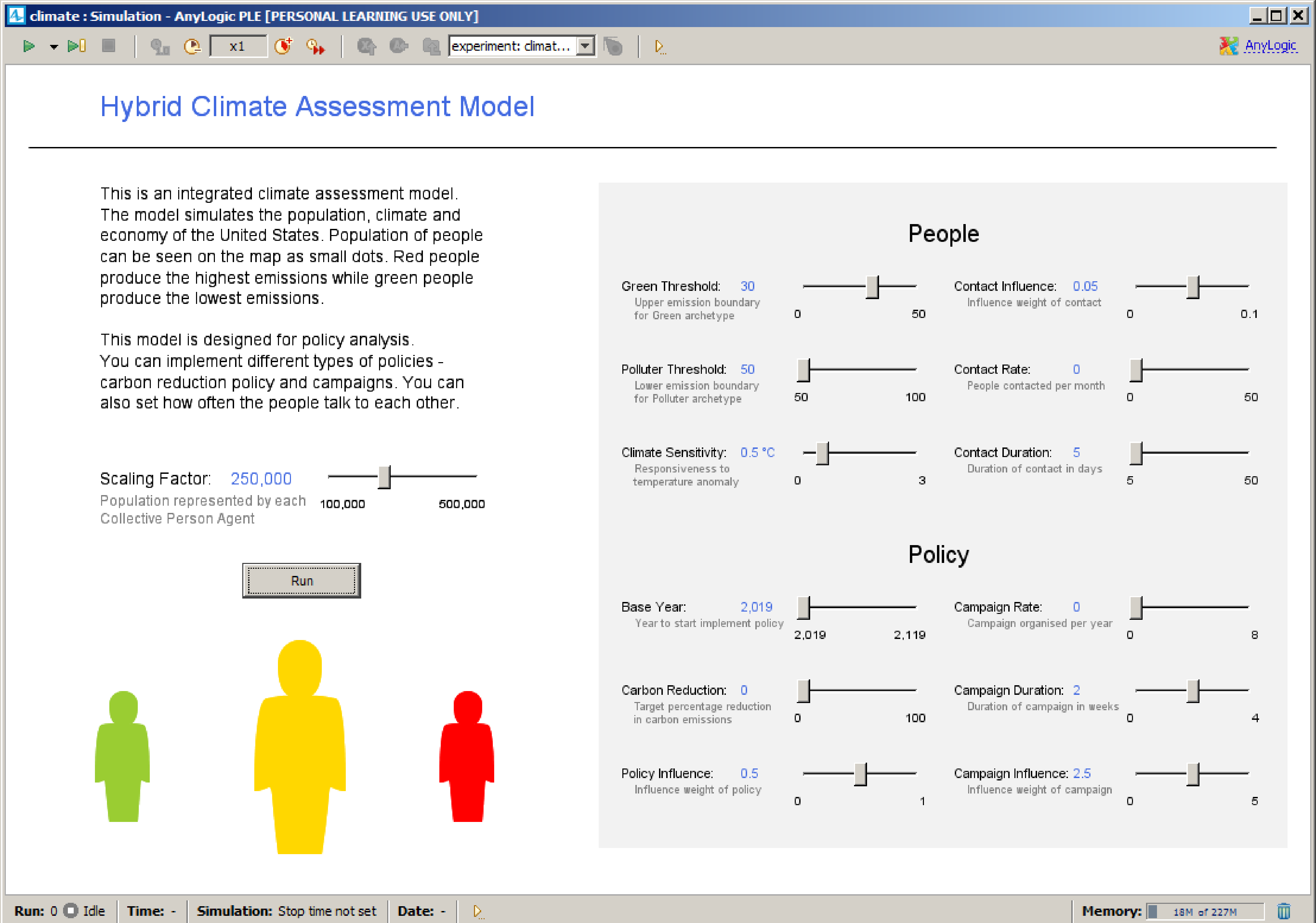
Conceptual Modelling

- Policies
  - Carbon reduction policy
    - Induces **motivation** on the people to cut down on their emissions
  - Awareness campaign policy
    - Raise public **awareness** on environmental issues

An Illustrative Example

- Our test case takes the settings of the USA
  - USA contributes to the majority of the global carbon footprints and is the largest economic power in the world
  - We investigate the carbon emissions and its relevant economic impacts on the nation

Given a constant amount of capital allocated for the climate mitigation sector, what is/are the most effective policy(s) that the federal government can invest the funds in to leverage the available resources?


