technische universität
dortmund

Department of Biochemical and Chemical Engineering
Process Dynamics and Operations Group (DYN)

A Framework for the Simulation and Validation of Distributed Control Architectures for Technical Systems of Systems

S. Nazari[*], S. Wenzel[*] , L.S. Maxeiner[*], C. Sonntag[*,**], S. Engell[*]

*Process Dynamics and Operations Group, Dept. of Biochemical and Chemical Engineering,
TU Dortmund, Germany

** euTeXoo GmbH, Germany

euTeXoo
connecting ideas

IFAC WC, Toulouse, France
July 9th- 14th , 2017

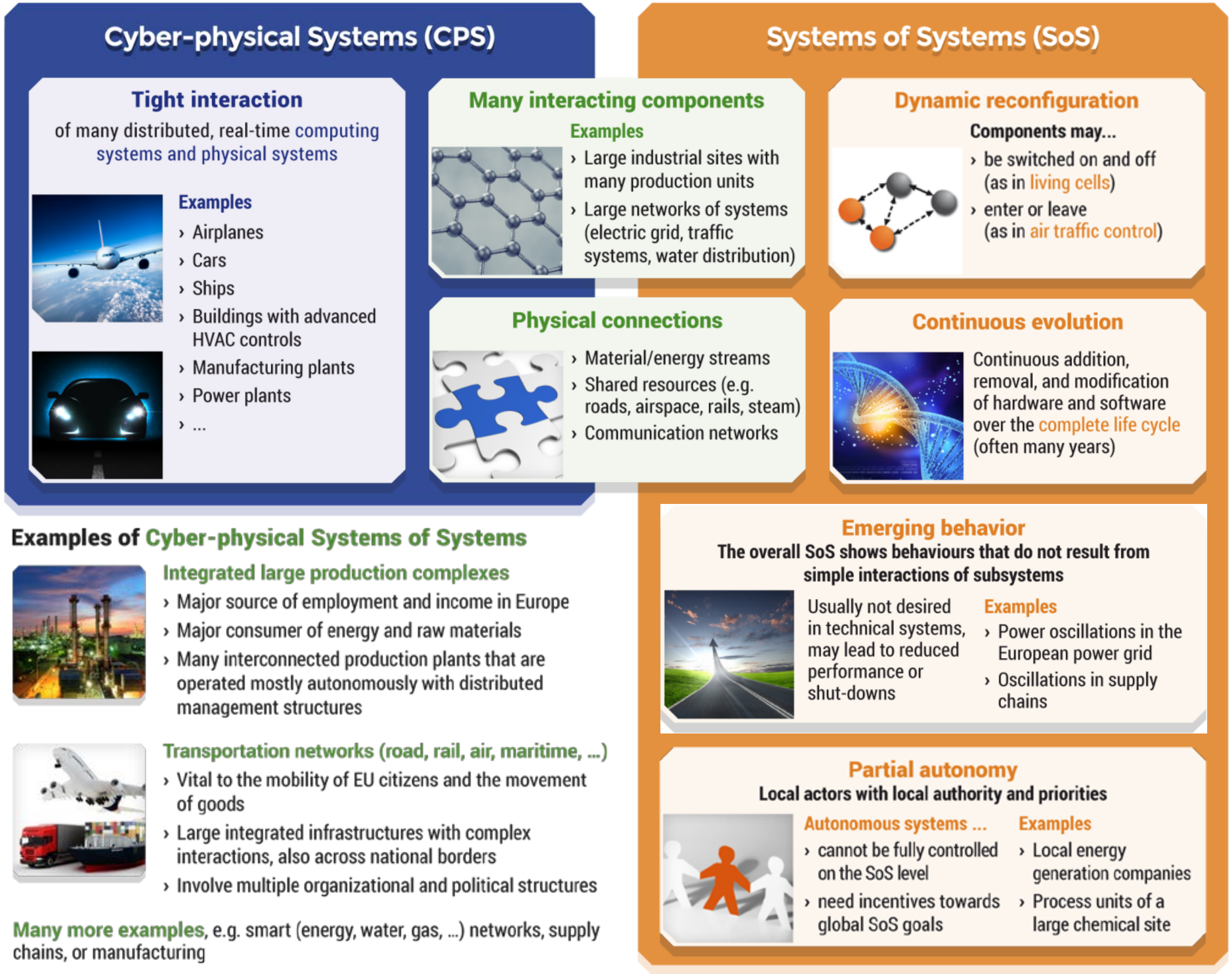
Process Dynamics
and Operations

Outline

- Cyber-Physical Systems of Systems (CPSoS)
- Hierarchical / Distributed Control of CPSoS
- Objective of this Work
- The Simulation and Validation Framework (SVF)
- Case Studies
  - An Integrated Chemical Production Site
  - A Network of three Multi-Product Semi-Batch Reactors
- Summary and Outlook

Cyber-Physical Systems of Systems (CPSoS)

Large, complex, often spatially distributed **Cyber-physical Systems (CPS)** that exhibit the features of **Systems of Systems (SoS)**



Cyber-physical Systems (CPS)

Tight interaction

of many distributed, real-time computing systems and physical systems

Examples

- Airplanes
- Cars
- Ships
- Buildings with advanced HVAC controls
- Manufacturing plants
- Power plants
- ...

