Towards a European Roadmap on Research and Innovation in Engineering and Management of Cyber-Physical Systems of Systems

Challenges in the Engineering and Management of Cyber-physical Systems of Systems

Sebastian Engell
Process Dynamics and Operations Group
Department of Biochemical and Chemical Engineering
TU Dortmund
Germany

DYMASOS – Dynamic Management of Physically Coupled Systems of Systems

Outline

- Examples of cyber-physical systems of systems
- Results of the CPSoS Project
  - Definition of cyber-physical systems of systems
  - Research challenges
    - Support for engineering and re-engineering
    - Distributed/ coordinated management
    - Cognitive cyber-physical systems – make use of “big data”
  - Medium-term research agenda
- Distributed optimization in cyber-physical systems of systems
  - Challenge
  - Market-based coordination
  - Simulation and validation framework
  - Case Study
  - Ongoing work
- Summary

Examples of Cyber-physical Systems of Systems

- **Electrical distribution grid**
  - Large-scale system
  - Transition from centralized to local generation
  - Increasing variability of the generation
  - Transition from hierarchical to distributed management

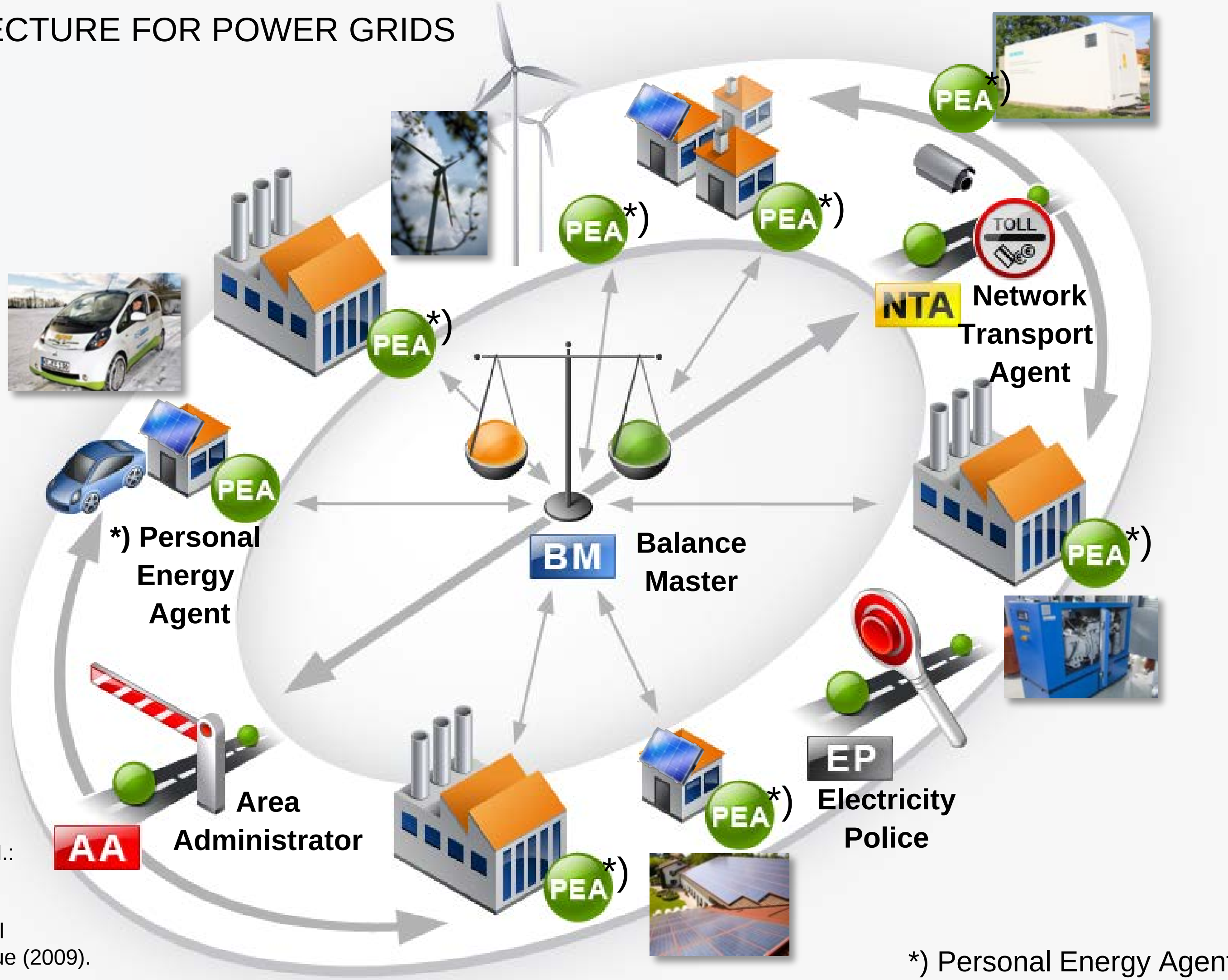
Self-Organizing Energy Automation Systems coordinating smart components within the grid

SIEMENS

MULTI-AGENT ARCHITECTURE FOR POWER GRIDS (SCHEMATIC)

Design Principles:

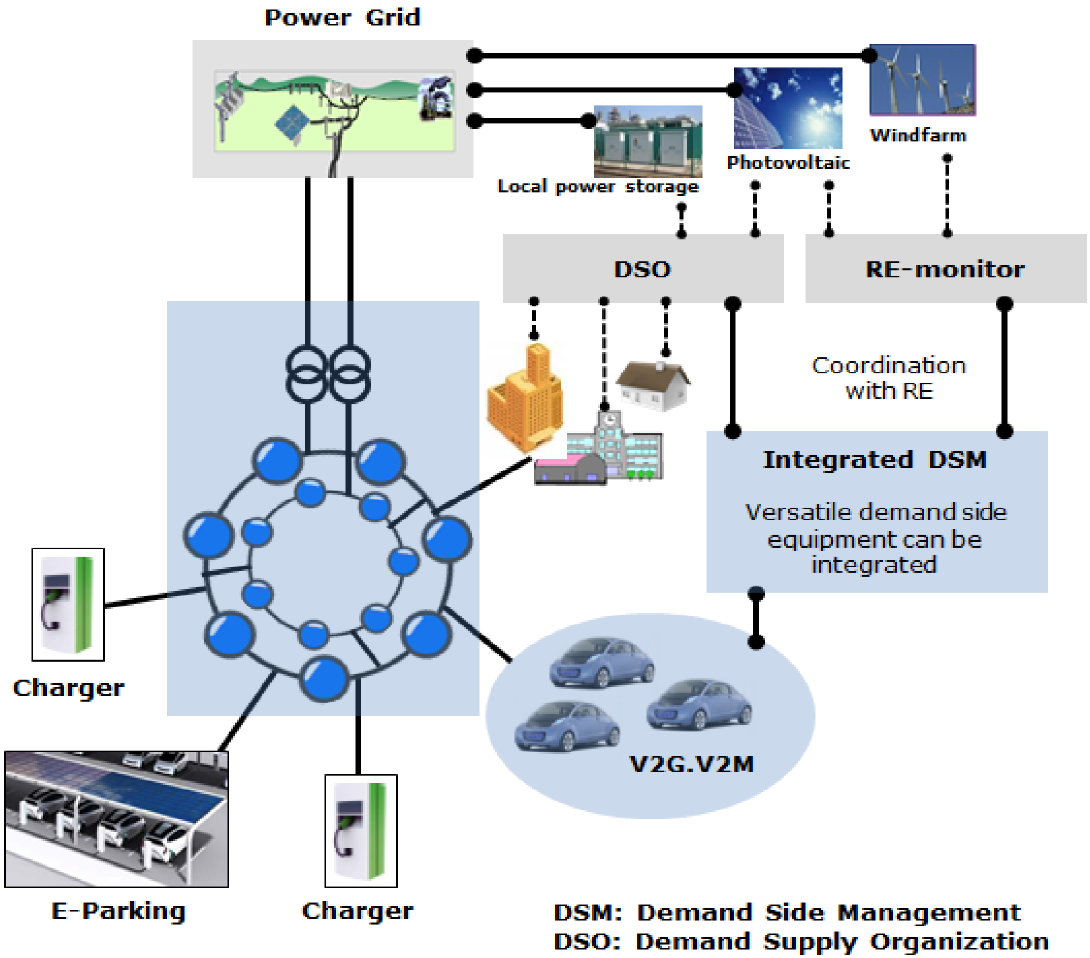
- Smart components.
- Use plug and play for engineering.
- Coordination of local algorithms whenever necessary



Böse, C.; Hoffmann, C; Kern, C.; Metzger M.: *New Principles of Operating Electrical Distribution Networks with a high Degree of Decentralized Generation,* 20th International Conference on Electricity Distribution, Prague (2009).

*) Personal Energy Agent

Charging Facilities for Electric Vehicles



There are **EV charging stations** with different technologies, different function modes, different maximum power, energy direction (V2G), etc.

They have the ability to operate at different times of day, affecting different sub-grids and consuming unforeseen total power.

It is essential that these new elements do not cause problems on the grid, and that they also do not affect the quality levels of the energy supply to be met by the grid.

Examples of Cyber-physical Systems of Systems

- Electrical distribution grid

- **Electrical vehicle charging**
  - Home charging
  - Charging points
  - **Different agents in action:**
    - Network operators
    - Electricity marketers
    - Parking owners
    - Car owners

Examples of Cyber-physical Systems of Systems

- Electrical distribution grid

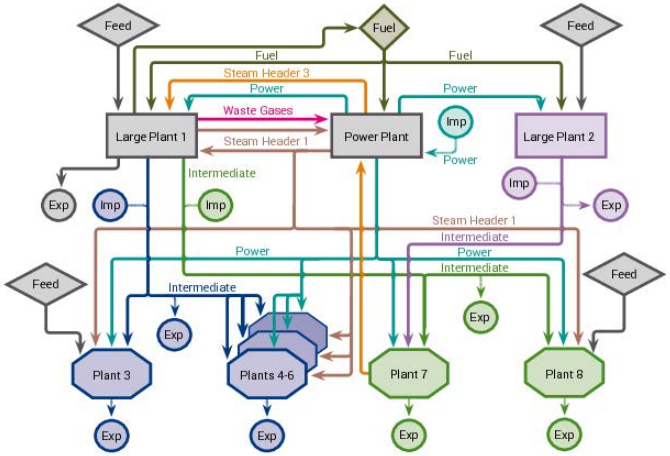
- **Electrical vehicle charging**
  - Home charging
  - Charging points
  - Goals:
    - Meet customer demands
    - Guarantee power network stability
    - Make best use of green energy, minimize carbon footprint