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
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experiment: climat...
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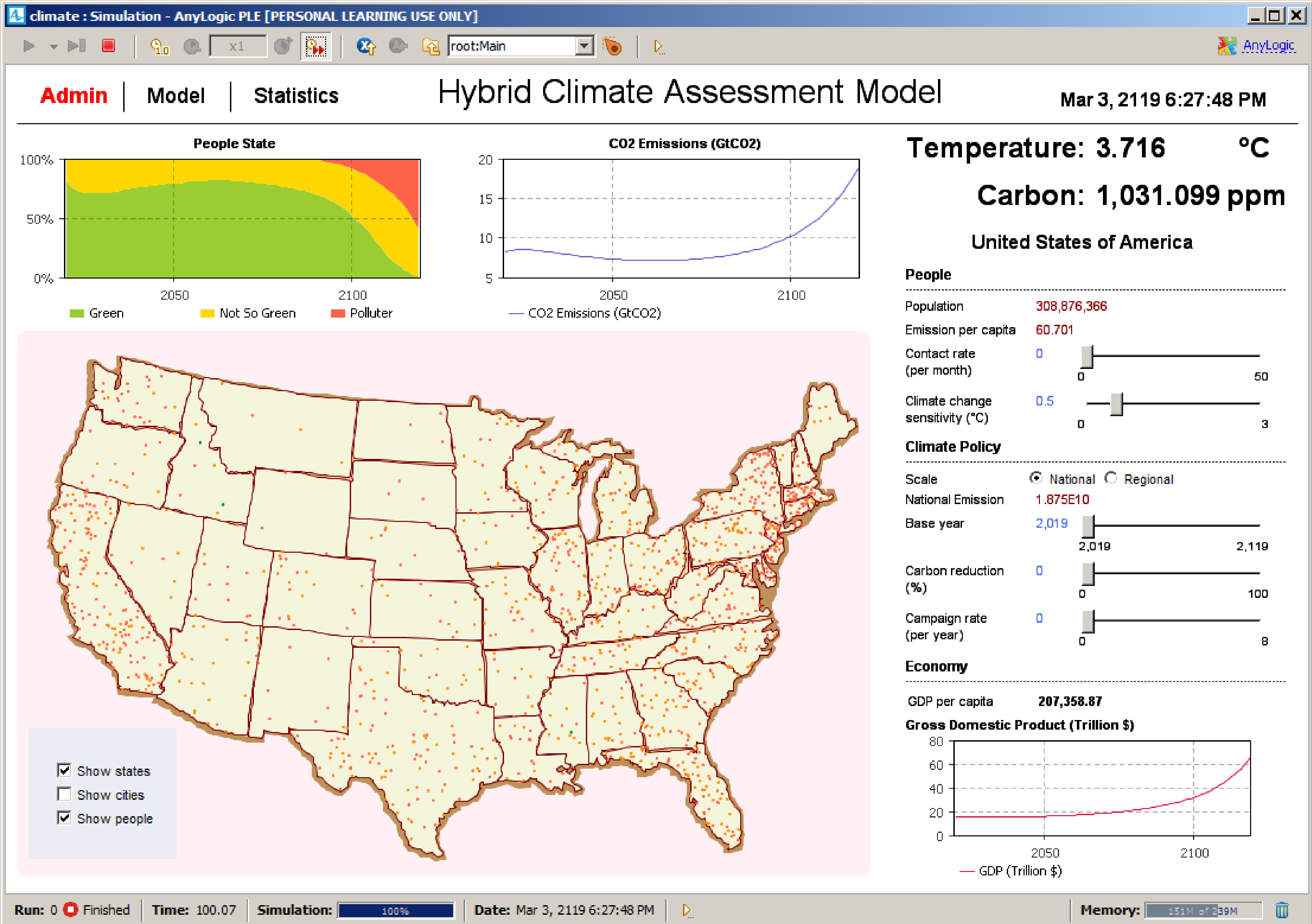
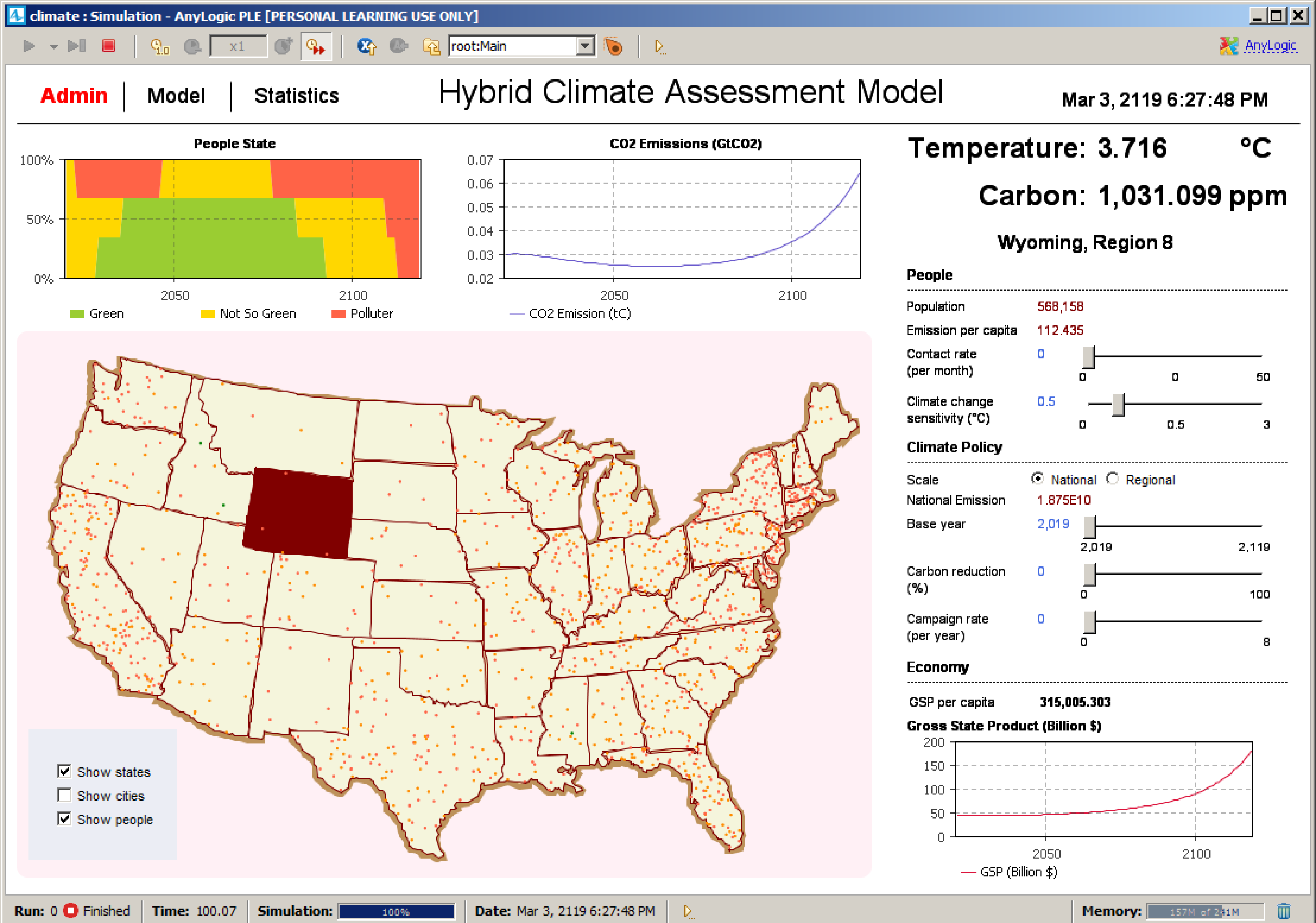
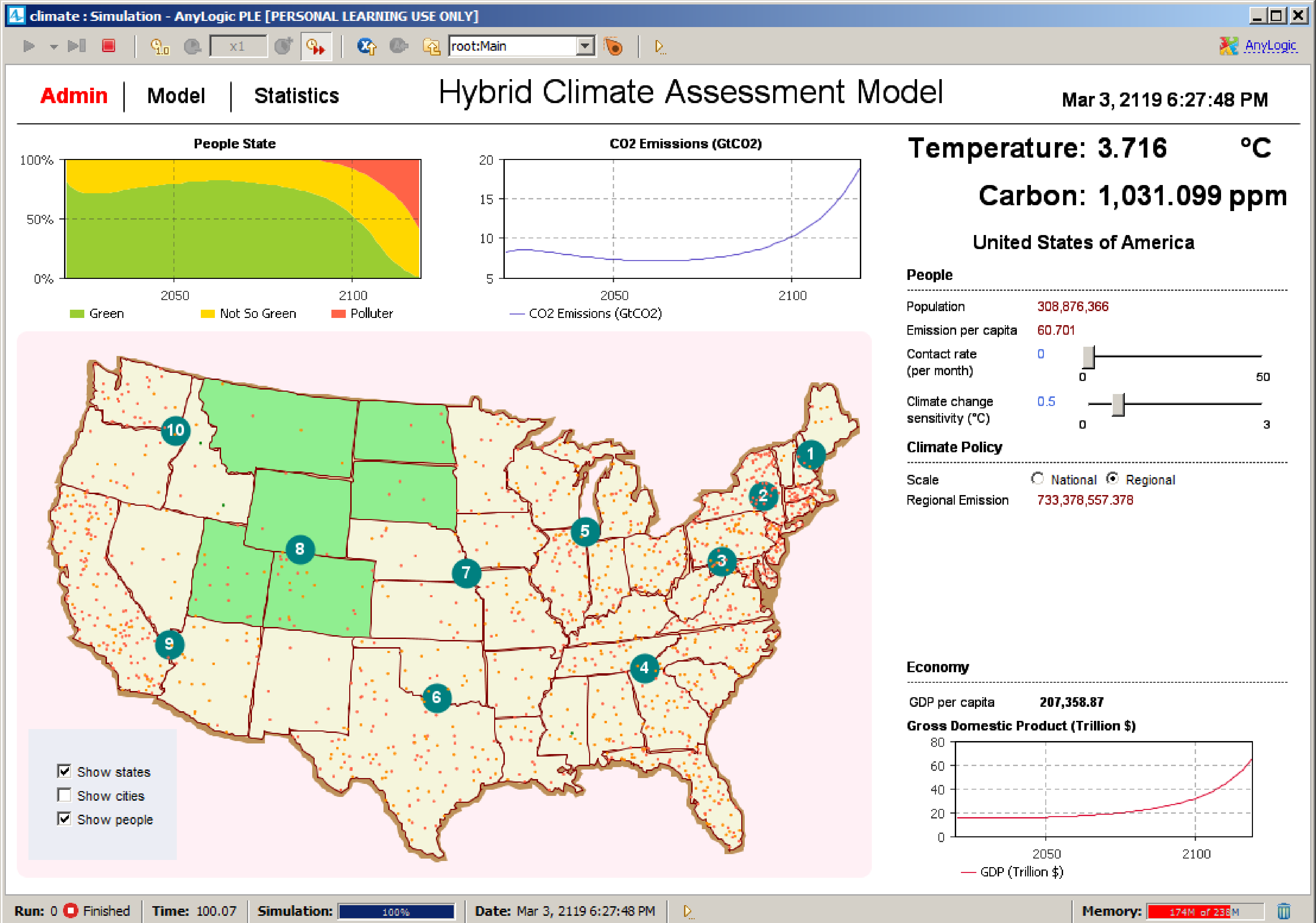
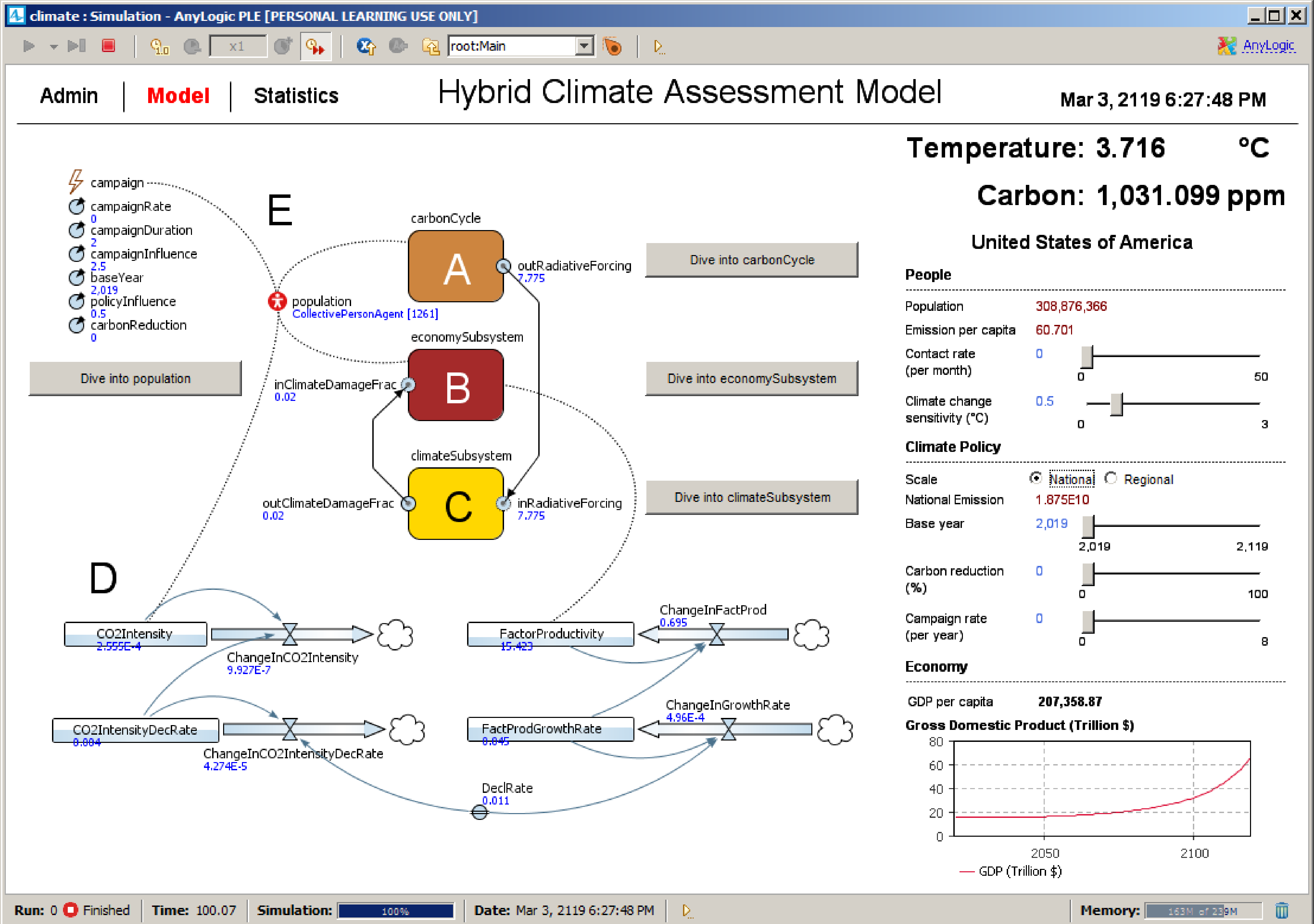
Hybrid Climate Assessment Model
This is an integrated climate assessment model. The model simulates the population, climate and economy of the United States. Population of people can be seen on the map as small dots. Red people produce the highest emissions while green people produce the lowest emissions.
This model is designed for policy analysis. You can implement different types of policies - carbon reduction policy and campaigns. You can also set how often the people talk to each other.
Scaling Factor: 250,000
Population represented by each Collective Person Agent
100,000
500,000
Run
People
Green Threshold: 30
Upper emission boundary for Green archetype
0
50
Contact Influence: 0.05
Influence weight of contact
0
0.1
Polluter Threshold: 50
Lower emission boundary for Polluter archetype
50
100
Contact Rate: 0
People contacted per month
0
50
Climate Sensitivity: 0.5 °C
Responsiveness to temperature anomaly
0
3
Contact Duration: 5
Duration of contact in days
5
50
Policy
Base Year: 2,019
Year to start implement policy
2,019
2,119
Campaign Rate: 0
Campaign organised per year
0
8
Carbon Reduction: 0
Target percentage reduction in carbon emissions
0
100
Campaign Duration: 2
Duration of campaign in weeks
0
4
Policy Influence: 0.5
Influence weight of policy
0
1
Campaign Influence: 2.5
Influence weight of campaign
0
5
Run: 0 Idle
Time: -
Simulation: Stop time not set
Date: -
Memory: 18M of 227M

