WP3 – Multilayer Distributed Control and Model Management

WIDE End User Panel Meeting

June 2010

SEVENTH FRAMEWORK PROGRAMME

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Workpackage at a glance

- **Model management**
  - Consistent modeling
  - Structure-respecting identification and order reduction
  - Experiment design
  - Subspace model ID for large-scale systems.

- **Distributed MPC and state estimation**
  - Decentralized MPC
  - Distributed price-coordinated MPC
  - Distributed state estimation.

- **Higher-level real-time optimization**
  - Dynamical real-time optimizers for plant-wide optimization: stability, performance and robustness
  - Optimal re-configuration of a network of distributed MPC controllers
  - Algorithms for distributed optimization of large-scale problems.

- **Prototyping and concept integration**
  - Matlab toolbox with core algorithms
  - Prototypes for DEMO
  - Support for integration with other work-packages.

Model management

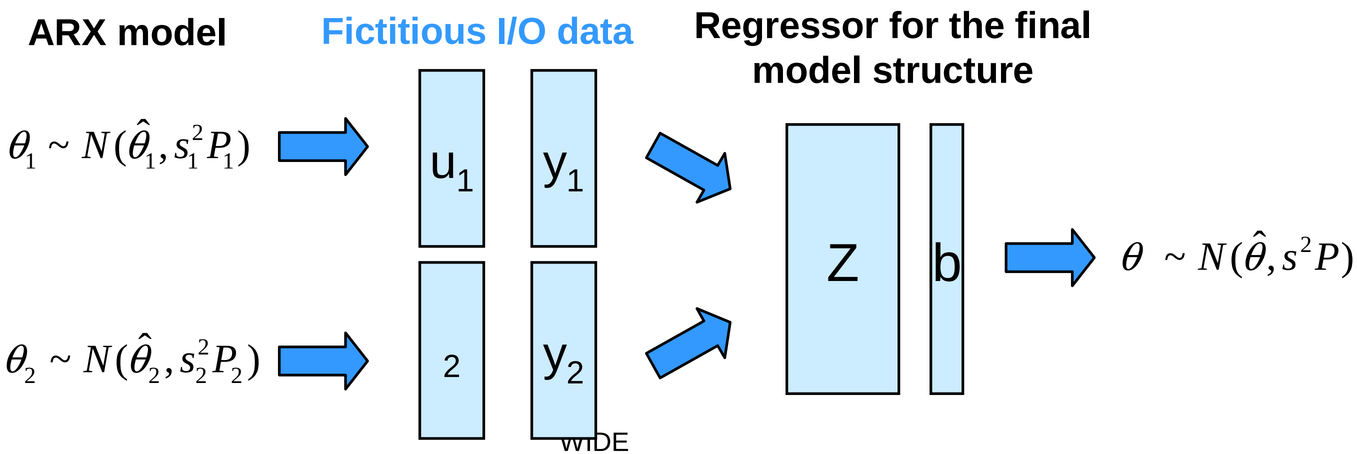
Model management

- **Objective:** modeling framework for large-scale hierarchical / distributed control and optimization
  - Models for control and optimization at different levels of decision/making
  - Different levels of fidelity (bandwidth, operational range) suitable for a particular purpose.
  - Consistent to each other
  - Uncertainty estimates to be available for robust control design