Chemical Production Sites

INEOS
THE WORD FOR CHEMICALS

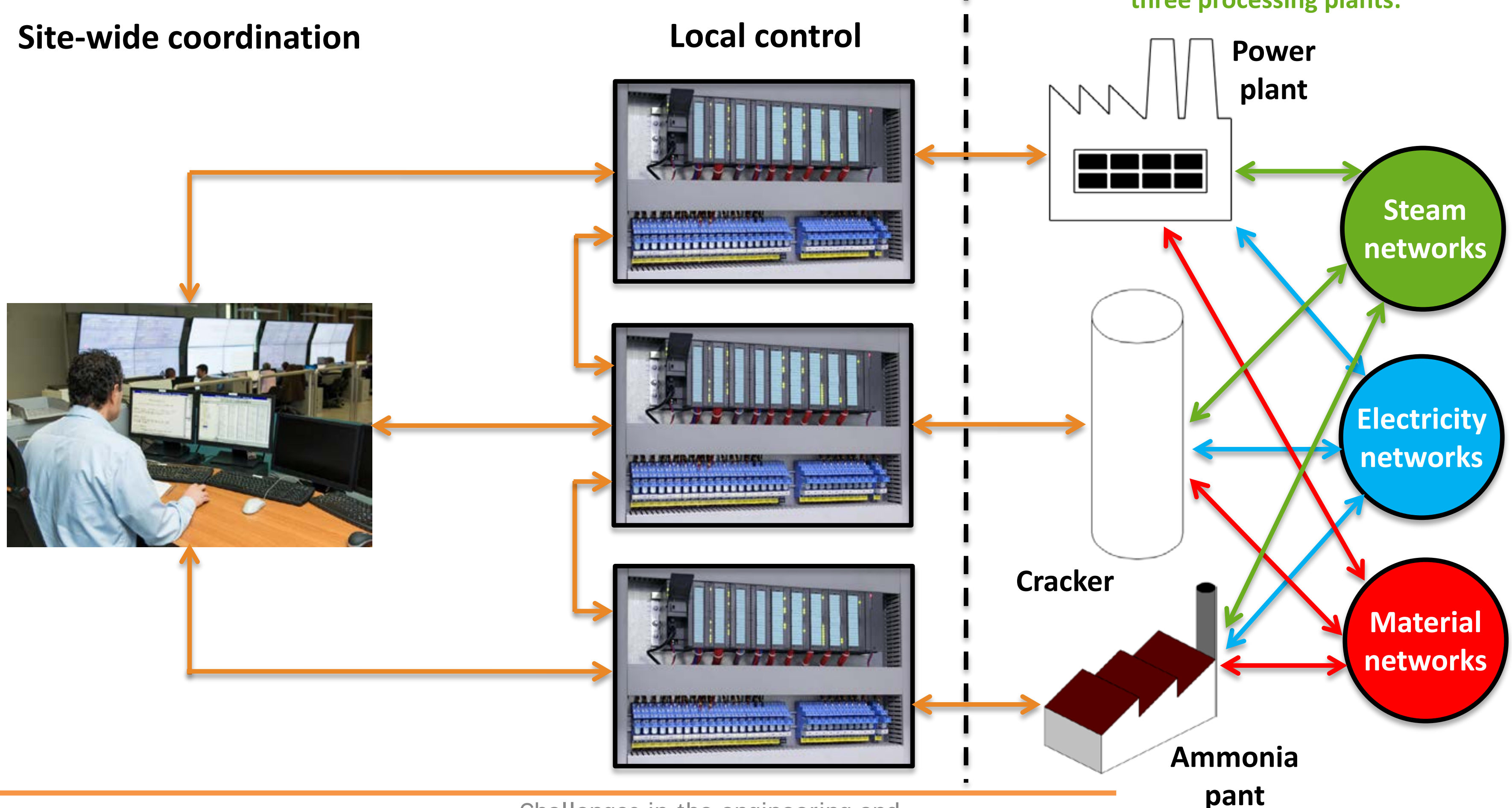
- Large integrated petrochemical production site
- 19 different plants
- Internal distribution networks for shared resources, e.g.,
  - Steam (30, 15, and 5 bar)
  - Electricity
  - Fuel gas
  - Intermediates
  - Products
- Cyber-physical system of systems

Source: INEOS in Köln



Chempark Dormagen / Cologne

- **Complex, interconnected, distributed automation architectures**



Examples of Cyber-physical Systems of Systems

- Electrical distribution grid
- Electrical vehicle charging

- **Chemical production sites**
  - Large distributed computer controlled installations
  - Plants coupled by various networks for steam, gas, intermediates
  - Individual business goals of the plants
  - Goal:
    - Reduction of total energy consumption and environmental impact
    - Minimization of the total operating cost

Cyber-physical Systems of Systems

- Key elements of the socio-technical infrastructure
- Providing essential services to the citizens
- Backbone of the industrial infrastructure
- Vulnerable
- Difficult to engineer and to operate
- Good engineering and efficient management is crucial for
  - Energy and resource efficiency
  - Economic competitiveness of the industries
  - Quality of life
- The main potential is on the system level, not on subsystem control and optimization

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Support Action CPSoS

Towards a European Roadmap on Research and Innovation in Engineering and Management of Cyber-physical Systems of Systems

SEVENTH FRAMEWORK PROGRAMME

Consortium of the CPSoS Project

- TU Dortmund (Coordinator)
  - Sebastian Engell
  - Christian Sonntag
  - Radoslav Paulen
- Haydn Consulting
  - Haydn Thompson
- TU Eindhoven
  - Michel Reniers
  - Wan Fokking
- Inno TSD
  - Svetlana Klessova
  - Bertrand Copigneaux

The CPSoS Working Groups

Working Group 1

Systems of Systems in Transportation and Logistics

Working Group Members:

Haydn Thompson
Haydn Consulting Ltd., chair
John Amoore
Rail Infrastructure Technology Ltd.
Carlos Canudas de Wit
CNRS GIPSA–Lab
Maria Victoria Cengarle
fortiss GmbH
Uwe Clausen
Fraunhofer IML & ITL, TU Dortmund
Judith Dahmann
MITRE Corp.
Christina Diakaki
Technical University of Crete
Charles Dibsdale
OSyS–Rolls Royce
Hermann Kopetz
Vienna University of Technology
Philippe Liatard
CEA–Leti
Antonio Pascoal
University of Lisbon

Working Group 2

Physically connected Systems of Systems

Working Group Members:

Sebastian Engell
TU Dortmund, chair
Göran Andersson
ETH Zürich
Francesco Brancati
ResilTech SRL
John Fitzgerald
Newcastle University
Vladimir Havlena
Honeywell
Alf Isaksson
ABB
Elias Kosmatopoulos
Technical University of Crete
Stefan Krämer
INEOS in Köln
John Lygeros
ETH Zürich
Patrick Panciatici
Réseau de Transport d'Electricité
Radoslav Paulen
TU Dortmund

Working Group 3

Tools for Systems of Systems Engineering and Management

Working Group Members:

Michel Reniers
TU Eindhoven, chair
Wil van der Aalst
TU Eindhoven
Alberto Bemporad
IMT Lucca
Marika Di Benedetto
University of l'Aquila
Alessandro Cimatti
Bruno Kessler Foundation
Bertrand Copigneaux
inno TSD
Wan Fokkink
TU Eindhoven
Peter Fritzson
Linköping University
Robert Howe
Verum Software Tools BV
Stefan Kowalewski
RWTH Aachen
Peter Gorm Larsen
Aarhus University
Erwin Schoitsch
Austrian Institute of Technology
Christian Sonntag
euTeXoo GmbH, TU Dortmund
Martin Törngren
KTH Stockholm

Characteristics: Physical System Elements

- *Significant* number of *interacting* components that are (partially) physically coupled and together fulfill a certain function, provide a service, or generate products.
- The components can provide services independently but the performance of the overall system depends on the "orchestration" of the components.
- After a removal of some components, the overall system can still fulfill its function, with reduced performance.

Characteristics: Control and Management

- Not performed in a completely centralized or top-down manner with one “authority” providing all the necessary control signals but with distributed decision power
- Structures vary from a (multi-layered) hierarchy to a fully decentralized structure where only technical constraints, economic incentives and human interactions connect the subsystems.
- **Partial autonomy** of the control and management systems of the components
  - Disturbances can be handled (to some extent) locally
  - Subsystems can exhibit “selfish” behaviour with local goals, and preferences.
  - Autonomy can result from human users or supervisors taking or influencing the local decisions.
- The “managerial element” of the components goes beyond classical local control loops (PID, MPC).

Dynamic Reconfiguration and Evolution

- Addition, modification, replacement or removal of components on different time scales
- Changes of the connectivity and the mode of operation
  - Components may come and go (e.g. in air traffic control)
  - Reaction to faults
  - Changes of system structures and management strategies following changes of demands, supplies or regulations.
- Systems operate and are continuously improved and modified over long periods of time.
  - The infrastructure "lives" for 30 or more years, and new functionalities or improved performance have to be realized with only limited changes.
  - Management and control software has long periods of service, while the computing hardware base and the communication infrastructure change much more rapidly.
- Engineering is re-engineering and takes place at run time.

Characteristics: Emerging Behaviour

- Occurrence of pattern formation, self-organization, oscillations and instabilities on the system level
- Not always anticipated in the design
- Many emerging phenomena are not intended in technical systems
- Simple feedback phenomena and design flaws should not be mixed up with emerging behaviour.

DYMASOS

CPSoS

What are Cyber-physical Systems of Systems?

Large, complex, often spatially distributed Cyber-physical Systems that exhibit the features of Systems of Systems

Cyber-physical Systems (CPS)

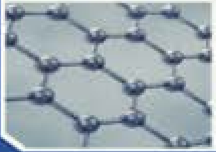
Tight interaction

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

Examples

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

Many interacting components



Examples

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

Physical connections

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

Systems of Systems (SoS)

Dynamic reconfiguration

Components may...

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

Continuous evolution

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

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

Emerging behavior

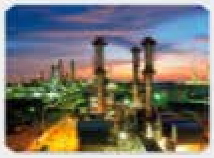
The overall SoS shows behaviours that do not result from simple interactions of subsystems

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

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 movements 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

Transdisciplinary Approach Needed

- **Cyber-physical systems of systems require a multi-disciplinary approach!**
- The behaviour of the physical part of the system must be modelled, simulated and analysed using methods from **continuous systems theory**, e.g. large-scale simulation, stability analysis, design of stabilizing controls
- Methods and tools from **computer science** for the modelling of distributed discrete systems, for verification and testing, assume-guarantee methods, contract-based assertions etc. are indispensable to capture both the behaviour on the low level (discrete control logic, communication, effects of distributed computing) and global effects, in the latter case based on abstract models of complete subsystems.
- **Logistic models** as well as models and **tools for performance analysis** of discrete systems are needed for system-wide performance analysis.
- **Theories from physics**, e.g. structure formation in large systems, and from **economics and social science** (market mechanisms, evolution of beliefs and activity in large groups) may also prove to be useful.

Research and Innovation Challenges in CPSoS

Analysis of the State of the Art

Kick off of 3 Working Groups (3… members)

Analysis of relevant programmes

38 intervie…

…ons

C…

…the art – reports

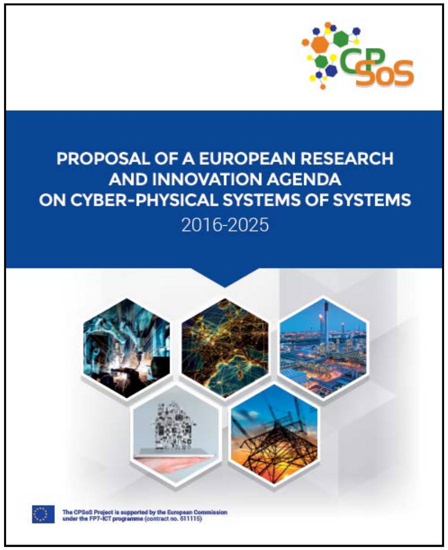
3 public meetings with 100+ participants

CPSoS State of th… art document and initial roadmap

MAJOR INDUSTRIES AND 17 SMEs INVOLVED

Research and Innovation Challenges

- **Engineering support for the design-operation continuum of cyber-physical systems of systems**
- **Distributed management of cyber-physical systems of systems**
- **Cognitive CPSoS** with innovative use of the large amounts of data that are collected in CPSoS