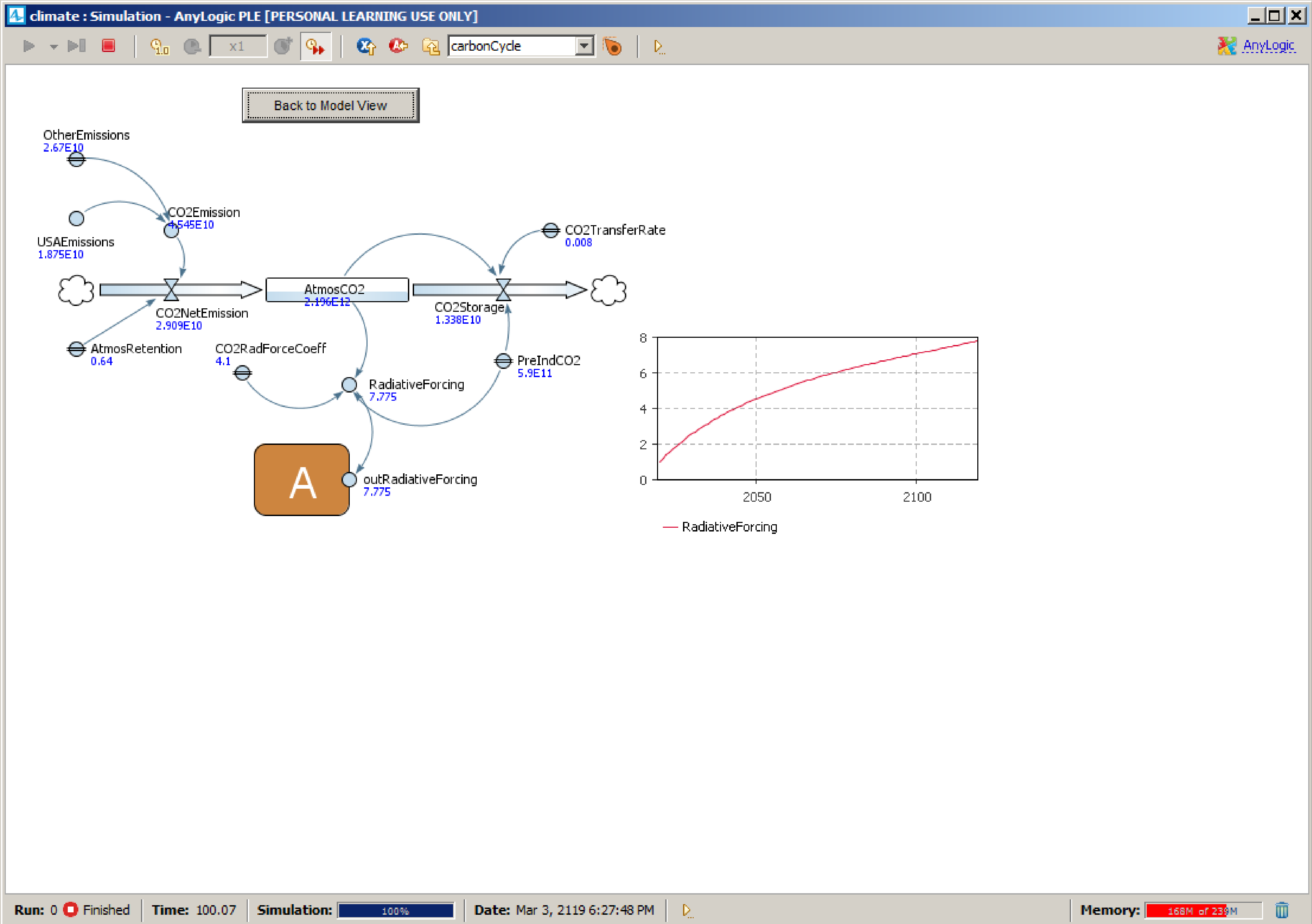

climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
root:Main
AnyLogic
Admin
Model
Statistics
Hybrid Climate Assessment Model
Mar 3, 2119 6:27:48 PM
People State
100%
50%
0%
2050
2100
Green
Not So Green
Polluter
CO2 Emissions (GtCO2)
20
15
10
5
2050
2100
CO2 Emissions (GtCO2)
Temperature: 3.716 °C
Carbon: 1,031.099 ppm
United States of America
People
Population 308,876,366
Emission per capita 60.701
Contact rate (per month) 0
0
50
Climate change sensitivity (°C) 0.5
0
3
Climate Policy
Scale National Regional
National Emission 1.875E10
Base year 2,019
2,019
2,119
Carbon reduction (%) 0
0
100
Campaign rate (per year) 0
0
8
Economy
GDP per capita 207,358.87
Gross Domestic Product (Trillion $)
80
60
40
20
0
2050
2100
GDP (Trillion $)
Show states
Show cities
Show people
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory:

