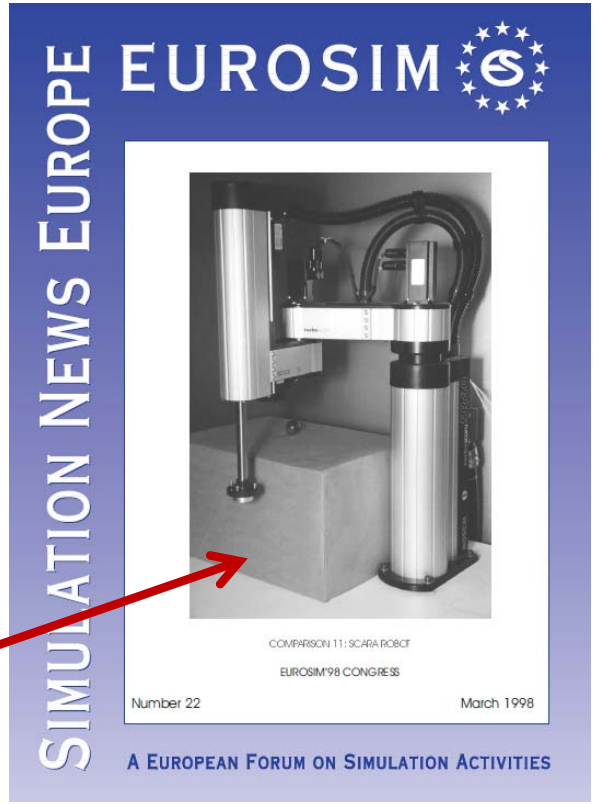
Multi-method Modelling and Simulation and Co-Simulation - Development, Trends and Education

Felix Breitenecker, Andeas Körner, Nikolas Popper

Mathematical Modelling and Simulation Group
Institute for Analysis and Scientific Computing,
Vienna Univ. of Technology, Austria

ARGESIM BENCHMARKS IN SNE

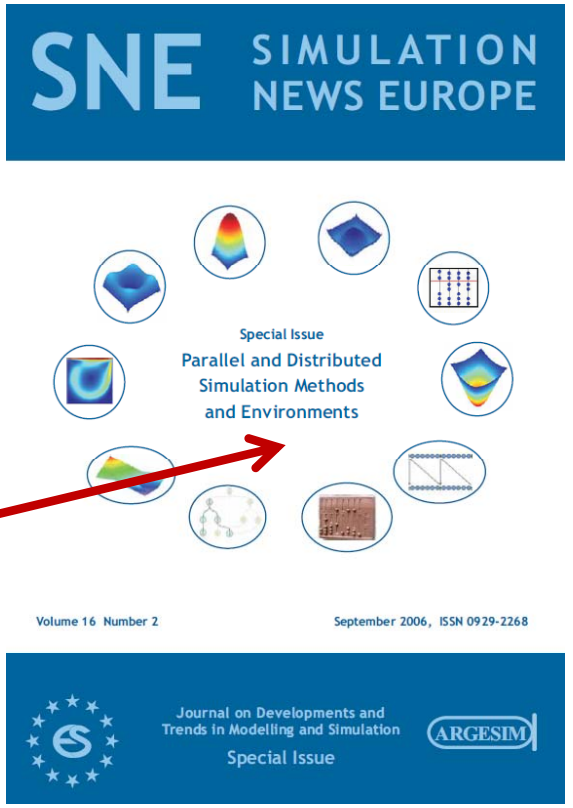
C1 Lithium-Cluster Dynamics, SNE 0(1), 1990
C2 Flexible Assembly System, SNE 1(1), 1991
C3 Generalized Class-E Amplifier, SNE 1(2), 1991
C4 Dining Philosophers I, SNE 1(3), 1991
C5 Two State Model, SNE 2(1), 1992
C6 Emergency Department SNE 2(3), 1992
C7 Constrained Pendulum, SNE 3(1), 1993
CP1 Parallel Simulation Techniques, SNE 4(1), 1994
C8 Canal-and-Lock System, SNE 6(1), 1996
C9 Fuzzy Control of a Two Tank System, SNE 6(2), 1996
C10 Dining Philosophers II, SNE 6(3), 1996
C11 SCARA Robot, SNE 8(1), 1998



Comparison of Simulation Software … … →

ARGESIM BENCHMARKS IN SNE

C12 Collision of Spheres, SNE 9(3), 1999
C13 Crane Crab and Embedded Control, SNE 11(1), 2001
C14 Supply Chain, SNE 11(2-3), 2001
C15 Clearance Identification, SNE 12(2-3), 2002
C16 Restaurant Business Dynamics, SNE 14(1), 2004
C17 Spatial Dynamics of SIR Epidemics, SNE 14(2-3), 2004;
C18 Neural Networks vs. Transfer Functions, SNE 15(1), 2005
C19 Pollution in Groundwater Flow, SNE 15(2-3), 2005
CP2 Parallel & Distributed Simulation, SNE 16(2), 2006



… → *Benchmarks for Modelling Approaches and Simulation Implementations*

ARGESIM BENCHMARKS IN SNE

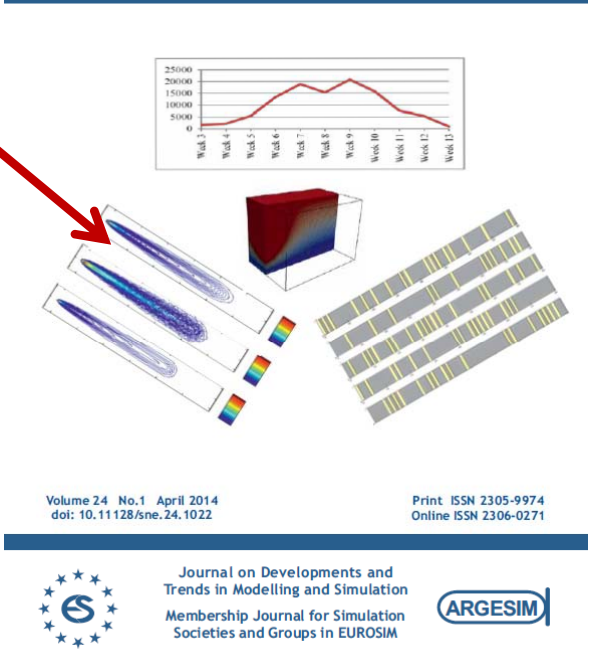
C17 Spatial Dynamics of SIR Epidemics, rev. SNE 25(2), 2015

C18 Neural Networks vs. Transfer Functions, SNE 15(1), 2005

C19 Pollution in Groundwater Flow, rev. SNE 16(3-4), 2006

CP2 Parallel & Distributed Simulation, SNE 16(2), 2006

C20 Complex Assembly System, SNE 21(3-4), 2011



- SNE is publishing revised definitions
- Extended solution documentation (> 1 page)
- Extended Benchmarks: SNE introduces extended benchmarks, comparing modelling and simulation paradigms, or dealing with more complex models and experiments
- Documentation and publication in SNE of ‘solutions’ may take more pages – up to 10 pages SNE.

