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Overview of the Modelica-based System Dynamics Library

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**MODELING OF SUSTAINABLE
ECONOMIC SYSTEMS**

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Linköping, Sweden



- ▶ This lecture borrows several pieces of content from presentations on global modeling and the Modelica-based library for System Dynamics kindly made available by [Prof. Dr. François E. Cellier \(emeritus\), ETH Zurich](#)

The System Dynamics methodology

- ▶ Introduced in the late sixties by J.W.Forrester
 - ▶ A tool for **visually organizing partial knowledge** about models of **poorly understood systems** in phenomenological sciences
 - ▶ Biology, Ecology, Macro economy, Sociology, etc.
- ▶ Low-level modeling paradigm: “Stocks and Flows”
 - ▶ **Stock** elements connected by material or non-material (e.g., information) **Flows**
 - ▶ **Flows** regulated by input-output **Rates**
 - ▶ A simplified way of dealing with differential equations
 - ▶ Shuns traditional calculus
- ▶ In this talk we shall learn about an **SD library** built with the **Modelica language** for equation-based modeling, and why it can be of help

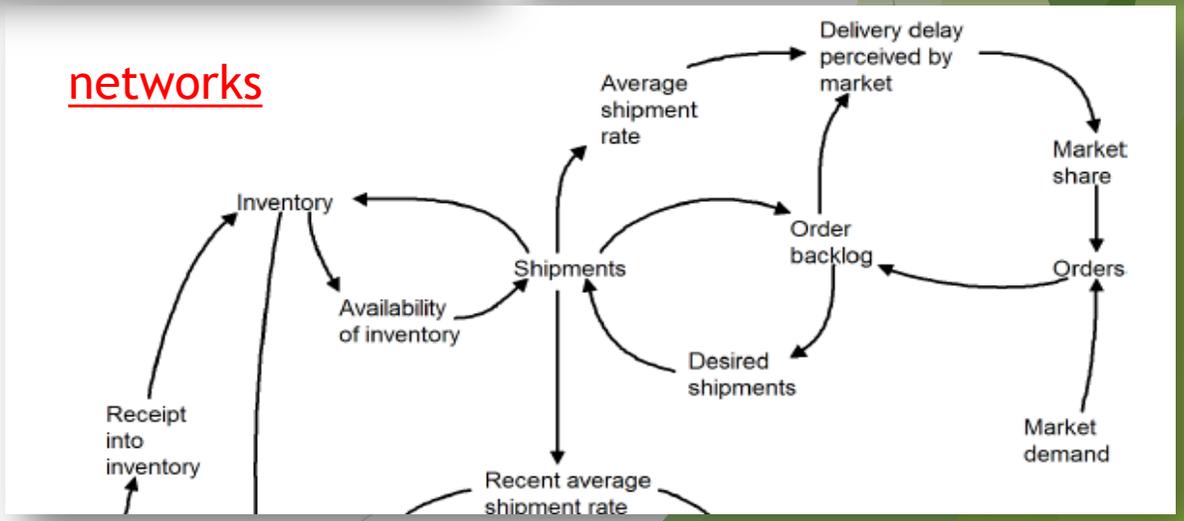
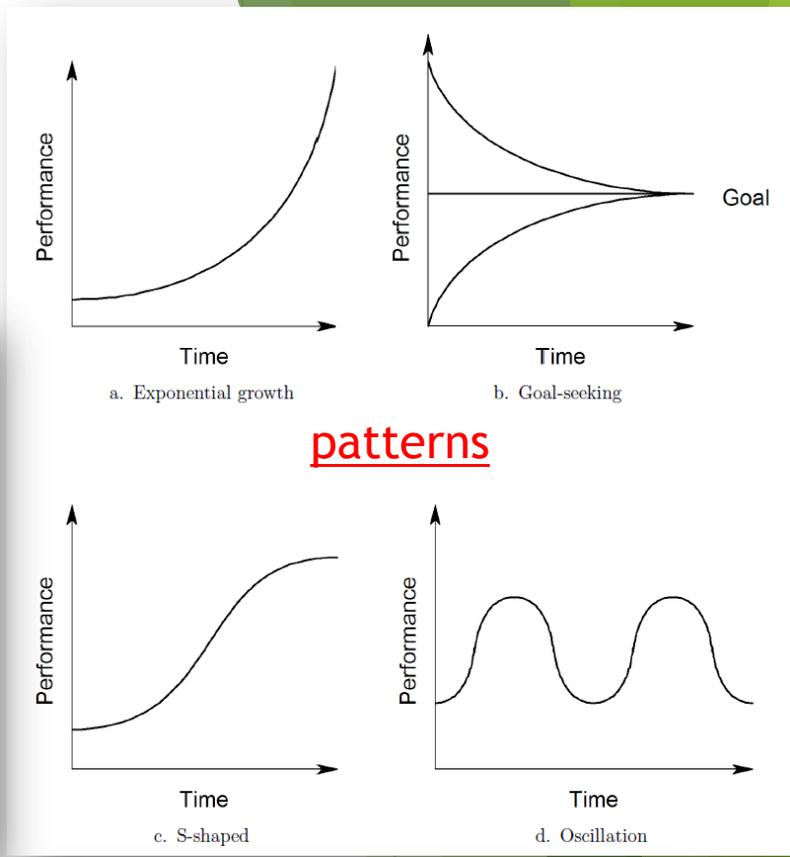
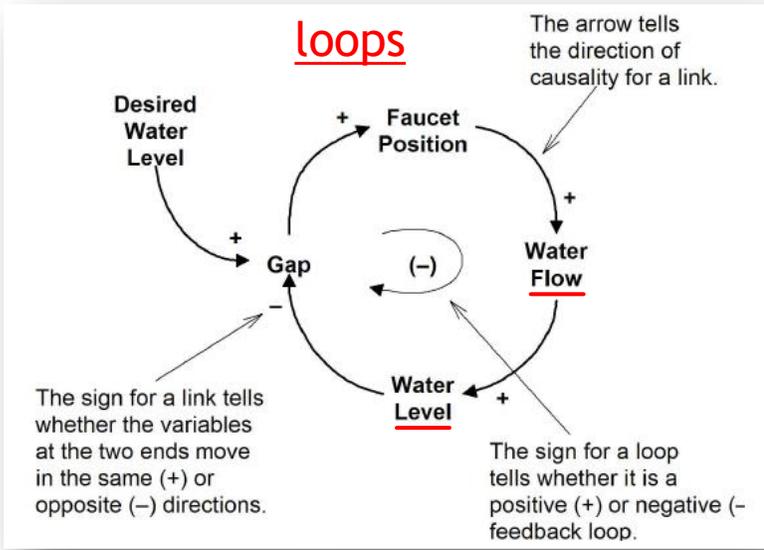
The System Dynamics methodology

- ▶ Physical systems call for **deductive modeling**
 - ▶ Well established **meta laws exist**. These are preserved:
 - ▶ across a wide range of spatio-temporal scales
 - ▶ under system composition/decomposition procedures
 - ▶ Very reliably modeled
 - ▶ *Example: a car (mechanical-electro-computerized system)*
- ▶ Ill-defined systems call for **inductive modeling**
 - ▶ Much more complex to model in a reliable way
 - ▶ Very weak, narrowly applicable, or totally **inexistent meta laws**
 - ▶ Difficult decomposability into subsystems (densely connected)
 - ▶ Submodel parameters are influenced by many system's variables **in similar orders of magnitude**
 - ▶ *Example: an ecosystem (bio-geo-chemical system)*
- ▶ System Dynamics
 - ▶ Applicable in both deductive and inductive modeling
 - ▶ Useful only when used carefully (avoid to incur in a “modern reductionism”)

The System Dynamics methodology

- ▶ Explore dynamic behavior of systems lacking universal laws
- ▶ Think visually in terms of:
 - ▶ Basic **system structures** as positive and negative **feedback loops**
 - ▶ **Patterns** of behavior
- ▶ Loops forming complex **interdependent networks**
 - ▶ Opposed to simplistic **independent unidirectional cause-effect** relations
- ▶ Also accounts for:
 - ▶ Time **delays** in internal system flows
 - ▶ **Nonlinear** effects

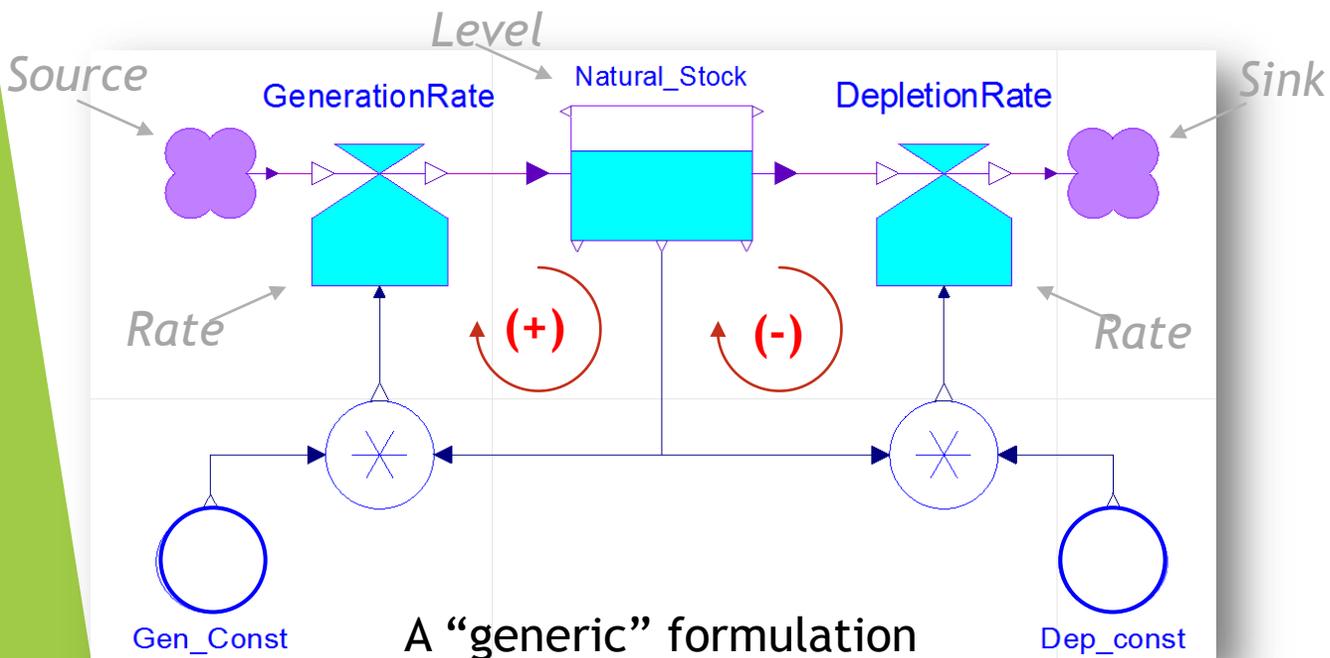
from *System Dynamics Methods: A Quick Introduction*, C. Kirkwood