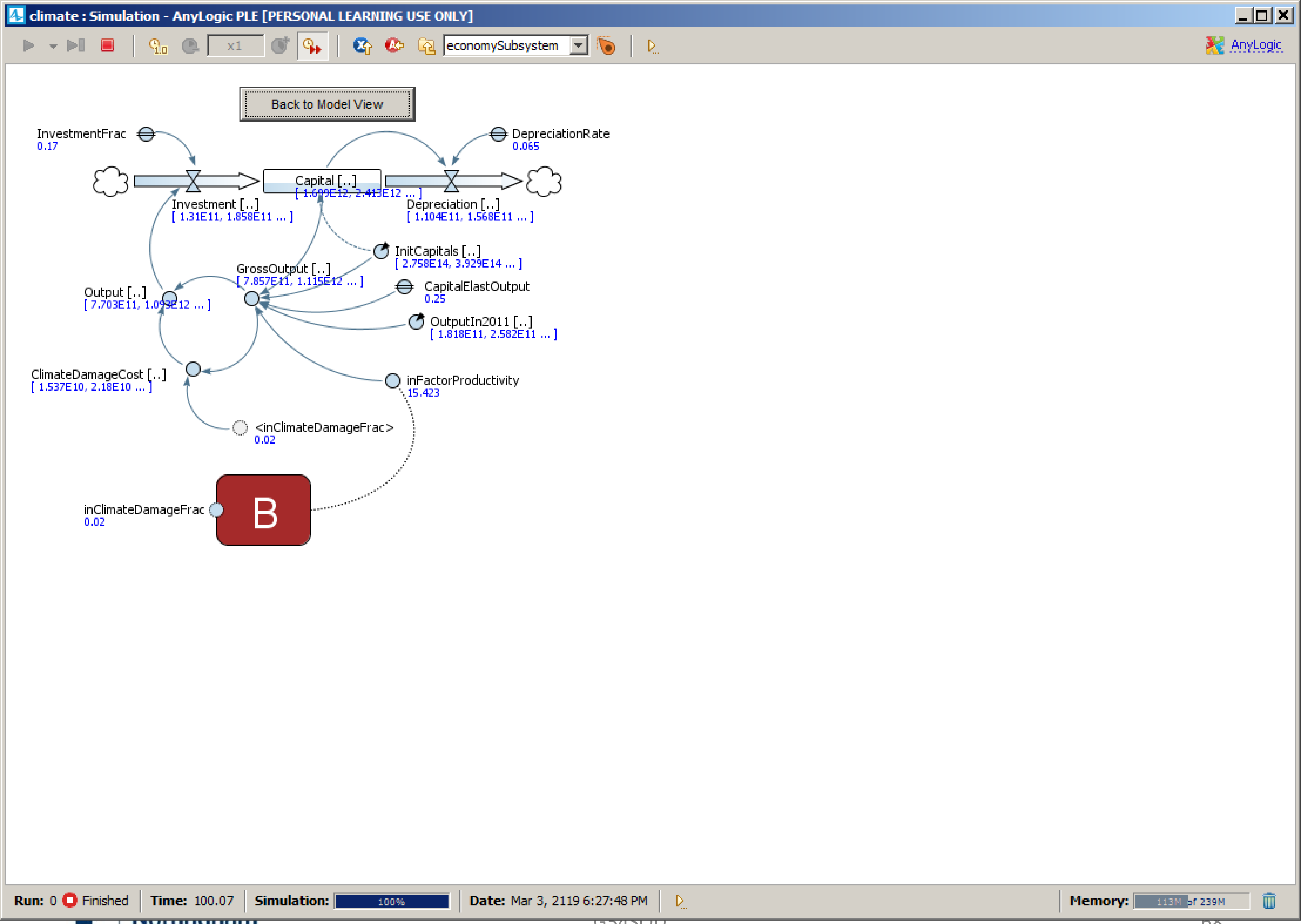


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
root:Main
AnyLogic
Admin
Model
Statistics
Hybrid Climate Assessment Model
Mar 3, 2119 6:27:48 PM
People State
100%
50%
0%
2050
2100
Green
Not So Green
Polluter
CO2 Emissions (GtCO2)
0.07
0.06
0.05
0.04
0.03
0.02
2050
2100
CO2 Emission (tC)
Temperature: 3.716 °C
Carbon: 1,031.099 ppm
Wyoming, Region 8
People
Population 568,158
Emission per capita 112.435
Contact rate (per month) 0
0 0 50
Climate change sensitivity (°C) 0.5
0 0.5 3
Climate Policy
Scale National Regional
National Emission 1.875E10
Base year 2,019
2,019 2,119
Carbon reduction (%) 0
0 100
Campaign rate (per year) 0
0 8
Economy
GSP per capita 315,005.303
Gross State Product (Billion $)
200
150
100
50
0
2050
2100
GSP (Billion $)
Show states
Show cities
Show people
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory: 157M of 241M


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
root:Main
AnyLogic
Admin | Model | Statistics
Hybrid Climate Assessment Model
Mar 3, 2119 6:27:48 PM
People State
100%
50%
0%
2050
2100
Green
Not So Green
Polluter
CO2 Emissions (GtCO2)
20
15
10
5
2050
2100
CO2 Emissions (GtCO2)
Temperature: 3.716 °C
Carbon: 1,031.099 ppm
United States of America
People
Population 308,876,366
Emission per capita 60.701
Contact rate (per month) 0
0 50
Climate change sensitivity (°C) 0.5
0 3
Climate Policy
Scale National Regional
Regional Emission 733,378,557.378
Economy
GDP per capita 207,358.87
Gross Domestic Product (Trillion $)
80
60
40
20
0
2050
2100
GDP (Trillion $)
Show states
Show cities
Show people
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory: 174M of 238M


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
root:Main
AnyLogic
Admin
Model
Statistics
Hybrid Climate Assessment Model
Mar 3, 2119 6:27:48 PM
Temperature: 3.716 °C
Carbon: 1,031.099 ppm
United States of America
People
Population 308,876,366
Emission per capita 60.701
Contact rate (per month) 0
0 50
Climate change sensitivity (°C) 0.5
0 3
Climate Policy
Scale National Regional
National Emission 1.875E10
Base year 2,019
2,019 2,119
Carbon reduction (%) 0
0 100
Campaign rate (per year) 0
0 8
Economy
GDP per capita 207,358.87
Gross Domestic Product (Trillion $)
80 60 40 20 0
2050 2100
GDP (Trillion $)
campaign
campaignRate 0
campaignDuration 2
campaignInfluence 2.5
baseYear 2,019
policyInfluence 0.5
carbonReduction 0
Dive into population
E
carbonCycle
A
outRadiativeForcing 7.775
population CollectivePersonAgent [1261]
economySubsystem
B
inClimateDamageFrac 0.02
climateSubsystem
C
outClimateDamageFrac 0.02
inRadiativeForcing 7.775
Dive into carbonCycle
Dive into economySubsystem
Dive into climateSubsystem
D
CO2Intensity 2.555E-4
ChangeInCO2Intensity 9.927E-7
CO2IntensityDecRate 0.004
ChangeInCO2IntensityDecRate 4.274E-5
FactorProductivity 15.423
ChangeInFactProd 0.695
FactProdGrowthRate 0.045
ChangeInGrowthRate 4.96E-4
DeclRate 0.011
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory: 163M of 239M


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
x1
carbonCycle
AnyLogic
Back to Model View
OtherEmissions
2.67E10
CO2Emission
4.545E10
USAEmissions
1.875E10
CO2TransferRate
0.008
AtmosCO2
2.196E12
CO2Storage
1.338E10
CO2NetEmission
2.909E10
AtmosRetention
0.64
CO2RadForceCoeff
4.1
PreIndCO2
5.9E11
RadiativeForcing
7.775
A
outRadiativeForcing
7.775
8
6
4
2
0
2050
2100
RadiativeForcing
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory: 168M of 239M