Systems of Systems (SoS)

Many interacting components

Examples

- Large industrial sites with many production units
- Large networks of systems (electric grid, traffic systems, water distribution)

Dynamic reconfiguration

Components may...

- be switched on and off (as in living cells)
- enter or leave (as in air traffic control)

Physical connections

- Material/energy streams
- Shared resources (e.g. roads, airspace, rails, steam)
- Communication networks

Continuous evolution

Continuous addition, removal, and modification of hardware and software over the complete life cycle (often many years)

Emerging behavior

The overall SoS shows behaviours that do not result from simple interactions of subsystems

Usually not desired in technical systems, may lead to reduced performance or shut-downs

Examples

- Power oscillations in the European power grid
- Oscillations in supply chains

Partial autonomy

Local actors with local authority and priorities

Autonomous systems ...

- cannot be fully controlled on the SoS level
- need incentives towards global SoS goals

Examples

- Local energy generation companies
- Process units of a large chemical site

Examples of Cyber-physical Systems of Systems

Integrated large production complexes

- Major source of employment and income in Europe
- Major consumer of energy and raw materials
- Many interconnected production plants that are operated mostly autonomously with distributed management structures

Transportation networks (road, rail, air, maritime, ...)

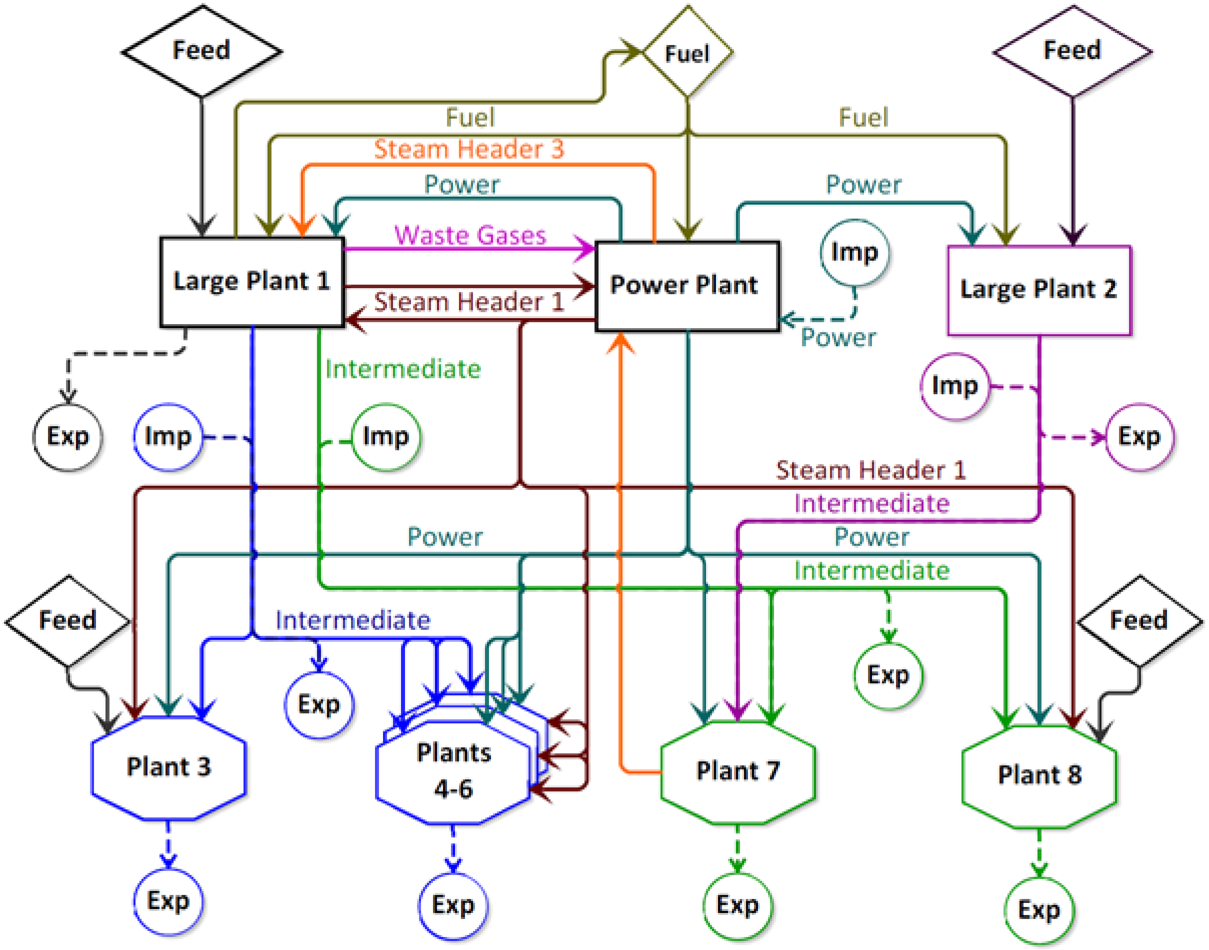
- Vital to the mobility of EU citizens and the movement of goods
- Large integrated infrastructures with complex interactions, also across national borders
- Involve multiple organizational and political structures