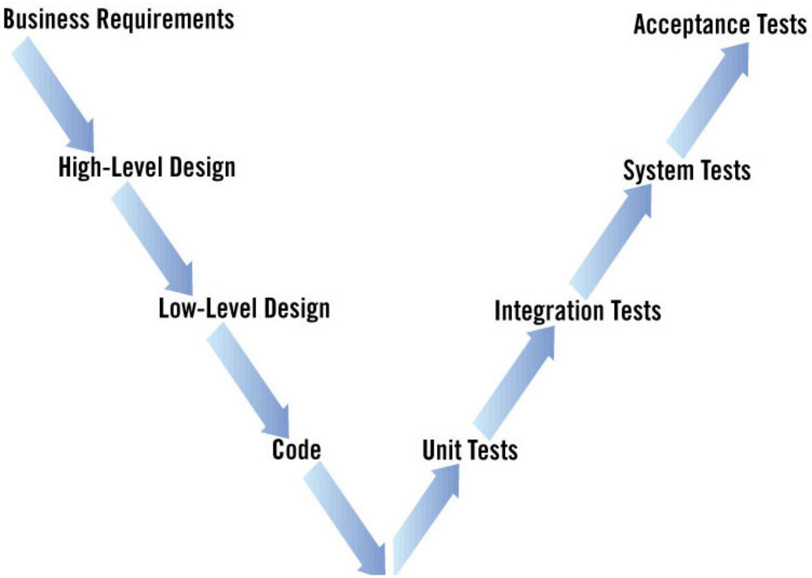
www.cpsos.eu/roadmap

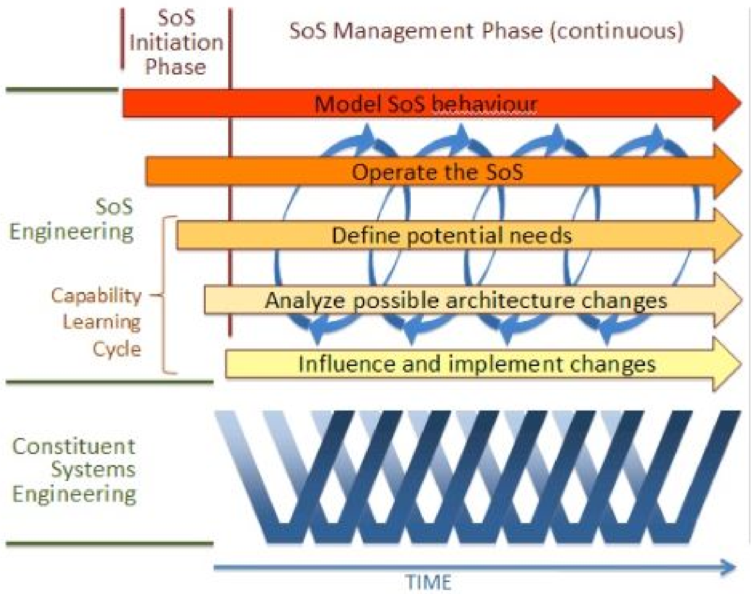
Engineering support for the design-operation continuum of cyber-physical systems of systems

Challenges

- CPSoS are continuously evolving which blurs the traditional separation between the engineering/design phases and the operational stages
- The high degree of heterogeneity and partial autonomy of CPSoS requires new, integrated approaches for their design, validation, and operation
- CPSoS are highly flexible and subject to frequent, dynamic reconfiguration, which must be supported by design support tools to enable efficient engineering
- Failures, abnormal states, and unexpected/emerging behaviours are the norm in CPSoS
- CPSoS are socio-technical systems in which machines and humans interact closely → human behaviour has to be taken into account

Development Cycle for CPSoS





Traditional

Iterative Approach (DANSE)

CPSoS are never finished!

CPSoS is supported by the European Commission under the 7th Framework Programme for Research & Technological Development (2007-2013) - ICT theme

Key Research Areas

- Integrated engineering of CPSoS over their full life-cycle
- Modelling, simulation, and optimization of CPSoS
- Establishing system-wide and key properties of CPSoS

Modelling, Simulation, and Optimization of CPSoS

Challenges

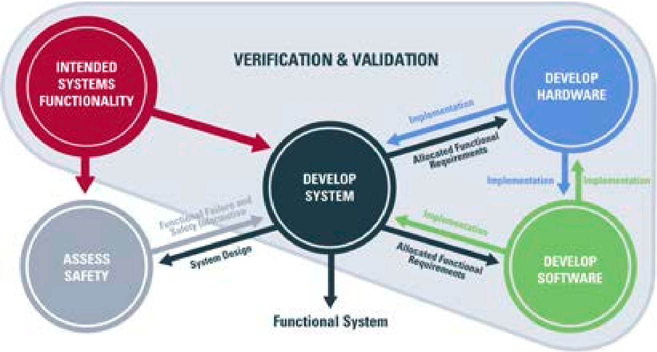
- High cost for building and maintaining models
- Modelling of human users and operators
- Simulation and analysis of stochastic behaviour
- Models for validation and verification purposes

Needs

- Tools for model management and for the integration of models from different domains. Model management requires meta-models
- Efficient simulation algorithms for system-wide simulation of large heterogeneous CPSoS, including dynamic on-the-fly reconfiguration
- Global high-level modelling and simulation for performance and risk analysis (including stochastic phenomena and the occurrence of abnormal states)
- Integration of legacy system simulations as well as open approaches for integration of models without revealing details

Establishing System-wide Key Properties of CPSoS

Challenges



- Establishment, validation, and verification of key properties of CPSoS

Needs

- New approaches for dynamic requirements management during the continuous evolution of a cyber-physical system of systems, and for verification especially on the system of systems level
- New algorithms and tools to enable the automatic analysis of complete, large-scale, dynamically varying and evolving CPSoS
- Theory for successive refinement and abstraction of continuous and discrete systems so that validation and verification at different levels of abstraction are correlated, and the joint use of and simulation-based (Monte Carlo) and exhaustive (model checking) verification techniques

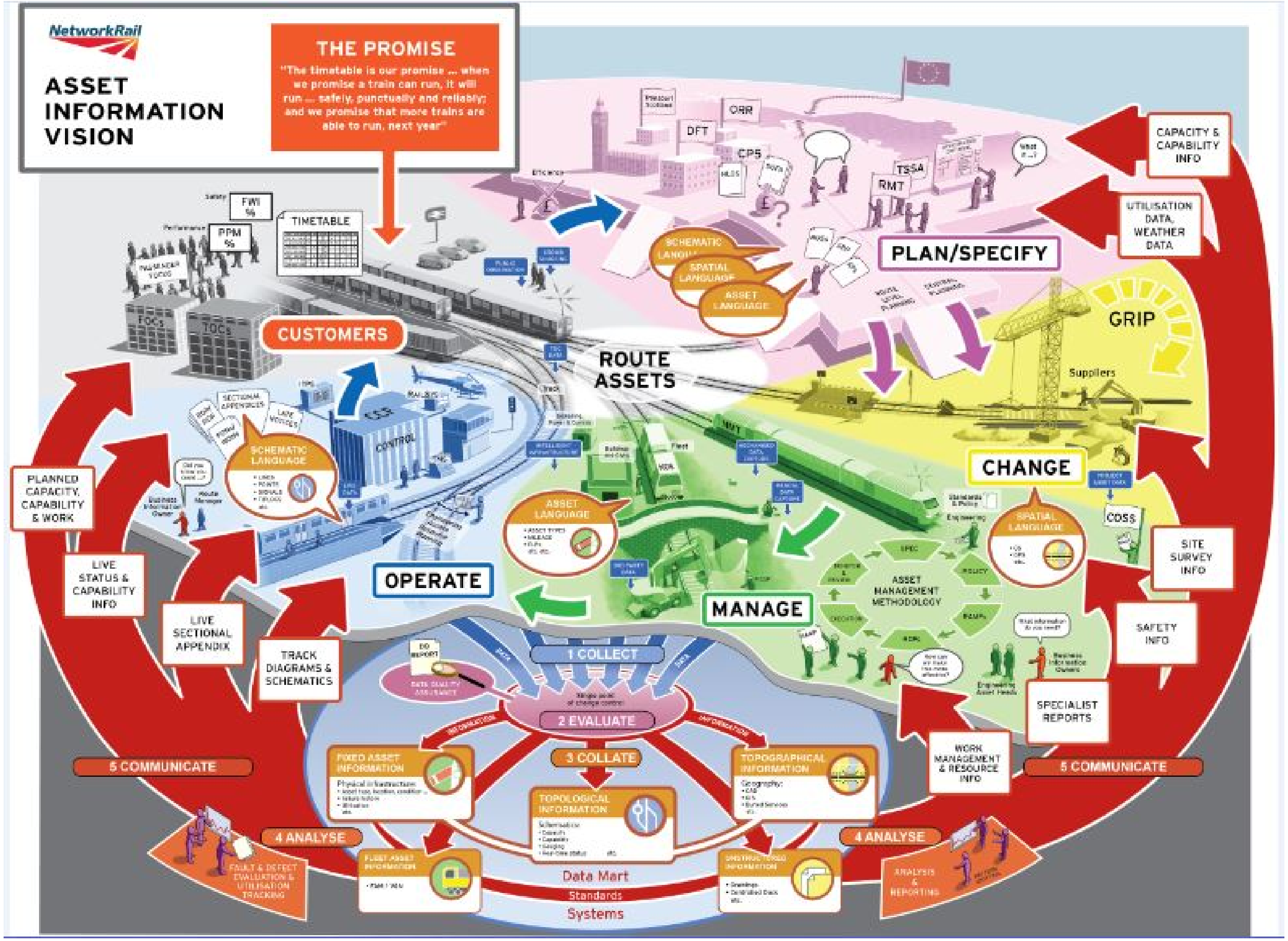
Distributed management of cyber-physical systems of systems

Distributed Management of Cyber-physical Systems of Systems

- Decision structures and system architectures
- Self-organization, structure formation, and emergent behaviour in technical systems of systems
- Real-time monitoring, exception handling, fault detection and mitigation of faults and degradation
- Adaptation and integration of new components
- Humans in the loop and collaborative decision making
- Trust in large distributed systems

Cognitive Cyber-physical Systems

Complexity of a Rail Network



Human-machine Interaction in Cyber-Physical Systems of Systems

- Need for improved **situational awareness**, however, gaining an overview of the entire SoS is inherently complicated by the presence of decentralized management and control
- The introduction of **cognitive features** to aid both operators and users of complex cyber-physical systems of systems is seen as a key requirement for the future to reduce the complexity management burden from increased interconnectivity and the data deluge presented by increasing levels of data acquisition

Research Topics

- Situational awareness in large distributed systems with decentralized management and control
- Handling large amounts of data in real time to monitor the system performance and to detect faults and degradation
- Learning good operation patterns from past examples, auto-reconfiguration and adaptation
- Analysis of user behaviour and detection of needs and anomalies

Towards a European Roadmap on Research and Innovation in Engineering and Management of Cyber-Physical Systems of Systems

Medium-term Research and Innovation Priorities in Cyber-physical Systems of Systems

SEVENTH FRAMEWORK PROGRAMME

Medium-term Research Priorities (1)

Methodological:

- System integration and dynamic reconfiguration
- Robust distributed system-wide control and optimization
- Resilience in systems of systems
- Overcoming the modelling bottleneck
- Humans in the loop
- Towards cognitive systems: data-based system operation

Overcoming the Modelling Bottleneck

- Faster model development and better model reuse, automated modelling
- Model maintenance and adaptation
- Collaborative environments for model exchange between competing companies, trust in models from others
- Integration of legacy system models
- Combination of models of different depth and different formalisms in system-wide models of CPSoS, co-simulation, hierarchical modeling, appropriate levels of abstraction
- Meta-modelling and model management to ensure model consistency
- Modelling over the full life cycle of the system
- Combination of model- and data-based optimization
- Economic / socio-technical modelling

Humans in the Loop

- Filtering and appropriate presentation of information to human users and operators for the acceptance of advanced computer-based solutions
- Investigation of the human capacity of attention and of measures to provide motivation for sufficient attention and consistent decision making
- Analysis of the cognitive models of system operators
- Monitoring of the actions of the users and anticipating their behaviours and their situation awareness
- Social phenomena (dynamics of user groups)
- Combination of the capabilities of humans and algorithms in real-time monitoring and decision making (collaborative decision making and control, e.g. autonomous cars)

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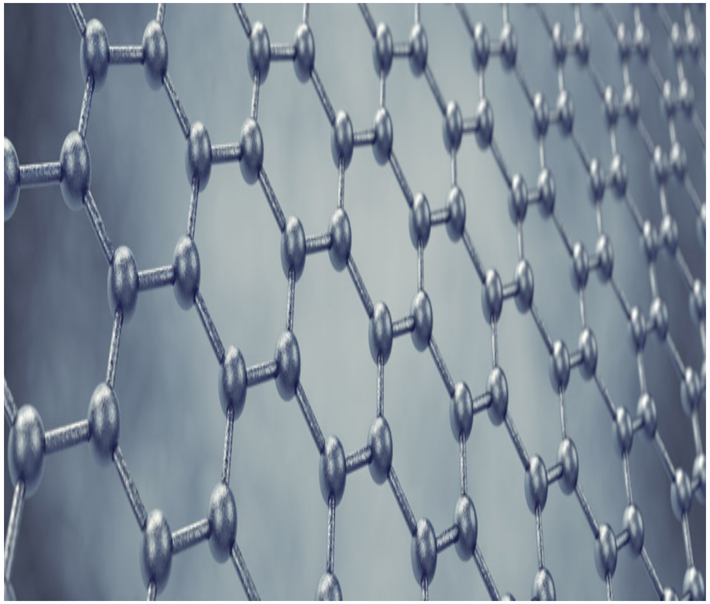
EU Project DYMASOS

Dynamic Management of Physically Coupled Systems of Systems

Dealt with systems that

- Possess partial local autonomy
- Are tightly interconnected by streams of material and energy
- Examples:
  - Electric power grid
  - Chemical plants
  - Smart buildings



DYMASOS

DYMASOS Consortium

BASF The Chemical Company

INEOS THE WORLD FOR CHEMICALS

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DYMASOS

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ayesa

HEPODS d.o.o.