ARGESIM BENCHMARKS IN SNE

C17 Spatial Dynamics of SIR Epidemics, rev. SNE 25(2), 2015

C18 Neural Networks vs. Transfer Functions, SNE 15(1), 2005

C19 Pollution in Groundwater Flow, rev. SNE 16(3-4), 2006

CP2 Parallel & Distributed Simulation – CO-Simulation, SNE 16(2), 2006

C20 Complex Assembly System, SNE 21(3-4), 2011

C21 State Events and Structural-dynamic Systems,
SNE 26(2), 2016

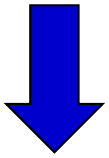
Benchmarks for Modelling Approaches and Simulation Implementations

C22 Multimethod Modelling and Simulation,
SNE 27, 2017

DEVELOPMENT OF SYSTEM SIMULATION

$$\dot{\vec{x}}(t) = \vec{f}(t, \vec{x}(t), \vec{u}(t)), \qquad \vec{x}(t_0) = x_0,$$

ODE



$$\dot{\vec{x}}(t) = \vec{f}(t, \vec{x}(t), \vec{z}(t), \vec{u}(t), \vec{p}), \qquad \vec{x}(t_0) = x_0$$
$$\vec{g}(\vec{x}(t), \vec{z}(t), \vec{u}(t), \vec{p}) = \vec{0}$$

DAE

$$h^B(\vec{x}(t), \vec{u}(t), \vec{p}) \overset{!\pm}{=} \vec{0} \overset{\hat{t}^B}{\Rightarrow} E^B\left(\vec{x}\left(\hat{t}^B\right), \vec{u}\left(\hat{t}^B\right), \vec{p}\right)$$
$$\dots$$

State Events

DEVELOPMENT OF SYSTEM SIMULATION

$$\dot{\vec{x}}(t) = \vec{f}(t, \vec{x}(t), \vec{z}(t), \vec{u}(t), \vec{p}), \qquad \vec{x}(t_0) = x_0$$

$$\vec{g}(\vec{x}(t), \vec{z}(t), \vec{u}(t), \vec{p}) = \vec{0}$$

$$h^B(\vec{x}(t), \vec{u}(t), \vec{p}) \overset{!\pm}{=} \vec{0} \overset{\hat{t}^B}{\Rightarrow} E^B\left(\vec{x}\left(\hat{t}^B\right), \vec{u}\left(\hat{t}^B\right), \vec{p}\right)$$

$$\dots$$

DAE

State Events

Event function

Event action

- Parameter change event – SE-P
- Input change event – SE-I
- State change event – SE-X
- Function change event – SE-F
- Structure change event – SE-S
- Output trace event – SE-O
- Algorithm event – SE-A

DEVELOPMENT OF SYSTEM SIMULATION

$$\dot{\vec{x}}(t) = \vec{f}(t, \vec{x}(t), \vec{z}(t), \vec{u}(t), \vec{p}), \qquad \vec{x}(t_0) = x_0$$

$$\vec{g}(\vec{x}(t), \vec{z}(t), \vec{u}(t), \vec{p}) = \vec{0}$$

$$h^B(\vec{x}(t), \vec{u}(t), \vec{p}) \overset{!\pm}{=} \vec{0} \overset{\hat{t}^B}{\Rightarrow} E^B\left(\vec{x}\left(\hat{t}^B\right), \vec{u}\left(\hat{t}^B\right), \vec{p}\right)$$

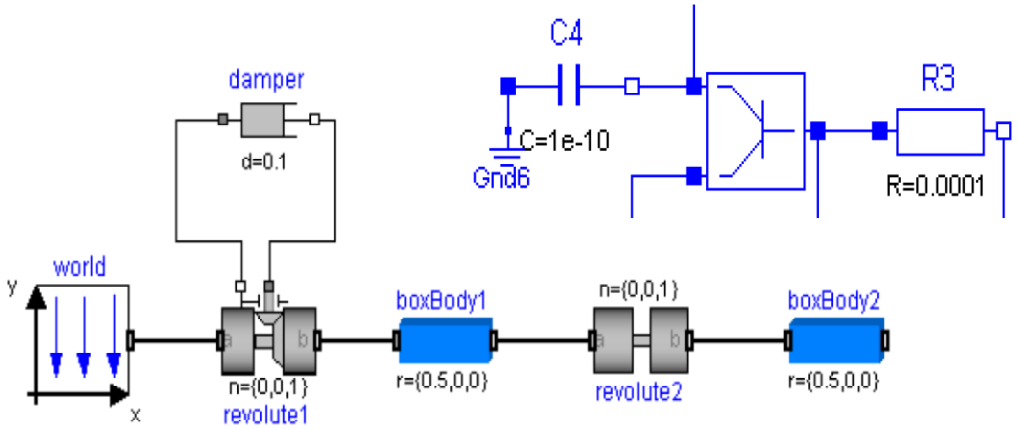
$$\ldots$$

DAE

State Events

Event function

Event action



Physical Modelling –

State Space ‚unknown‘

STATE EVENT HANDLING

$$\dot{\vec{x}}(t) = \vec{f}(t, \vec{x}(t), \vec{z}(t), \vec{u}(t), \vec{p}), \qquad \vec{x}(t_0) = x_0$$

$$\vec{g}(\vec{x}(t), \vec{z}(t), \vec{u}(t), \vec{p}) = \vec{0}$$

$$h^B(\vec{x}(t), \vec{u}(t), \vec{p}) \overset{!\pm}{=} \vec{0} \overset{\hat{t}^B}{\Rightarrow} E^B\left(\vec{x}\left(\hat{t}^B\right), \vec{u}\left(\hat{t}^B\right), \vec{p}\right)$$

$$\dots$$

DAE

State Events

- Parameter change event – SE-P
- Input change event – SE-I
- State change event – SE-X
- Function change event – SE-F
- Structure change event – SE-S
- Output trace event – SE-O
- Algorithm event – SE-A

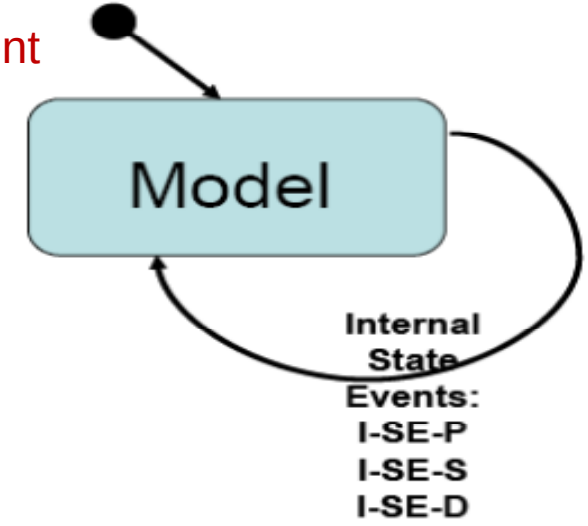
Structural-dynamic Systems

Structural-dynamic Systems

$$h^B(\vec{x}(t),\vec{u}(t),\vec{p}) \begin{matrix} !\pm \\ = \\ \dots \end{matrix} \vec{0} \overset{\hat{t}^B}{\Rightarrow} E^B\left(\vec{x}\left(\hat{t}^B\right),\vec{u}\left(\hat{t}^B\right),\vec{p}\right)$$

1. *Detection* of the event
2. *Localisation* of event
3. **Event *Action***
4. *Restart* of solver

- Parameter change event –
- Input change event
- State change event
- Function change event
- Structure change event
- Output trace event
- Algorithm event