Many more examples, e.g. smart (energy, water, gas, ...) networks, supply chains, or manufacturing

www.cpsos.eu

Hierarchical / Distributed Control of CPSoS (1)

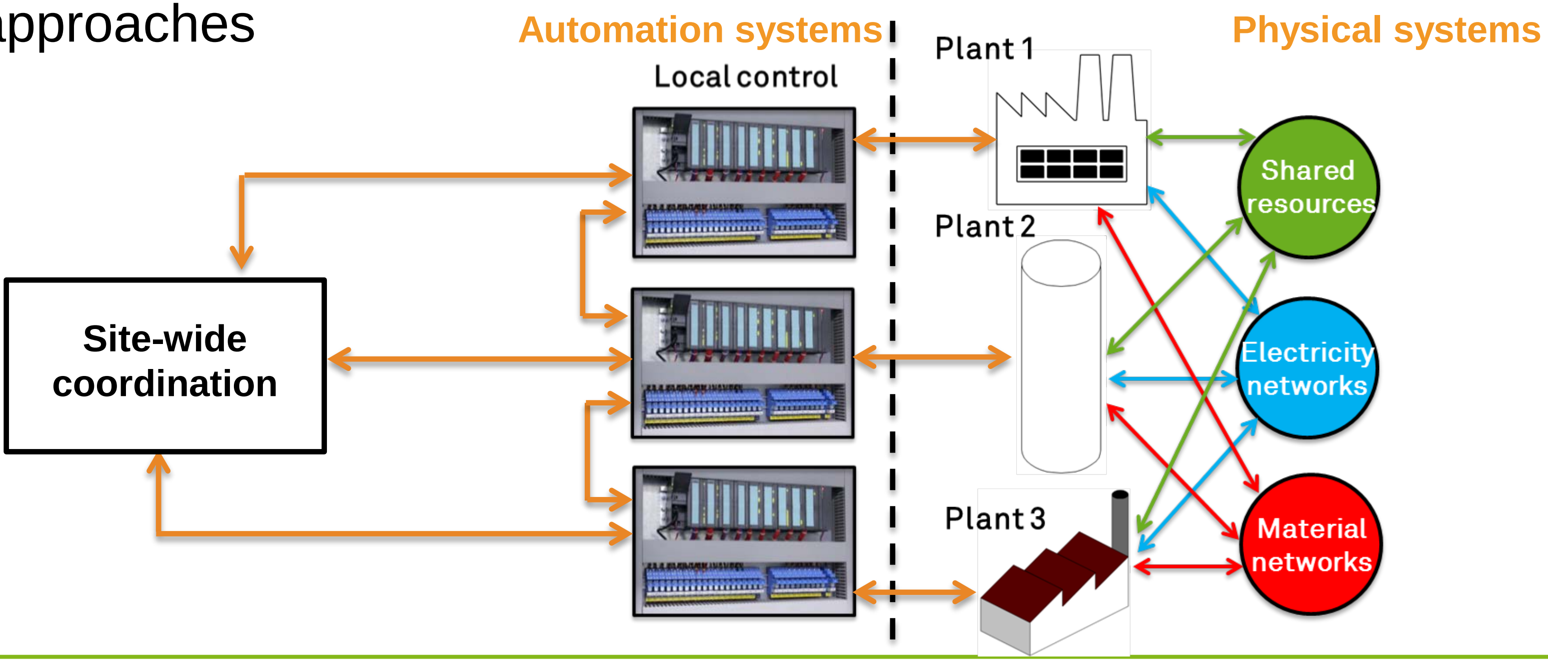
- Partial autonomy and distributed decisions in an integrated chemical production site



Hierarchical / Distributed Control of CPSoS (2)

- Centralized control of CPSoS is preferable, but not always feasible or desired
  - Complexity of the management problem
  - Privacy concerns may prohibit the sharing of operational details of the subsystems