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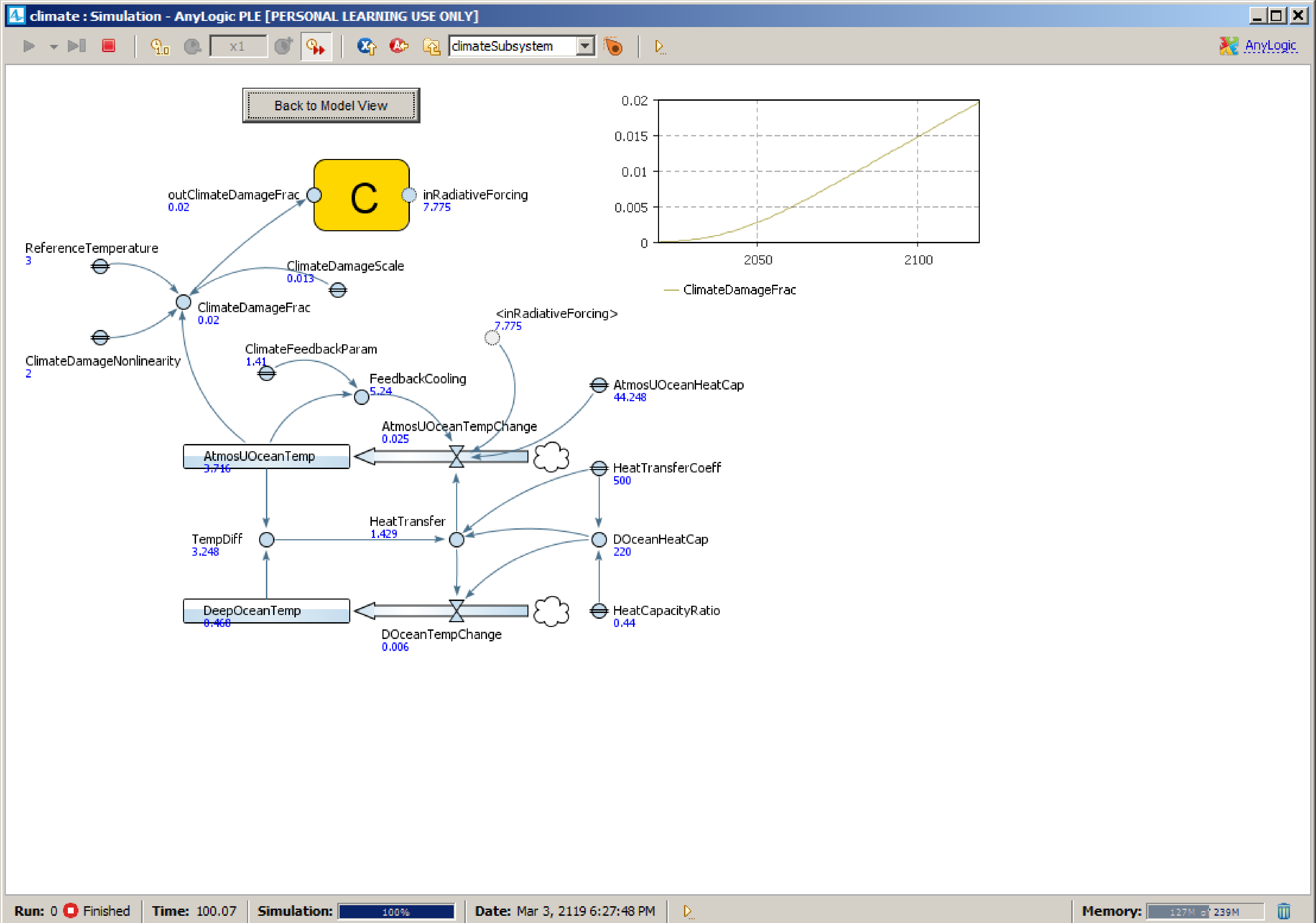
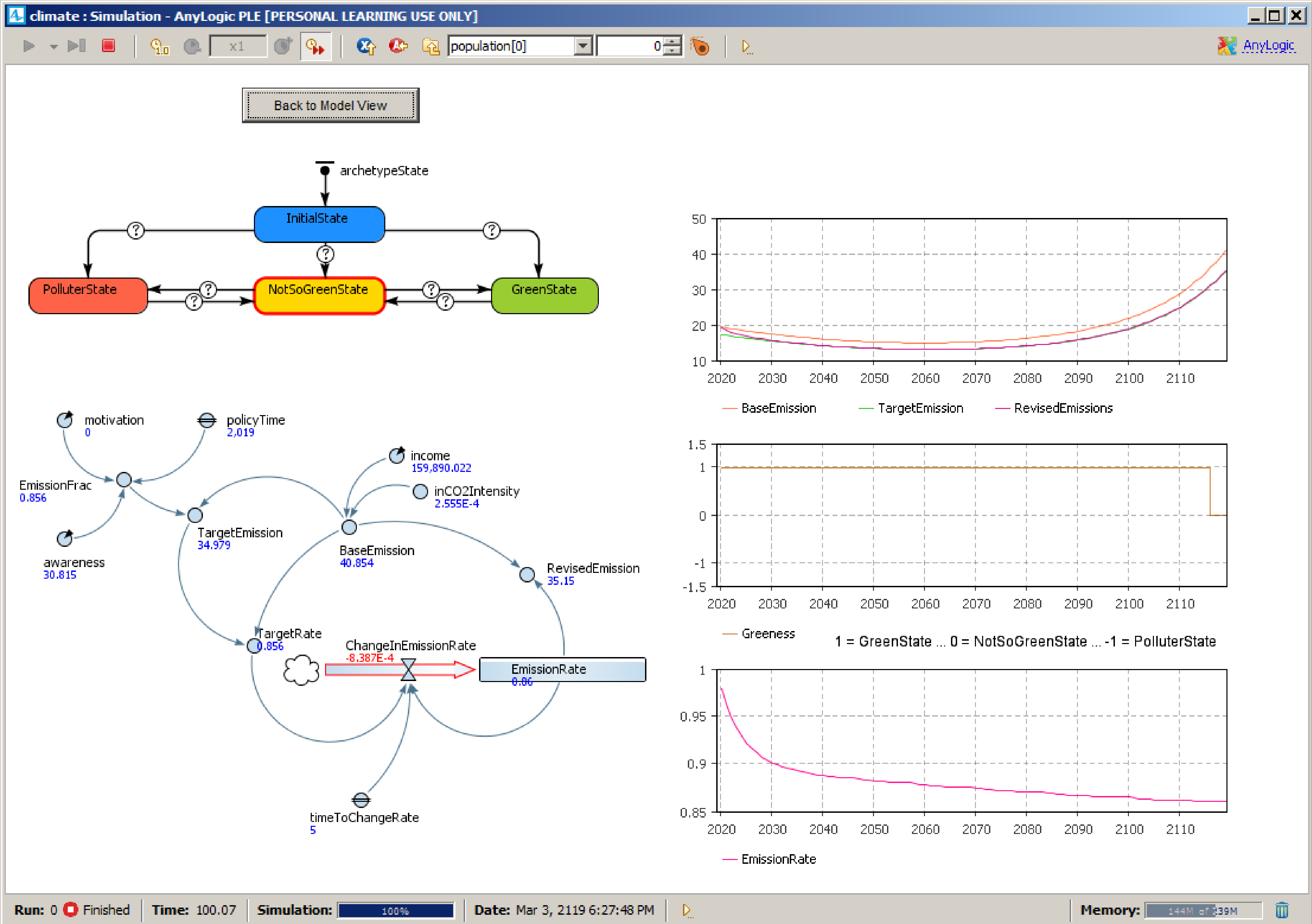