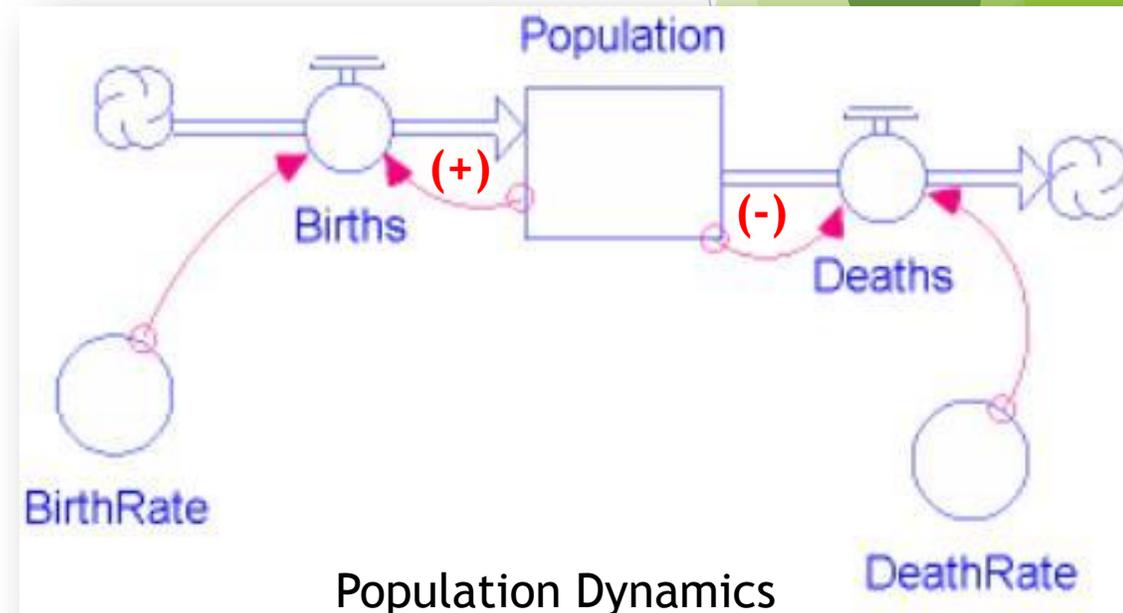
Simple exponential generation/depletion model

- ▶ Example with two loops: 1 negative, 1 positive
- ▶ Levels and Rates
- ▶ Sources and Sinks
 - ▶ Provided for optical purposes only (System Dynamics modelers are used to them)
 - ▶ These models do not represent equations.

E.g.: The Modelica-based **SD Library** + OpenModelica Tool

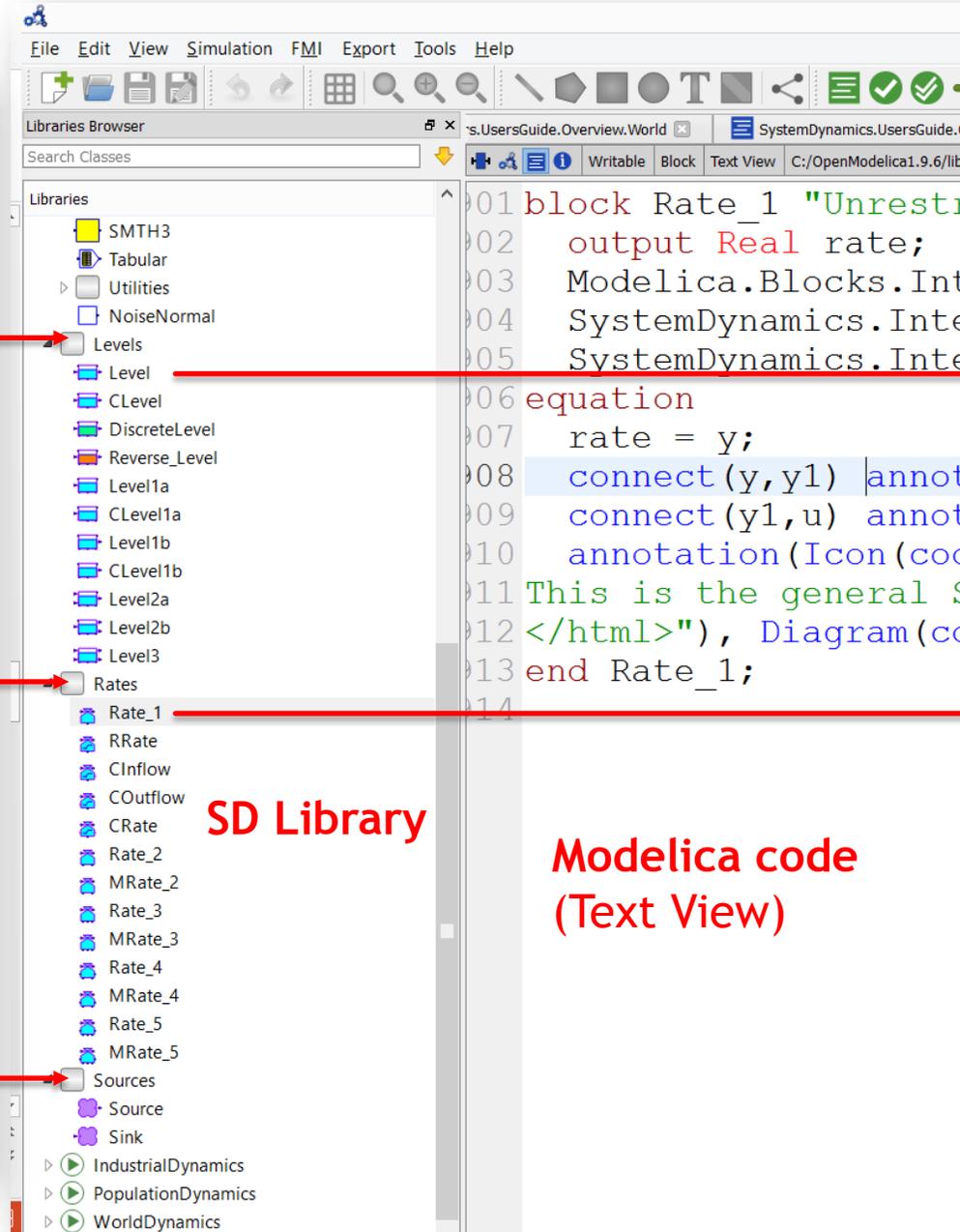
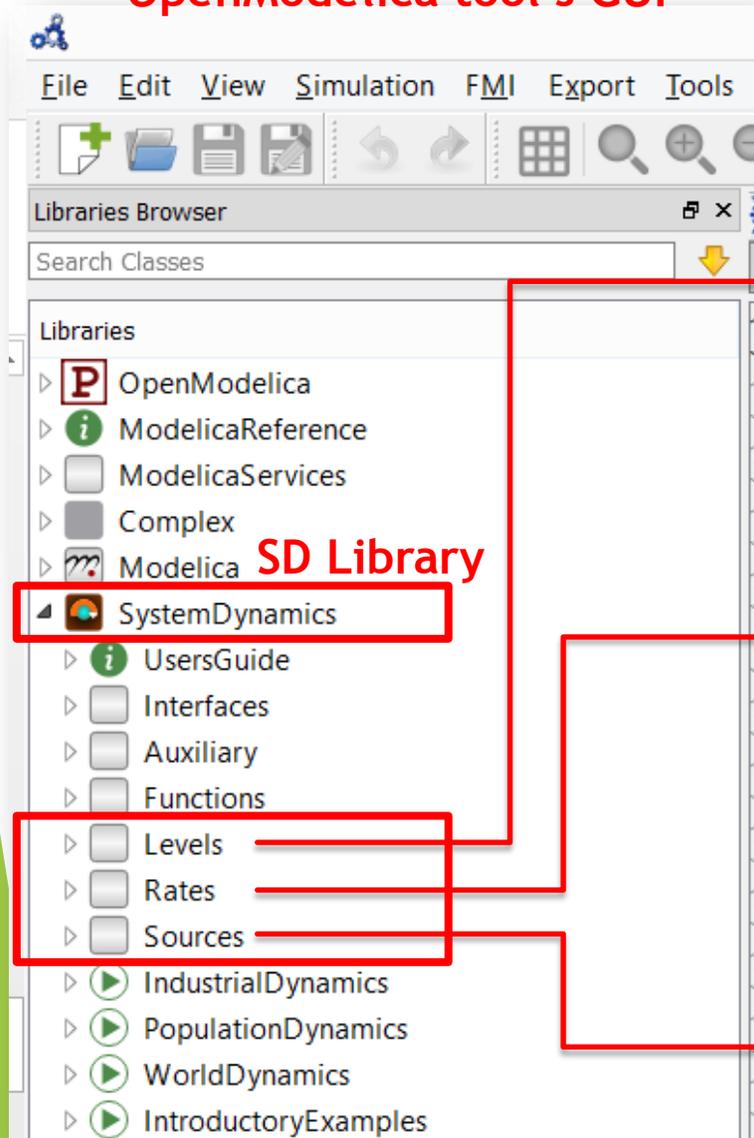


