DYMASOS – Dynamic Management of Physically Coupled Systems of Systems

# Optimal resource allocation in industrial complexes by distributed optimization and dynamic pricing

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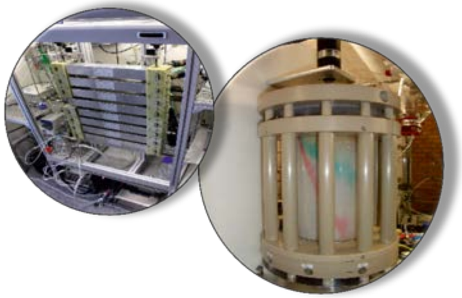
## The Dortmund Process Dynamics and Operations Group

- about 25 PhD candidates from many countries, having degrees in (Bio-)Chemical Engineering, Computer Science, Electrical Engineering, Automation and Robotics …
- Currently 5 PostDocs: Weihua Gao, Radoslav Paulen, Maren Urselmann, Jian Cui, Elrashid Idris
- 2 part-time secretaries, 1 technician
- More than 65 finished PhD theses since 1990

# Research



## Process Control Methods and Applications

- ERC Advanced Grant MOBOCON
- Economics optimizing control
- Robust model-based control
- Iterative optimization using gradient modifiers
- Control of polymerization processes
- Control of chromatographic separations
- Control of the miniplants in the DFG Transregio InPROMPT

## Process Management

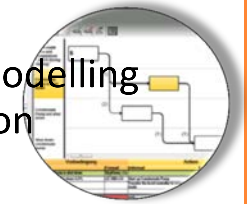
- Market-like mechanisms for the coordination of coupled units
- Real-time monitoring and optimization of resource efficiency
- Simulation environment for the distributed management of systems of systems
- Demand-side management

## Control of Biotechnological Production Processes

- Modeling and control of yeast fermentations
- Modeling and model-based optimization of CHO cultures

## Process Automation

- Intuitive specification of logic control programs
- Heterogeneous modelling and tool integration



## Production Scheduling

- Planning and scheduling under uncertainty
- Timed automata based scheduling
- Reactive scheduling

## Process Design.

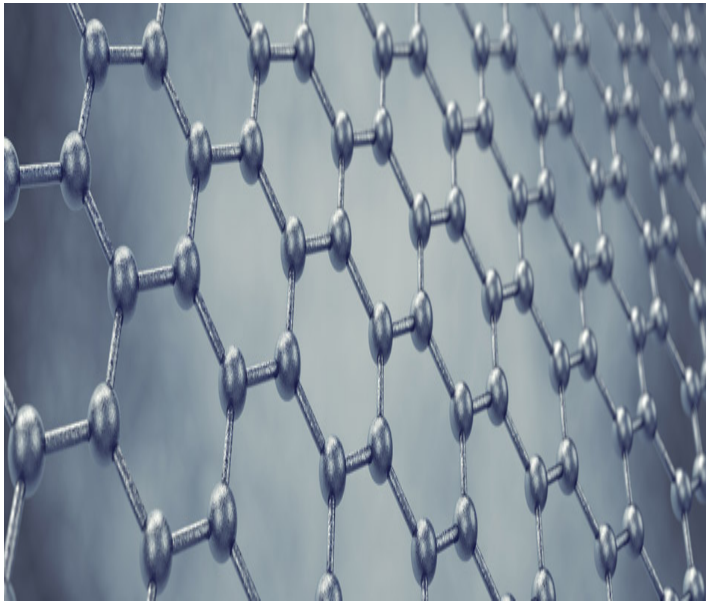
- Model-based support for the early stages of process development
- Algorithms for design problems with many local optima
- Batch-to-conti transfer for co-polymerizations

# 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 Consortium

BASF The Chemical Company

Chemical production and operation

INEOS THE WORLD FOR CHEMICALS

ayesa

Electric power distribution systems

HEPODS d.o.o.

**DYMASOS**

Funded by the European Union under FP7 1.10.2013 – 30.9.2016

inno

euTeXoo

SMEs

idener

Universidad de Sevilla

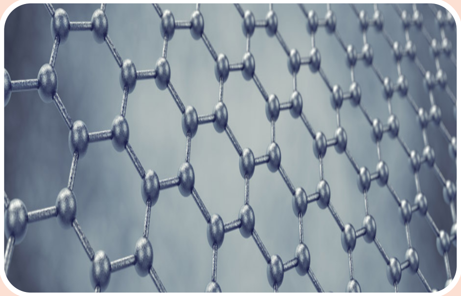
ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

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

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

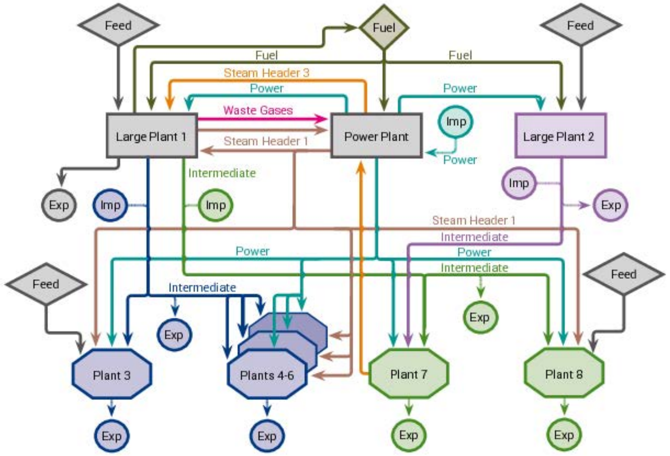
*Coalition games*, where agents group dynamically to pursue common goals

# INEOS in Köln

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




DYMASOS

# 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

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

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

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

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

complicating constraint

# INEOS in Köln – Need for distributed optimization

Centralized optimization cannot be applied: Mathematical and technical 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)

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

# Outline

- Distributed optimization and market-based techniques
- Case study
- Simulation results
- Conclusions and outlook