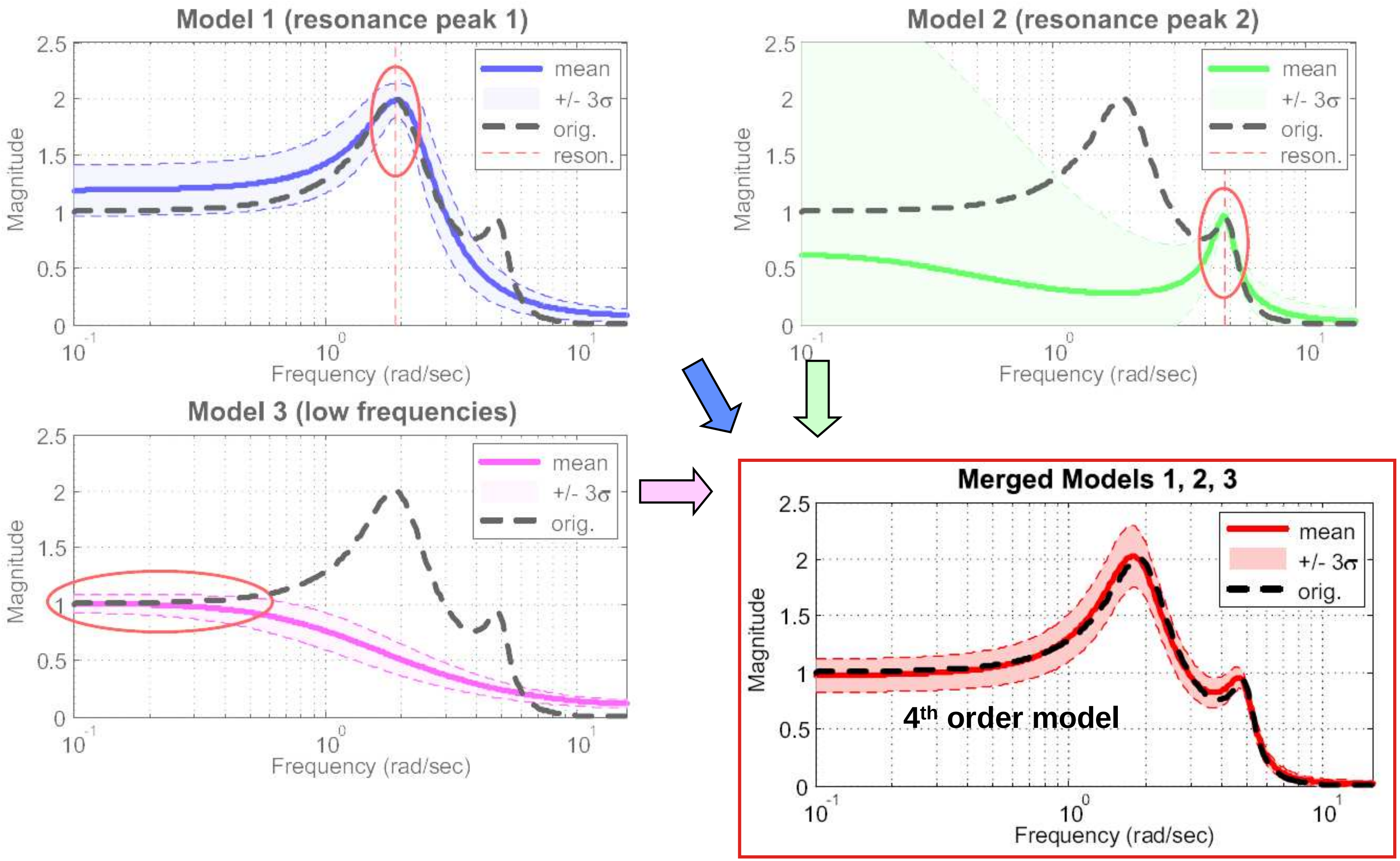
- **Issues:** model identification and order reduction in large-scale interconnected systems
  - Managing complexity
  - Exploiting *a priori* known structure
  - Designing identification experiments to obtain optimal models for a specific control purpose

Model merging 1

- **System ID of large-scale interconnected systems**
    1. Identifying subsystems
    2. Connect sub-models
- **Challenges**
    - Correct interconnections of sub-models (considering cross-correlations)
    - Consistent handling of overlaps in identified models
- **Merging ARX models of the same process**
    - Different model orders
    - Different spectra of the excitation signals – different quality of models
    - Merging not possible in parameter space
- **A novel method was obtained based on fictitious I/O data**