→ Distributed management, coordination, and optimization approaches

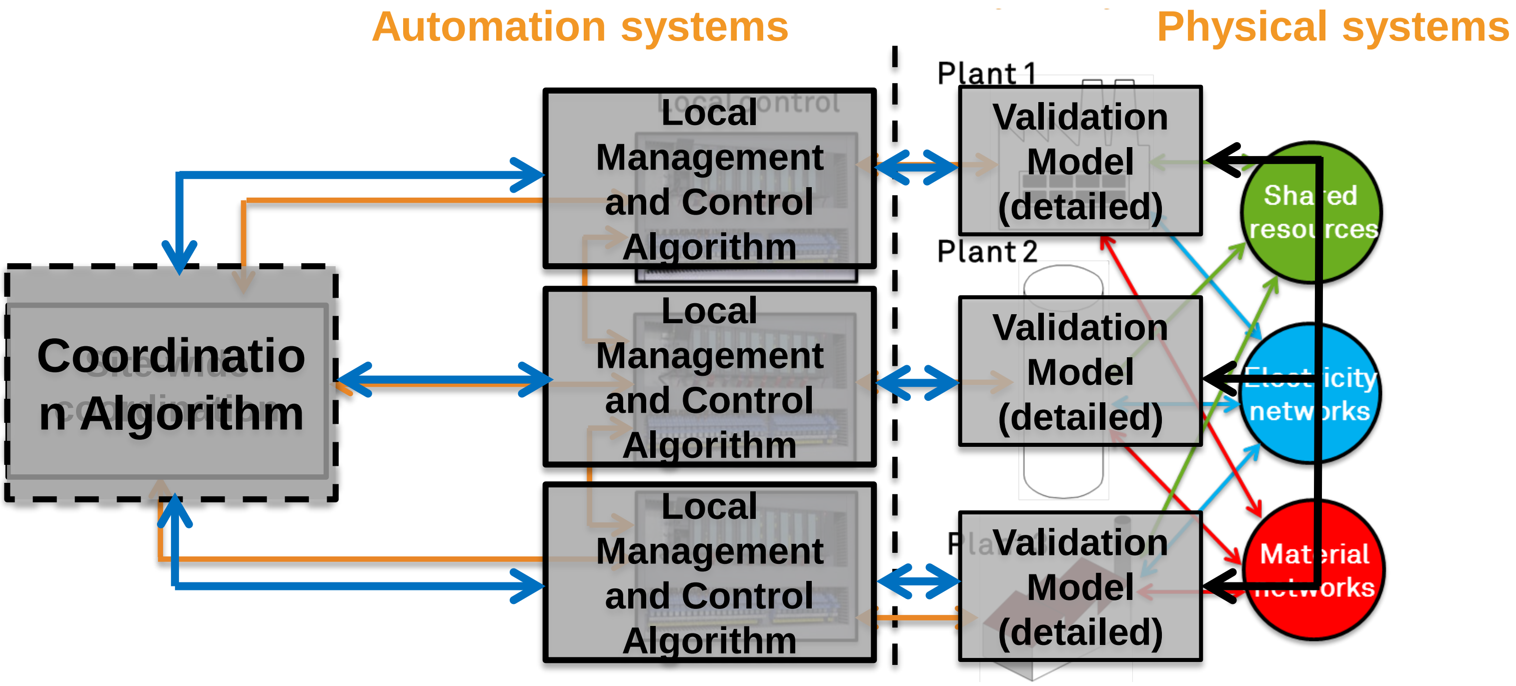


Objective of this Work

- How can state-of-the-art distributed control algorithms be systematically validated on simulation models while...
  - …re-using (pre-existing) simulation models
    - Heterogeneous, possibly from different simulation environments
  - … not having to implement the communication and automation architectures manually? (which is time-consuming and error-prone)
  - … being able to connect management methods to different CPSoS models effortlessly?
    - Avoiding proprietary implementations