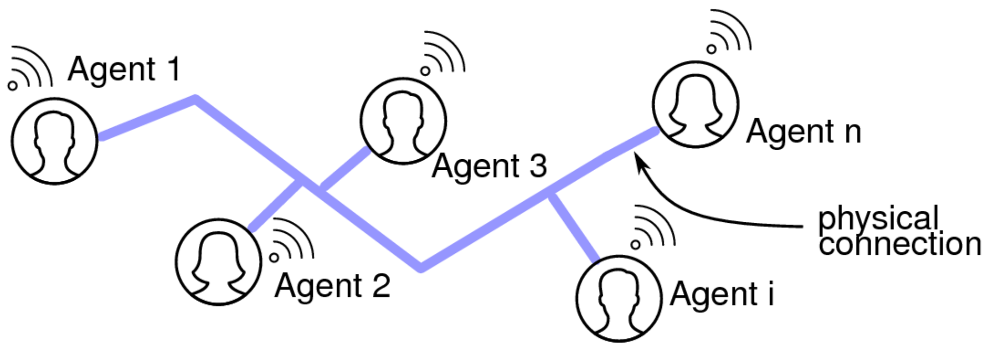
# MARKET-BASED TECHNIQUES FOR DISTRIBUTED OPTIMIZATION

# Distributed optimization problem

## Resource constrained optimization problem

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

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




## Requirements for the coordination mechanism:

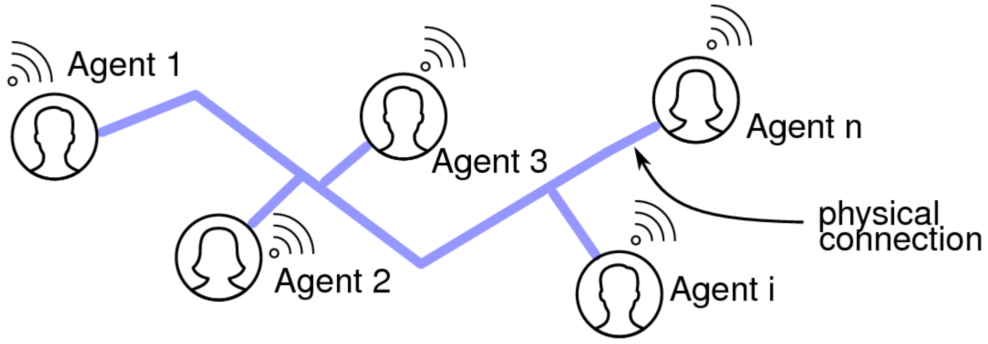
- Small or no changes to the individual cost functions (leads to higher acceptance)
- Restricted communication
  - Quantity (frequency of exchanges)
  - Quality (which data) of shared information

# Distributed optimization problem

Resource constrained optimization problem

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

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




Different decomposition methods:

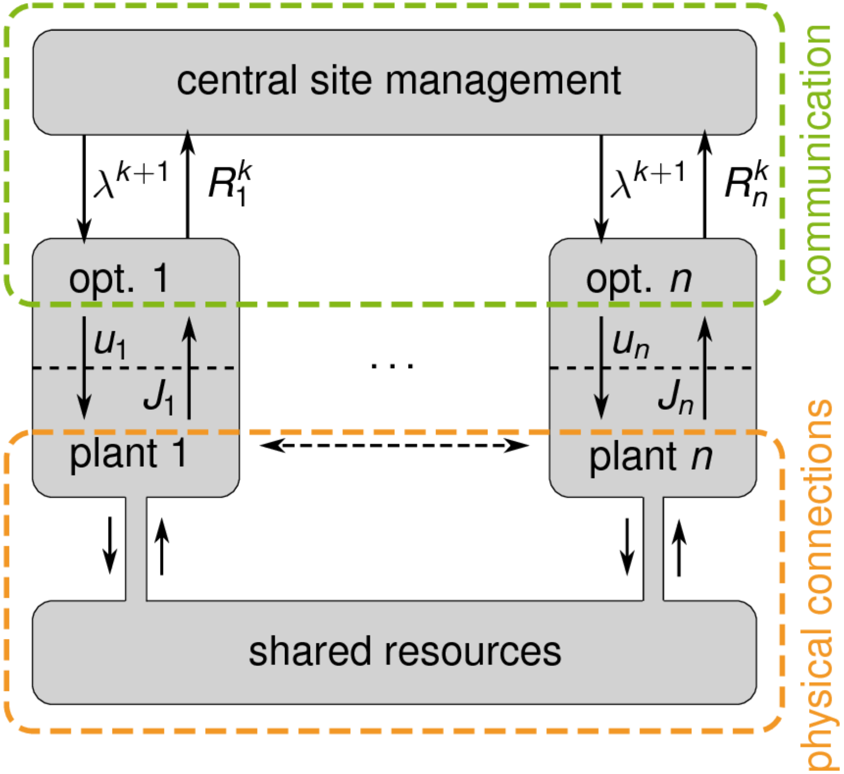
- Price-based coordination
- Primal decomposition
- ADMM
- Population control
- …

- 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 $\lambda^*$
  → balanced networks

Excess demand: $\lambda$ ⇗
Excess supply: $\lambda$ ⇘



# Price-based coordination

## Minimization of the Lagrangian

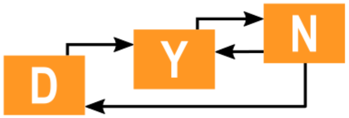
$$\min_{u_i \in \mathcal{U}_i, \forall i} \mathcal{L}(u_i, \lambda) = \min_{u_i \in \mathcal{U}_i, \forall i} \sum_{i=1}^{n} J_i(u_i) + \lambda^T \sum_{i=1}^{n} R_i(u_i),$$

- Lagrange multipliers $\lambda$ 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: $+ \; 25\,€/\mathrm{t} \cdot 34\,\mathrm{t/h}$

DYMASOS



# Price-based coordination – Subgradient price-update

$$\lambda^{k+1} = \lambda^k + \alpha^k \sum_{i=1}^{n} R_i(u_i)^k \quad \Big\} \text{ coordinator}$$

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

Strategy converges under strict assumptions, e.g. strict convexity, sufficiently small $\alpha^k$

$\Rightarrow$ 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

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

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

## 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

$$\lambda^{k+1} = \lambda^k + \frac{\rho^k}{n}\sum_{i=1}^{n} R_i(u_i)^k$$

$$z_i^{k+1} = R_i(u_i)^k - \frac{1}{n}\sum_{i}^{n} R_i(u_i)^k$$

coordinator, $z$ = addtional ref.

$$u_i^{*,k+1} = \arg\min_{u_i} J_i(u_i) + \lambda^{k+1,T} R_i(u_i) + \frac{\rho}{2}\left\|\left(R_i(u_i) - z_i^{k+1}\right)\right\|_2^2$$

$$R_i^{k+1} = R_i(u_i^{*,k+1})$$

plants

# Challenge: Speed of convergence

## Available strategies:

- A large amount of iterations is needed
- Unrealistic if applied to semi-automated systems of systems (humans in the loop).