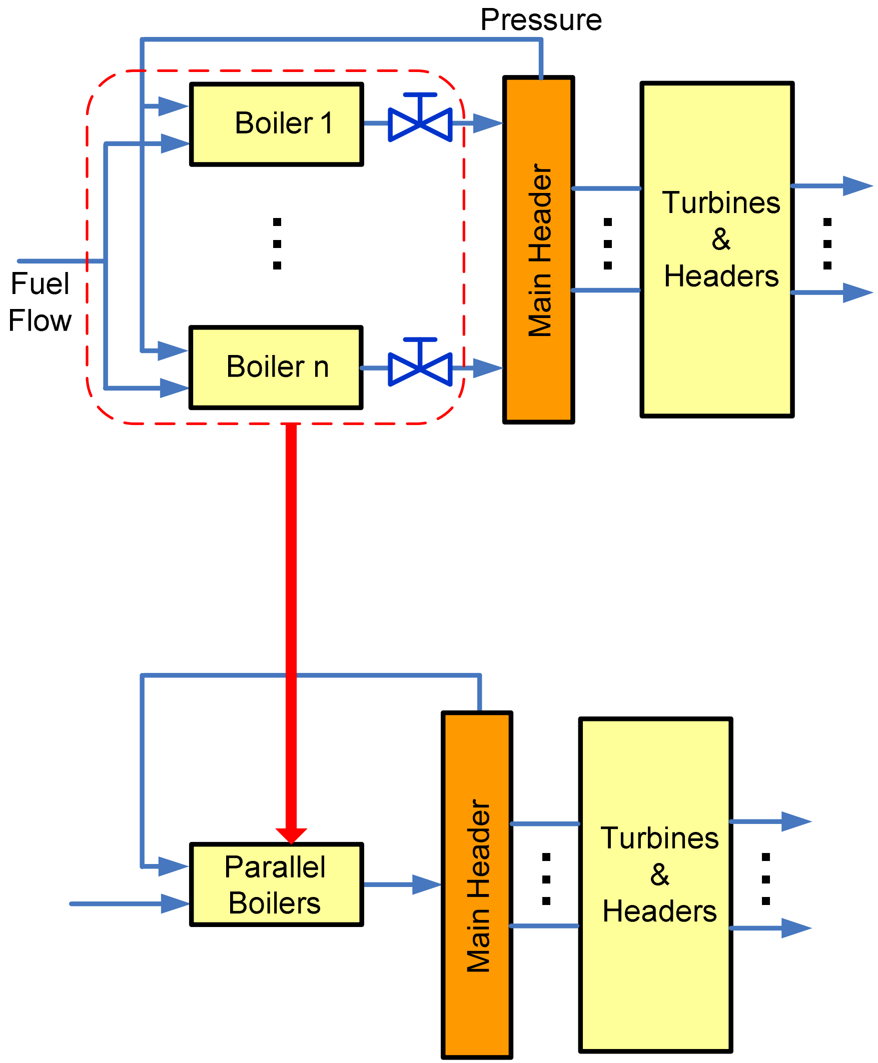


Model merging 2



Structure-respecting modeling

- **Structured order reduction**
  - Goal: obtaining reduced-order model preserving interconnection structure
  - Prior KTH result – order reduction of serial connection
  - Extension in WIDE: order reduction for parallel systems.
- **Motivation**
  - Units operating in parallel frequently occur in the industry (e.g. boilers feeding steam to a common header).
  - Not all units operate simultaneously – combinatorial number of configurations of different control models
  - A systematic procedure was proposed
- **Proposed solution outperforms non-structured reduction method and is comparable to a heuristics for boilers**



Distributed MPC and state estimation

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Distributed MPC and state estimation

- **Objectives:**
  - Developing novel methods for model-based predictive control for large-space systems
  - State-estimation for output-feedback distributed MPC.
- **Approach**
  - Distributing computational load among multiple units
  - Different schemes of inter-unit communication
    - Decentralized
    - Cooperating
    - Coordinated
- **Issues**
  - Handling complexity – limitations on computational resources
  - Control issues – stability, robustness
  - Communication issues – integration with WP4
  - Flexibility – robustness to topological changes in controlled network.