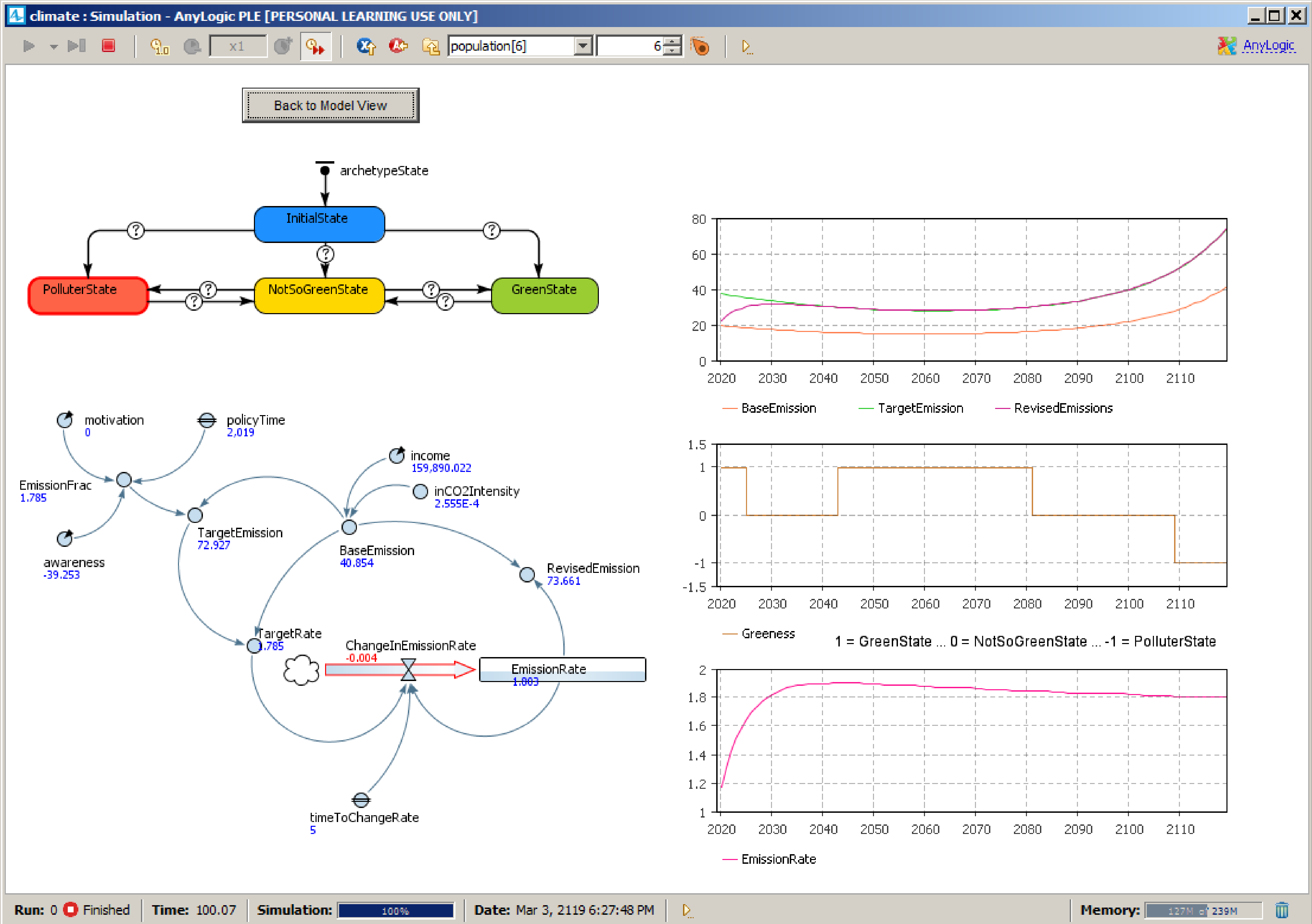
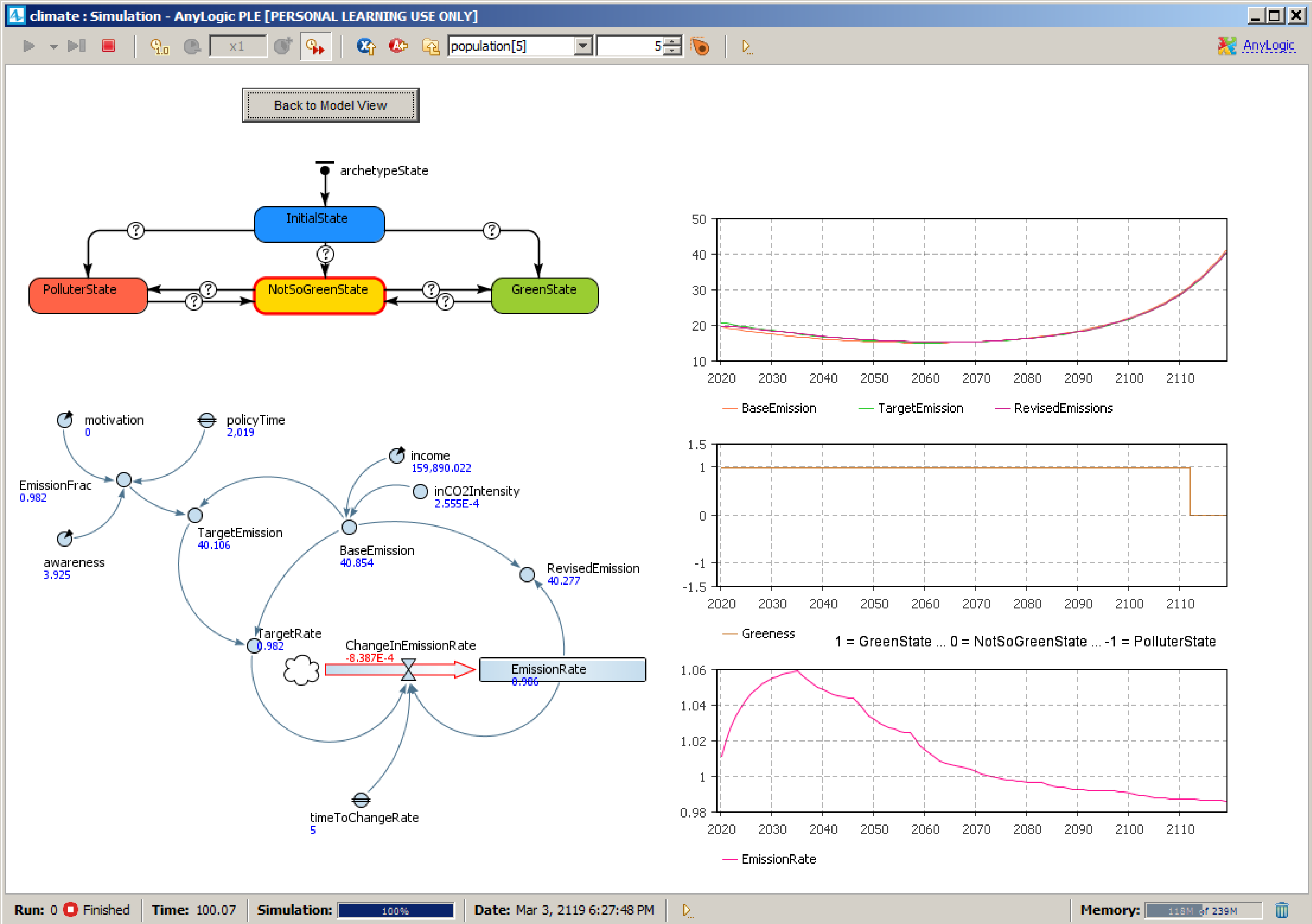
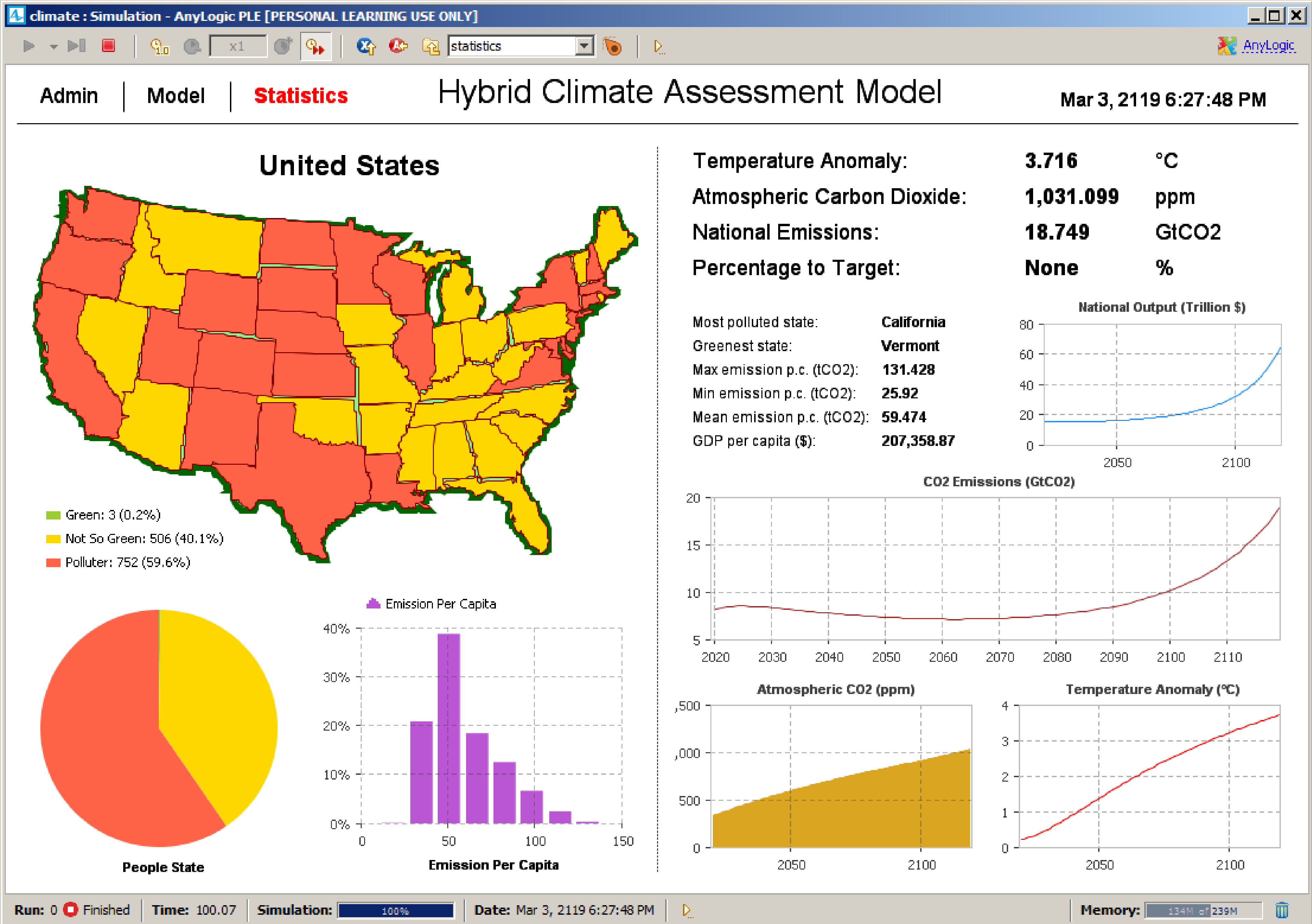
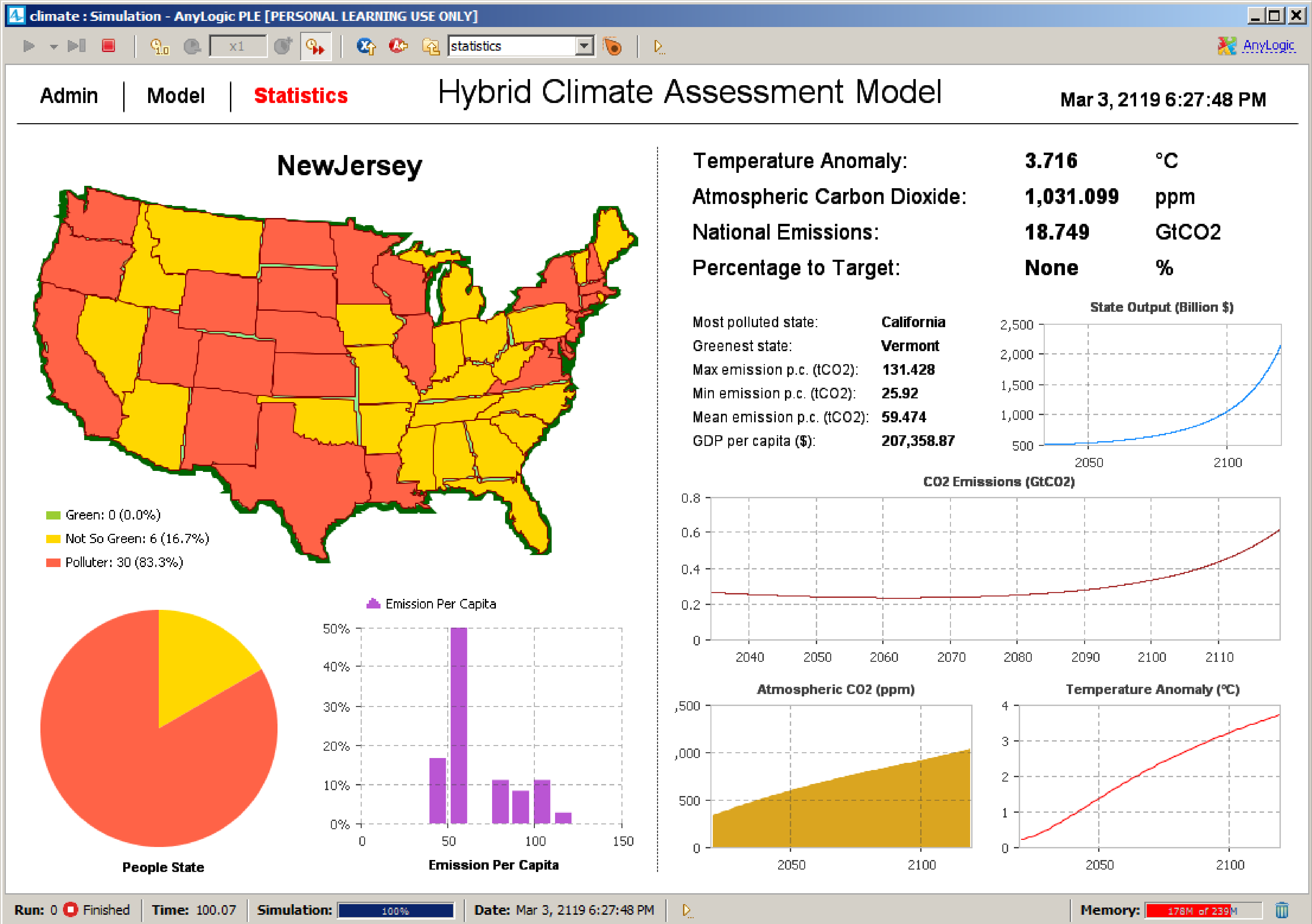

climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
climateSubsystem
AnyLogic
Back to Model View
C
outClimateDamageFrac
0.02
inRadiativeForcing
7.775
ReferenceTemperature
3
ClimateDamageScale
0.013
ClimateDamageFrac
0.02
ClimateDamageNonlinearity
2
<inRadiativeForcing>
7.775
ClimateFeedbackParam
1.41
FeedbackCooling
5.24
AtmosUOceanHeatCap
44.248
AtmosUOceanTempChange
0.025
AtmosUOceanTemp
3.716
HeatTransferCoeff
500
HeatTransfer
1.429
TempDiff
3.248
DOceanHeatCap
220
DeepOceanTemp
0.468
HeatCapacityRatio
0.44
DOceanTempChange
0.006
0.02
0.015
0.01
0.005
0
2050
2100
ClimateDamageFrac
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory: 127M of 239M


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
population[0]
AnyLogic
Back to Model View
archetypeState
InitialState
PolluterState
NotSoGreenState
GreenState
motivation
0
policyTime
2,019
income
159,890.022
inCO2Intensity
2.555E-4
EmissionFrac
0.856
TargetEmission
34.979
BaseEmission
40.854
RevisedEmission
35.15
awareness
30.815
TargetRate
0.856
ChangeInEmissionRate
-8.387E-4
EmissionRate
0.86
timeToChangeRate
5
BaseEmission
TargetEmission
RevisedEmissions
Greeness
1 = GreenState ... 0 = NotSoGreenState ... -1 = PolluterState
EmissionRate
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory:


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
population[6]
AnyLogic
Back to Model View
archetypeState
InitialState
PolluterState
NotSoGreenState
GreenState
motivation
0
policyTime
2,019
EmissionFrac
1.785
awareness
-39.253
income
159,890.022
inCO2Intensity
2.555E-4
TargetEmission
72.927
BaseEmission
40.854
RevisedEmission
73.661
TargetRate
1.785
ChangeInEmissionRate
-0.004
EmissionRate
1.803
timeToChangeRate
5
BaseEmission
TargetEmission
RevisedEmissions
Greeness
1 = GreenState ... 0 = NotSoGreenState ... -1 = PolluterState
EmissionRate
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory: 127M of 239M


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
population[5]
AnyLogic
Back to Model View
archetypeState
InitialState
PolluterState
NotSoGreenState
GreenState
motivation
0
policyTime
2,019
income
159,890.022
inCO2Intensity
2.555E-4
EmissionFrac
0.982
TargetEmission
40.106
BaseEmission
40.854
awareness
3.925
RevisedEmission
40.277
TargetRate
0.982
ChangeInEmissionRate
-8.387E-4
EmissionRate
0.986
timeToChangeRate
5
BaseEmission
TargetEmission
RevisedEmissions
Greeness
1 = GreenState ... 0 = NotSoGreenState ... -1 = PolluterState
EmissionRate
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory:


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
statistics
AnyLogic
Admin
Model
Statistics
Hybrid Climate Assessment Model
Mar 3, 2119 6:27:48 PM
United States
Green: 3 (0.2%)
Not So Green: 506 (40.1%)
Polluter: 752 (59.6%)
People State
Emission Per Capita
Emission Per Capita
Temperature Anomaly: 3.716 °C
Atmospheric Carbon Dioxide: 1,031.099 ppm
National Emissions: 18.749 GtCO2
Percentage to Target: None %
Most polluted state: California
Greenest state: Vermont
Max emission p.c. (tCO2): 131.428
Min emission p.c. (tCO2): 25.92
Mean emission p.c. (tCO2): 59.474
GDP per capita ($): 207,358.87
National Output (Trillion $)
CO2 Emissions (GtCO2)
Atmospheric CO2 (ppm)
Temperature Anomaly (°C)
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory: 134M of 239M


climate : Simulation - AnyLogic PLE [PERSONAL LEARNING USE ONLY]
statistics
AnyLogic
Admin
Model
Statistics
Hybrid Climate Assessment Model
Mar 3, 2119 6:27:48 PM
NewJersey
Green: 0 (0.0%)
Not So Green: 6 (16.7%)
Polluter: 30 (83.3%)
People State
Emission Per Capita
Temperature Anomaly: 3.716 °C
Atmospheric Carbon Dioxide: 1,031.099 ppm
National Emissions: 18.749 GtCO2
Percentage to Target: None %
Most polluted state: California
Greenest state: Vermont
Max emission p.c. (tCO2): 131.428
Min emission p.c. (tCO2): 25.92
Mean emission p.c. (tCO2): 59.474
GDP per capita ($): 207,358.87
State Output (Billion $)
CO2 Emissions (GtCO2)
Atmospheric CO2 (ppm)
Temperature Anomaly (°C)
Run: 0 Finished
Time: 100.07
Simulation: 100%
Date: Mar 3, 2119 6:27:48 PM
Memory: 178M of 239M

Illustrative Example

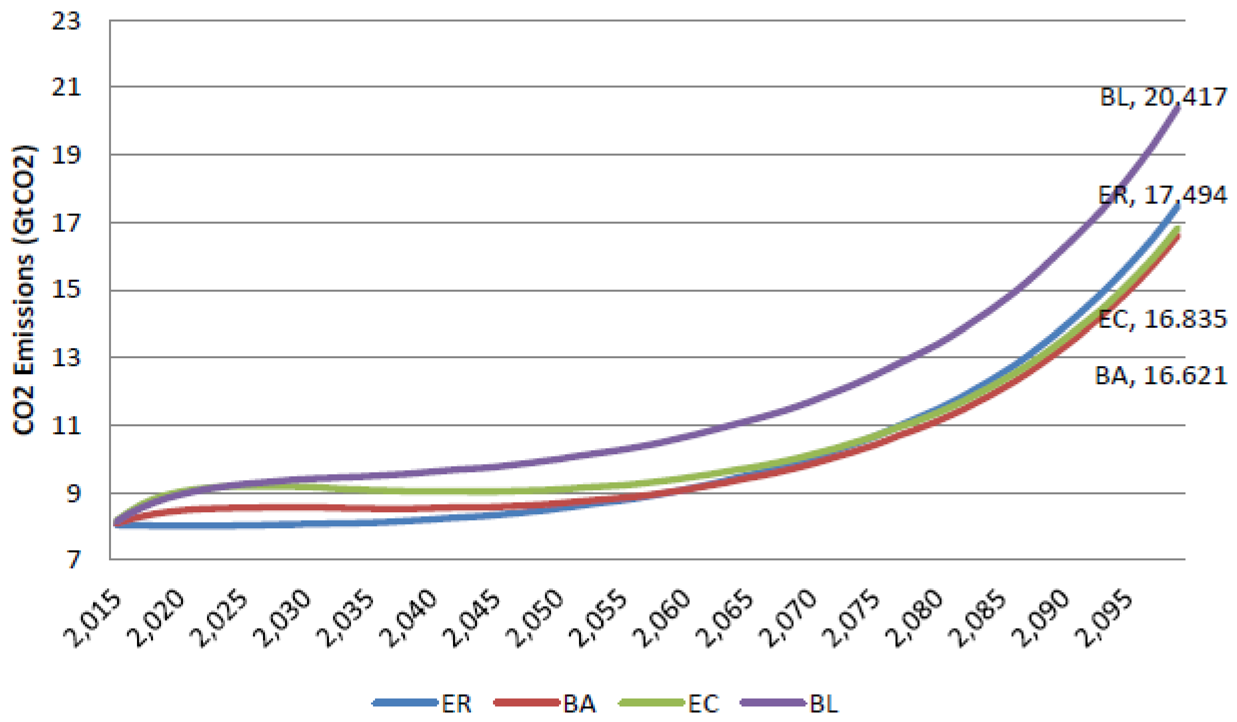
- Experimentation
  - Question: Given a constant amount of capital allocated for the climate mitigation sector, what is/are the most effective policy(s) that the federal US government can invest the funds in to leverage the available resources?
    - Baseline scenario: no mitigation actions
    - Balanced 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	
		Carbon reduction (%)	Campaigns (per year)
Scenario	Baseline (BL)	0	0
	Balanced (BA)	17	4
	Extreme Campaign (EC)	0	8
	Extreme Reduction (ER)	34	0