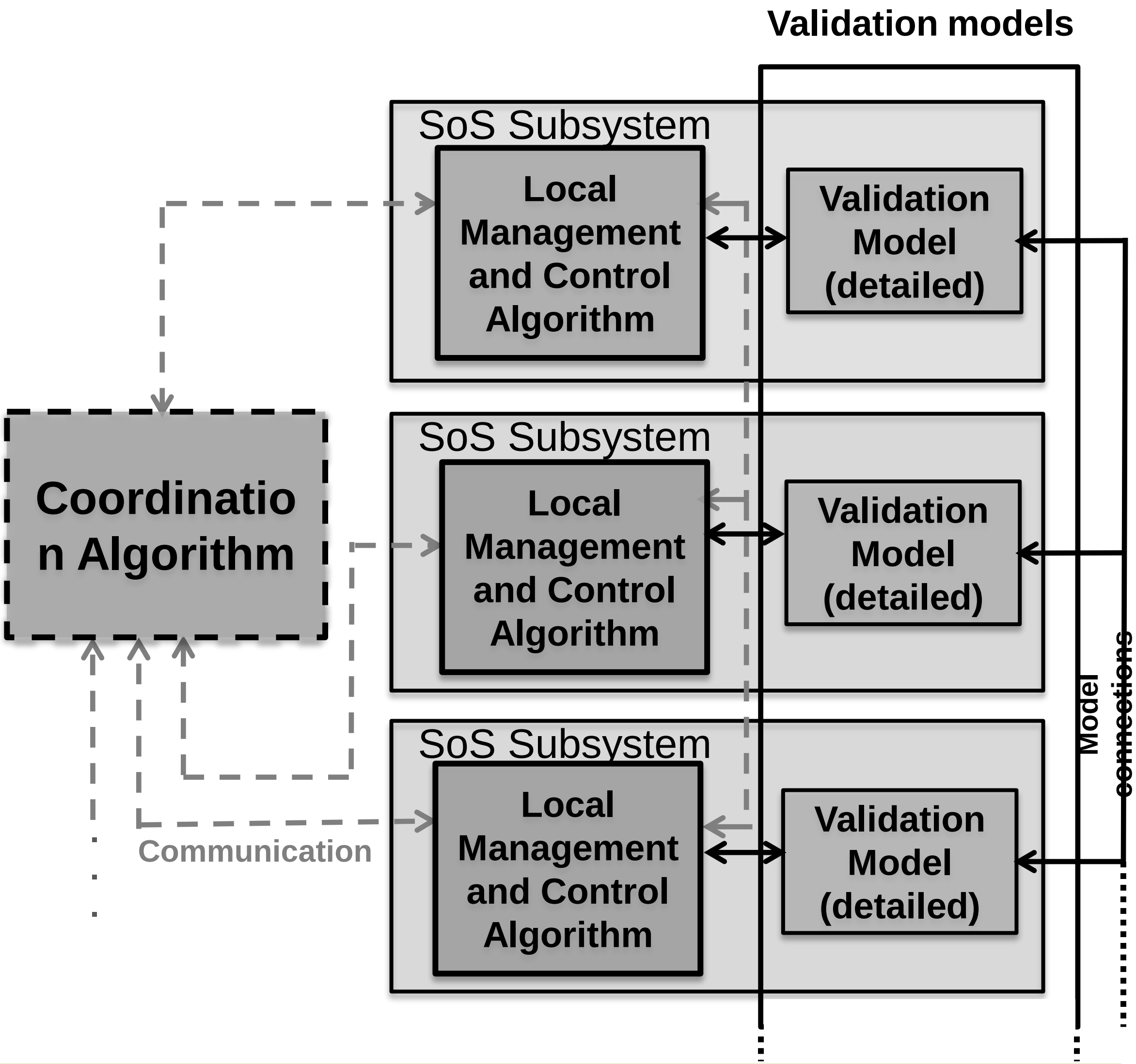
The Simulation and Validation Framework (SVF) (1)

- A plug-and-play based approach



The Simulation and Validation Framework (SVF) (2)

- *Modelica*-based framework for the systematic interconnection of
  - Validation models
  - Local and high-level optimization algorithms
    - Event-driven communication
- Standard interfaces for
  - The interconnection of physical models
  - The interconnection of physical models and controllers
  - The interconnection of controllers



The Model Management Engine (MME)

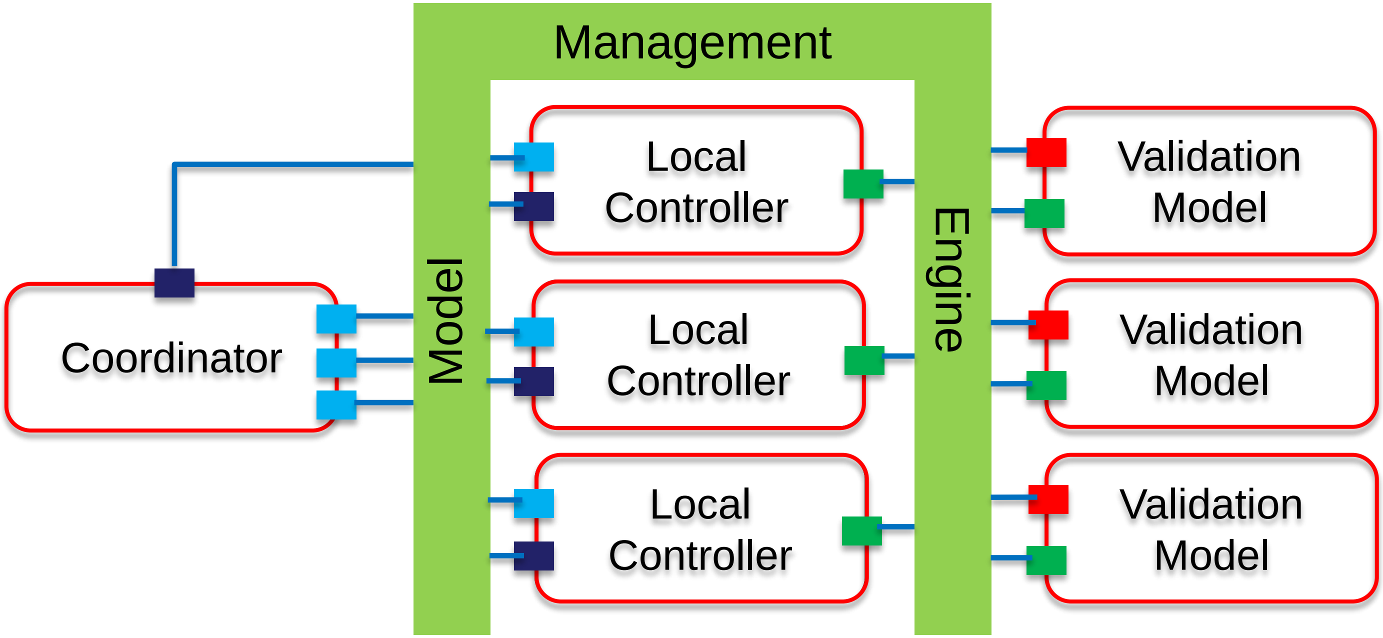
- An intermediary component responsible for the coordination of the model components during simulation, e.g.:
  - Data communication between the components
  - Propagation of discrete events