Distributed MPC

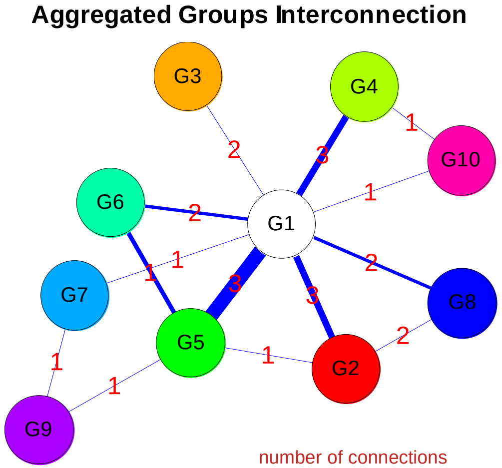
- **Decentralization based on Dual decomposition of Quadratic Programming:**
  - ***Each controller solves its own local optimization problem.***
  - Each local optimization problem includes a term related to fulfillment of coupling constraints scaled by coordinate prices.
  - The ***coordinator*** manipulates prices in order to minimize the disagreement on coupling constraints.
  - Under convexity assumption, equilibrium prices are found that all coupling constraints are achieved and the ***global optimum is reached***.

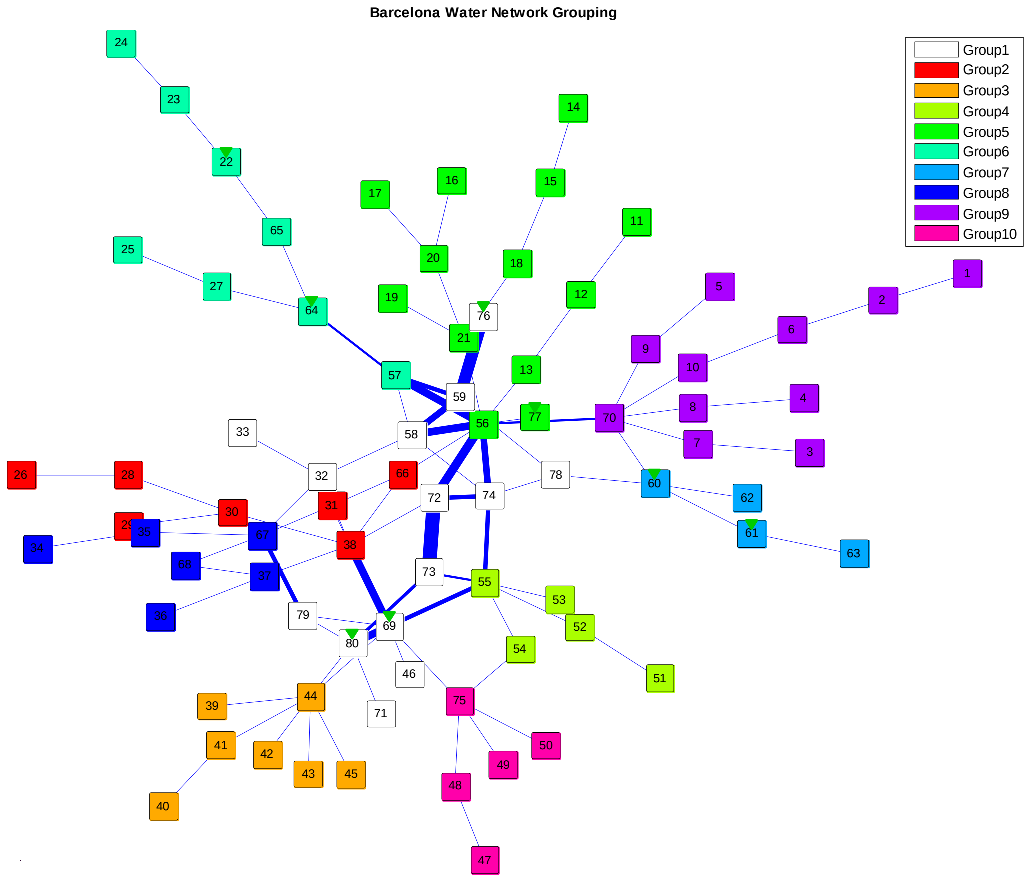
- **Iterative algorithm (~10^2 iterations in 1 sampling period)**
  - Trading high computational load for large data exchange
  - **Suitable for slow processes as water networks**

- **Coordination algorithm**
  - **Centralized** (hierarchical architecture) – faster convergence
  - **Decentralized** (peer-to-peer communication) – slower but tolerant to topology changes