Illustrative Example

- Experimentation results

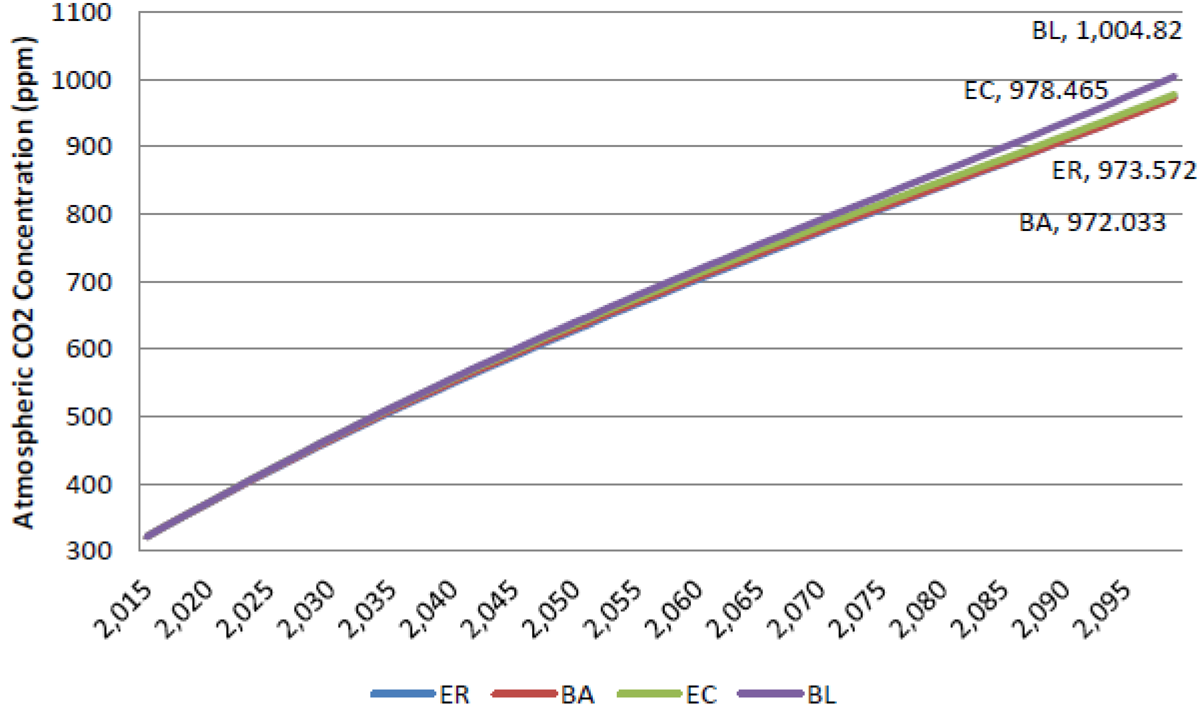
7.3.1 CO_2 emissions



Illustrative Example

- Experimentation results

7.3.2 Atmospheric CO_2



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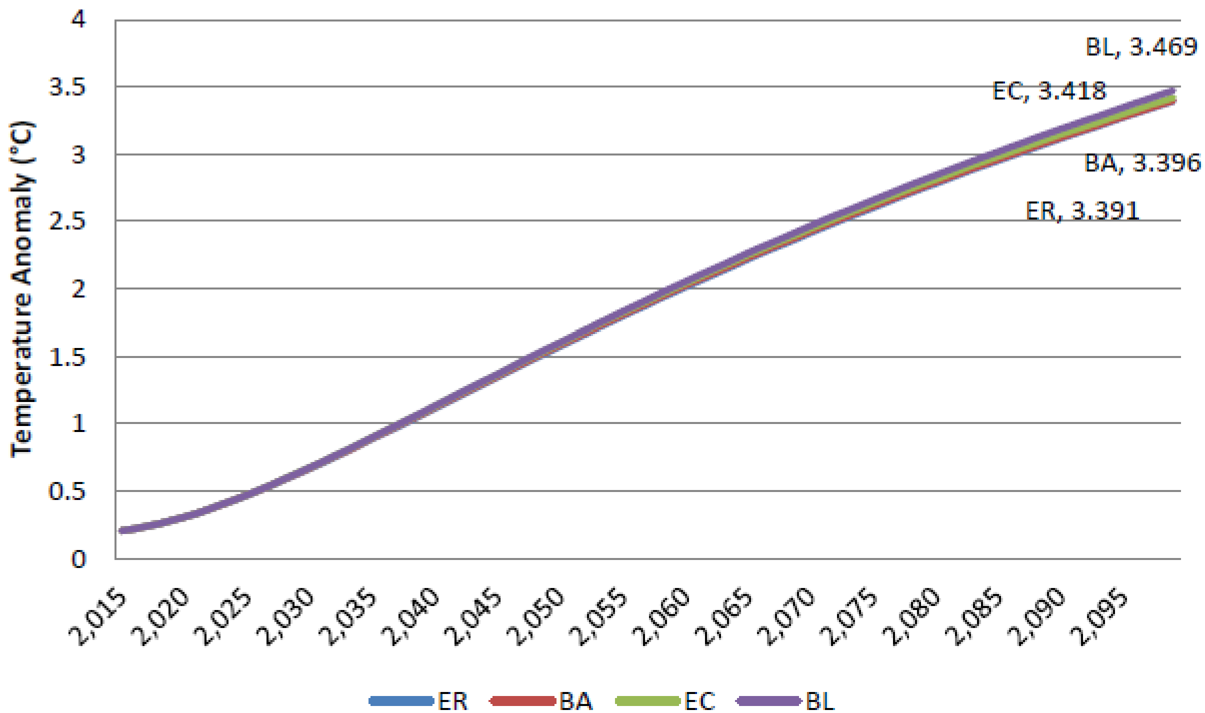
Illustrative Example

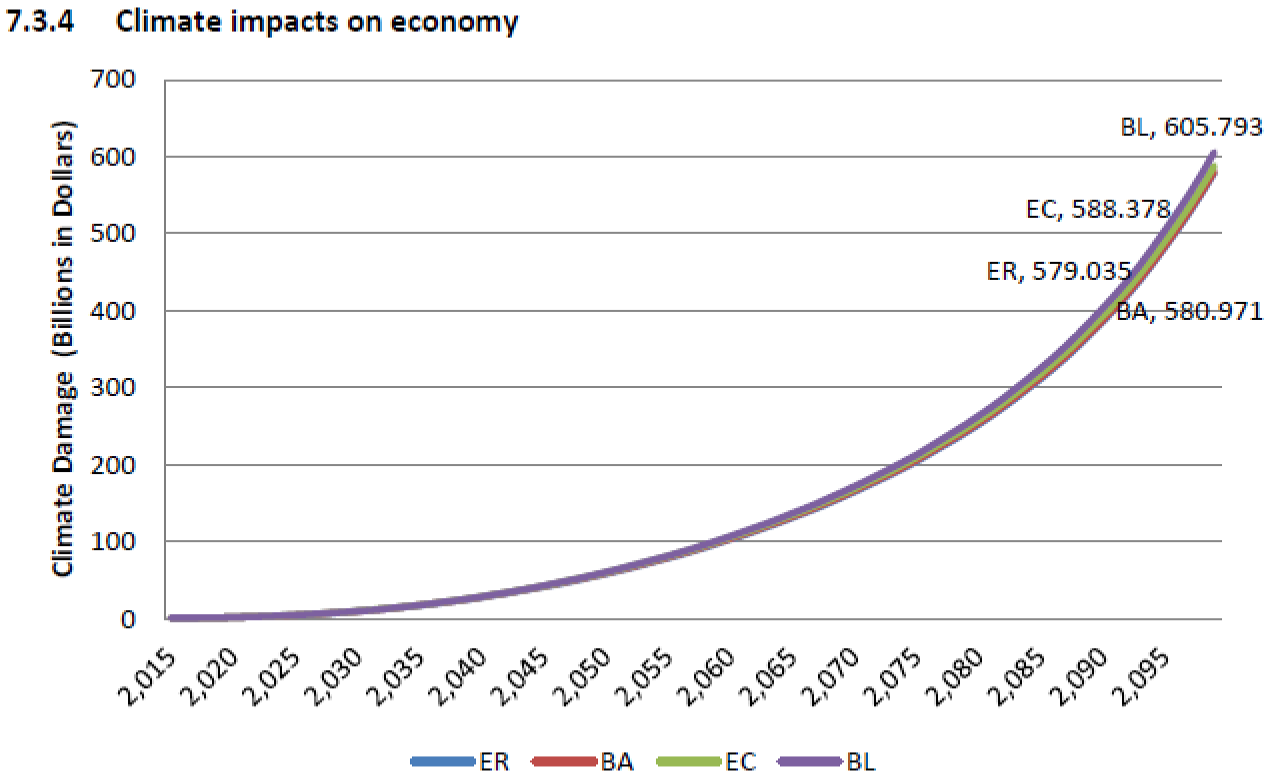
- Experimentation results

7.3.3 Temperature anomaly



Illustrative Example

- Experimentation results



Further Reading & Acknowledgement

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

Contents lists available at ScienceDirect

Journal of Operations Management

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

ELSEVIER

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, could be modeled, leading to an 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) and Fishwick (2011)

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 Conferences (1983-2018) (https://www.systemdynamics.org/past-conferences)
- Siebers PO, Lim ZE, Figueredo GP, and Hey J (under review) An Innovative Approach to Multi-Method Integrated Assessment Modelling of Global Climate Change.
- Sterman JD et al (2015) System Dynamics Perspectives and Modeling Opportunities for Research in Operations Management. Journal of Operations Management. Vol. 39-40, pp1-5