Universidad de Sevilla

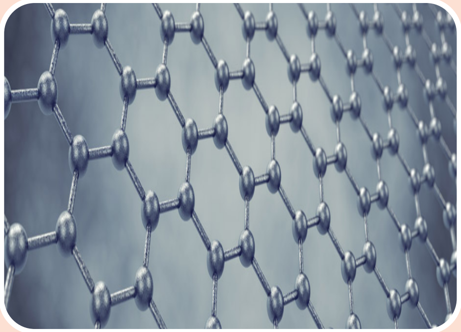
ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

RWTH AACHEN UNIVERSITY

FER University of Zagreb Faculty of Electrical Engineering and Computing

tu technische universität dortmund

Management Methods



Population-control techniques that are motivated by the behavior of biological systems

ETH Zürich

Market-like mechanisms that achieve global optimality by the iterative setting of prices or resource constraints

TU Dortmund

Coalition games, where agents group dynamically to pursue common goals

U Sevilla

INEOS in Köln

INEOS
THE WORD FOR CHEMICALS

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- 19 different plants
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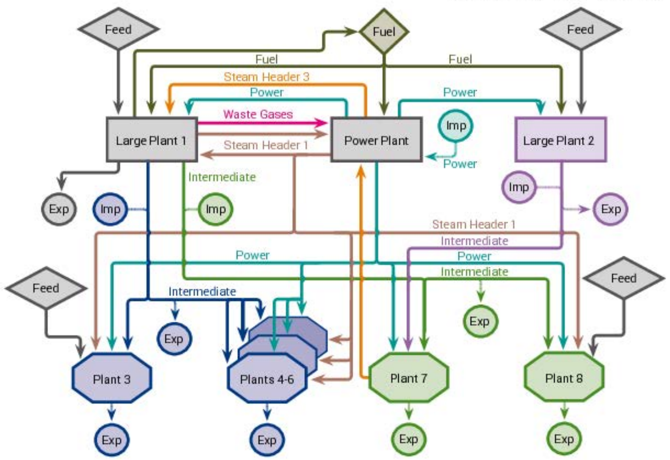

INEOS in Köln – Site management

INEOS
THE WORD FOR CHEMICALS

- The units are managed by different business units
- Individual optima and site-optimum may conflict

$$u^* \neq [u_1^*, \dots, u_n^*]$$

The goal is to reduce the total cost of operation of the site while meeting the production targets.

Goal: Site-wide optimum

plants

economic cost functions

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

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

complicating constraint

INEOS in Köln – Need for distributed optimization

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Centralized optimization cannot be applied: Mathematical, technical and “social” reasons

- Problem size
- Missing information / failures
- Scalability (adding new subsystems)
- Confidentiality

- Confidentiality

  Distributed solutions offer the possibility to keep certain data confidential (e.g. profit functions)

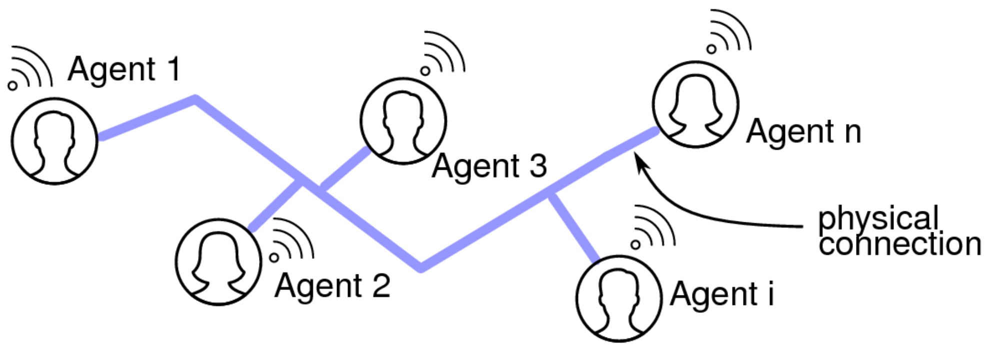
  ⇒ One can handle competing business units or several chemical companies within a Chempark or cluster.

Distributed optimization problem

Resource constrained optimization problem

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

$$\text{s.t.} \sum_{i=1}^{n} R_i(u_i) = 0 \Big\} \quad \text{network constraint}$$



Requirements for the coordination mechanism:

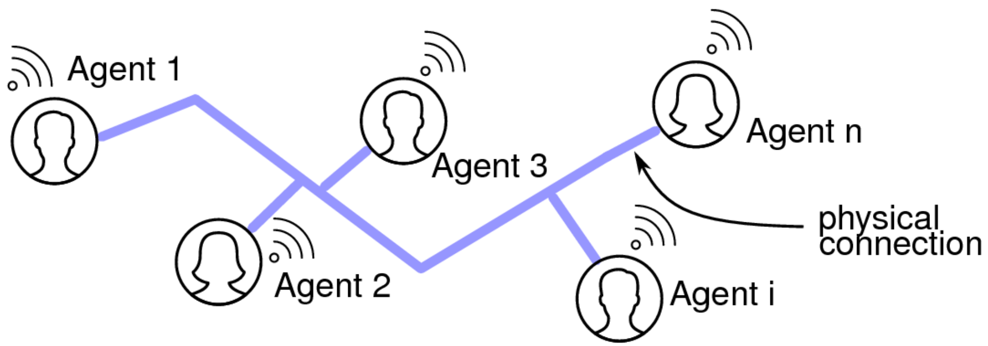
- Small or no changes to the individual cost functions (leads to higher acceptance)
- Restricted communication
  - Quantity (frequency of exchanges)
  - Quality (which data) of shared information

Distributed optimization problem

Resource constrained optimization problem

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

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



Different decomposition methods:

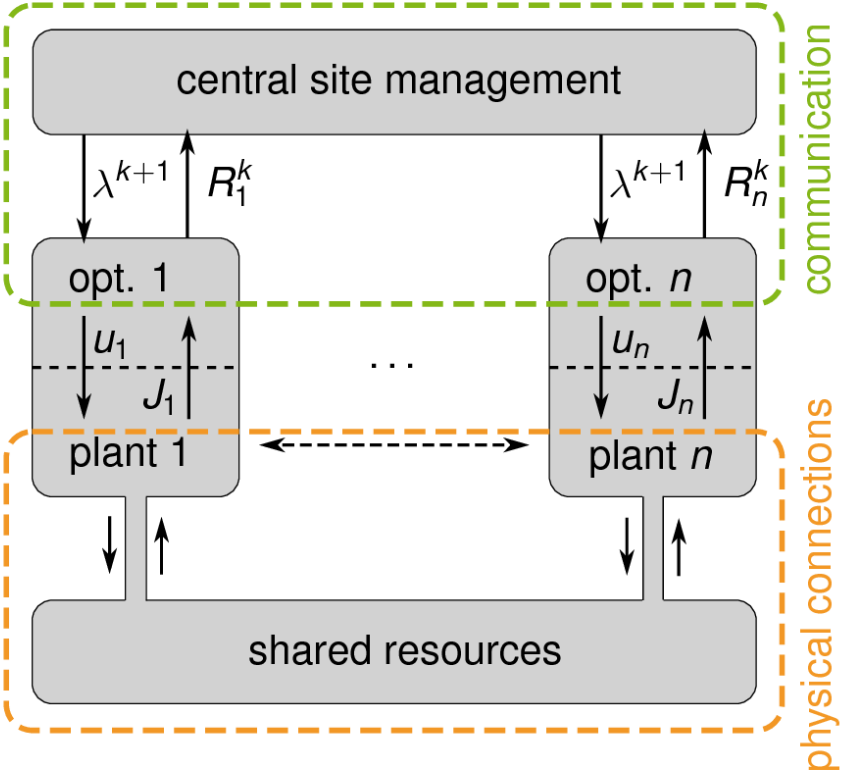
- Price-based coordination
- Primal decomposition
- ADMM
- Population control
- …

- Different communication mechanisms and degrees of autonomy of the subsystems

Tatônnement process – Walrasian Auction

- Auctioneer (invisible hand of the market) adjusts the prices iteratively until supply and demand match
- Only resource utilization or production and prices are shared
- Objective: find the equilibrium price of the market λ^*
  → balanced networks

Excess demand: λ ⇗
Excess supply: λ ⇘



Price-based coordination

Minimization of the Lagrangian

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

- Lagrange multipliers λ can be interpreted as transfer prices → *Price-based coordination*
- Problem is decomposable

$$\min_{u_i \in \mathcal{U}_i} \mathcal{L}_i(u_i, \lambda) = \min_{u_i \in \mathcal{U}_i} J_i(u_i) + \lambda^T R_i(u_i)$$

Example: $+ \; 25\, €/\mathrm{t} \cdot 34\, \mathrm{t}/\mathrm{h}$

Price-based coordination – Subgradient price-update

$$\left.\boxed{\lambda^{k+1}} = \lambda^k + \alpha^k \sum_{i=1}^{n} R_i(u_i)^k \right\} \text{coordinator}$$

$$\left.\begin{aligned} u_i^{*,k+1} &= \arg\min_{u_i} \left(J_i(u_i) + \lambda^{k+1,T} R_i(u_i) \right) \\ \boxed{R_i^{k+1}} &= R_i(u_i^{*,k+1}) \end{aligned}\right\} \text{plants}$$

Strategy converges under strict assumptions, e.g. strict convexity, sufficiently small α^k

$\Rightarrow$ Need for a more robust coordination strategy

Augmented Lagrangian

$$\min_{u_i \in \mathcal{U}_i, \forall i} \mathcal{L}(u_i, \lambda) = \min_{u_i \in \mathcal{U}_i, \forall i} \sum_{i=1}^{n} J_i(u_i) + \lambda^T \sum_{i=1}^{n} R_i(u_i) + \frac{\rho}{2} \left\| \sum_{i=1}^{n} R_i(u_i) \right\|_2^2$$

- The augmentation term convexifies the problem.
- Direct decomposition no longer possible.
- Alternating Direction Method of Multipliers (ADMM) is an extension that enables decomposition.