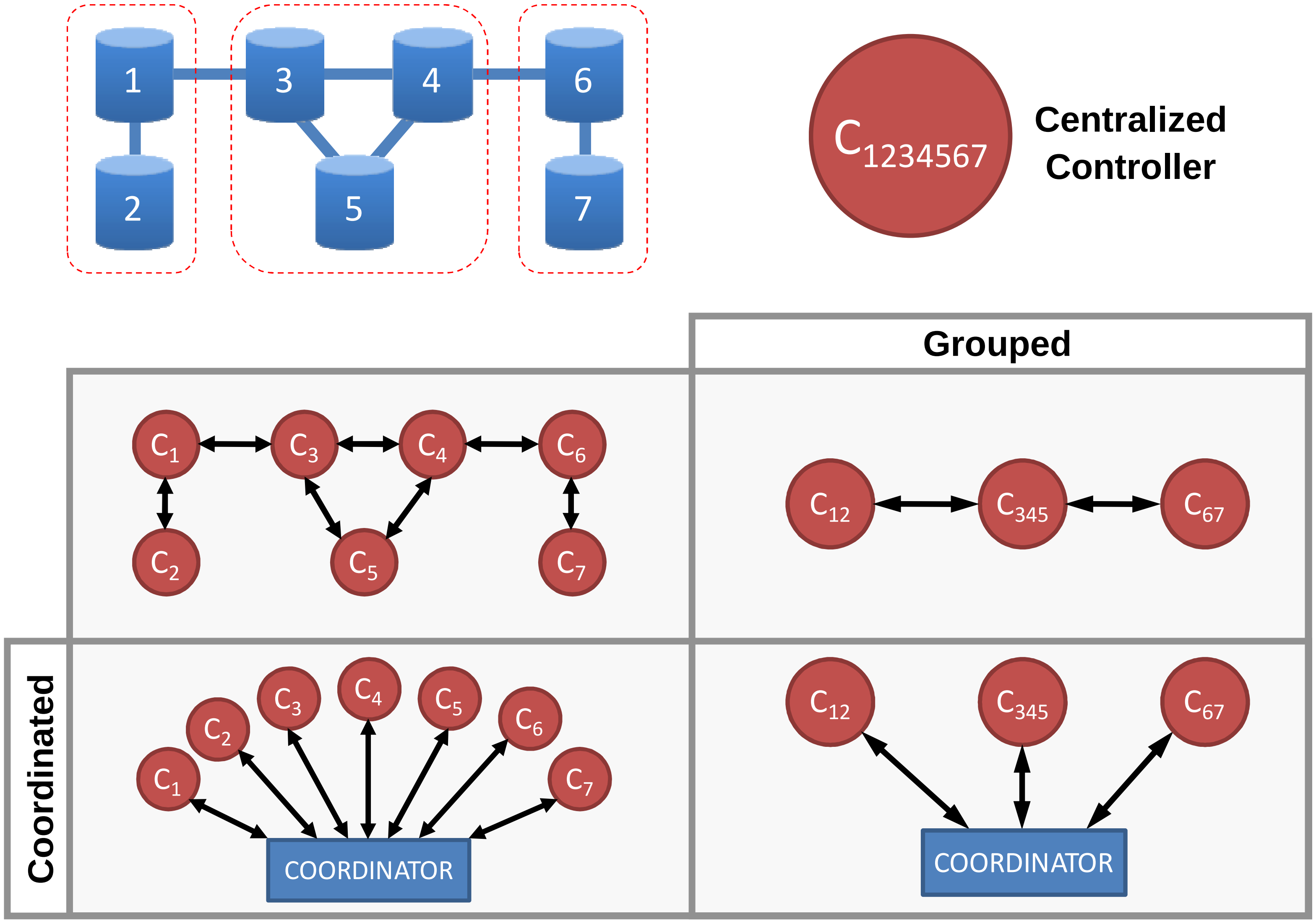
Distributed MPC – water network example

- **Network decomposition**
  - **WN → graph** (edge weight ~ pumping capacity between tanks)
  - **Step 1:** Condensation of leaves (condense all leaves with parents)
  - **Step 2:** Epsilon decomposition of the remaining network