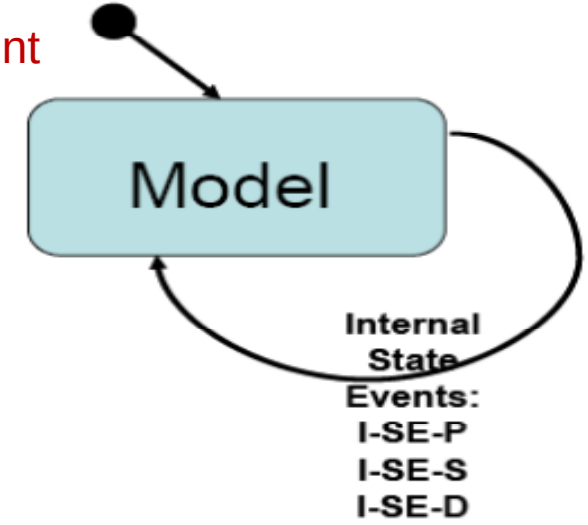


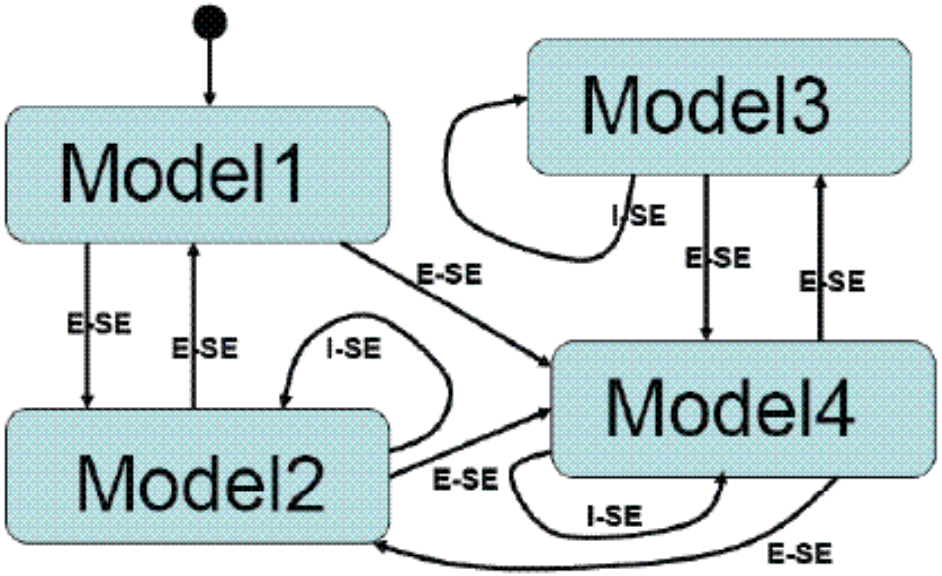
Structural-dynamic Systems

$$h^B(\vec{x}(t),\vec{u}(t),\vec{p}) \begin{matrix} !\pm \\ = \\ \dots \end{matrix} \vec{0} \overset{\hat{t}^B}{\Rightarrow} E^B\left(\vec{x}\left(\hat{t}^B\right),\vec{u}\left(\hat{t}^B\right),\vec{p}\right)$$

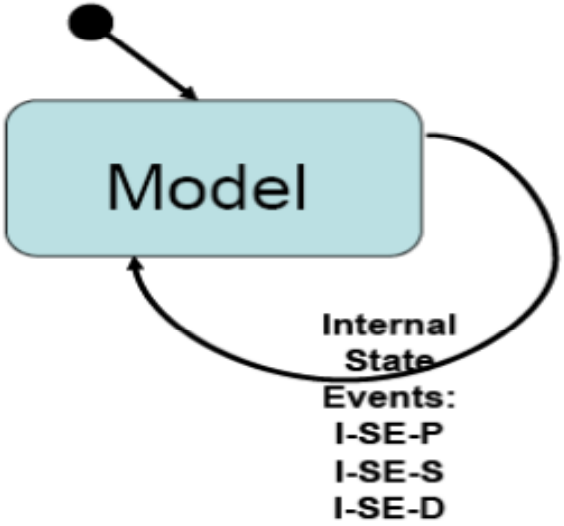
1. *Detection* of the event
2. *Localisation* of event
3. **Event *Action***
4. *Restart* of solver

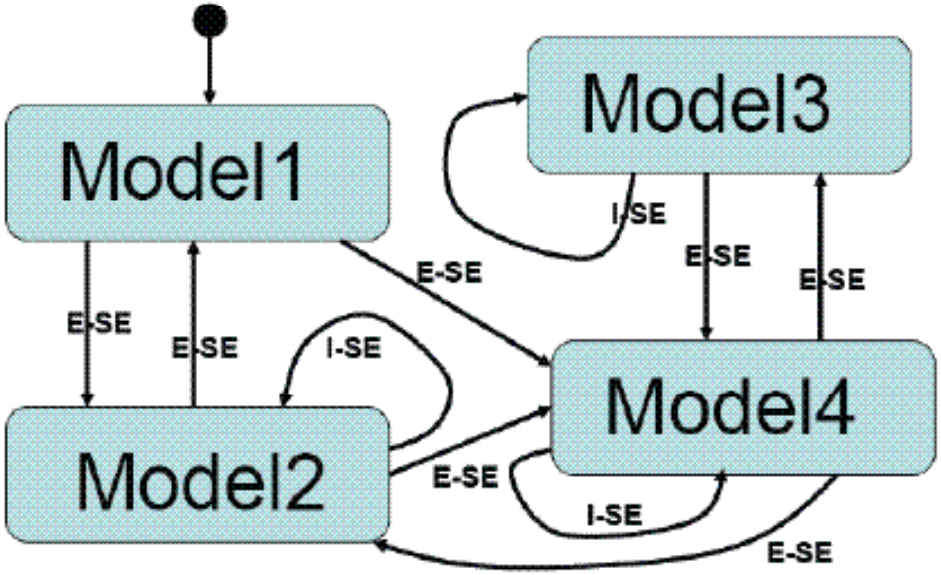
- Parameter change event –
- Input change event
- State change event
- Function change event
- Structure change event
- Output trace event
- Algorithm event





Multimethod Modelling





Multimethod Modelling

DAEs

Diff Eq.

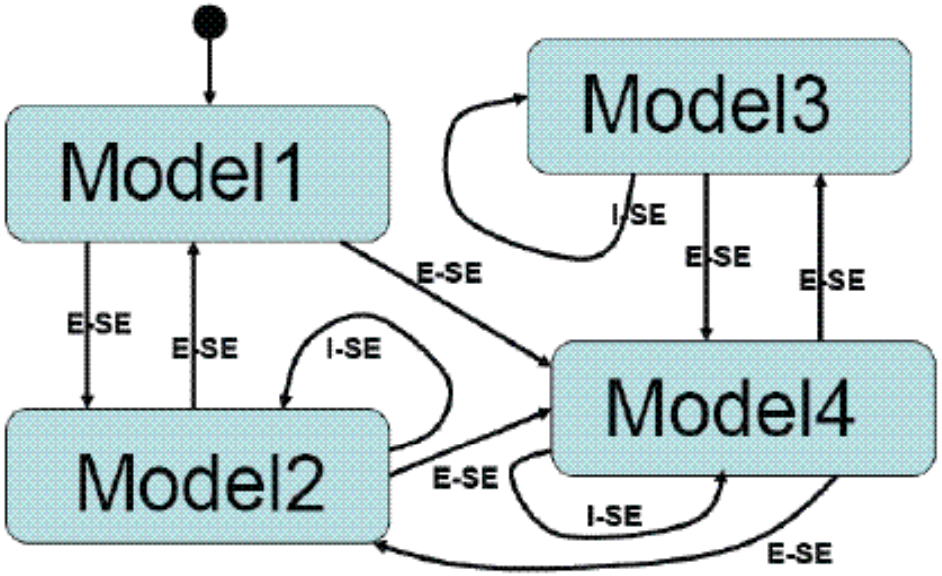
PDEs

Event Mod

DEVS

Process Mod

Agent-based



Charact. Functions

Static Mod

Multimethod Modelling

DAEs

Diff Eq.