ADMM – Reformulated network constraint

$$\left.\min_{u_i \in \mathcal{U}_i, \forall i} \sum_{i=1}^{n} J_i(u_i) \right\} \text{ cost reduction}$$

$$\left.\begin{aligned} \text{s.t.} \quad & R_i(u_i) - z_i = 0 \ \forall i \\ & \sum_{i=1}^{n} z_i = 0 \end{aligned}\right\} \text{ reformulated constraint}$$

Minimization of the augmented Lagrangian

$$\min_{u_i \in \mathcal{U}_i, \forall i} \mathcal{L}_\rho(u_i, z_i, \lambda) = \min_{u_i \in \mathcal{U}_i, \forall i} \sum_{i=1}^{n} J_i(u_i) + \lambda^T \sum_{i=1}^{n} R_i(u_i) + \frac{\rho}{2} \sum_{i=1}^{n} \|(R_i(u_i) - z_i)\|_2^2$$

ADMM – Update steps

Additional variables z_i need to be updated by the coordinator

$$\left.\begin{aligned}
\boxed{\lambda^{k+1}} &= \lambda^k + \frac{\rho^k}{n}\sum_{i=1}^{n} R_i(u_i)^k \\
\boxed{z_i^{k+1}} &= R_i(u_i)^k - \frac{1}{n}\sum_{i}^{n} R_i(u_i)^k
\end{aligned}\right\} \text{coordinator, } z = \text{addtional ref.}$$

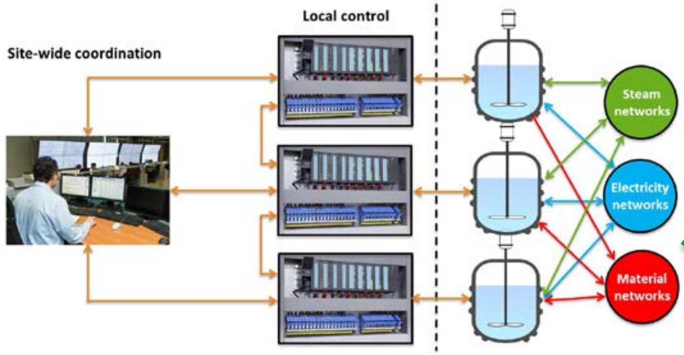
$$\left.\begin{aligned}
u_i^{*,k+1} &= \arg\min_{u_i} J_i(u_i) + \lambda^{k+1,T} R_i(u_i) + \frac{\rho}{2}\left\| \left(R_i(u_i) - z_i^{k+1} \right) \right\|_2^2 \\
\boxed{R_i^{k+1}} &= R_i(u_i^{*,k+1})
\end{aligned}\right\} \text{plants}$$

Outline

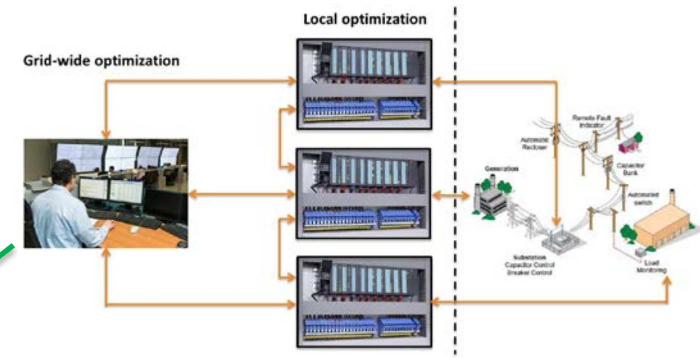
- Examples of cyber-physical systems of systems
- Results of the CPSoS Project
  - Definition of cyber-physical systems of systems
  - Research challenges
    - Support for engineering and re-engineering
    - Distributed/ coordinated management
    - Cognitive cyber-physical systems – make use of "big data"
  - Medium-term research agenda
- Distributed optimization in cyber-physical systems of systems
  - Challenge
  - Market-based coordination
  - **Simulation and validation framework**
  - Case Study
  - Ongoing work
- Summary

Modeling and Simulation of Cyber-physical Systems of Systems (1)

Multi-product batch-plant

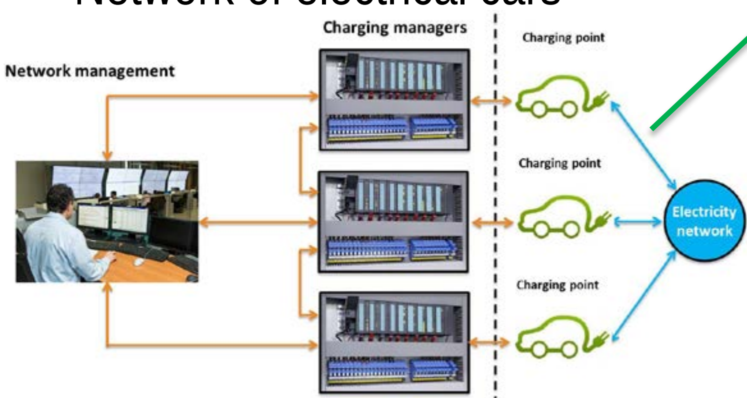


Electrical distribution grid

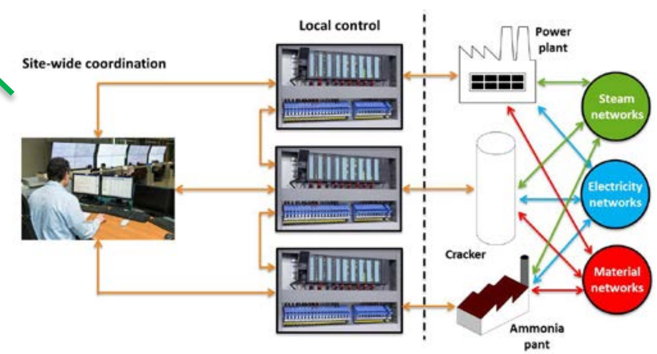


Complex, interconnected, distributed automation structures

Network of electrical cars



Chemical production site

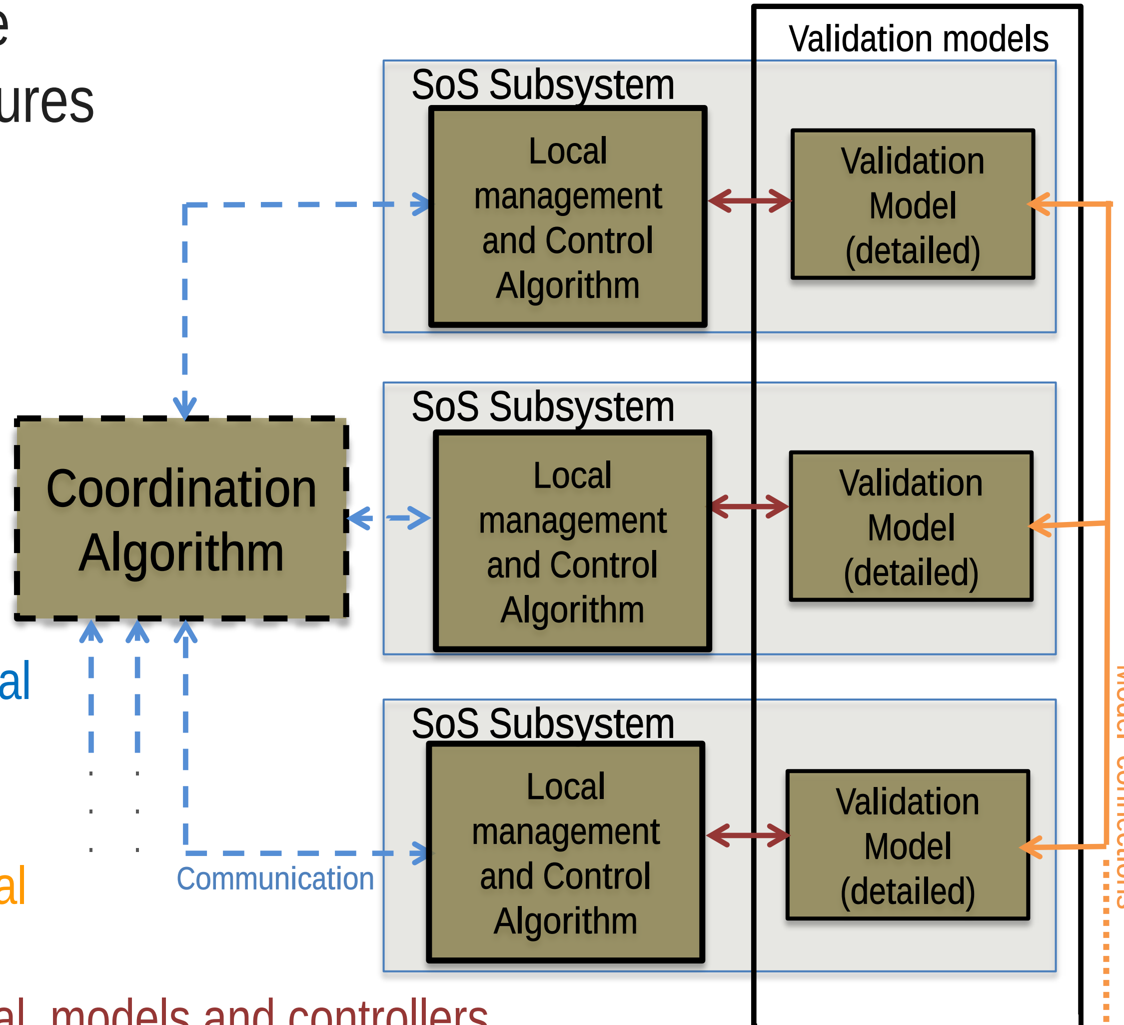


Modeling and Simulation of Cyber-physical Systems of Systems (2)

- Goals
  - Evaluation of different coordination algorithms
    - Different control structures
  - Evaluation of coordination algorithms on different set of models
    - From different modeling domains, already existing, black-box, different modeling environments, …
- Our solution → A modeling, simulation and validation framework that is specially designed for facilitating the simulation-based validation of distributed control architectures for large scale systems
  - ✓ Uses a plug and play approach
  - ✓ Supports different modeling and simulation environments
  - ✓ Facilitates the modification/adding/removal of components

The DYMASOS Simulation and Validation Framework

- A framework which fits to the discussed automation structures
  - A System of System (SoS) implementation
    - A number of subsystems
    - A coordination algorithm
    - Interconnected via standard interfaces
- Standard interfaces for
  - The interconnection of the local and global management systems
  - The interconnection of physical models
  - The interconnection of physical models and controllers

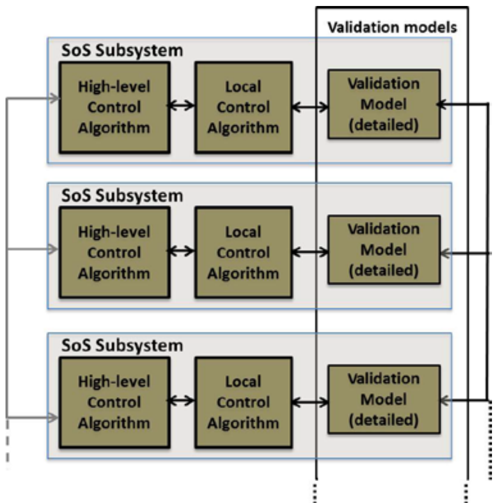


The DYMASOS Simulation and Validation Framework
Main Features (1)

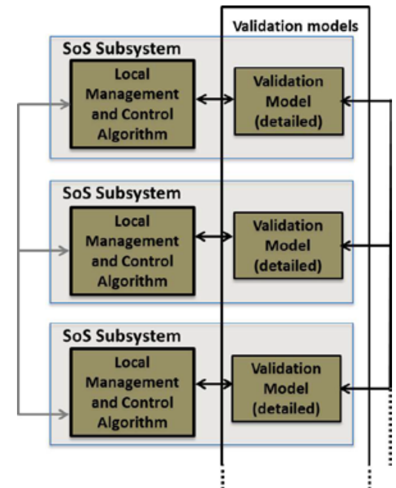
- Standardized interfaces
  - Facilities model re-use
  - Plug-and-play replacement of algorithms and models
  - A basis for industrial deployment
- Systematic structuring of the controlled system, with generation of the interconnections and the communication structure
- Based on *Modelica*
  - Support of heterogeneity due to object orientation
  - Efficiency due to equation-oriented modeling
  - Integration of model components in different modeling languages
    - Validation models via co-simulation via fmi FUNCTIONAL MOCK-UP INTERFACE
      - MATLAB SIMULINK
    - Controller components via external function call (white-box as well as black-box)
      - THE C PROGRAMMING LANGUAGE

The DYMASOS Simulation and Validation Framework Main Features (2)

- Support for different communication structures
  - Example:



Decentralized control structures



Distributed control structures in presence of agent negotiations

- Support for different time-discretization mechanisms
  - Discrete-time, discrete- event, …