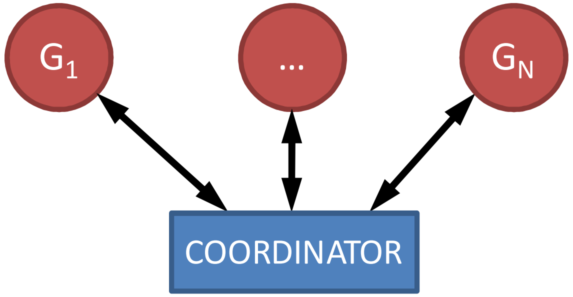




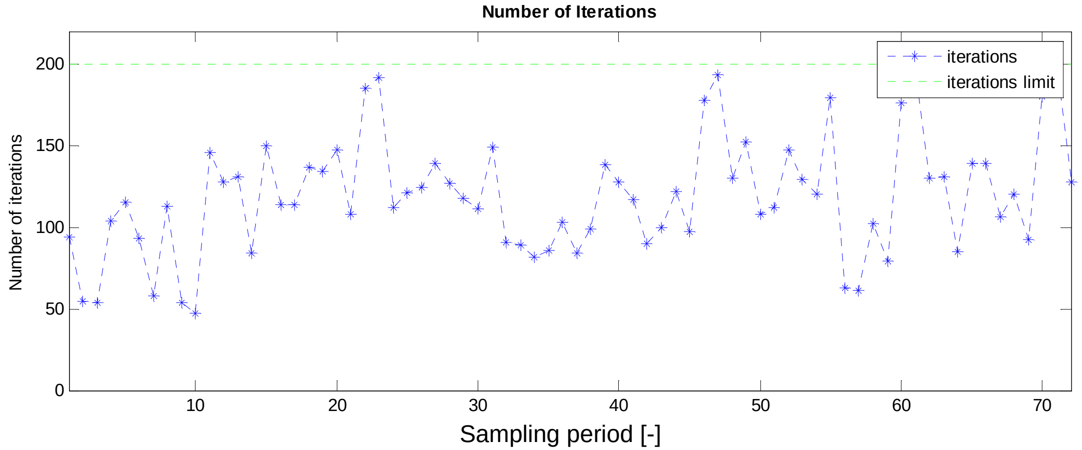
Architectures for distributed control

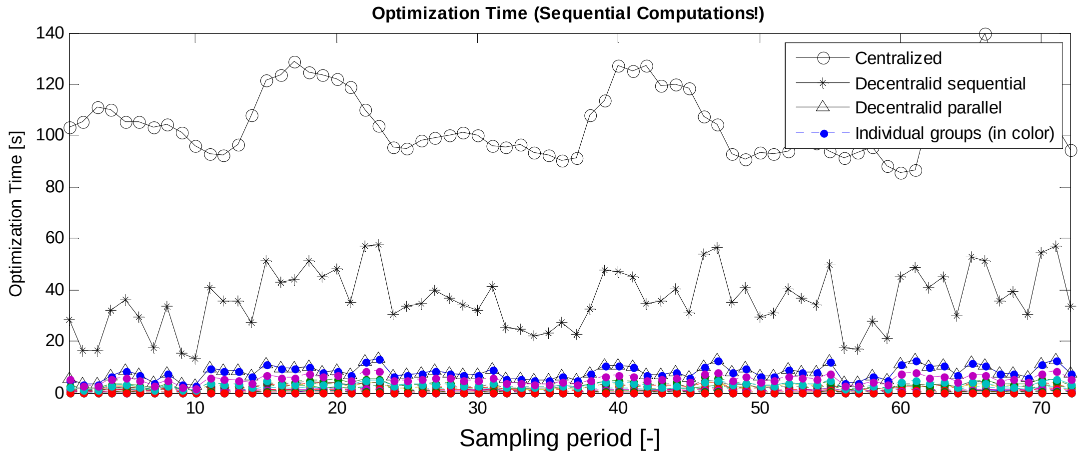


Distributed MPC – central coordinator



- **19 subsystems**
- **Central coordinator**
  - Quasi-Newton L-BFGS
- **Stopping condition:**
  - worst consensus error < 1 m^3/hrs