Interface Model <-> Model

Interface Model <-> Controller

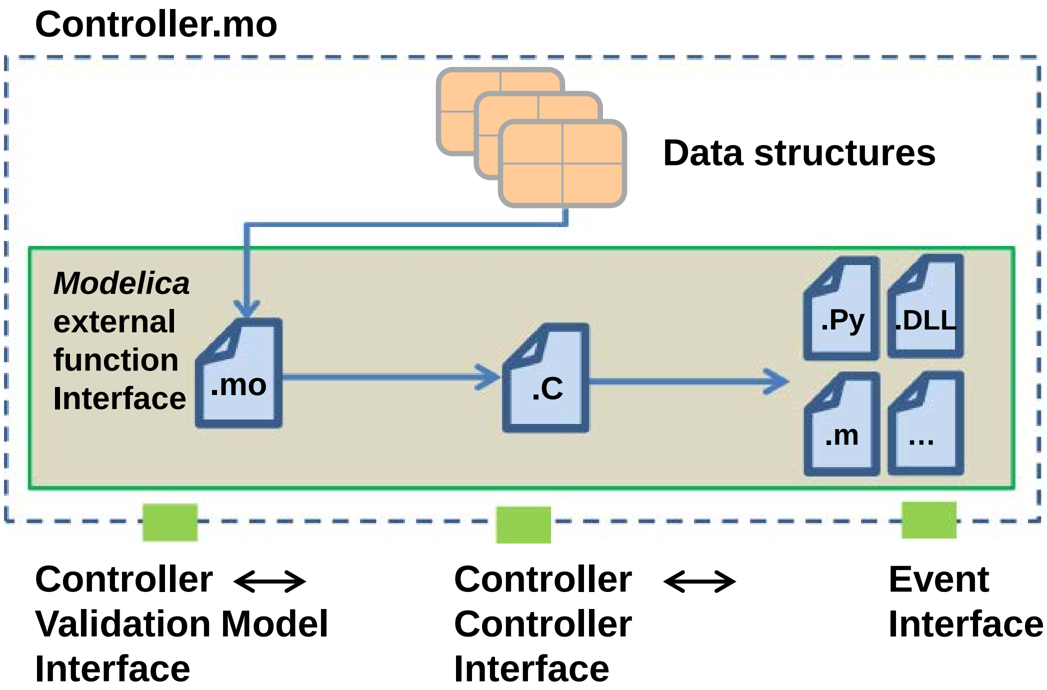
Interface Controller <-> Controller

Interface (Events)



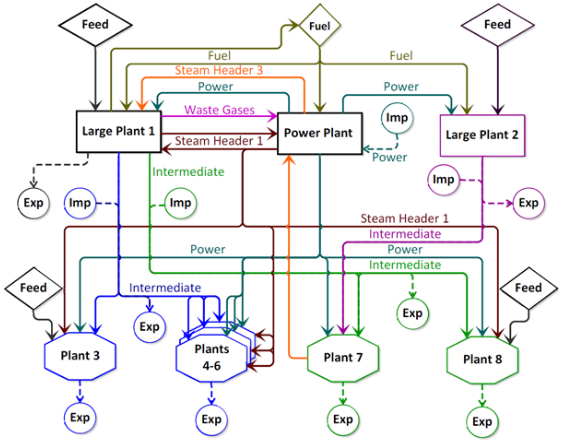
SVF- Supported Languages and Features

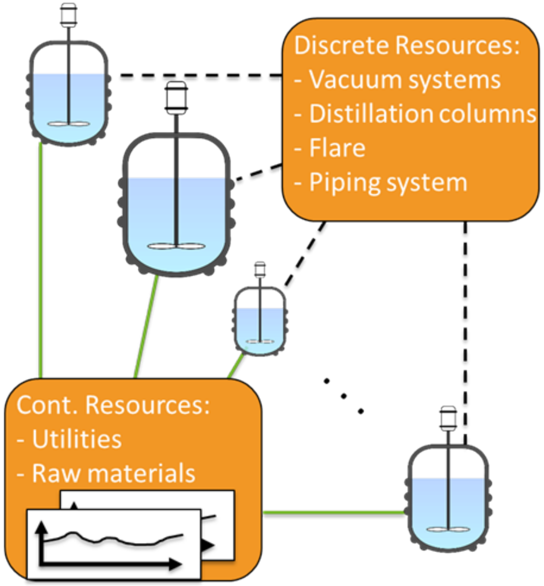
- Support for:
  - White-box *Modelica* models and black-box models via co-simulation (FMI)
  - *Modelica*-based controllers, white-box and black-box external controllers
    - External support is done via the SVF External Function Interface
    - Python, Matlab and C are supported
- Generation of the communication structure
  - Via a generic XML-based configuration file
  - Reduces risk of errors