PDEs

Event Mod

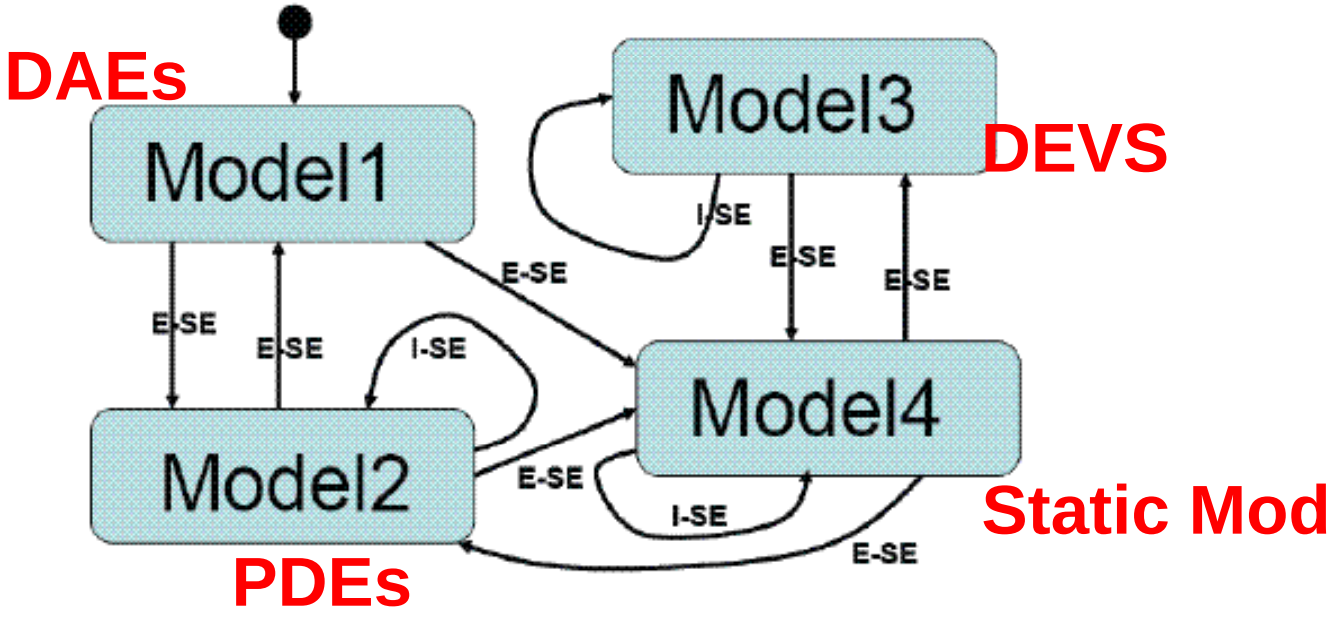
DEVS

Process Mod

Agent-based

Charact. Functions

Static Mod



Multimethod Modelling

DAEs

Diff Eq.

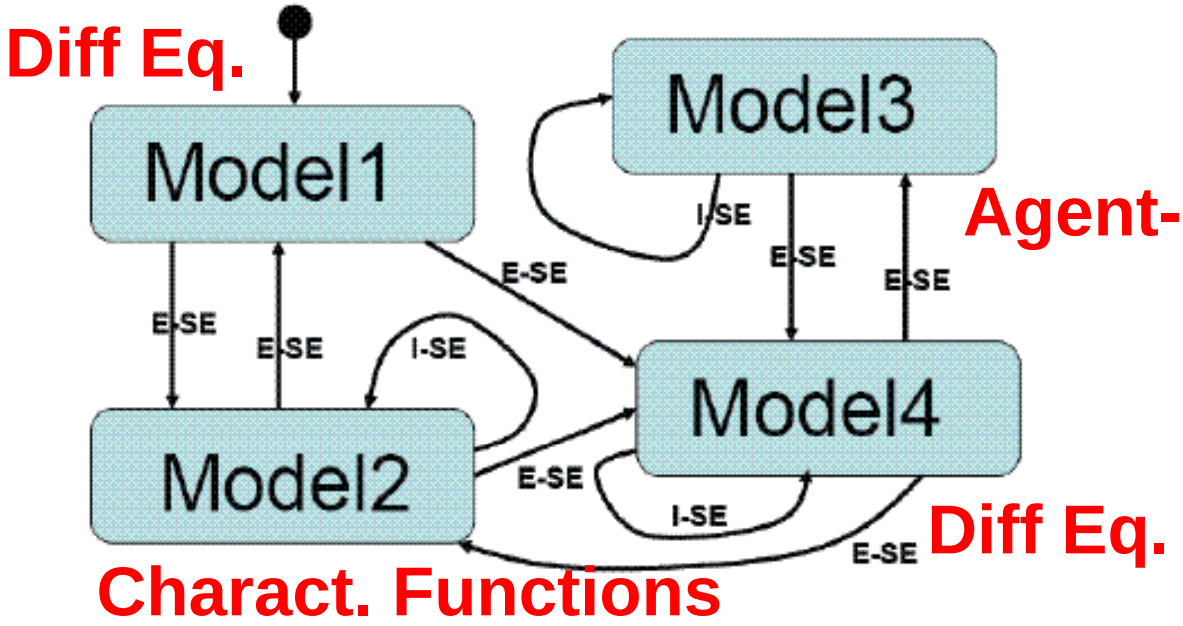
PDEs

Event Mod

DEVS

Process Mod

Agent-based



Charact. Functions

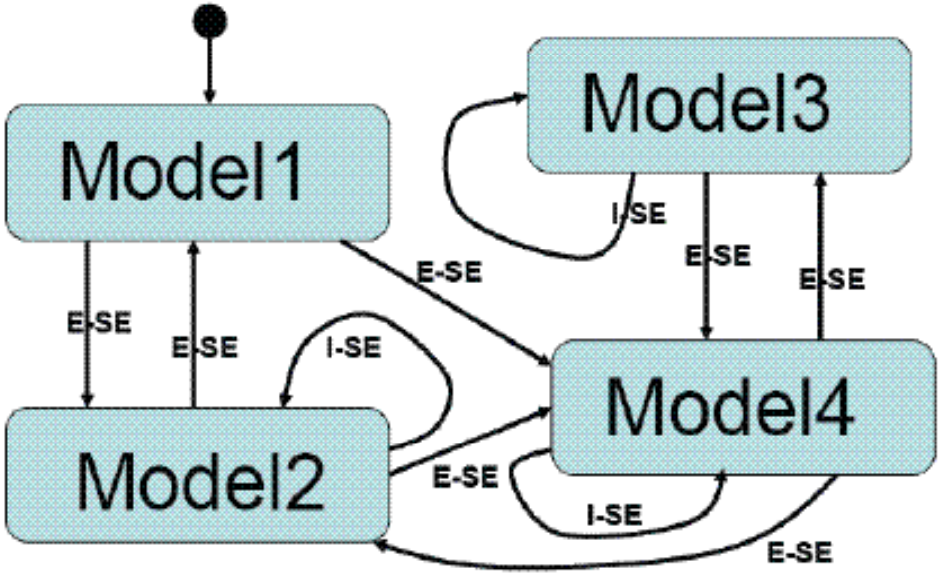
Static Mod

Multimethod Modelling

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Multimethod Modelling

DAEs

Diff Eq.