E.g. The Stella **SD-based Tool**



Mod-SD: The SystemDynamics library for Modelica

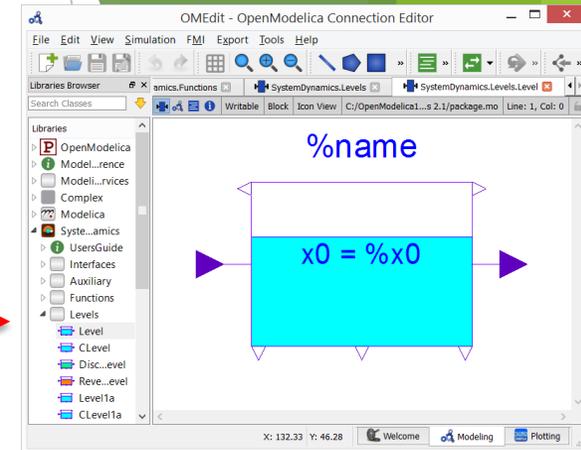
OpenModelica tool's GUI



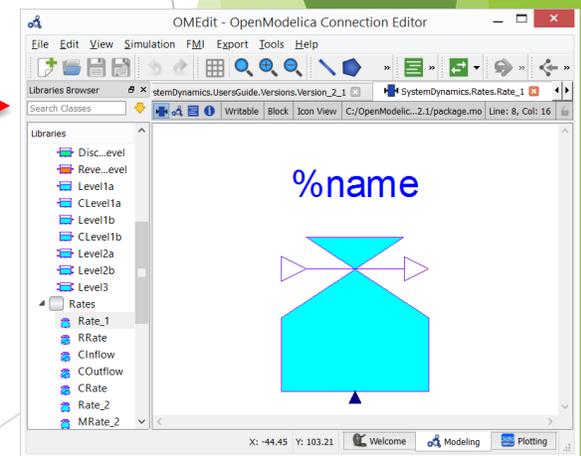
SD Library

Modelica code (Text View)

Levels

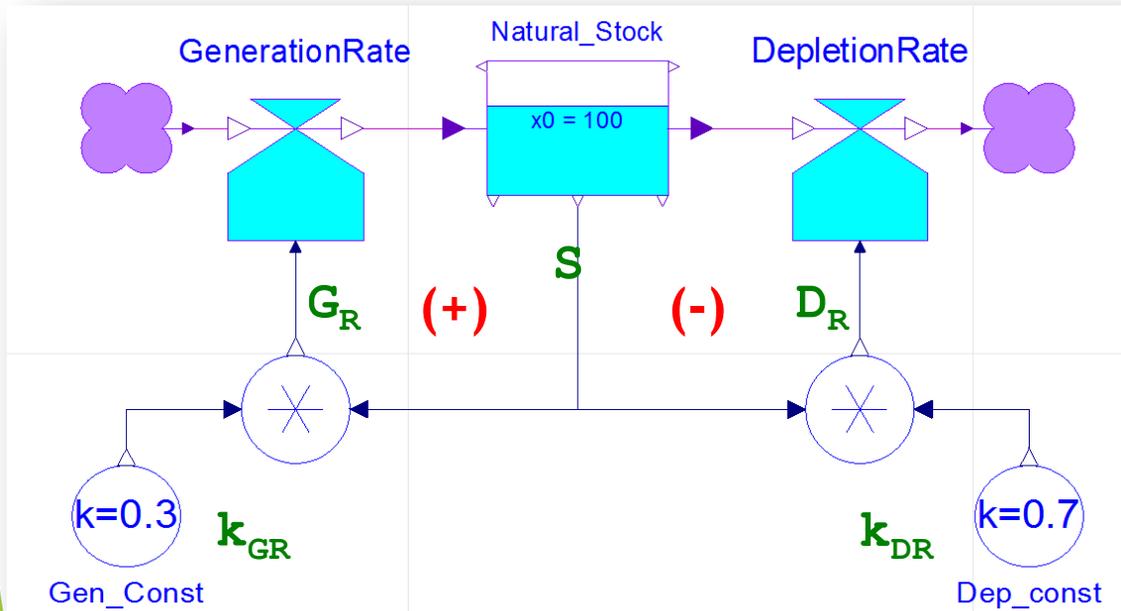


Rates



Simple exponential generation/depletion model

- ▶ Required **model** parameters:
 - ▶ Level: initial condition
 - ▶ Rates: constant coefficients
- ▶ Required **simulation** parameters:
 - ▶ Initial and final simulation time
 - ▶ Numerical accuracy desired



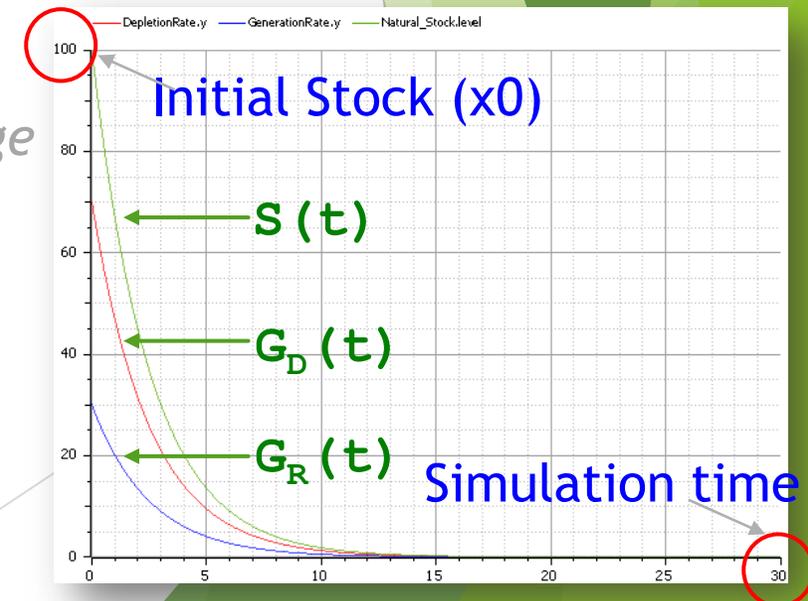
Rate of Level change

$$\dot{S} = + G_R - D_R$$

$$S(t=0) = x_0$$

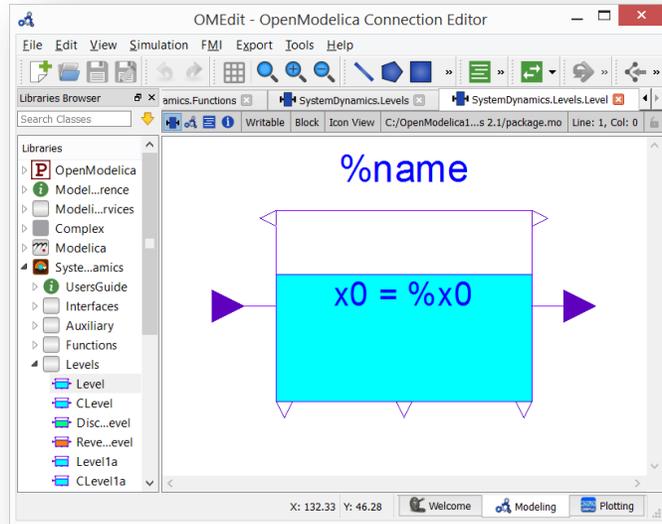
$$G_R = k_{GR} \cdot S$$

$$D_R = k_{DR} \cdot S$$



Mod-SD: Levels

Icon View



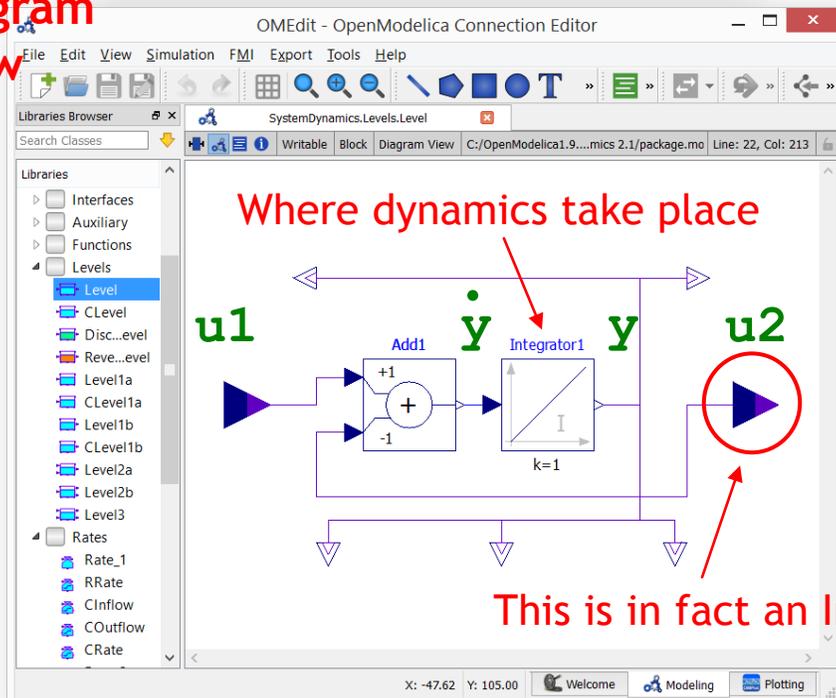
Levels represent the **state variables** of the System Dynamics modeling methodology.