Case Studies

- Integrated chemical production complex
  - 9 processing plants whose models are derived from planning data
  - **Goal:** Balancing of the two steam networks
- Network of three semi-batch reactors that are operated autonomously
  - The reactors are coupled via discrete and continuous resources
  - Exothermic reaction $A + B \rightarrow C$
  - Goal: produce as much product C as possible for a given final time of 30 hours using a moving horizon optimization





Discrete Resources:
- Vacuum systems
- Distillation columns
- Flare
- Piping system

Cont. Resources:
- Utilities
- Raw materials

Image source: https://en.wikipedia.org/wiki/Batch_reactor#/media/File:Batch_reactor_STR.svg

Case Studies – Problem Formulation (1)

- For the chemical complex, the Alternating Direction Method of Multipliers (ADMM) is used [1]

centralized problem for n subsystems:

$$\min_{u_i \in \mathcal{U}_i, \forall i} \sum_{i=1}^{n} J_i(u_i)$$

Balance of the shared resource networks

$$\text{s.t.} \quad \sum_{i=1}^{n} r_i(u_i) = 0$$

$$\mathcal{L}_{\rho,i} = J_i(u_i) + (\lambda^k)^T \sum_{i=1}^{n} r_i(u_i) + \frac{\rho}{2} \sum_{i=1}^{n} ||r_i(u_i) - z_i^k||_2^2$$

[1] S. Boyd, N. Parikh, E. Chu, B. Peleato, J. Echstein, Distributed optimization and statistical learning via the alternating direction method of multipliers, Foundation and Trends in Machine Learning 3 (1) (2011) 1-122.

Case Studies – Problem Formulation (2)

- For the chemical complex, the Alternating Direction Method of Multipliers (ADMM) is used [1]

centralized problem for n subsystems:

$$\boxed{\begin{aligned} \min_{u_i \in \mathcal{U}_i, \forall i} \sum_{i=1}^{n} J_i(u_i) \\ \text{s.t.} \quad r_i(u_i) = z_i \end{aligned}}$$

Solved by the subsystems

Balance of the shared resource networks

$$\boxed{\sum_{i=1}^{n} z_i = 0.}$$

Solved by a high-level controller, i.e. the coordinator

$$\mathcal{L}_{\rho,i} = J_i(u_i) + (\lambda^k)^T \sum_{i=1}^{n} r_i(u_i) + \frac{\rho}{2} \sum_{i=1}^{n} ||r_i(u_i) - z_i^k||_2^2$$

- Relaxing of the coupling constraint
- Local systems → u_i
- The coordinator manipulates the local decisions by setting the internal shared resource prices λ and values of z_i

[1] S. Boyd, N. Parikh, E. Chu, B. Peleato, J. Echstein, Distributed optimization and statistical learning via the alternating direction method of multipliers, Foundation and Trends in Machine Learning 3 (1) (2011) 1-122.

Case Studies – Problem Formulation (3)

- For the reactor network, price-based coordination is used
  - The local problem for subsystem i

$$\min_{u_i \in \mathcal{U}_i} J_i(u_i) + \lambda^T r_i(u_i)$$

→ Solved for u_i

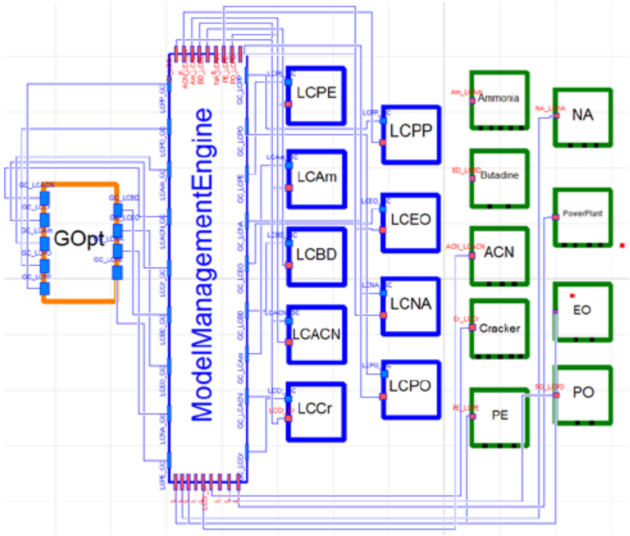
  - The coordinator manipulates the local decisions by setting the internal shared resource prices λ