PDEs

Event Mod

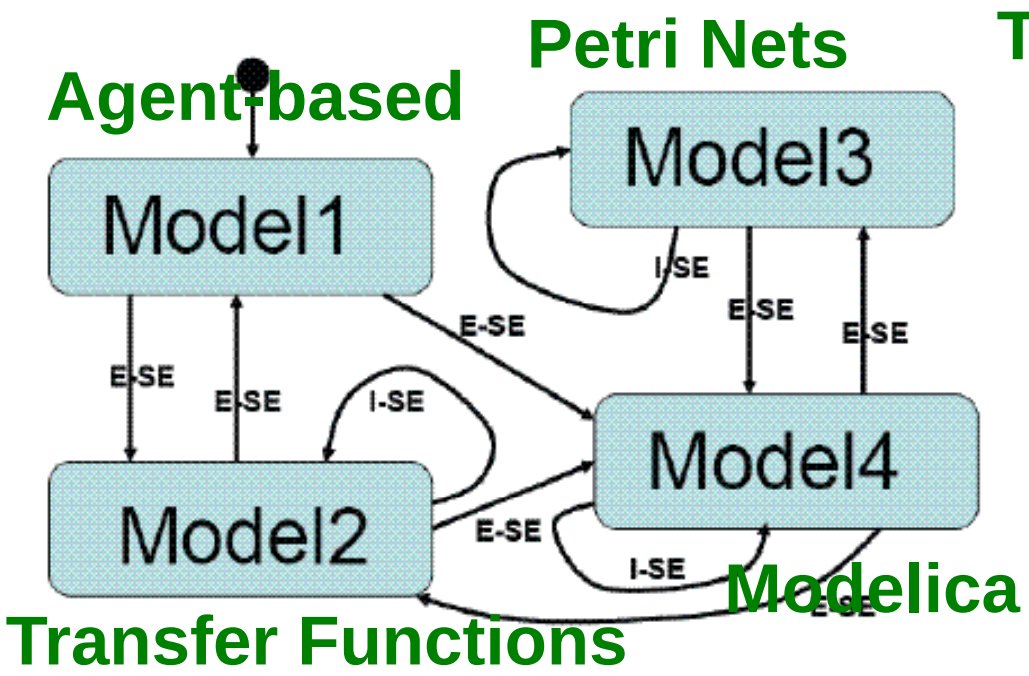
DEVS

Process Mod

Agent-based

Charact. Functions

Static Mod



Transfer Functions

System Dynamics

Modelica

Bond Graphs

Agent-based

Petri Nets

CA Mod

State Automata

Multimethod Modelling

DAEs

Diff Eq.

PDEs

Event Mod

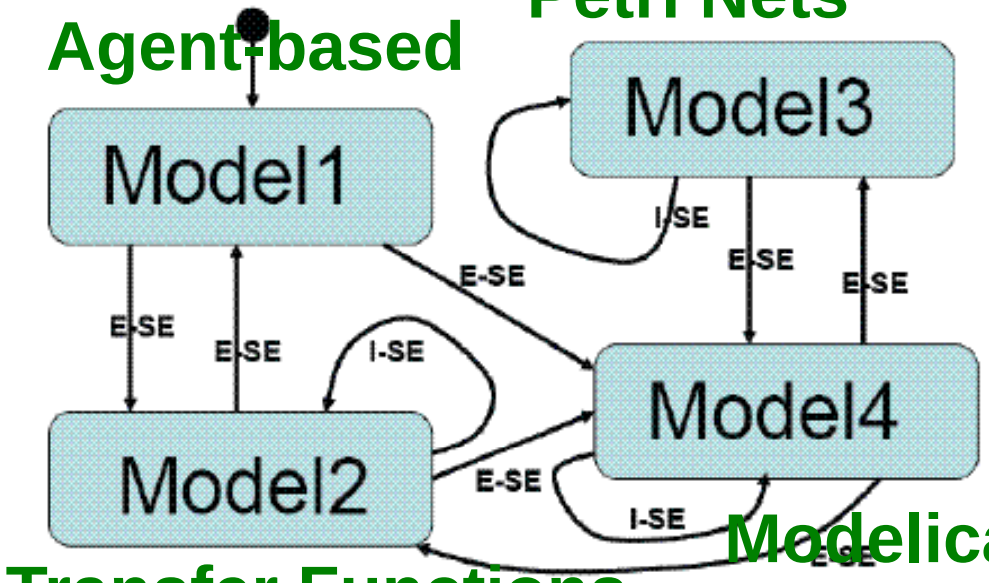
DEVS

Process Mod

Agent-based

Charact. Functions

Static Mod



Transfer Functions

System Dynamics

Modelica

Bond Graphs

Agent-based

Petri Nets

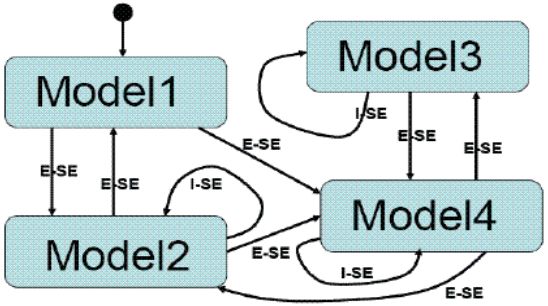
CA Mod

State Automata

Multimethod Modelling

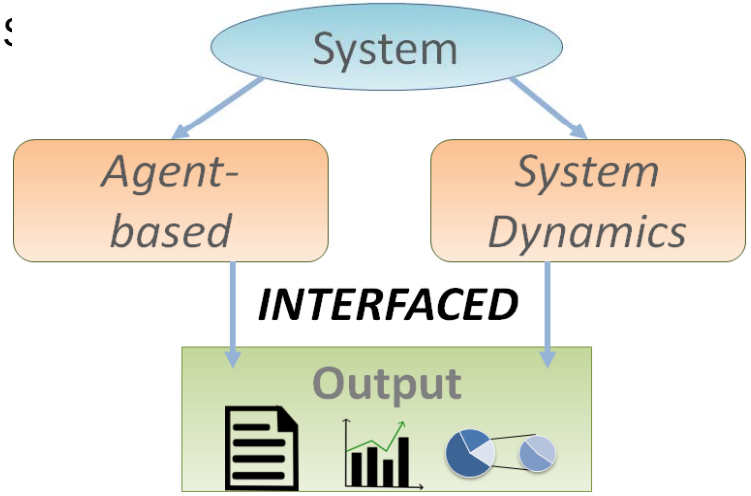
DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