$$\dot{y} = + u1 - u2$$

Text View

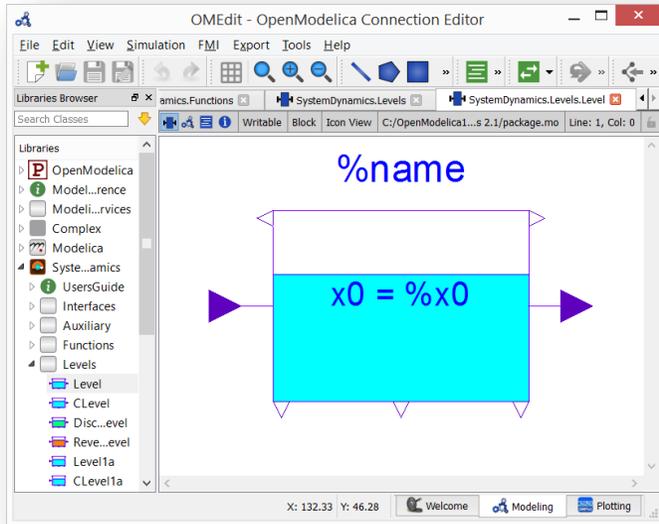
```
584 block Level "General System Dynamics level"
585   parameter Real x0 = 0 "Initial condition";
586   output Real level "Continuous state variable";
587   Modelica.Blocks.Math.Add Add1(k2 = -1)
588   Modelica.Blocks.Continuous.Integrator Integrator1(y_start = x0)
589   SystemDynamics.Interfaces.MassInPort u1 "Inflow variable"
590   SystemDynamics.Interfaces.MassInPort u2 "Outflow variable"
591   SystemDynamics.Interfaces.MassOutPort y "State variable"
592   SystemDynamics.Interfaces.MassOutPort y1 "State variable"
593   SystemDynamics.Interfaces.MassOutPort y2 "State variable"
594   SystemDynamics.Interfaces.MassOutPort y3 "State variable"
595   SystemDynamics.Interfaces.MassOutPort y4 "State variable"
596 equation
597   level = y;
598   connect (Add1.y, Integrator1.u)
599   connect (y, Integrator1.y)
600   connect (u1, Add1.u1)
601   connect (u2, Add1.u2)
602   connect (y1, Integrator1.y)
603   connect (y2, Integrator1.y)
604   connect (y3, Integrator1.y)
605   connect (y4, Integrator1.y)
606
```

Diagram View



Mod-SD: Levels

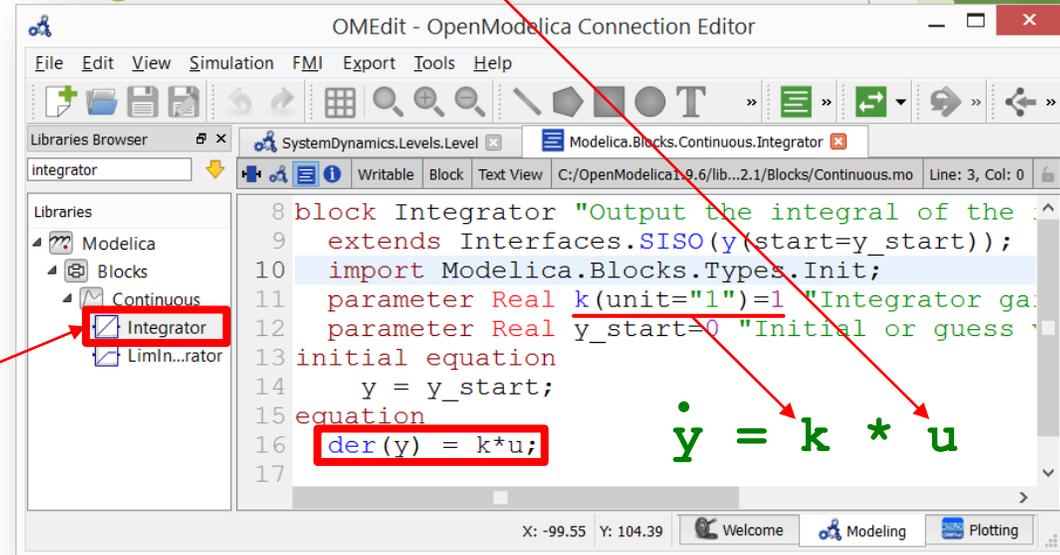
Icon
View



Levels represent the **state variables** of the System Dynamics modeling methodology.

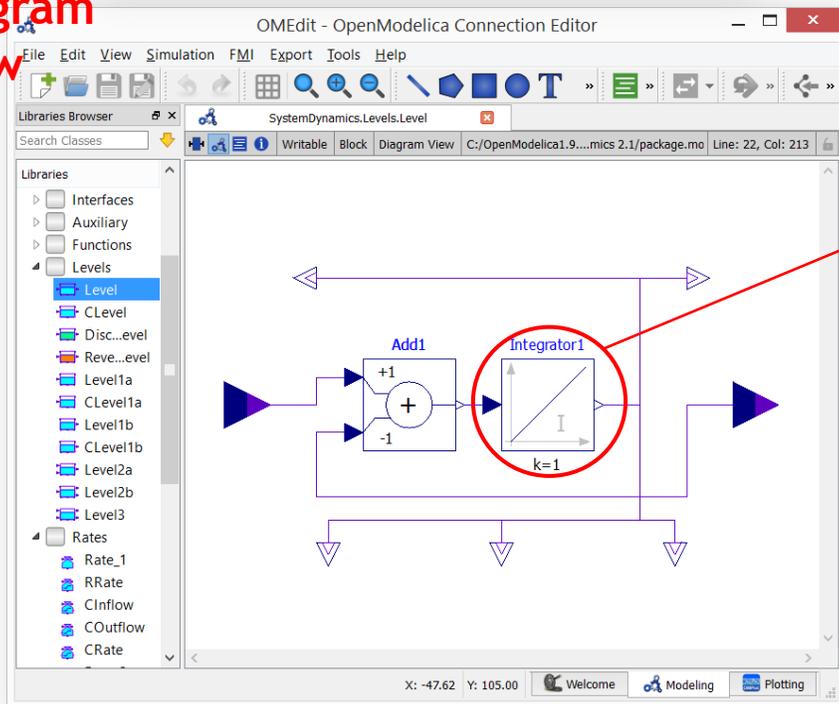
$$\dot{y} = + u1 - u2$$

Integrator block



$$\dot{y} = k * u$$

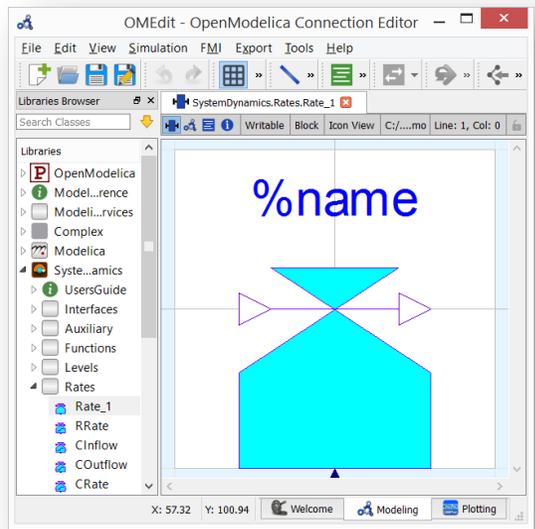
Diagram
View



- The integration operation is defined in an independent standard block
- It is not required to decide on the time step for the numerical solution
- Model is separated from simulation

Mod-SD: Rates

Icon View



Rates define the **state derivatives** of the System Dynamics modeling methodology.