## New price-update strategies are required that

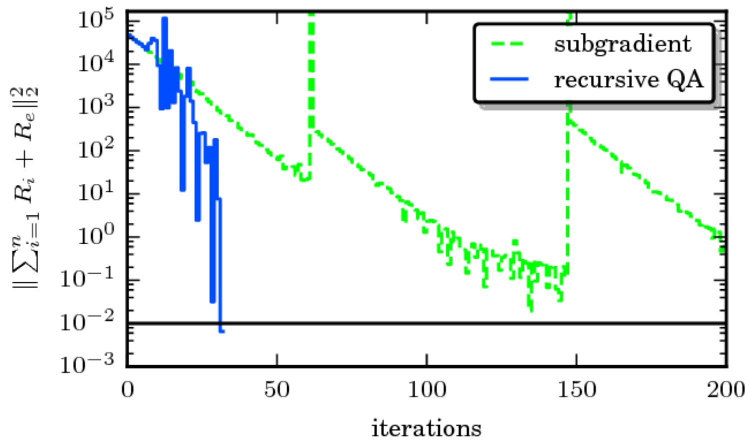
- Preserve confidentiality.
- Have a significantly lower number of communication rounds.

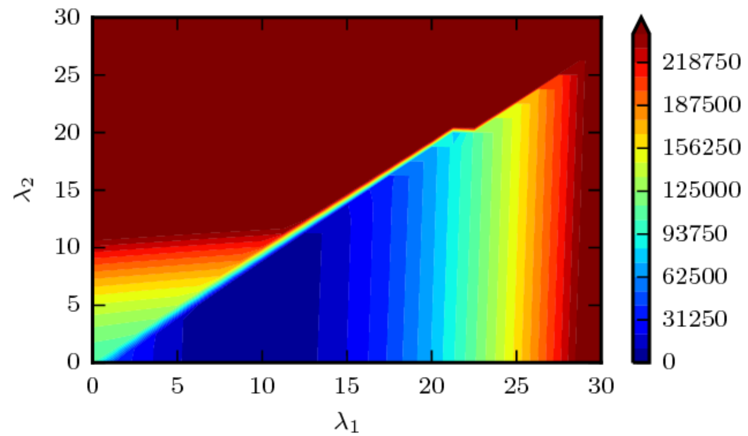
## DYMASOS:

- Novel price update strategy in LR by quadratic approximation of the response to speed up convergence.

# Promising simulation results

- It was shown that the approach outperforms the simple subgradient updates in simulation studies.
- Works well if no (few) individual constraints of the subsystems are active.




S. Wenzel et al., "Optimal resource allocation in industrial complexes by distributed optimization and dynamic pricing," at – Automatisierungstechnik, vol. 64, pp. 428–442, Jun 2016.

# Comparison

**Price-based**

- Minimal communication
- Strict assumptions
- Many iterations
- Difficult to tune (possible divergence)

**Augm. Lagr.**

- Less assumptions
- Not suited for completely distributed coordination

**ADMM**

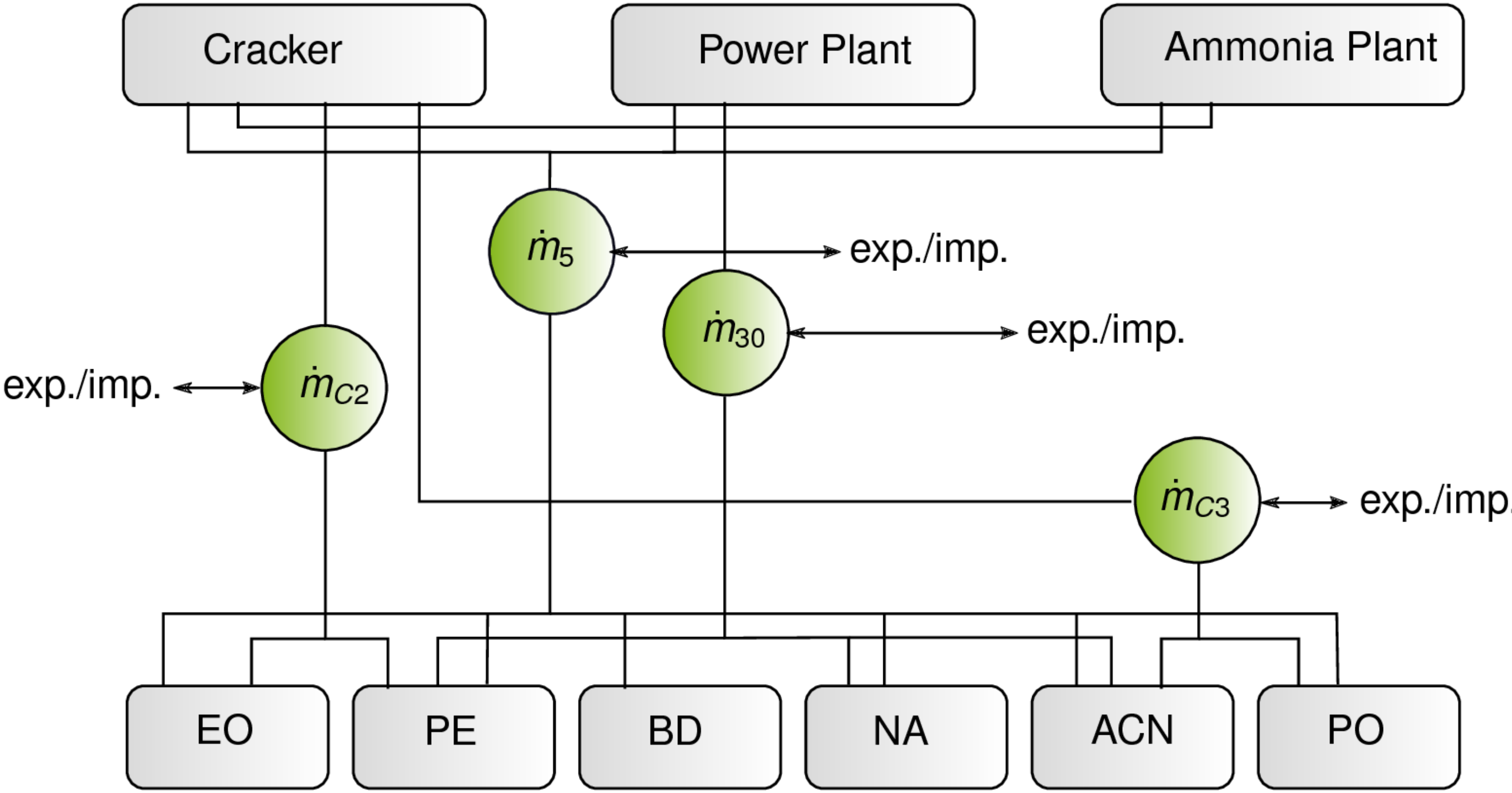
- Robust
- Difficult to tune
- Communica-tion of z variables