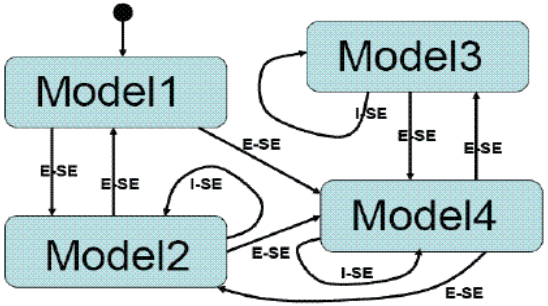
Charact. Functions



Multimethod Modelling

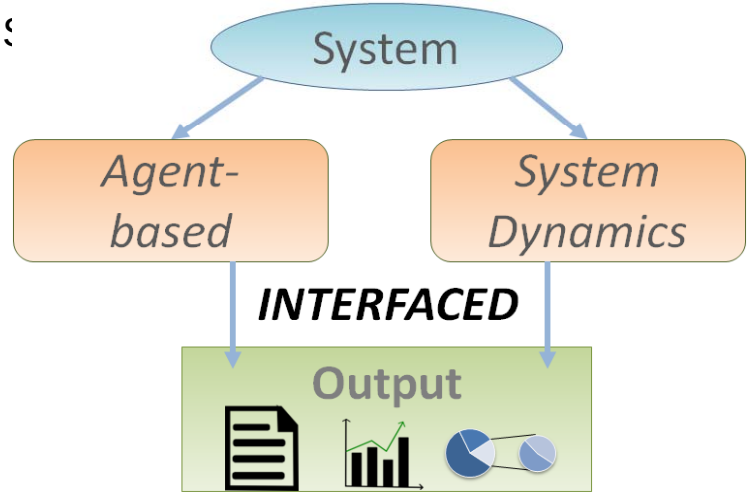
DAEs
Diff Eq.
PDEs

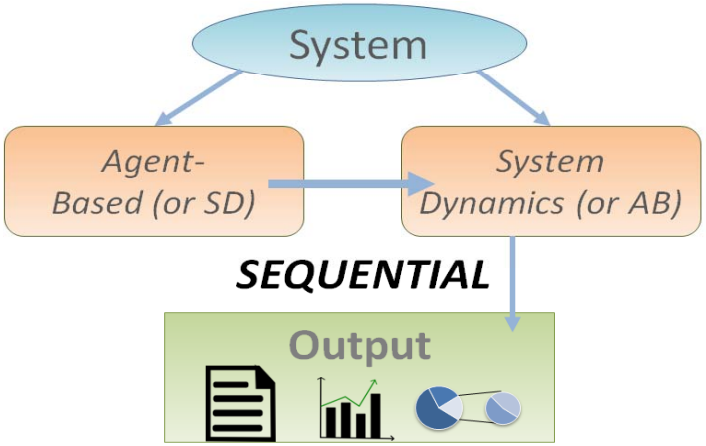
Event Mod
DEVS
Process Mod
Agent-based



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

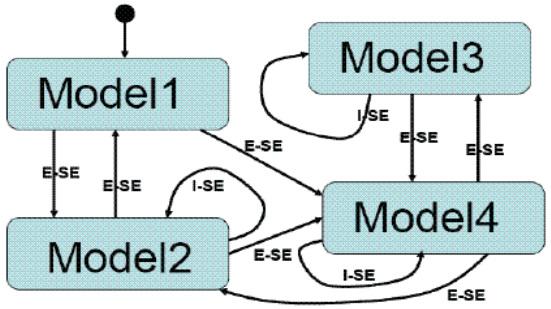
Charact. Functions





Multimethod Modelling

DAEs
Diff Eq.
PDEs
Event Mod
DEVS
Process Mod
Agent-based
Charact. Functions
Static Mod



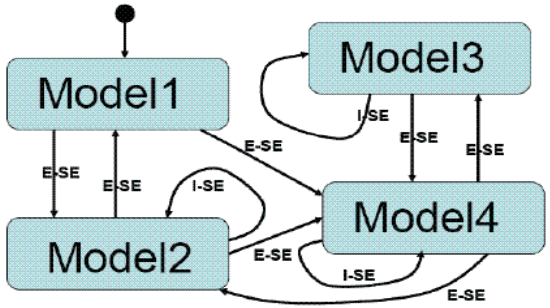
Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Technical Infrastructure	Landside Access	Terminals	Airside & Access
Energy	Access Roads	Passenger terminals	Airport Control Zones
Telecom	Railway Access	Air Cargo Terminals & Warehouses	ATC Facilities
Water, Waste	Landside Transportation		Aprons, Airside Road System
Sewage	Internal Road System	Air Mail Facilities	Safety & Security Facilities

ASC TU VIENNA Mathematical Modelling and Simulation

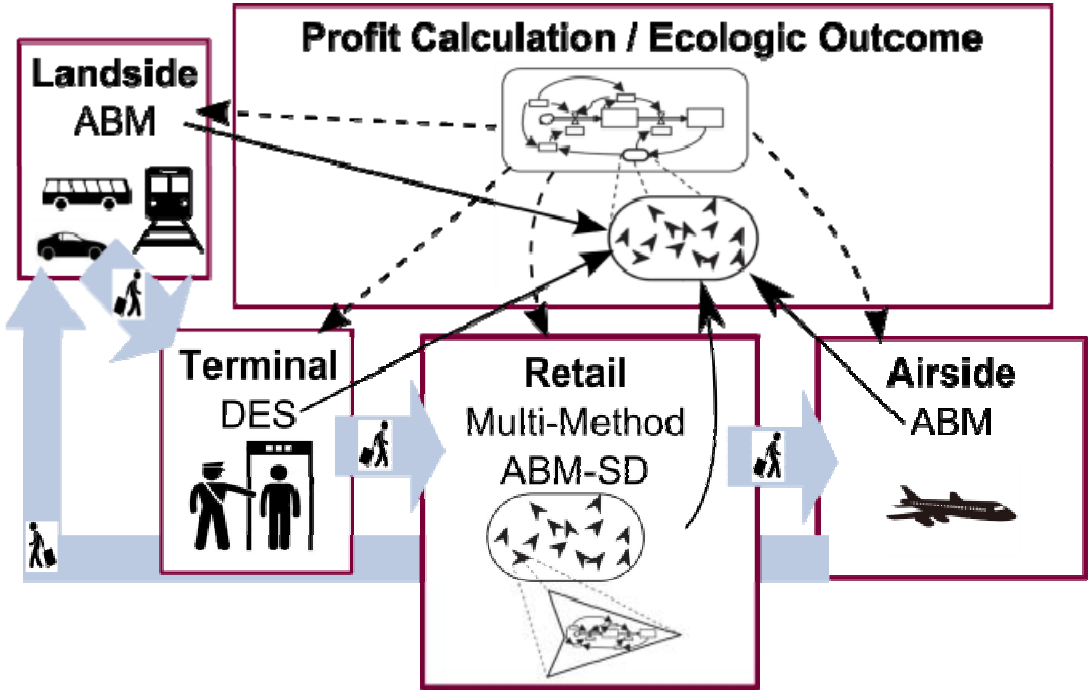
Multimethod Modelling

DAEs
Diff Eq.
PDEs
Event Mod
DEVS
Process Mod
Agent-based
Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Technical Infrastructure	Landside Access	Terminals	Airside & Access
Energy	Access Roads	Passenger terminals	Airport Control Zones
Telecom	Railway Access	Air Cargo Terminals & Warehouses	ATC Facilities
Water, Waste	Landside Transportation		Aprons, Airside Road System
Sewage	Internal Road System	Air Mail Facilities	Safety & Security Facilities