Text View

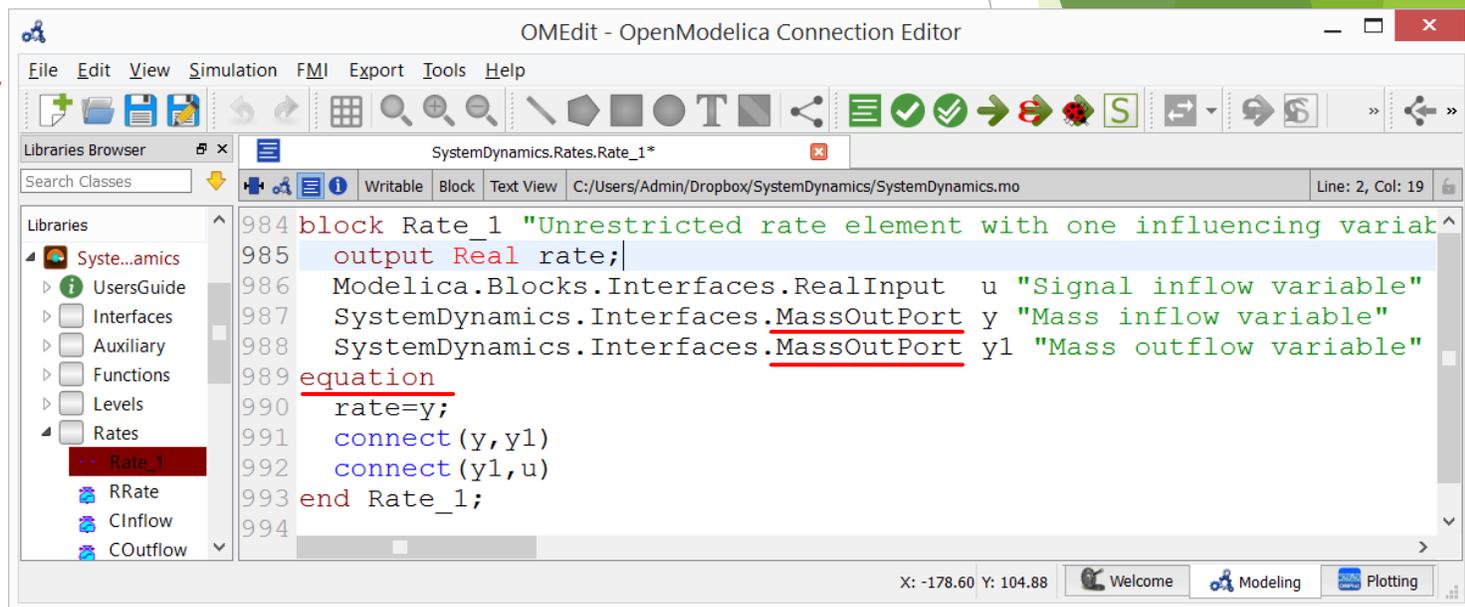
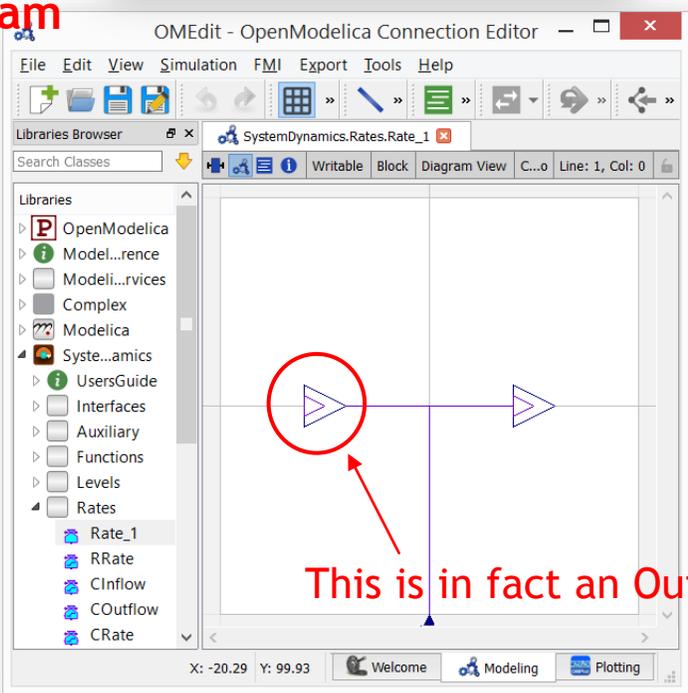


Diagram View

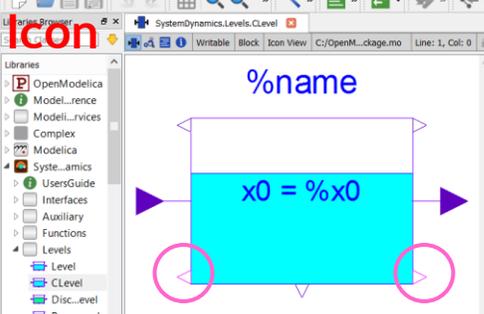
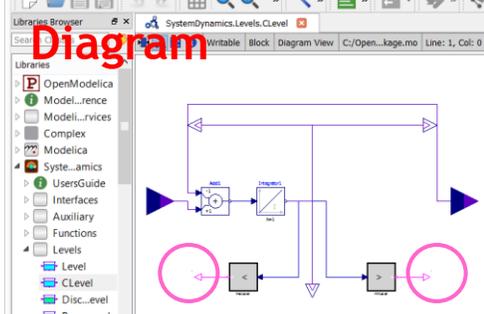


This is in fact an OutPort !

- No “dynamics” defined in this model
- Only a wiring of information delivered to other components connected to it

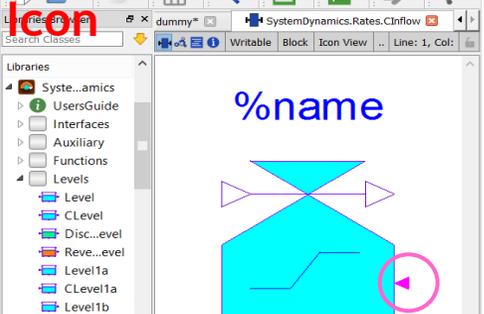
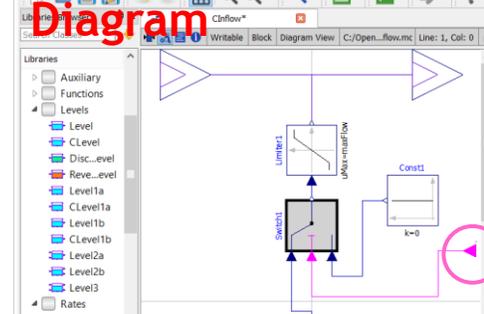
Mod-SD: Extended convenience models

Controlling Level

Icon  **Diagram** 

Outputs logical information on whether minimum or maximum thresholds are crossed

Controlled Inflow Rate, with saturation

Icon  **Diagram** 

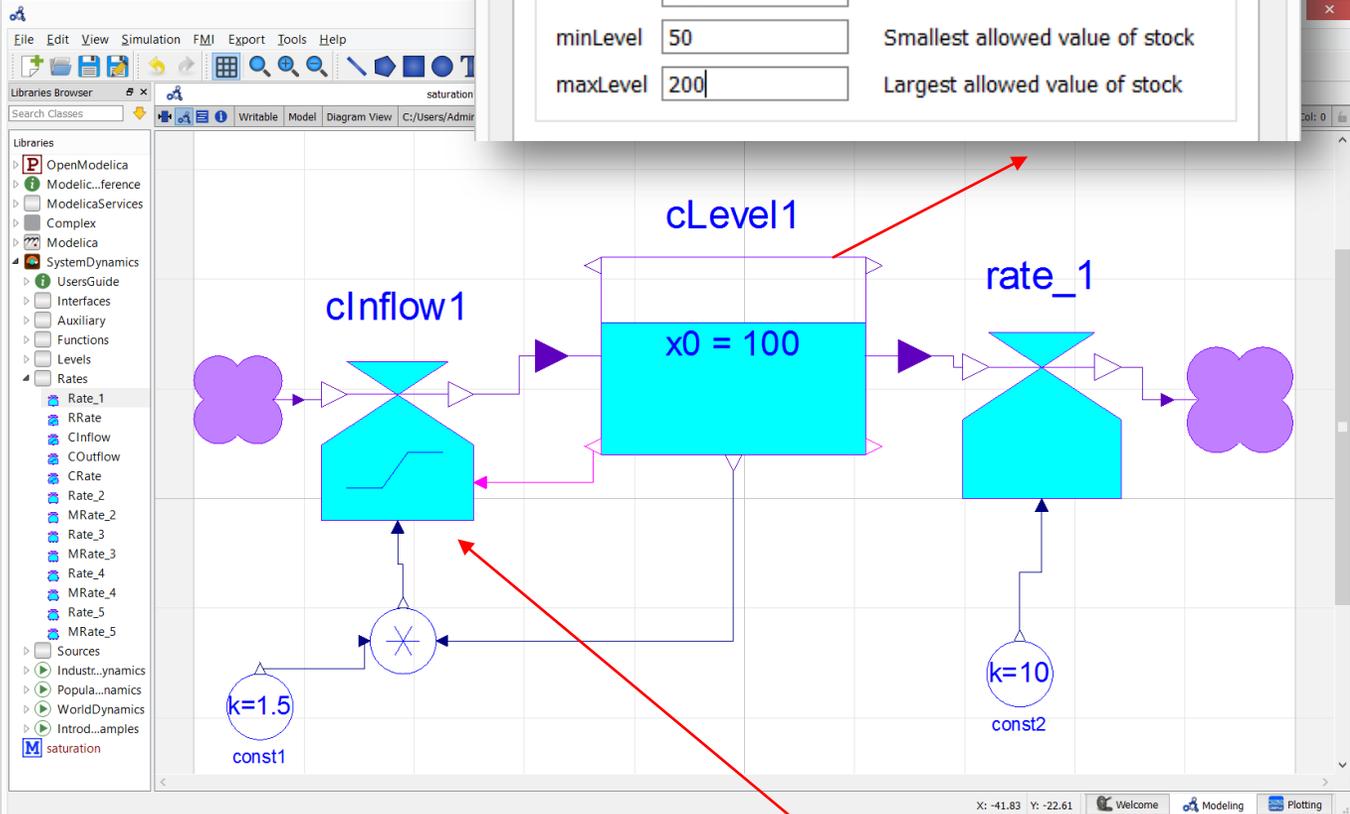
Saturates at certain lower and upper values, and can switch to a constant if commanded so

Parameters

x0	100	Initial condition
minLevel	50	Smallest allowed value of stock
maxLevel	200	Largest allowed value of stock