**RQA**

- Minimal comminication
- Less iterations
- No proof for convergence
- Open issue of individual active constraints

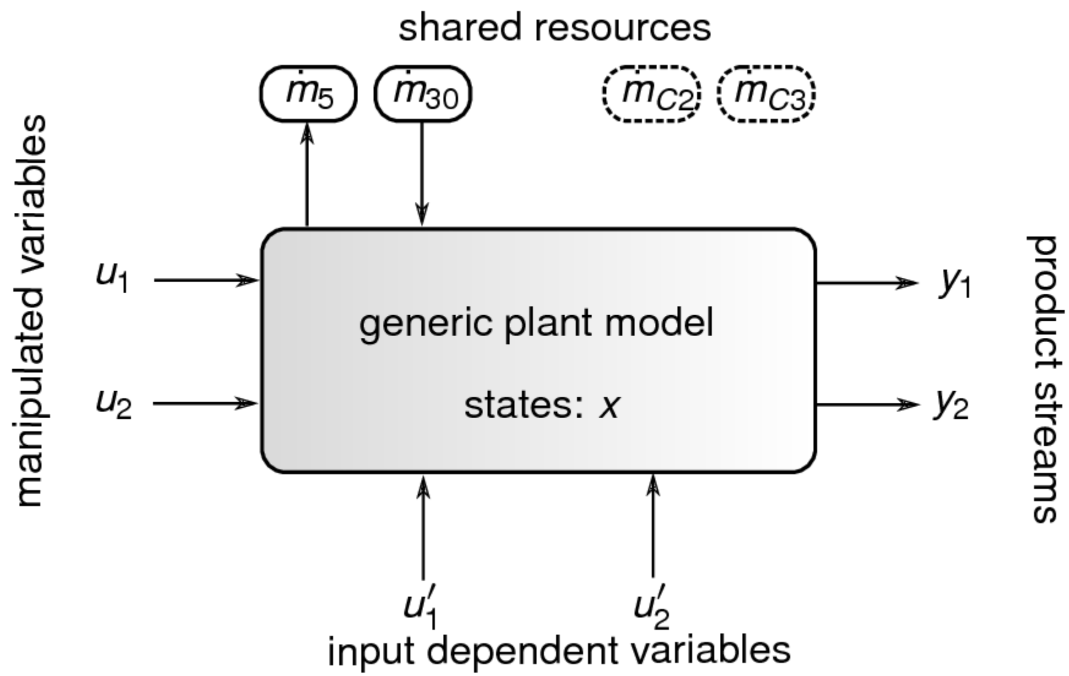
# CASE STUDY: INEOS SITE MANAGEMENT

# Topology of the case study



# Mathematical modeling: generic plant

## Model equations




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

- 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.

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

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

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

$$\min_{u_i \forall i} \quad \sum_{i}^{n} J_i(u_i)$$

$$\text{s.t.} \quad u_i \in \mathcal{C}_i \forall i \ldots \text{individual constraints}$$