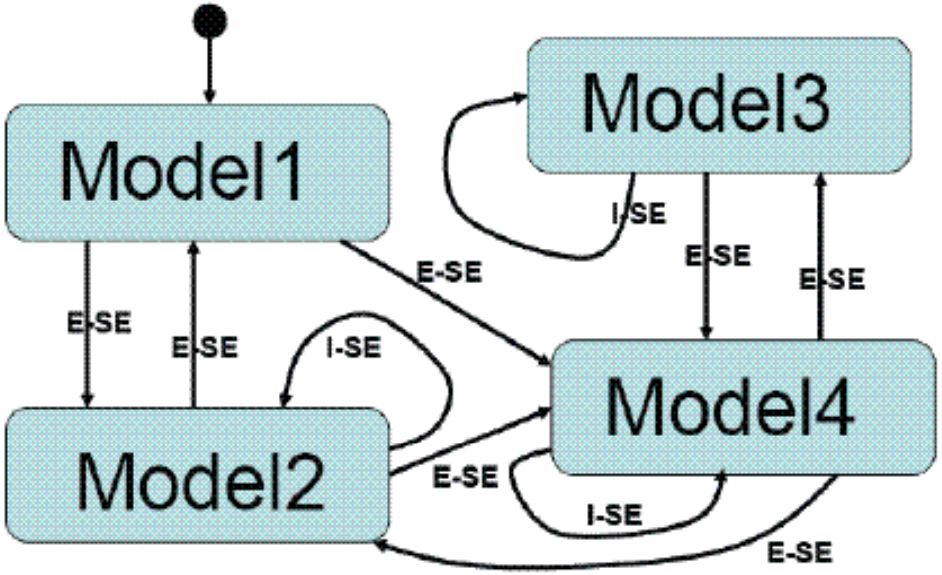


Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

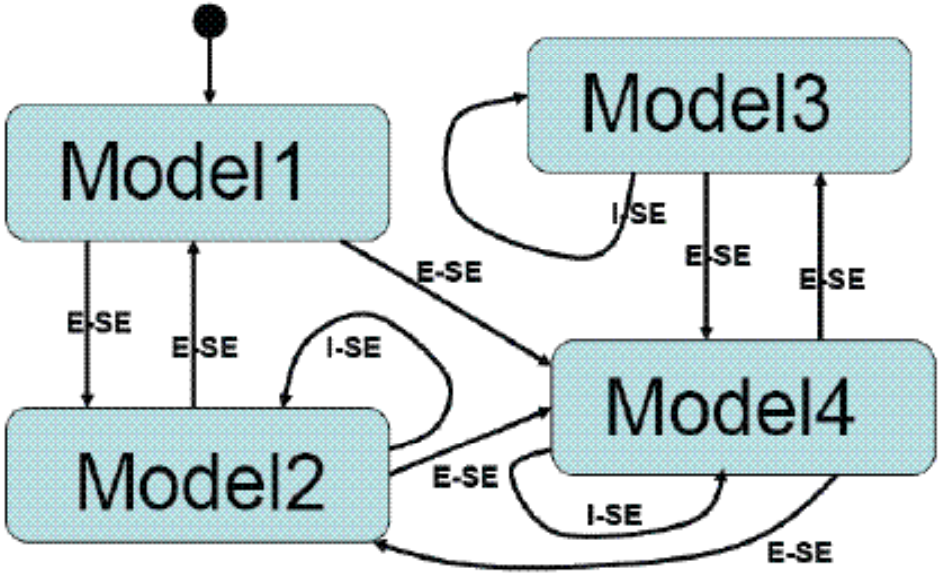
Consequences for Edu in ModSim ?

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

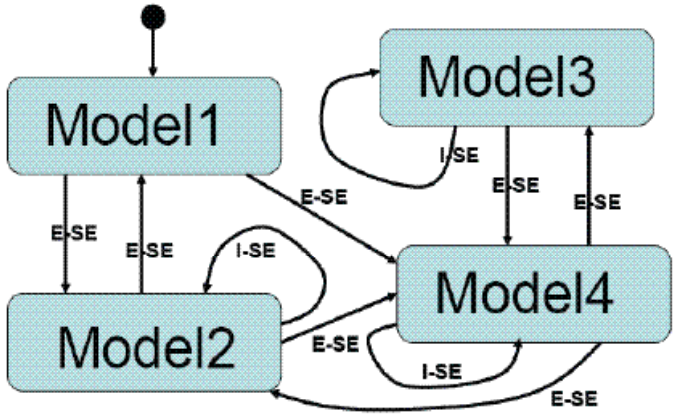
Challenge

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge

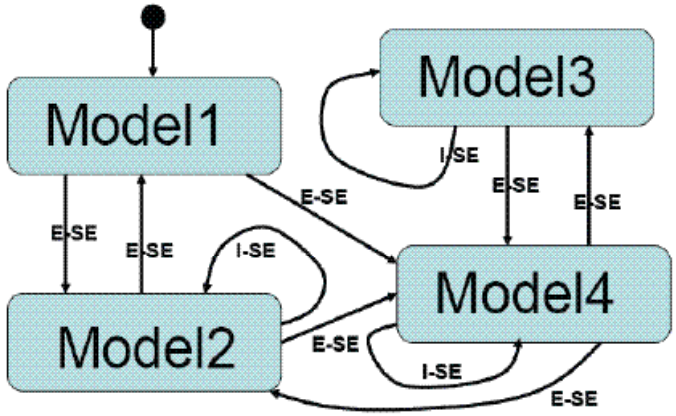
-Interdisciplinary Edu in ModSim

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge

-Interdisciplinary Edu in ModSim

-Basic Method Edu in ModSim

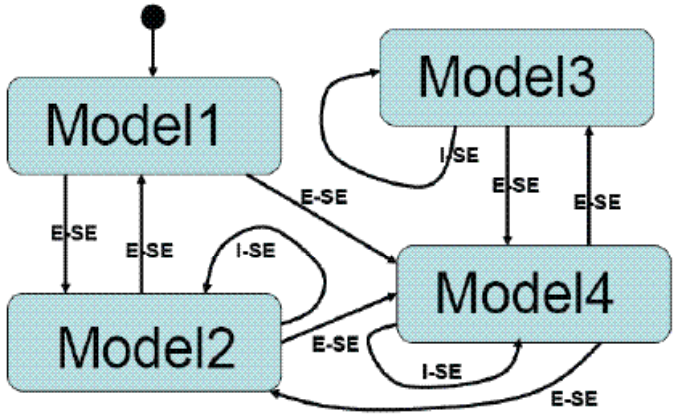
-Basic Tool Edu in ModSim

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge

-Interdisciplinary Edu in ModSim

-Basic Method Edu in ModSim

-Basic Tool Edu in ModSim

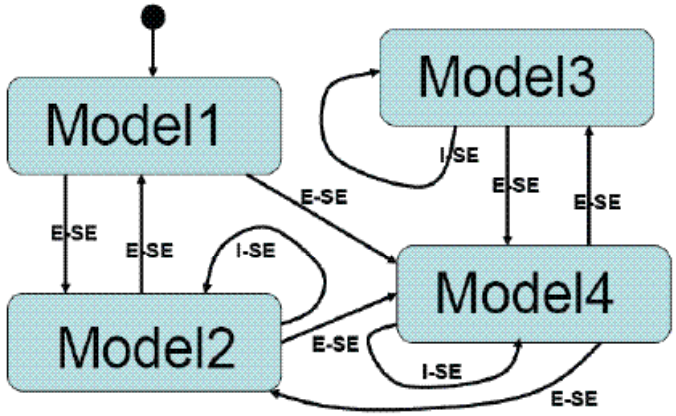
-Specialisation Edu in ModSim

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge — Possible Solutions

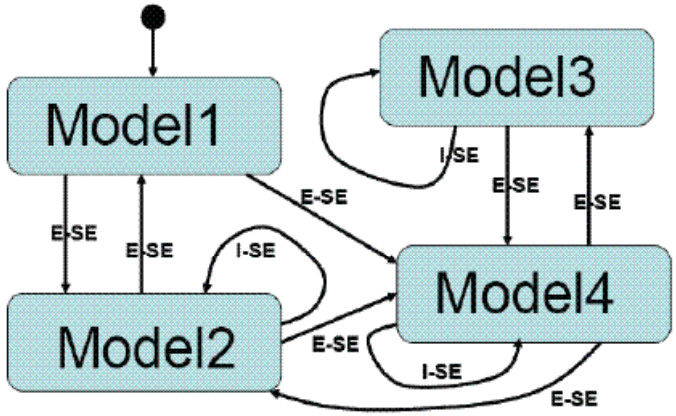
- Interdisciplinary Edu in ModSim
- Basic Method Edu in ModSim
- Basic Tool Edu in ModSim
- Specialisation Edu in ModSim