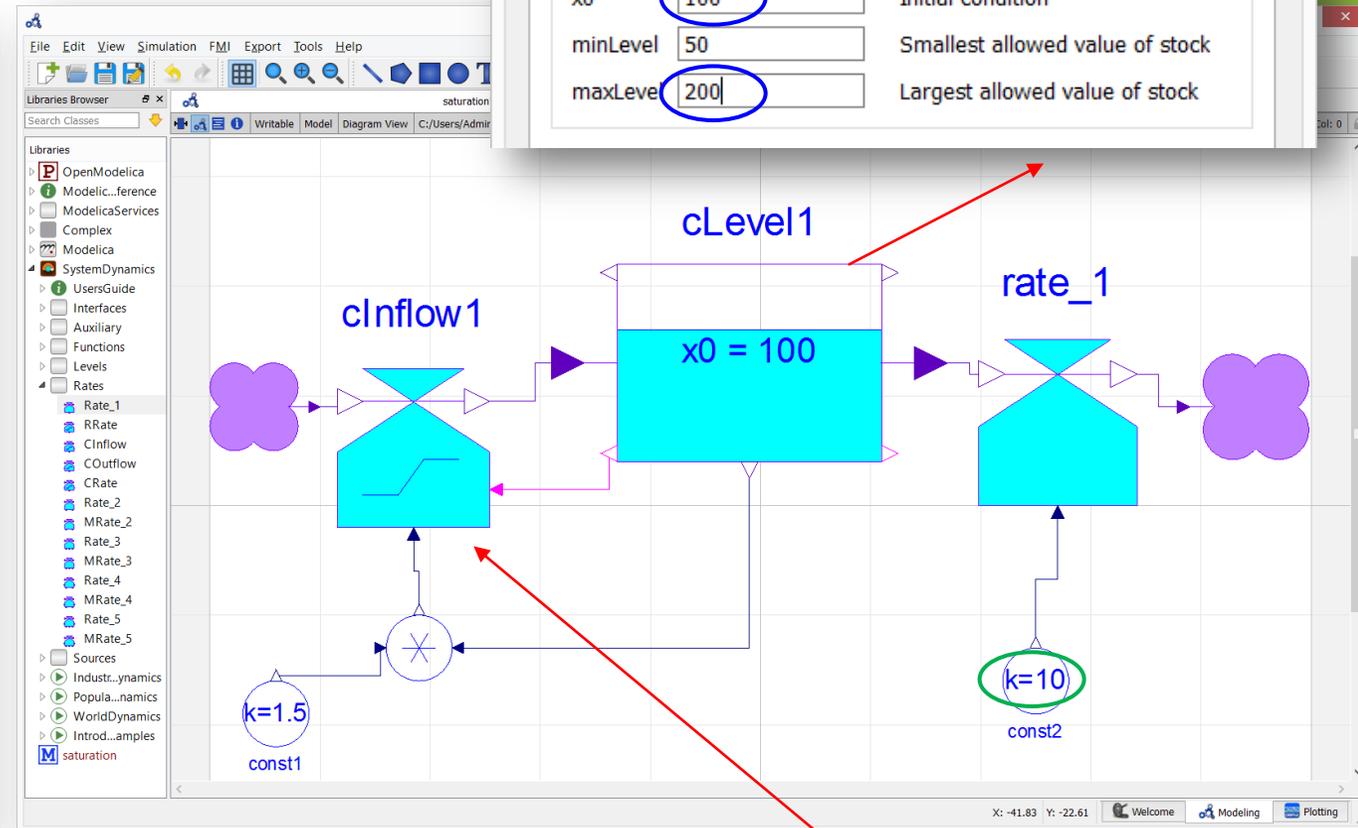
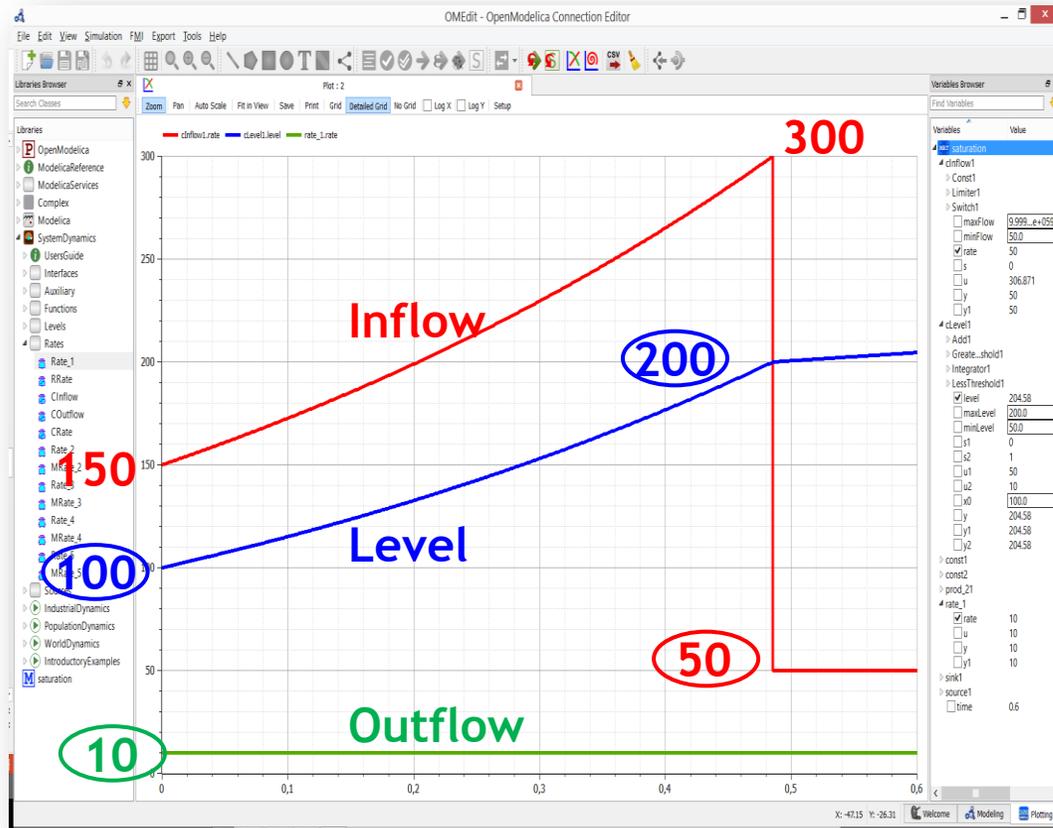
Parameters

minFlow	50	Smallest allowed flow
maxFlow	inf	Largest allowed flow



Mod-SD: Extended convenience models

► Example results

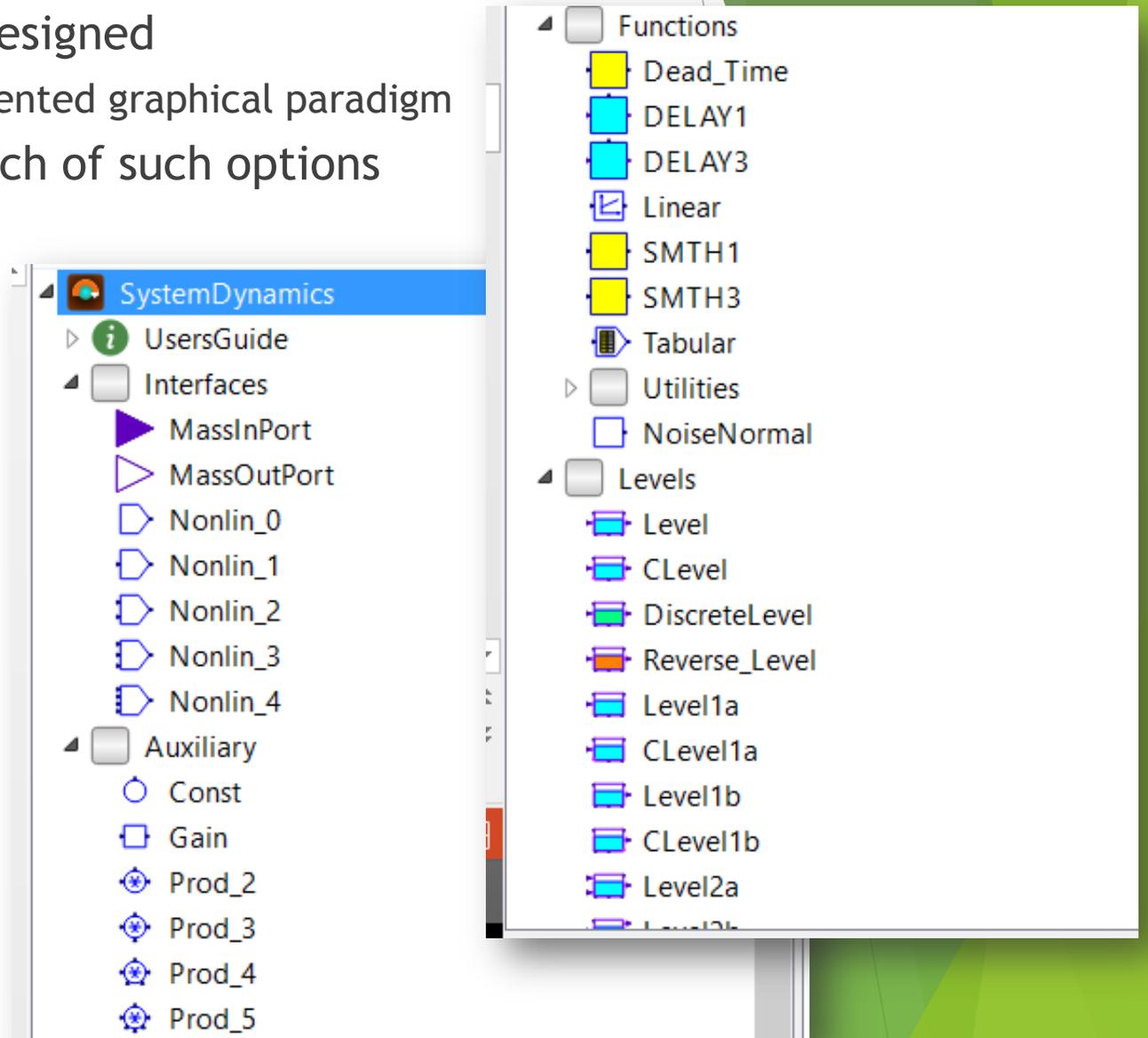


Parameters		
x0	100	Initial condition
minLevel	50	Smallest allowed value of stock
maxLevel	200	Largest allowed value of stock