$$\sum_{i}^{n} R_i = 0 \ldots \text{complicating (network) constraint}$$

Compact form of plant $i$

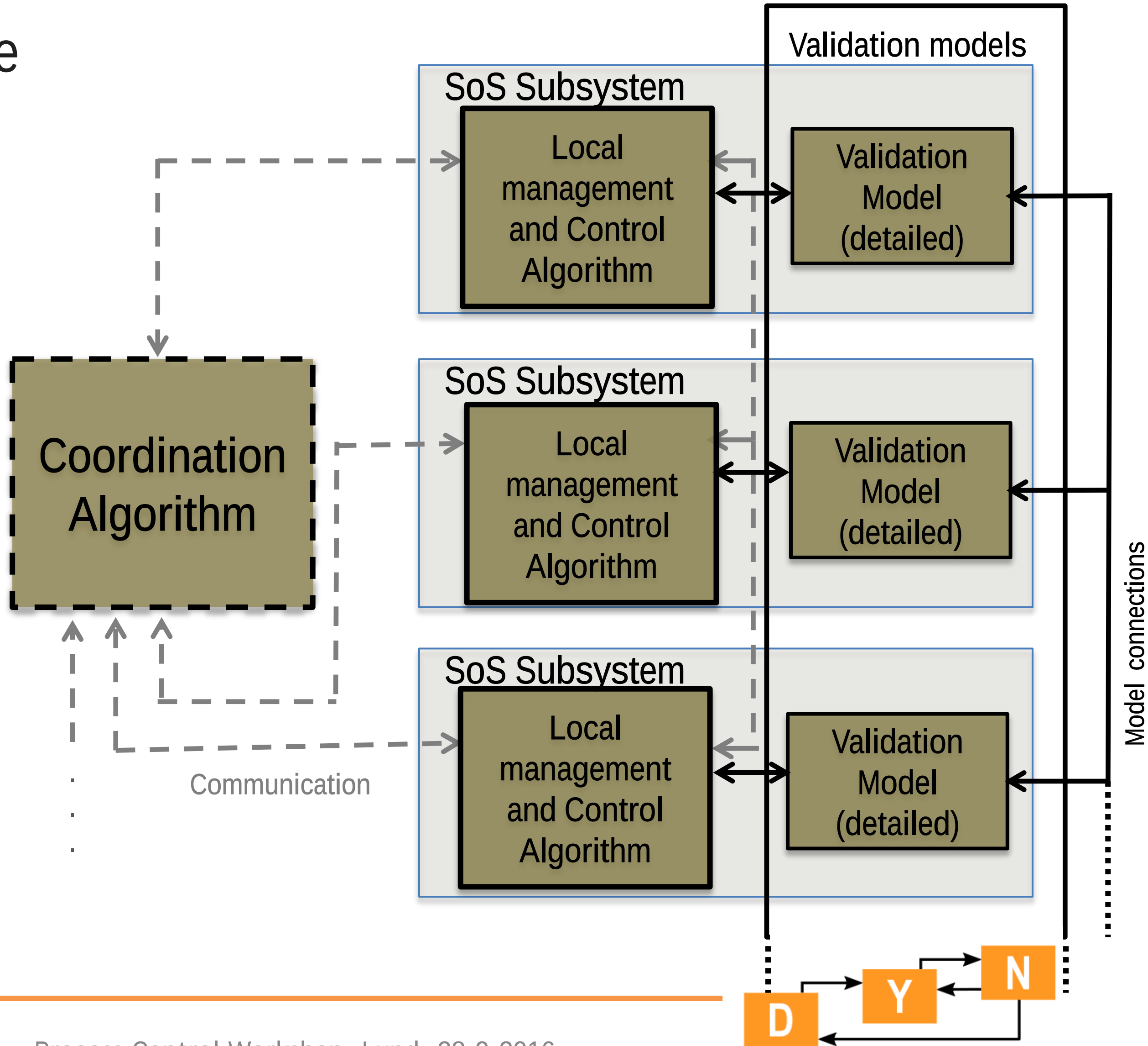
$$\min_{u_i} \quad J_i(u_i)$$

$$\text{s.t.} \quad u_i \in \mathcal{C}_i$$

# SIMULATION RESULTS

# The DYMASOS Simulation and Validation Framework

- Designed to facilitate the simulation of SoS with distributed coordination mechanisms
- Standard interfaces for
  - The interconnection of the local and global management systems
  - The interconnection of physical models
  - The interconnection of physical models and the management systems



# The DYMASOS Simulation and Validation Framework

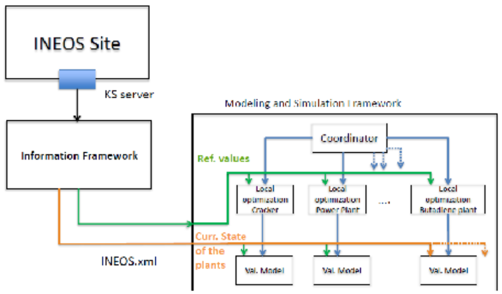
- Modelica-based environment
- Features
  - Different communication structures
  - Different time discretization mechanisms
    - Discrete-event, discrete-time,…
  - Co-simulation of non Modelica-based models
    - Tested environment:
  - Simulation of non external white-box and black-box controllers
    - Tested model implementations:

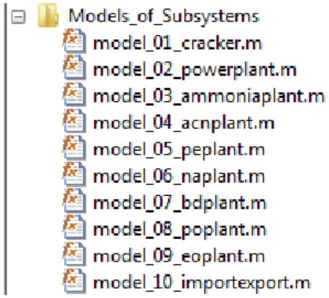
MATLAB SIMULINK python™ THE C PROGRAMMING LANGUAGE fmi FUNCTIONAL MOCK-UP INTERFACE

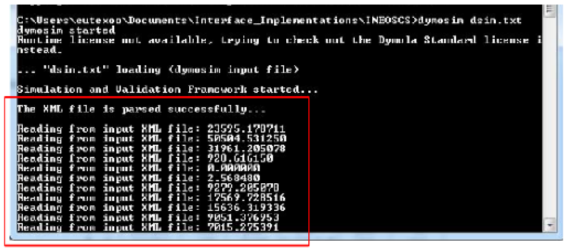
1- www.fmi-standard.org

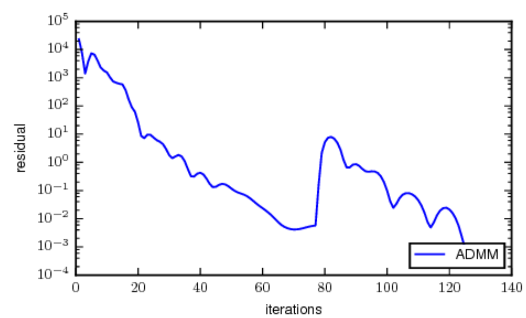
# Implementation of the simulation study

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



# Setup of the simulation study

- Initial point $(\lambda^0, u_i^0)$ 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 $\lambda^*$ (one operating point) for which the networks are balanced.

Goal: balance all networks

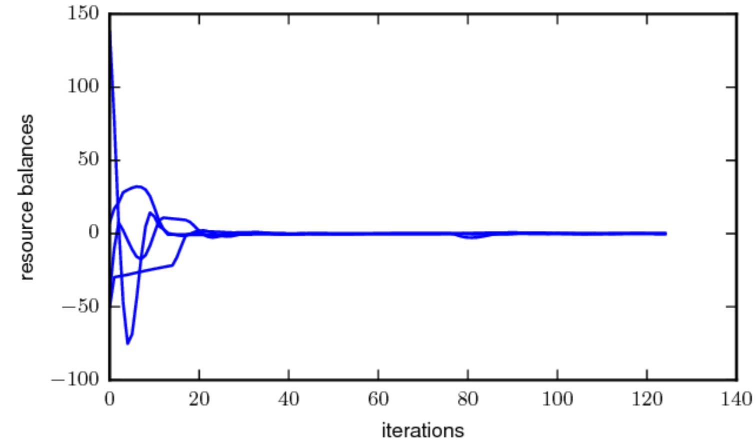
- 9 production plants and one export/import node coupled by four networks:
  - 5 bar + 30 bar steam networks
  - C2 and C3 intermediate streams

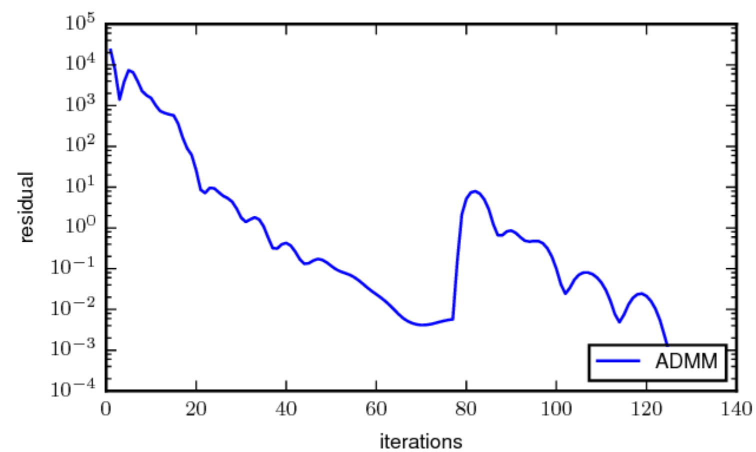
$$\sum_i R_i \rightarrow \mathbf{0} = \begin{pmatrix} \sum_i \dot{m}_5 = 0 \\ \sum_i \dot{m}_{30} = 0 \\ \sum_i \dot{m}_{C2} = 0 \\ \sum_i \dot{m}_{C3} = 0 \end{pmatrix}$$