Outline

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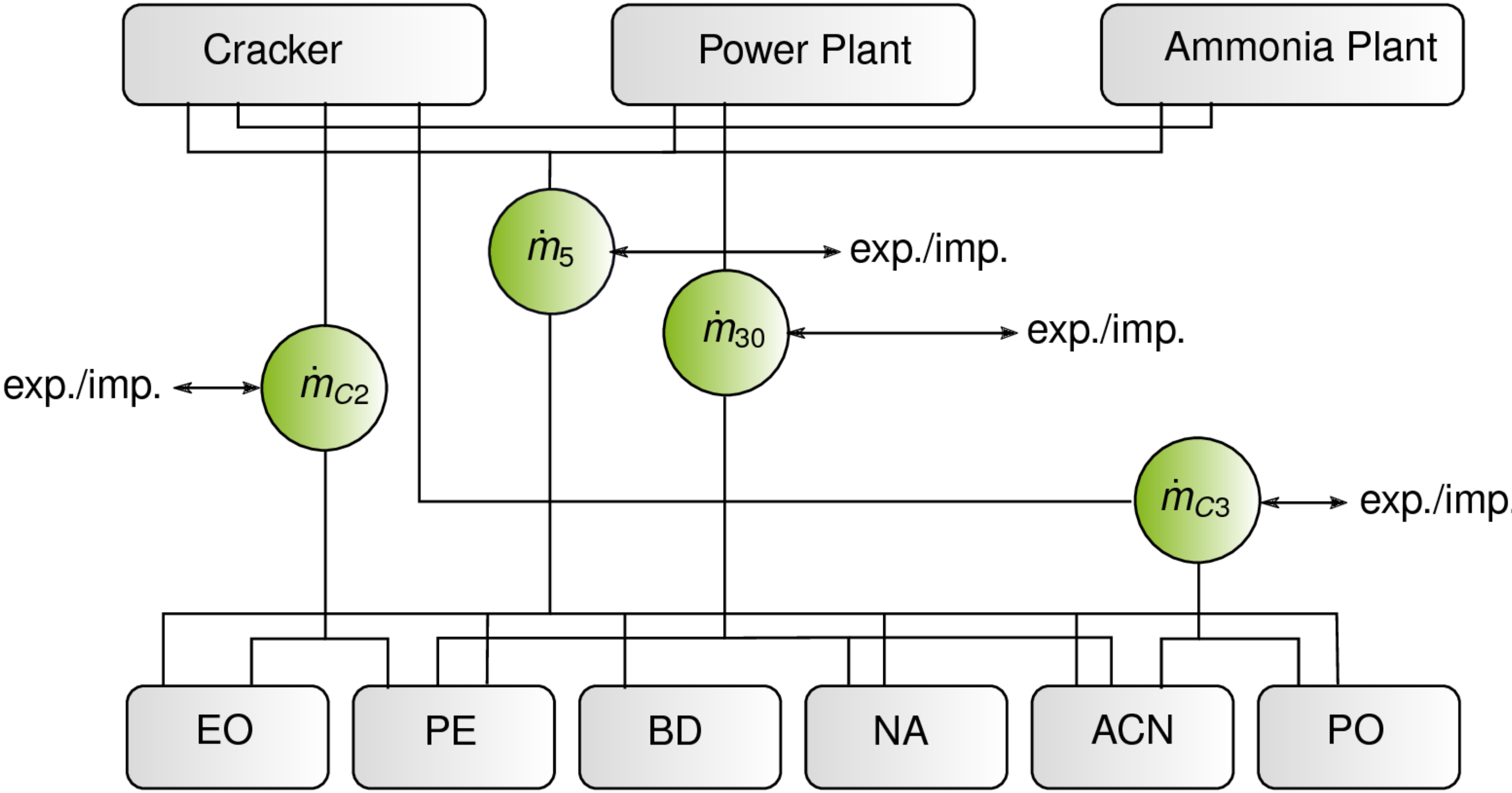
  - Medium-term research agenda
- Distributed optimization in cyber-physical systems of systems
  - Challenge
  - Market-based coordination
  - Simulation and validation framework
  - **Case Study**
  - Ongoing work
- Summary

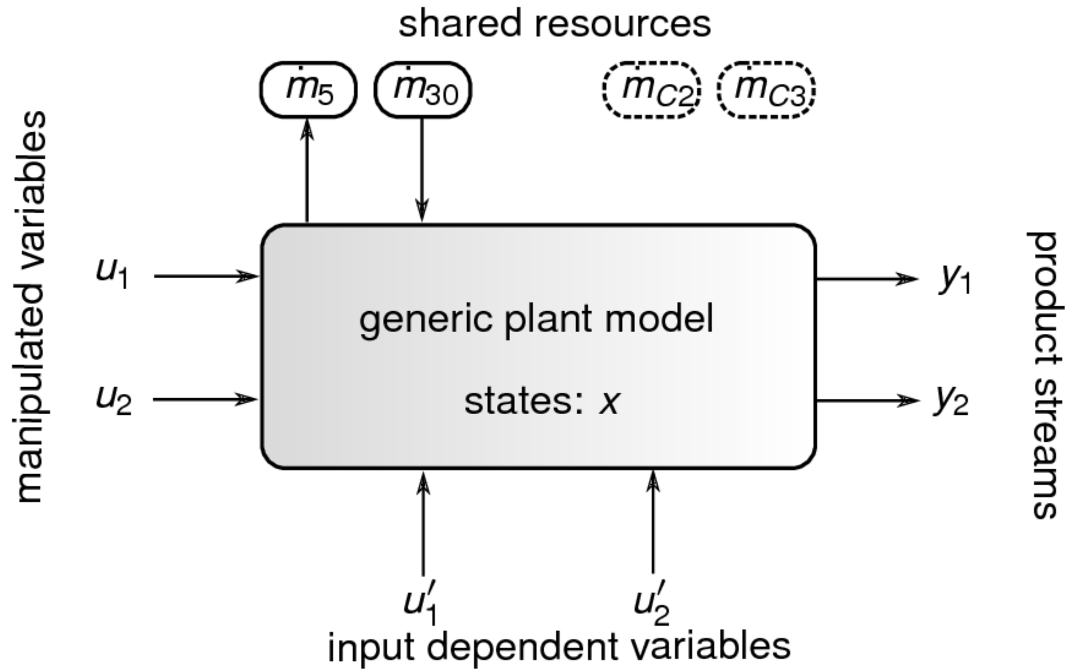
Topology of the case study



Mathematical modeling: generic plant

Model equations

$$x = M_{ux} \cdot u + V_x$$
$$y = M_{xy} \cdot x$$
$$R = M_{uR} \cdot u + M_{xR} \cdot x$$
$$= (M_{uR} + M_{xR} M_{ux}) \cdot u + M_{xR} V_x$$



- Linear (affine) functions of the manipulated variables
- The shared resources are a linear combination of states and inputs

The individual optimization problems

Formulation of the optimization problems

$$\min_{u} \quad \underbrace{p_u\, u + p_x\, x + p_R\, R - p_y\, y}_{\text{linear economic terms}} \underbrace{+ \frac{1}{2} \Delta y^T W_y \Delta y}_{\text{tracking}}$$

s. t.

$$\Delta y = y - y_{ref}$$

$$\left.\begin{aligned} lb \le u \le ub \\ A_{ineq} \cdot u \le b_{ineq} \\ u \in \mathcal{C} \end{aligned}\right\} \text{equipment and input constraints}$$

Model equations.

The site-wide optimization problem

- The site-wide optimization problem is made up of the single plant problems
- Additionally, the complicating constraint is added

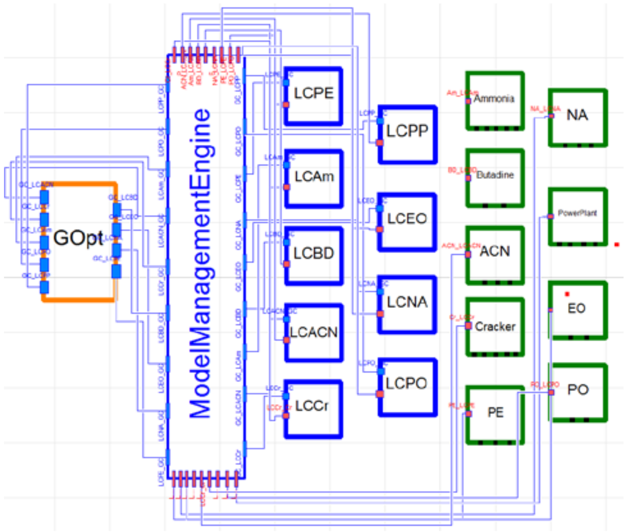
Compact form of plant i

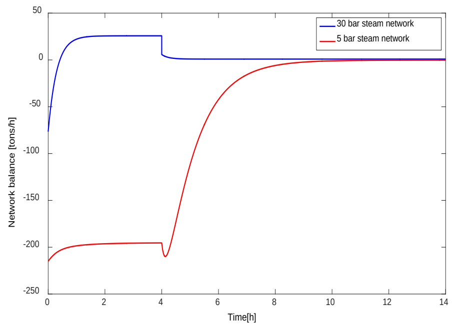
$$\min_{u_i} \quad J_i(u_i)$$
$$\text{s.t.} \quad u_i \in \mathcal{C}_i$$

$$\min_{u_i \forall i} \quad \sum_{i}^{n} J_i(u_i)$$
$$\text{s.t.} \quad u_i \in \mathcal{C}_i \forall i \ldots \text{individual constraints}$$
$$\sum_{i}^{n} R_i = 0 \ldots \text{complicating (network) constraint}$$

Implementation in the DYMASOS Simulation and Validation Framework

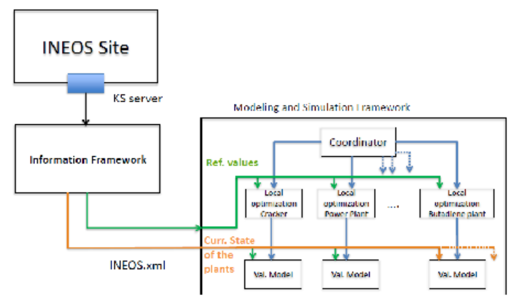
- Petrochemical production site
  - Goal: Site-wide balance of the shared resource networks
  - Control algorithm: Price-based coordination
  - Validation models: *Modelica*-based
  - Controllers: *MATLAB*-based
  - Discrete-event simulation at every sampling time until the balancing of the shared resource network is achieved

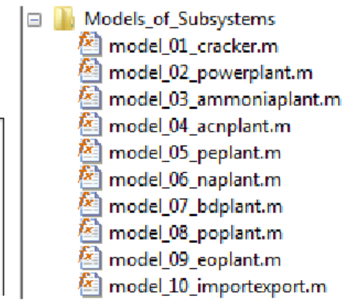


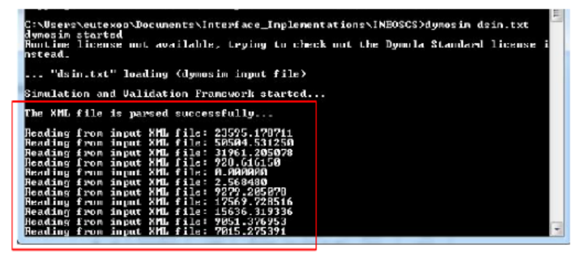


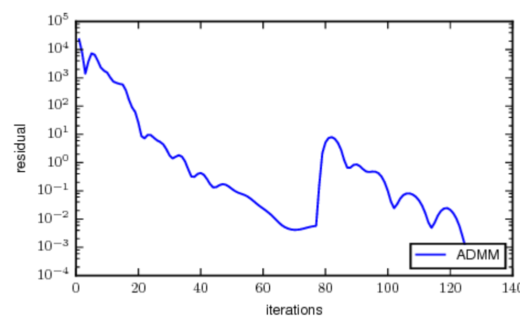
Implementation of the simulation study

- Modular implementation of the subsystems in Matlab®
- The simulation and validation framework (SVF) calls the models as *.dll files.
- *DYMASOS Information Platform* collects data from the IT systems of the plant (production levels, references).
- The coordination is done via ADMM within the SVF.