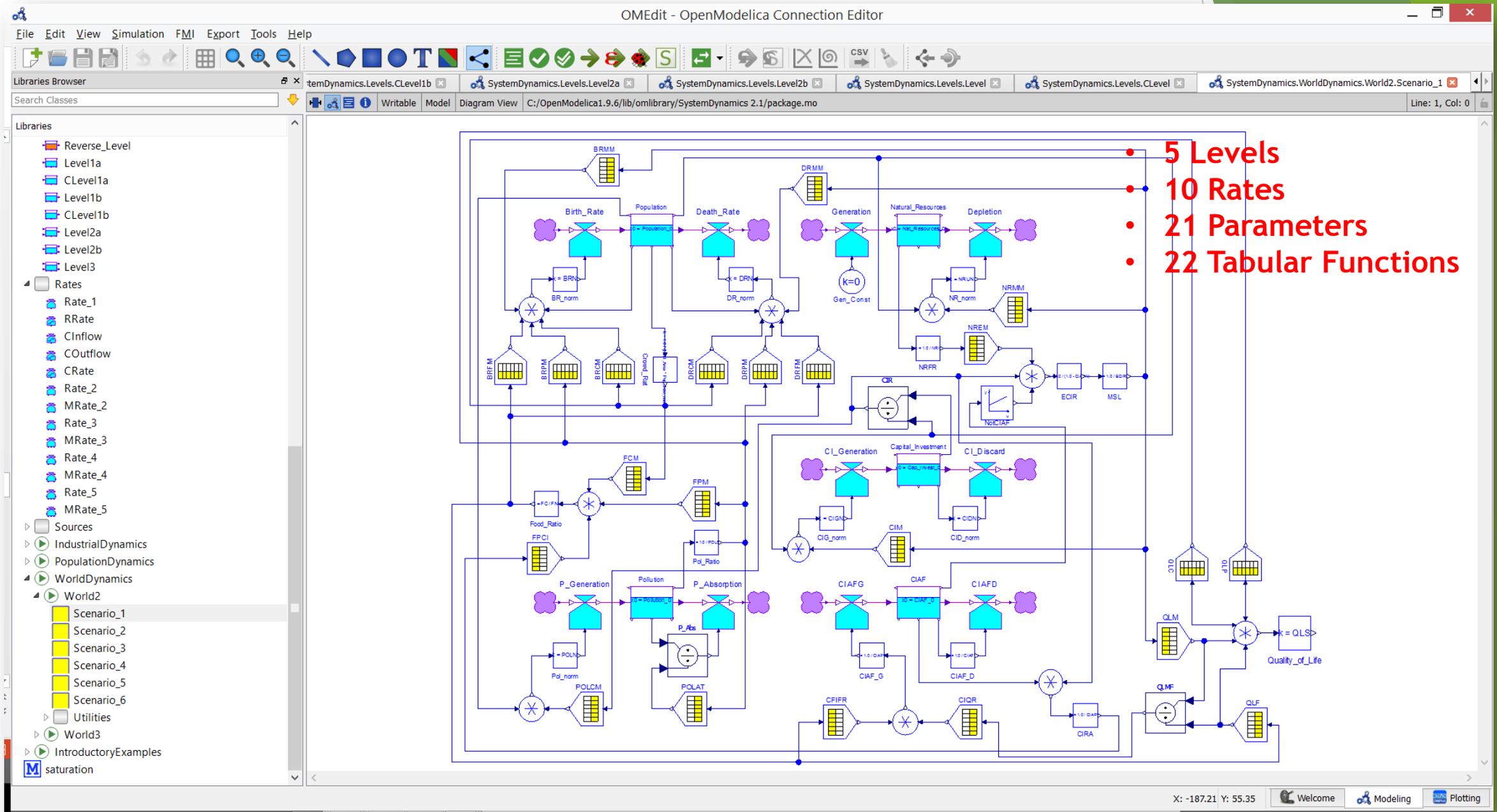
Parameters		
minFlow	50	Smallest allowed flow
maxFlow	inf	Largest allowed flow

Mod-SD: Extended convenience models

- ▶ New advanced/handy basic elements can be designed
 - ▶ Relying on the Modelica language and its block-oriented graphical paradigm
- ▶ The standard Mod-SD library comes with a bunch of such options
 - ▶ Rates
 - ▶ Controlled/Saturated Rates
 - ▶ Multiplicative Rate with several inputs
 - ▶ Additive Rate with several inputs
 - ▶ Levels
 - ▶ Controlled/Saturated Levels
 - ▶ Discrete time Level
 - ▶ Reverse time Level
 - ▶ Multiple inputs/Multiple outputs Level
 - ▶ Interfaces, Auxiliary, Functions
 - ▶ Delays
 - ▶ Dead Time
 - ▶ Smoothers
 - ▶ Tabular, Linear and Non Linear Functions
 - ▶ Gains, Constants, Multi-input products

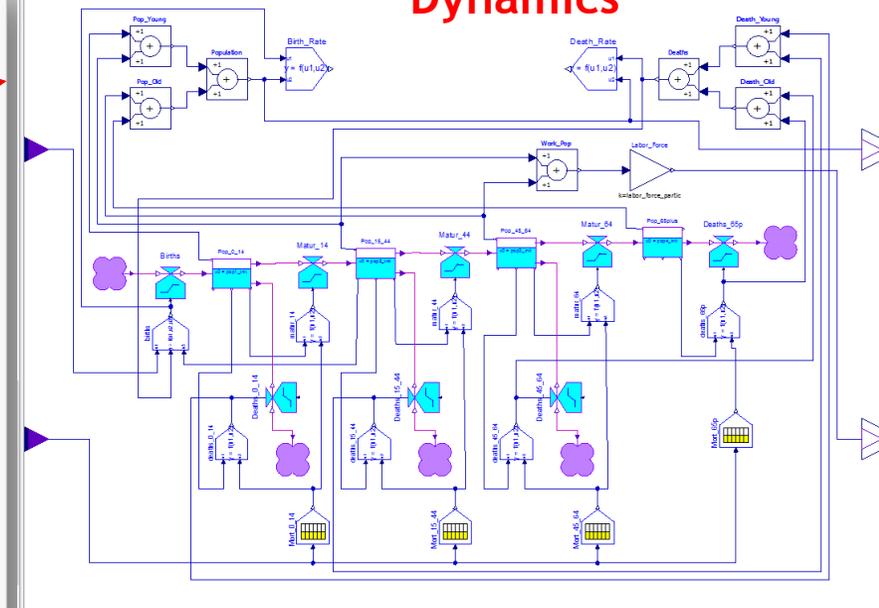


A simple World Model with Mod-SD: World2

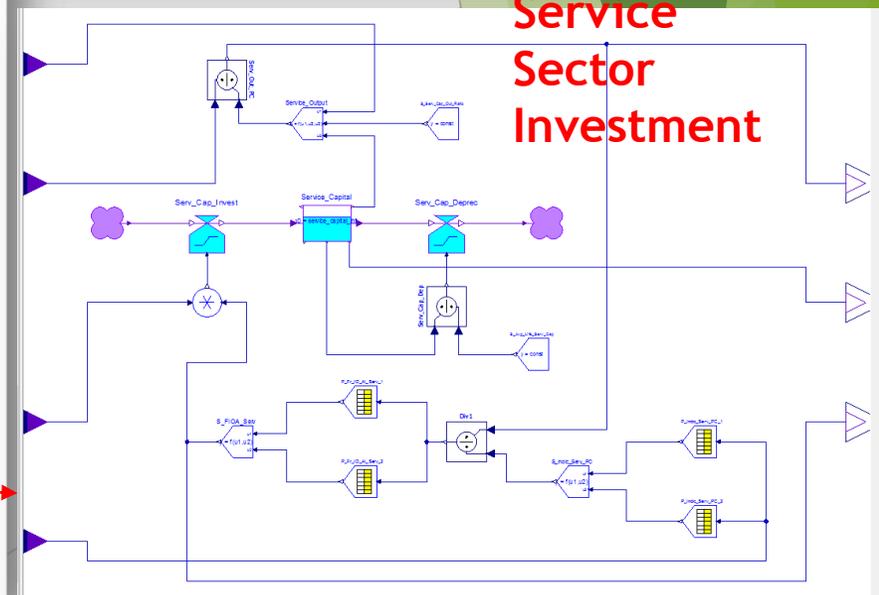


A complex World Model with Mod-SD: World3

Population Dynamics



Service Sector Investment



OMEdit - OpenModelica Connection Editor

File Edit View Simulation FMI Export Tools Help

Libraries Browser

Search Classes

SystemDynamics.WorldDynamics.World3.Scenario_1 SystemDynamics.WorldDynamics.World3.Population_Dynamics

Line: 1, Col: 0

Libraries

- WorldDynamics
 - World2
 - Scenario_1
 - Scenario_2
 - Scenario_3
 - Scenario_4
 - Scenario_5
 - Scenario_6
 - Utilities
 - World3
 - Arable_Land_Dynamics
 - Food_Production
 - Human_Ecological_Footprint
 - Human_Fertility
 - Human_Welfare_Index
 - Industrial_Investment
 - Labor_Utilization
 - Land_Fertility
 - Life_Expectancy
 - NR_Resource_Utilization
 - Pollution_Dynamics
 - Population_Dynamics
 - Service_Sector_Investment
 - Scenario_1
 - Scenario_2
 - Scenario_3
 - Scenario_4
 - Scenario_5
 - Scenario_6
 - Scenario_7
 - Scenario_8
 - Scenario_9
 - Scenario_10