# Imbalance in the networks

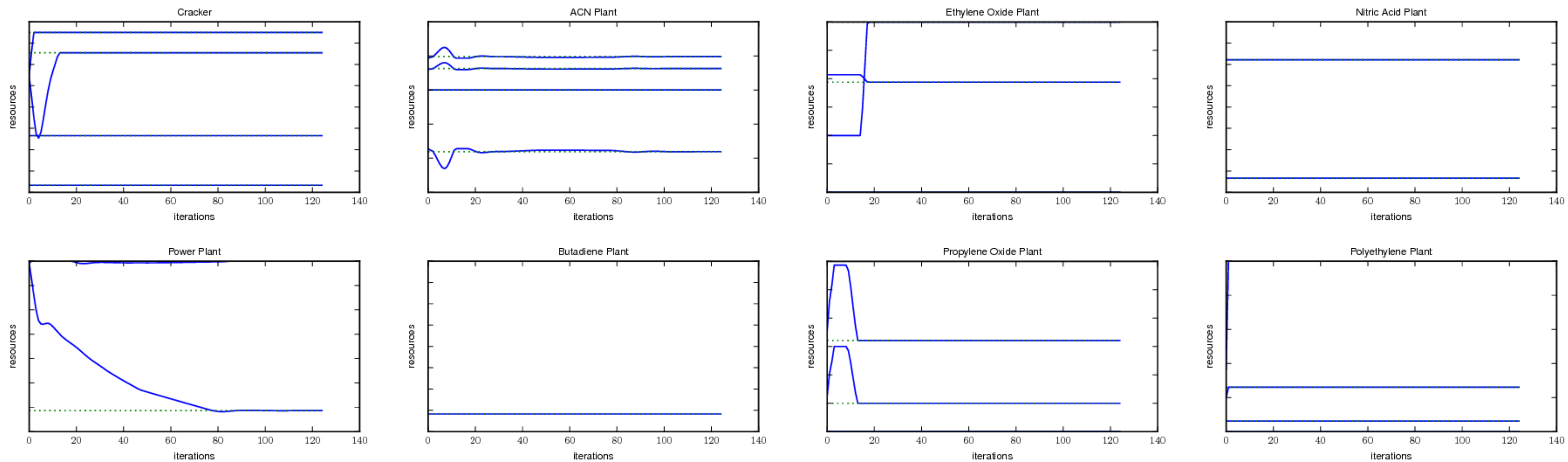
- Initial imbalance for $\lambda^0$ for all four networks
- Fast initial reduction of the imbalance
- Many iterations to fulfill the convergence criterion

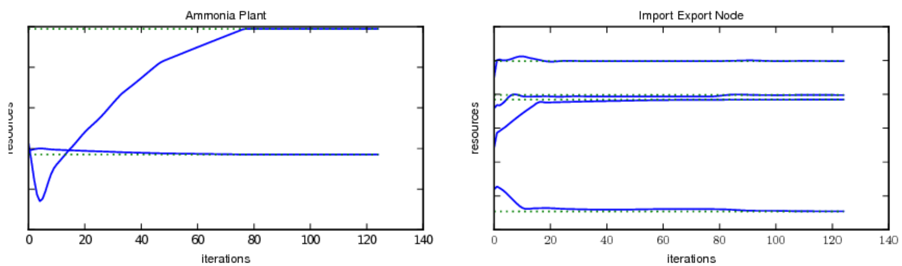
$$\left\| \sum_{i}^{n} R_i^k \right\|_2^2 < \epsilon = 10^{-3}$$



# Adjustment of resource consumption and production (1)



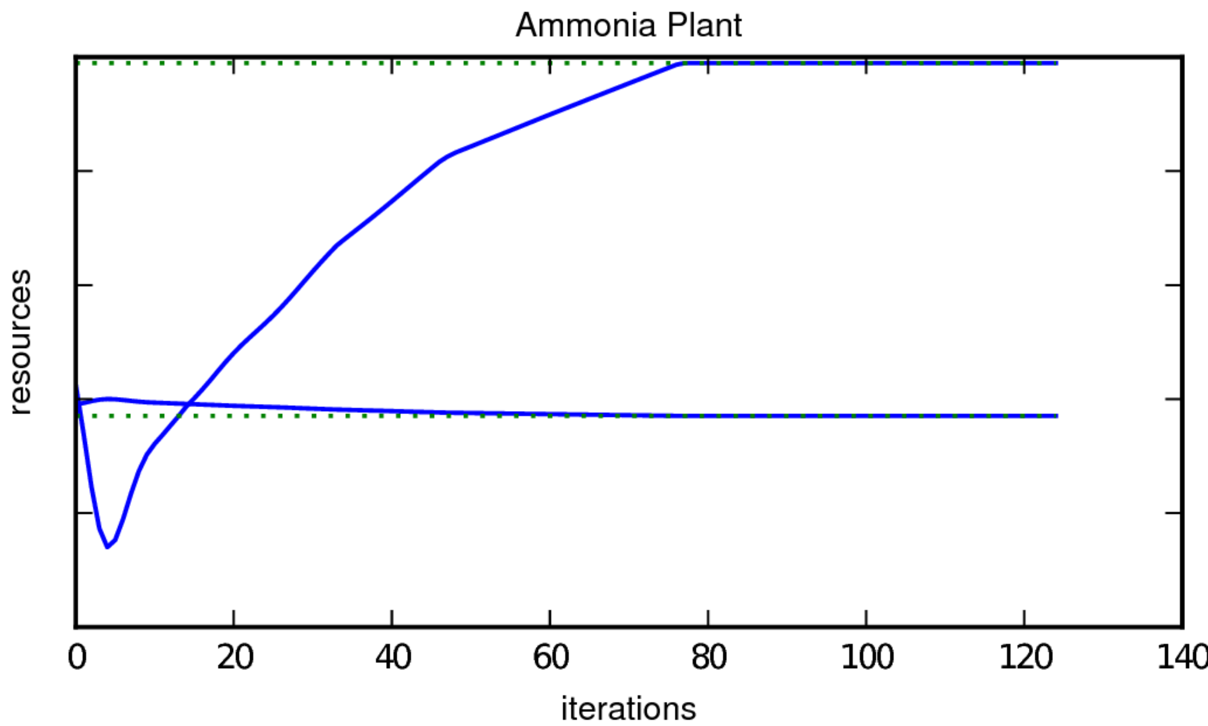




The different plants adjust their resource consumption and production as a result of changing transfer prices.
→ The neworks become balanced.