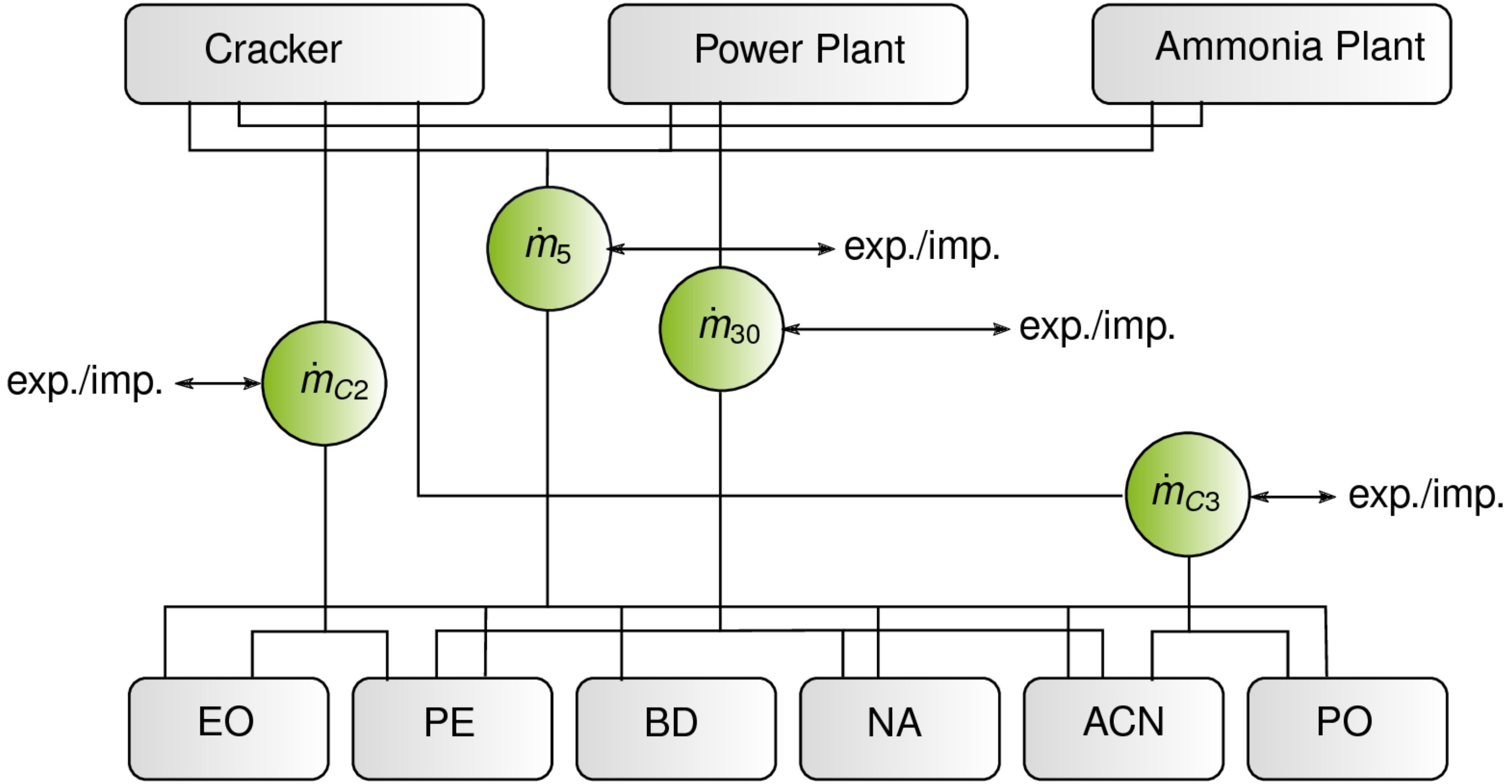








Topology of the case study



Setup of the simulation study

- Initial point (λ^0, u_i^0) is announced at the start of the simulation.
- The first responses cause imbalanced networks (selfish plants).
- ADMM is used to find a new equilibrium price vector λ^* (one operating point) for which the networks are balanced and the site is operated optimally.

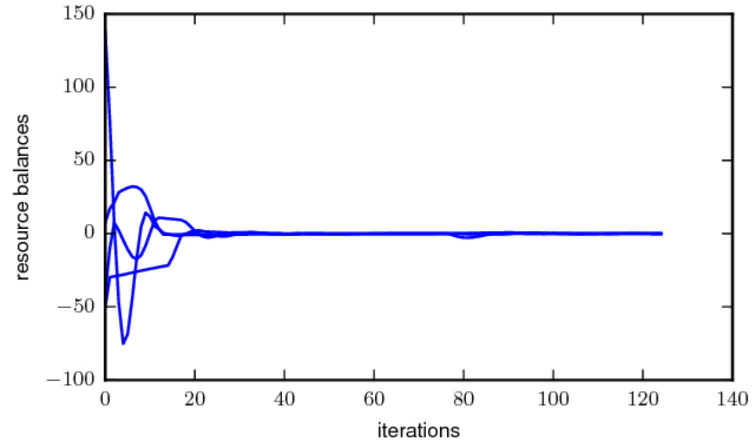
- 9 production plants and one export/import node coupled by four networks:
  - 5 bar + 30 bar steam networks
  - C2 and C3 intermediate streams

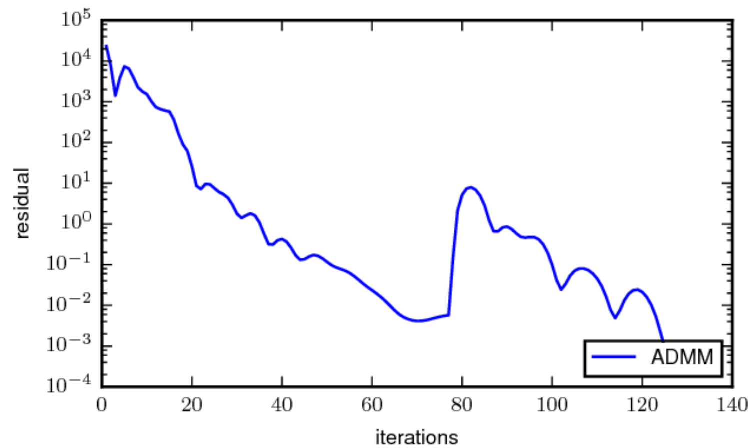
$$\sum_i R_i \rightarrow \mathbf{0} = \begin{pmatrix} \sum_i \dot{m}_5 = 0 \\ \sum_i \dot{m}_{30} = 0 \\ \sum_i \dot{m}_{C2} = 0 \\ \sum_i \dot{m}_{C3} = 0 \end{pmatrix}$$

Imbalance in the networks

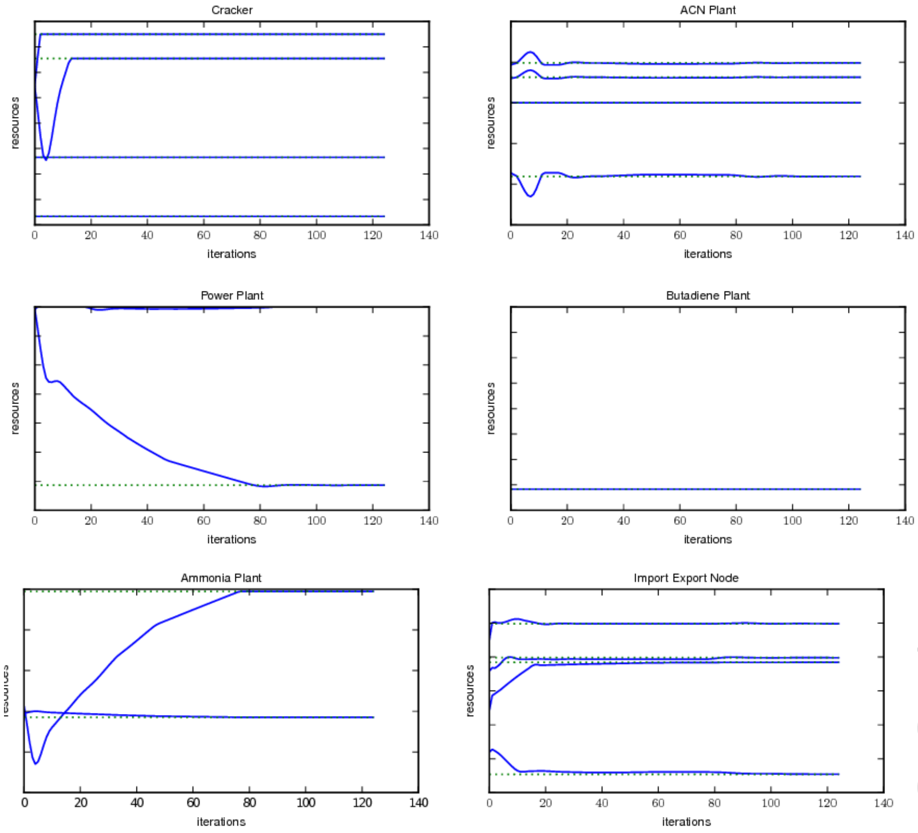
- Initial imbalance for λ^0 for all four networks
- Fast initial reduction of the imbalance
- Many iterations to fulfill the convergence criterion

$$\left\|\sum_{i}^{n} R_i^k\right\|_2^2 < \epsilon = 10^{-3}$$





Adjustment of resource consumption and production (1)

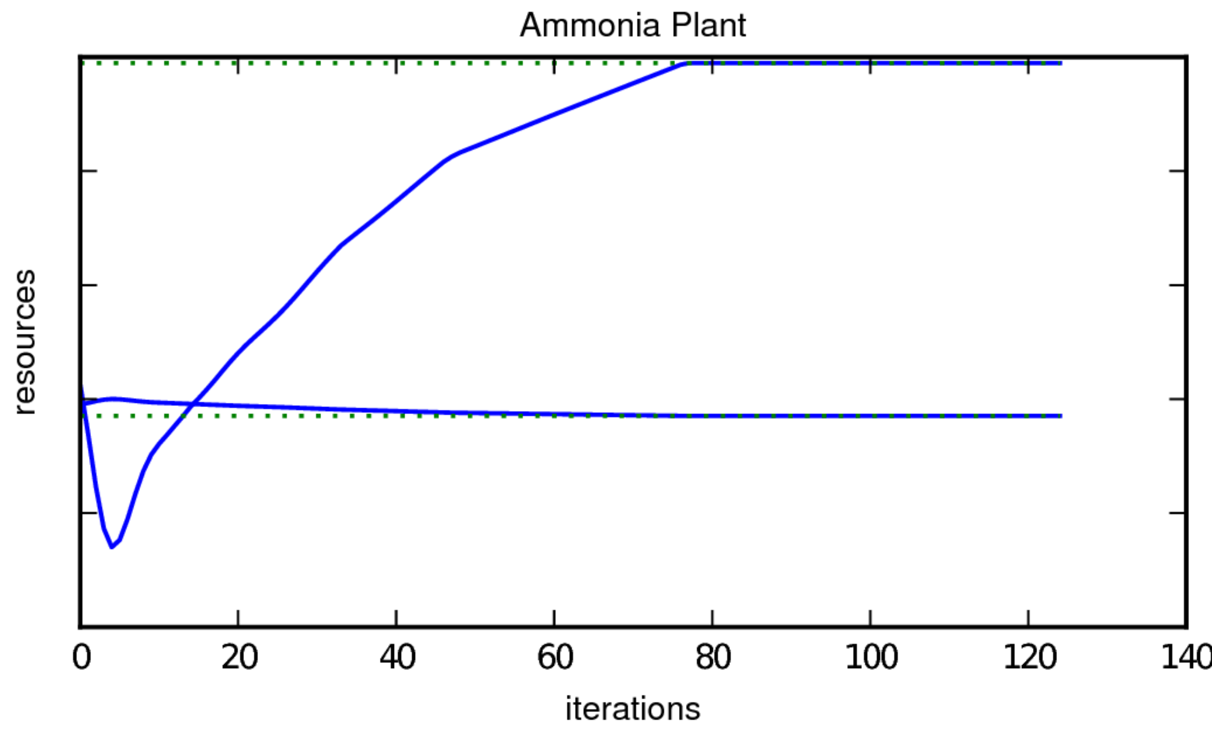


The different plants adjust their resource consumption and production as a result of changing transfer prices.
→ The neworks become balanced.