Population Dynamics

Human Fertility

Human Ecological Footprint

Pollution Dynamics

Industrial Investment

Human Welfare Index

Arable Land Dynamics

Labor Utilization

Life Expectancy

Food Production

Land Fertility

NR Resource Utilization

Service Sector Investment

- 13 “aspects”
- 12+5 Levels
- 26 Rates
- 70 Parameters
- 54 Tabular Functions

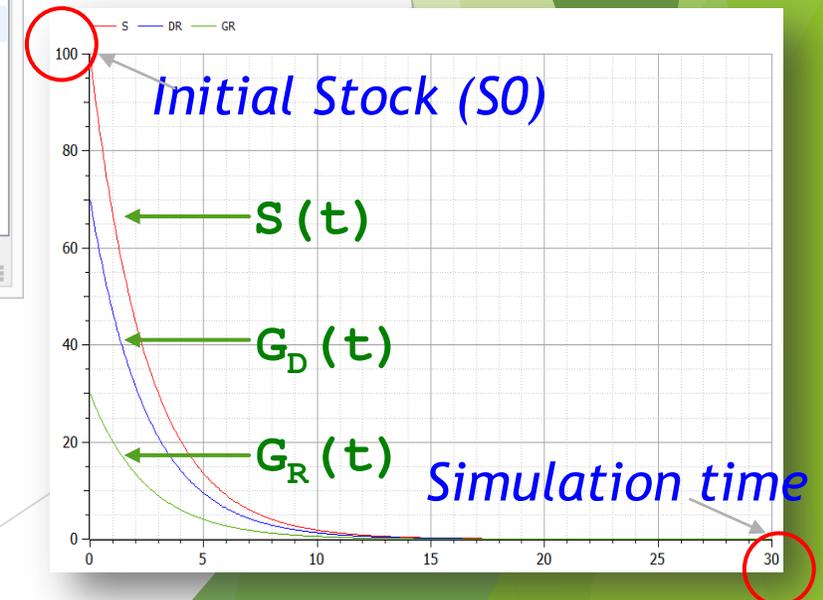
X: 291.06 Y: 225.62 Welcome Modeling Plotting

Simple exponential generation/depletion model (again)

- ▶ “Pure Modelica” code required for our simple growth model

```
1 model GenDep
2   parameter Real S0 = 100 "Stock Initial condition";
3   parameter Real kGR = 0.3 "Generation Rate multiplier";
4   parameter Real kDR = 0.7 "Depletion Rate multiplier";
5   Real GR "Generation Rate";
6   Real DR "Depletion Rate";
7   output Real S "Continuous state variable";
8   initial equation
9     S = S0;
10  equation
11    der(S) = + GR - DR;
12    GR = kGR * S;
13    DR = kDR * S;
14 end GenDep;
```

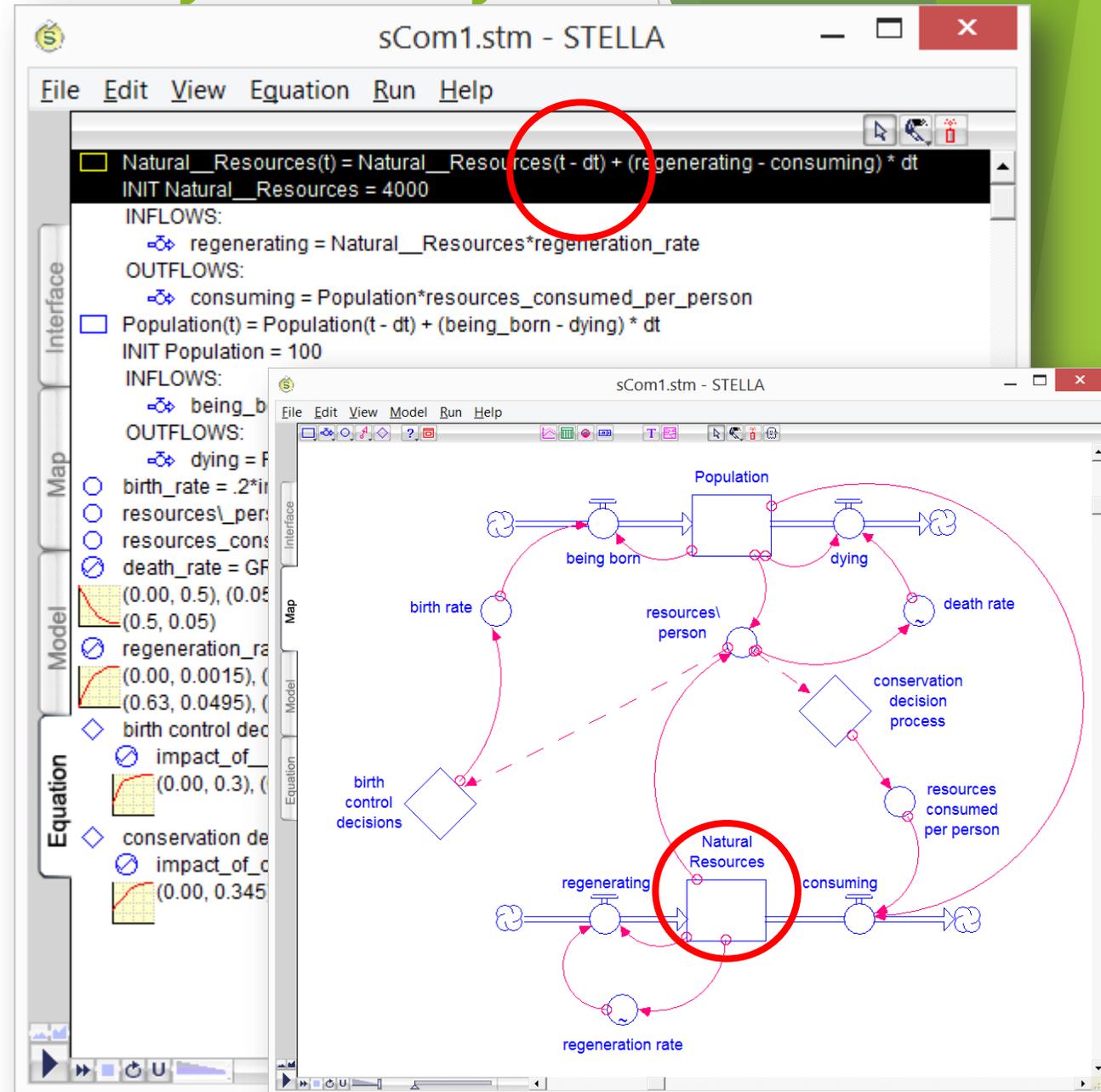
$$\dot{S} = + G_R - D_R$$
$$S(t=0) = S_0$$
$$G_R = k_{GR} \cdot S$$
$$D_R = k_{DR} \cdot S$$



- ▶ Much more compact ! Exactly the same results
- ▶ So... why Mod-SD ? What do we gain ?

The tool-centered approach to System Dynamics

- ▶ No separation between GUI, Model and Simulation
- ▶ At the very heart of System Dynamics there is a tight bind between the models and the numerical simulation aspects
- ▶ Textual model specifications are not standardized
 - ▶ Different tools lead to different code



A Modelica-based System Dynamics Library

- ▶ System Dynamics is a fairly low-level modeling paradigm
 - ▶ Its implementation does not place heavy demands on the modeling software
 - ▶ **Modelica** may be an overkill for dealing with System Dynamics models
 - ▶ **Levels, Rates and Transformations** are the core of System Dynamics
 - ▶ Are so simple that their implementation in Modelica requires very little time and effort
- ▶ The value of the **Mod-SD** library is not in its basic models, but rather in the resulting **standard and open application codes**
- ▶ Methodologically it offers a **sound bridge between deductive and inductive modeling**
 - ▶ Combination of System Dynamics models with the **vast object-oriented, multi-formalism, cyber-physical modeling capabilities** of Modelica
- ▶ Sound integrated treatment of heterogeneous **socio-technical systems**
 - ▶ Continuous-time, discrete-time, and discrete-event aspects

A Modelica-based System Dynamics Library

- ▶ Key issues: **scalability, flexibility, modularity, robustness**
 - ▶ For entry level systems we can be well off with almost any tool for SD
 - ▶ When the complexity of systems grows (dynamics/structure/size) we need **scale up safely and flexibly**: we need **more robust tools**
 - ▶ A **MUST** in serious interdisciplinary global modeling. E.g. the MOSES collaboration
- ▶ Modelica is currently the most advanced technology for equation-based systems modeling
- ▶ Mod-SD can accommodate flexibly different **levels of expertise**:
 - ▶ High level modeling: Graphical reasoning on complex systems (out-of-the-box “usual SD”)
 - ▶ Low level modeling: New/advanced models, structures (“extended SD”)
 - ▶ Advanced simulation: performance, optimization, sensitivity analysis, etc.

Conclusions

- ▶ Based on the **Modelica ecosystem of technologies**, we can leverage the pre existing knowledge base of System Dynamics to cope with the requirements of the next generation of global models
- ▶ System dynamics was introduced as a methodology that allows us to formulate and capture partial knowledge about any soft-science application, knowledge that can be refined as more information becomes available
- ▶ Systems dynamics is the most widely used modeling methodology in all of soft sciences. Tens of thousands of scientists have embraced and used this methodology in their modeling endeavors

Questions



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<http://dc.uba.ar/People/rcastro>