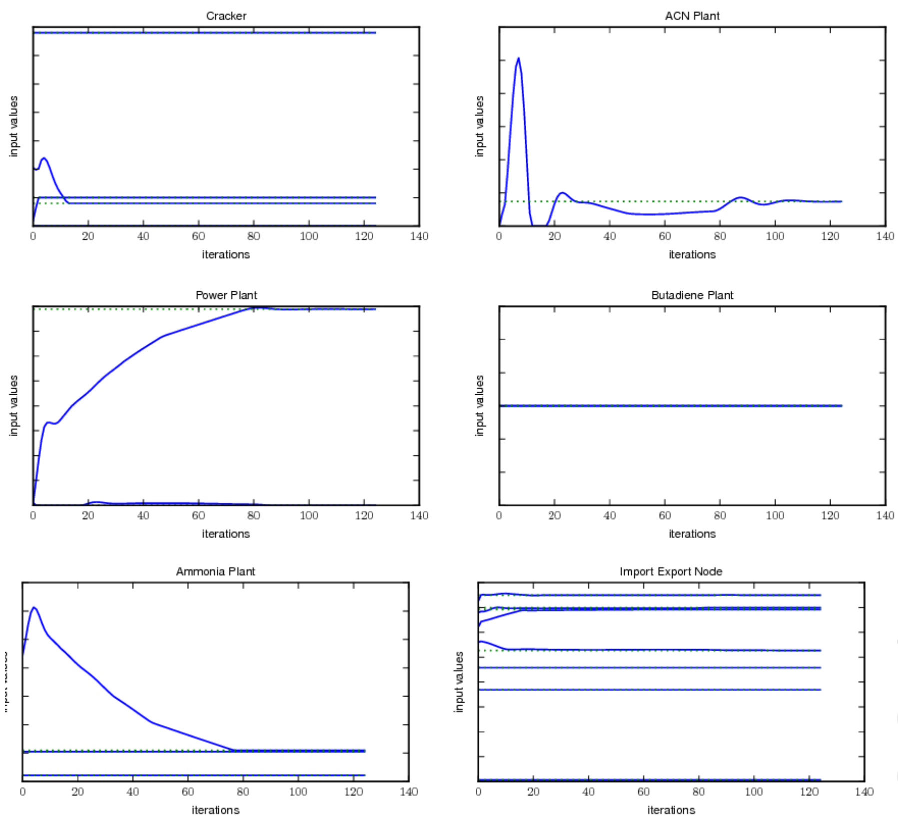
# Adjustment of resource consumption and production (2)

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 (1)

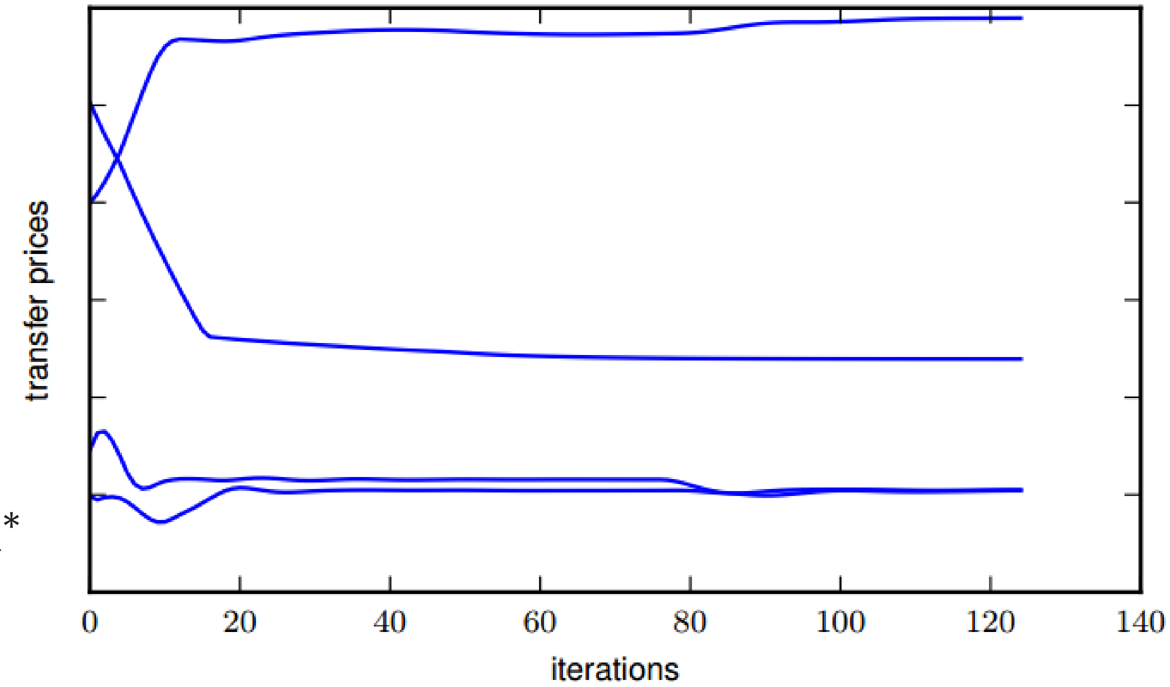



The different plants adjust their resource consumption and production as a result of changing transfer prices.
→ The neworks become balanced.