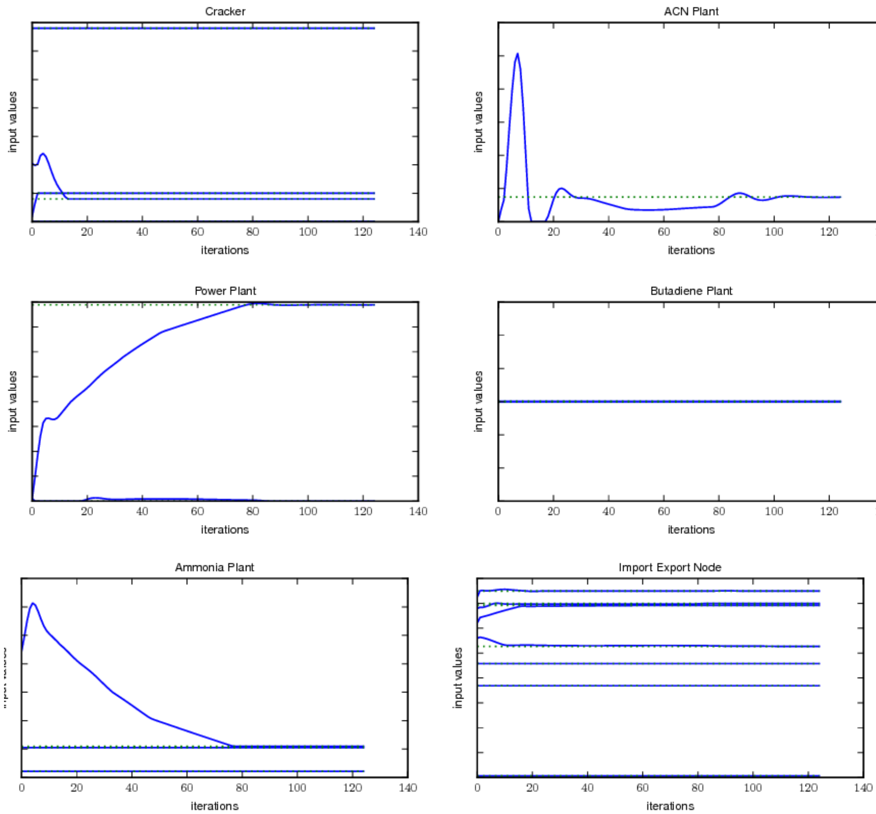
Adjustment of resource consumption and production (2)

Ammonia Plant

- Initially reduces the consumption of one resource
- Then slow increase of one resource and slight reduction of two others
- Centralized solution is reached upon convergence



Adjustment of inputs

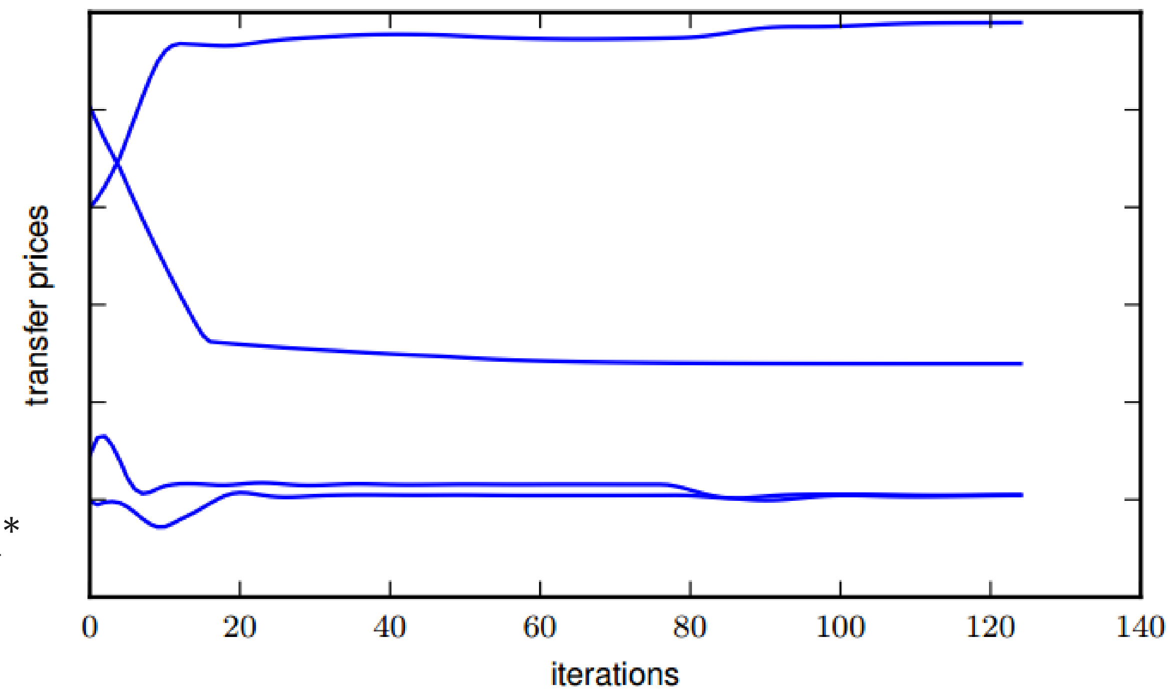


The different plants adjust their resource consumption and production as a result of changing transfer prices.
→ The neworks become balanced.

Changes of transfer prices

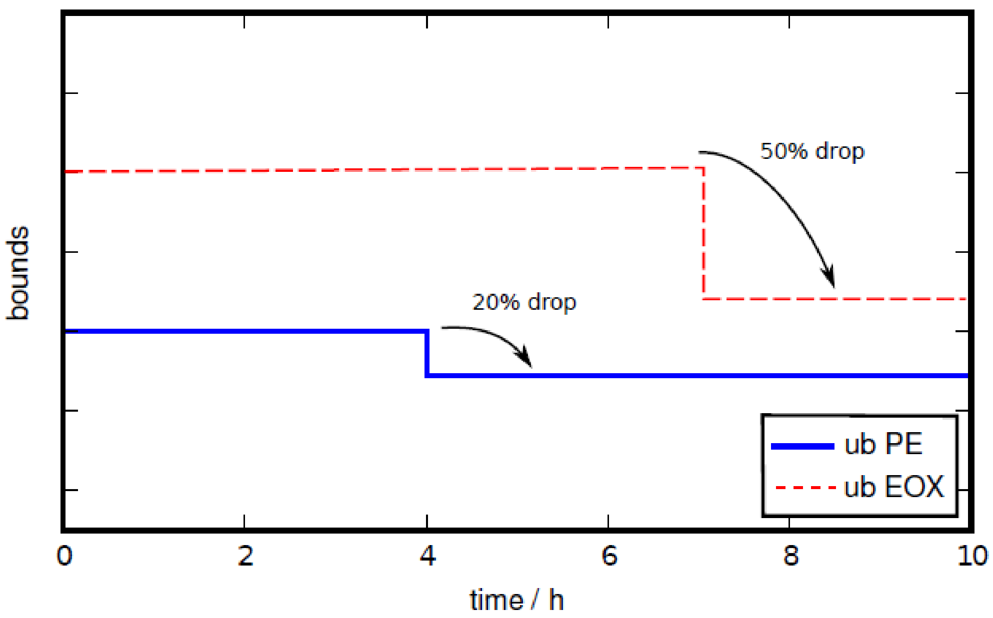
Observations

- Iterative update of the prices during the auction
- Price lowered for excess supply of resources
- Price raised for excess demand of resources
- The prices gradually settle to the equilibrium prices λ^*



Reacting to a dynamic scenario

- Recoordination every hour
- After 4 and after 7 hours major changes occur
- The PE plant reduces significantly its capacity (20%)
- The C2 intake capacity of the EO plant is reduced by 50%

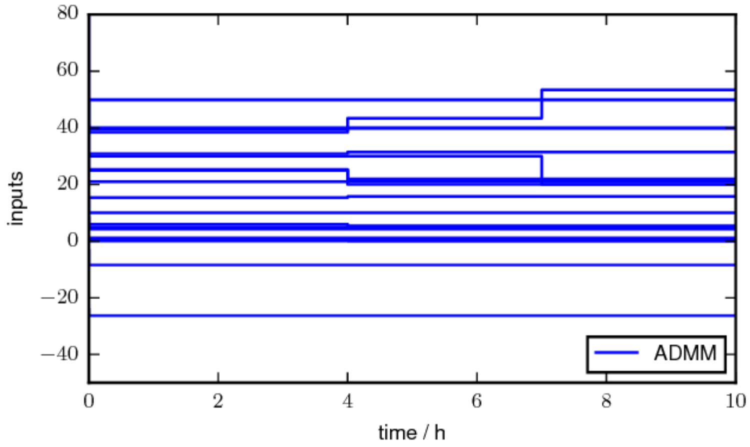


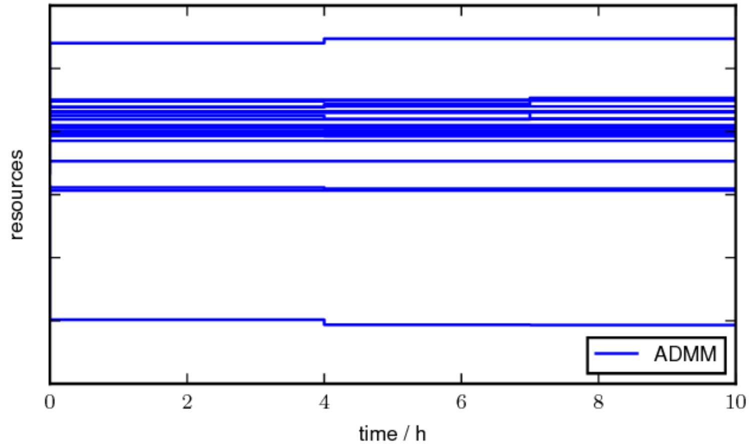
The market-based mechanism is able to balance the networks for the investigated scenario!

Dynamic response

- Recoordination every hour
- After 4 and after 7 hours major changes occur
- The PE plant reduces its capacity by 20%
- The ethylene intake capacity of the EO plant is reduced by 50%

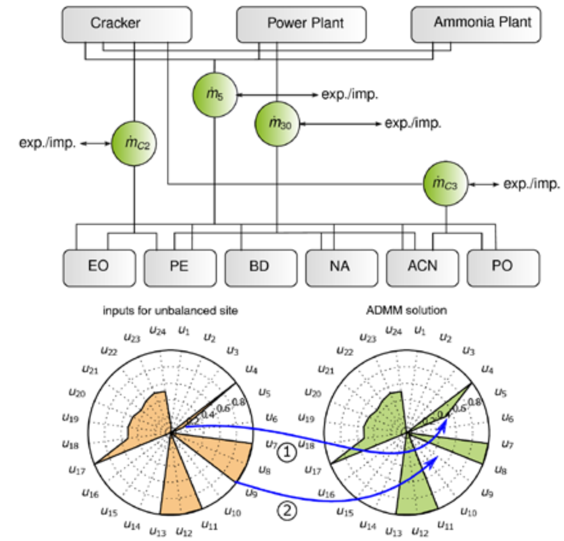
The market-based mechanism is able to balance the networks for the investigated scenario!

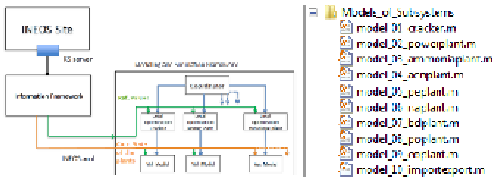


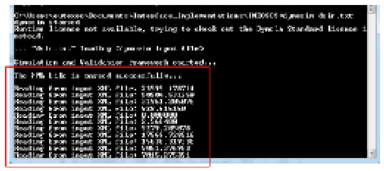


Conclusions

- Realistic case study based on real data of INEOS in Köln
- Market-based coordination balances the site and reaches the site-wide optimum with a high level of confidentiality.
- Implementation and validation was done using the Modelica-based *DYMASOS Simulation and Validation Framework* (TUDO and euTeXoo) with access to real plant data of INEOS in Köln via the *DYMASOS Information Platform* (RWTH Aachen).







Outlook

Future research

- Including discrete decisions (e.g., partial shutdown of single plants).
- Improving the speed of convergence (less iterations, less communication)
- External sources/ sinks
- Balancing resources between companies (within an industrial cluster)

CoPro
COORDINATED PRODUCTION
FOR BETTER RESOURCE EFFICIENCY

Contributors to Part 2

- Stefan Krämer (INEOS)
- Benedikt Beisheim (INEOS)
- Goran Stojanovski
- Simon Wenzel
- Radoslav Paulen
- Lukas Maxeiner
- Christian Sonntag
- Shaghayegh Nazari

Summary

- Cyber-physical systems of systems are the next big challenge
- **IoT + CPS = CPSoS**
- From management and engineering of isolated systems to large-scale distributed interacting systems of systems
- From hierarchical decision structures to coordinated autonomous systems
- From the design **V** to incremental systems engineering
- From data visualization to cognitive systems
- From systems with an HMI to synergetic interactions of cyber-physical systems and human users and operators

Thank you very much for your attention!

www.cpsos.eu/roadmap

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