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge **Possible Solutions**

-Interdisciplinary Edu in ModSim **In existing or new curricula**

-Basic Method Edu in ModSim

-Basic Tool Edu in ModSim

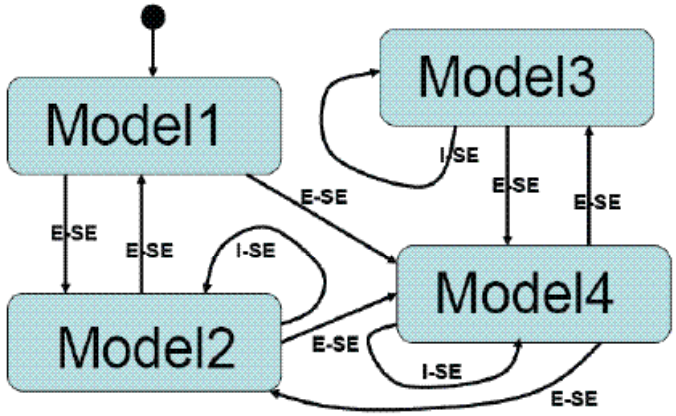
-Specialisation Edu in ModSim

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge

-Interdisciplinary Edu in ModSim

-Basic Method Edu in ModSim

-Basic Tool Edu in ModSim

-Specialisation Edu in ModSim

Possible Solutions

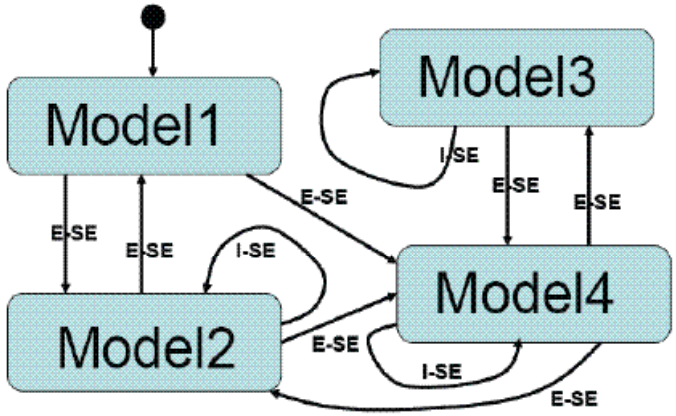
In existing or new curricula
In pref. ‚more' Univ. Sites

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge

-Interdisciplinary Edu in ModSim

-Basic Method Edu in ModSim

-Basic Tool Edu in ModSim

-Specialisation Edu in ModSim

Possible Solutions

In existing or new curricula

In pref. ‚more' Univ. Sites

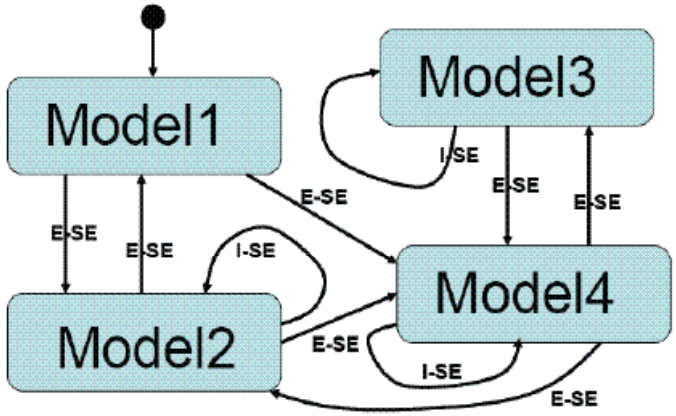
Student Exchange

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge

-Interdisciplinary Edu in ModSim

-Basic Method Edu in ModSim

-Basic Tool Edu in ModSim

-Specialisation Edu in ModSim

Possible Solutions

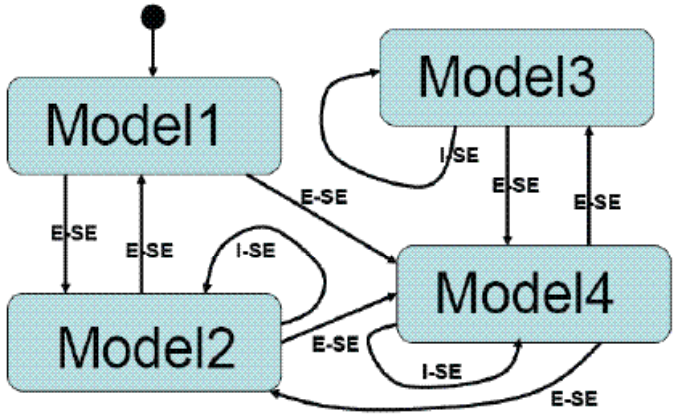
In existing or new curricula
In pref. ‚more' Univ. Sites
Student Exchange
Lecturer Exchange

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge

-Interdisciplinary Edu in ModSim

-Basic Method Edu in ModSim

-Basic Tool Edu in ModSim

-Specialisation Edu in ModSim

Possible Solutions

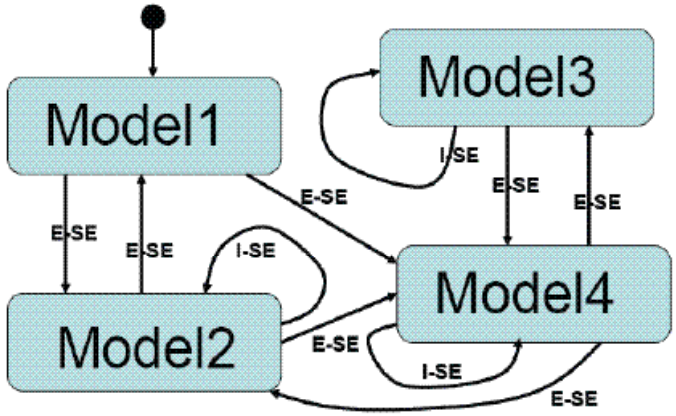
In existing or new curricula
In pref. ‚more' Univ. Sites
Student Exchange
Lecture(r) Exchange

Multimethod Modelling and CoSim

DAEs
Diff Eq.
PDEs

Event Mod
DEVS
Process Mod
Agent-based

Charact. Functions
Static Mod



Transfer Functions
System Dynamics
Modelica
Bond Graphs
Agent-based
Petri Nets
CA Mod
State Automata

Consequences for Edu in ModSim ?

Challenge	Possible Solutions
-Interdisciplinary Edu in ModSim	In existing or new curricula
-Basic Method Edu in ModSim	In pref. ‚more' Univ. Sites
-Basic Tool Edu in ModSim	Student Exchange
-Specialisation Edu in ModSim	Lecturer Exchange
	Lecture Exchange - EL,DL

ASC TU VIENNA Mathematical Modelling and Simulation

Multimethod Modelling and CoSim

Thank you for Attention
On good Cooperation !

Consequences for Edu in ModSim ?

Challenge	Possible Solutions
-Interdisciplinary Edu in ModSim	In existing or new curricula
-Basic Method Edu in ModSim	In pref. ‚more' Univ. Sites
-Basic Tool Edu in ModSim	Student Exchange
-Specialisation Edu in ModSim	Lecturer Exchange
	Lecture Exchange - EL,DL