# Changes of transfer prices

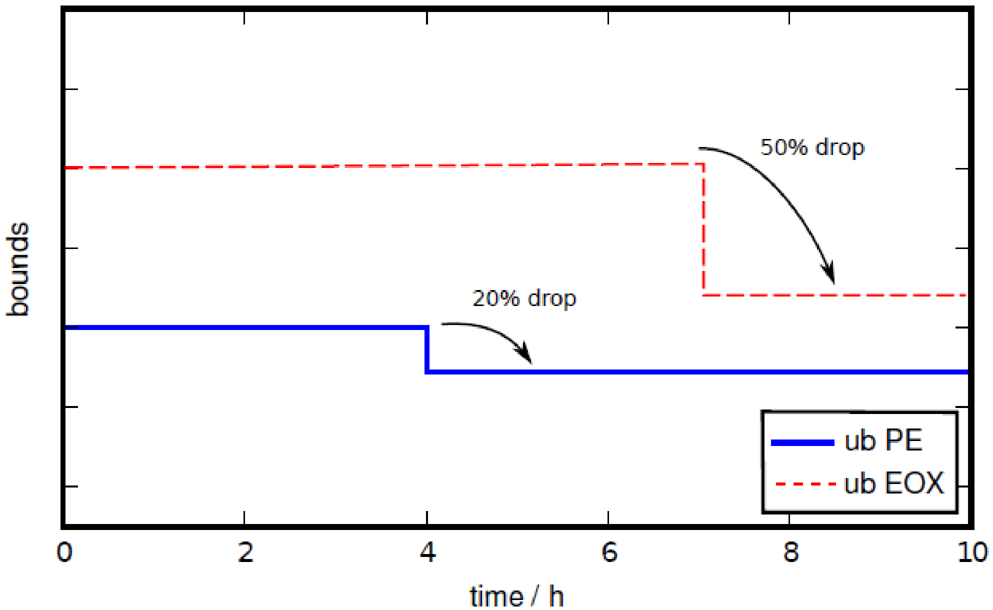
## Observations

- 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 $\lambda^*$



# Reacting to the scenario

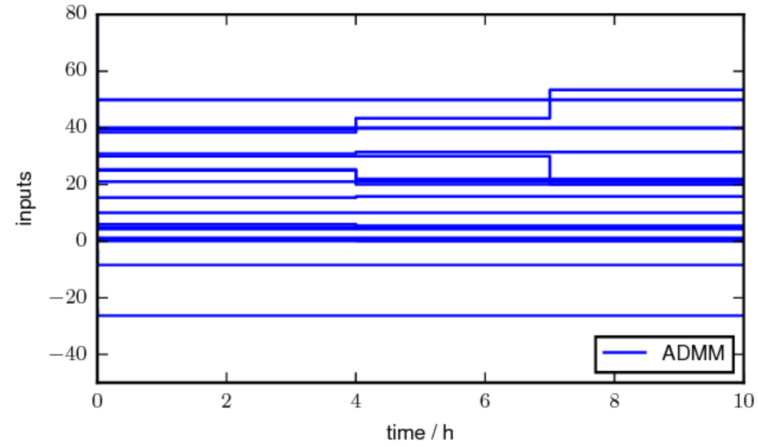
- Recoordination every hour
- After 4 and after 7 hours major changes occur
- The PE plant reduces significantly its capacity (20%)
- The C2 intake capacity of the EO plant is reduced by 50%

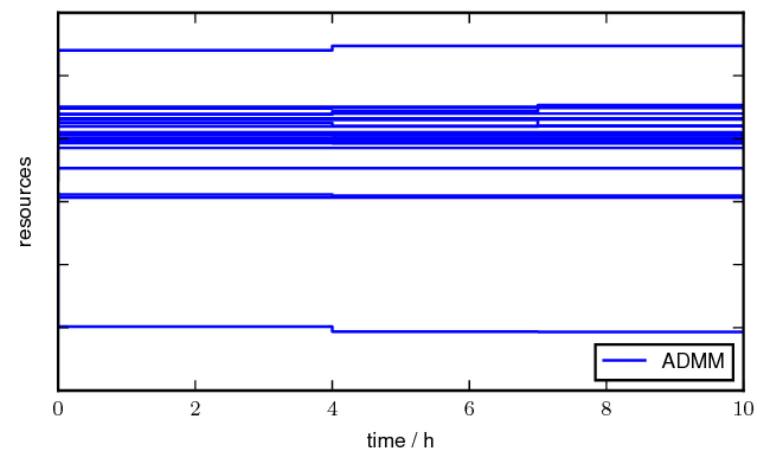



The market-based mechanism is able to balance the networks for the investigated scenario!

# Dynamic response

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



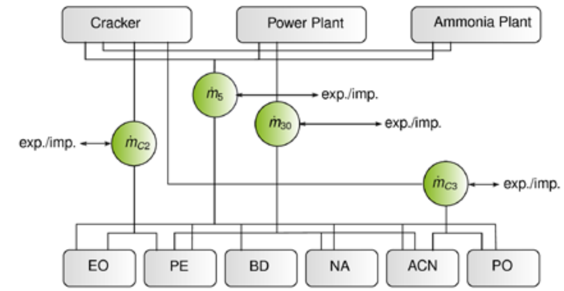



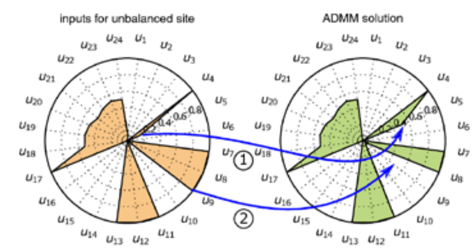

The market-based mechanism is able to balance the networks for the investigated scenario!

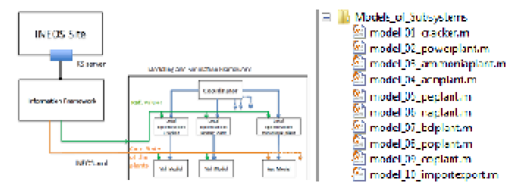
# CONCLUSIONS AND OUTLOOK

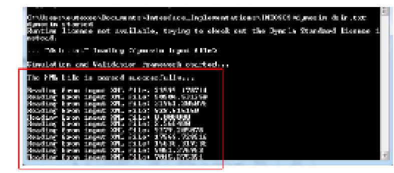
# Conclusions

- 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

- Strong industrial interest in discrete decisions (e.g., partial shutdown of single plants).
- Improve the speed of convergence (less iterations, less communication)
- Extension of the  methodology to balance resources between companies (within an industrial cluster)

New EU Project (under the last SPIRE Call):

CoPro – *Improved energy and resource efficiency by better coordination of production in the process industries*

(Start Nov. 2016)

# Thank you very much for your attention!

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# Selected DYMASOS publications


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