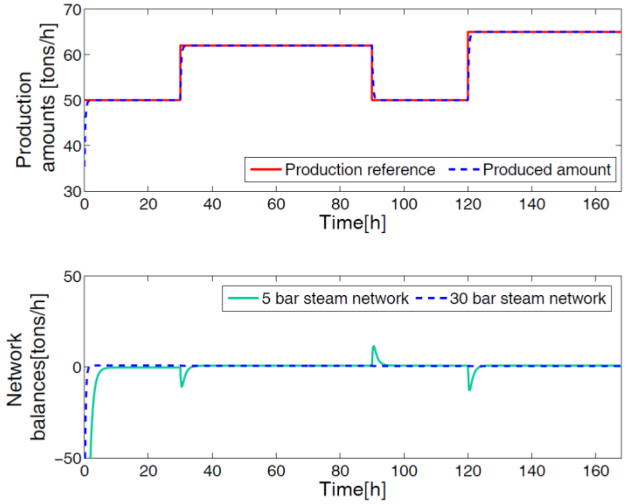
$$d(\lambda) = \sum_{i=1}^{n} r_i(u_i(\lambda)) = 0$$

Chemical Production Complex– SVF Implementation

- *Matlab*-based implementations of local optimization algorithms and the coordinator
  - C-based DLL files (black box) are created using the *Matlab* compiler
- Iterative information exchange via event-driven communication architecture

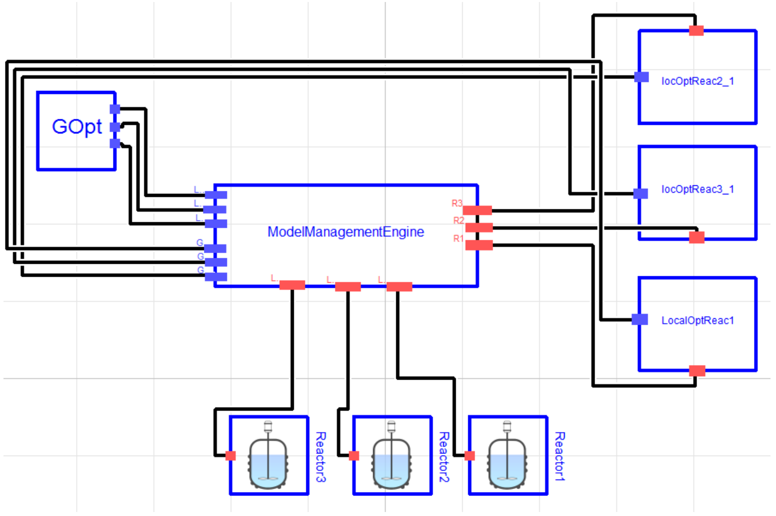
The diagram view of the implementation in Dymola

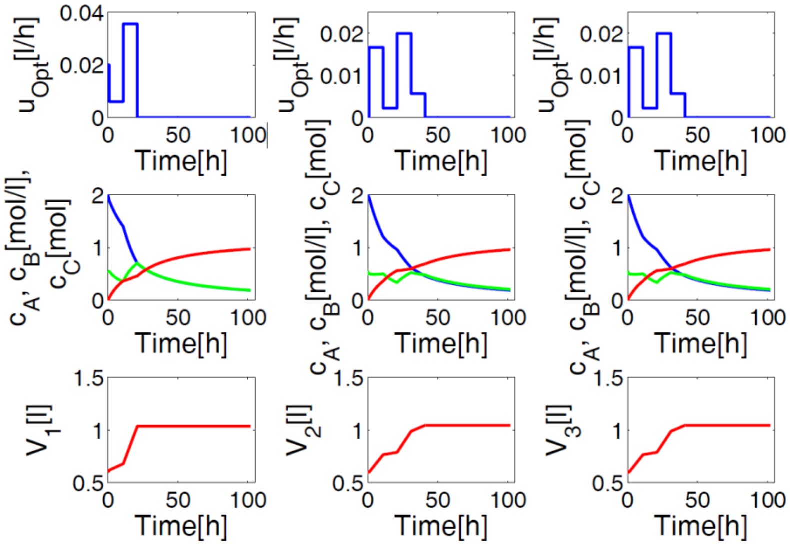




Reactor Network– SVF Implementation

- Python-based implementations of local Model Predictive Controllers (NMPC) and the coordinator
  - Integrated using the C-Python API and the SVF external function interface
- Iterative information exchange via the event-driven communication architecture





Summary and Outlook

- A plug-and-play approach for simulation-based validation of distributed management and coordination architectures on simulation models of CPSoS
  - Reduces the currently large engineering effort by defining standard interfaces
    - Increased re-usability
    - Simplifies the deployment of new distributed architecture to real-world automation hardware
  - The *Modelica*-based framework provides an interface for the connection of external controller software components

- Under development: A software for the automatic generation of the interconnections and the communication structure

Thank you for your attention!

DYMASOS

This project has received funding of European Commission under grant agreement number 611281.

www.dymasos.eu