Sub-problem sizes:

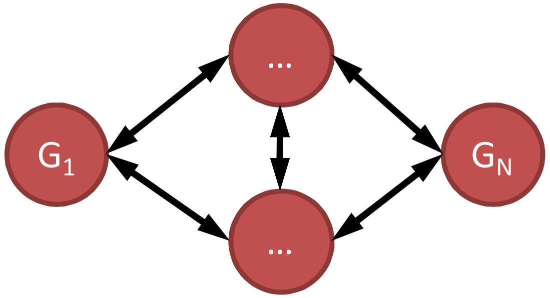
Group 1:
- Number of variables = 220
- Non-equality constraints = 440

Group 2:
- Number of variables = 140
- Non-equality constraints = 280

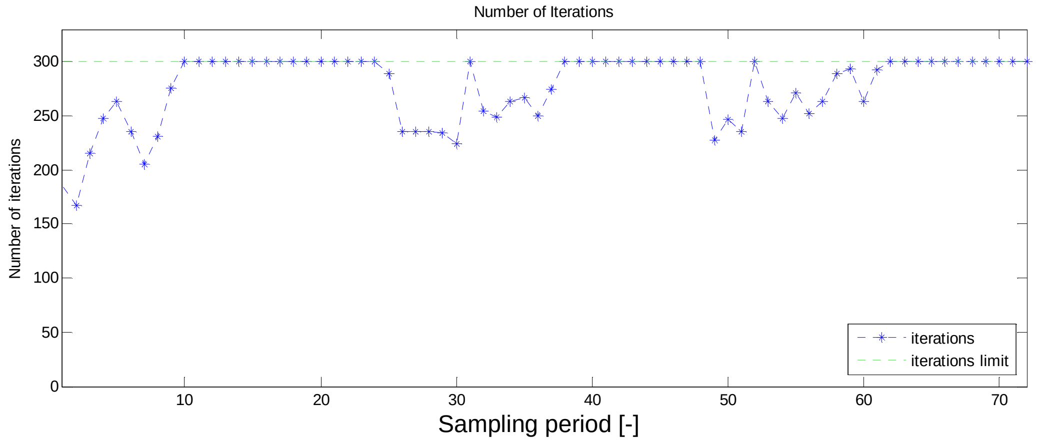
Group 3:
- Number of variables = 150
- Non-equality constraints = 300

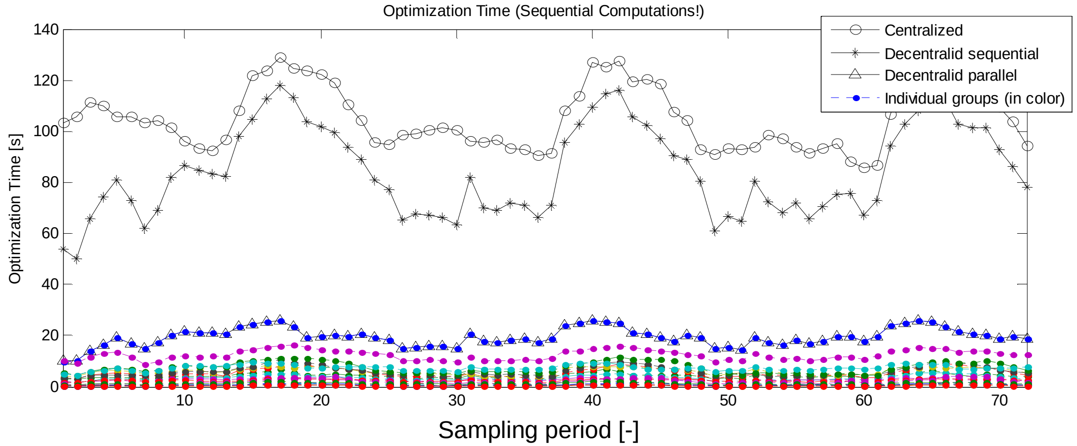
…

Distributed MPC – decentralized coordinator



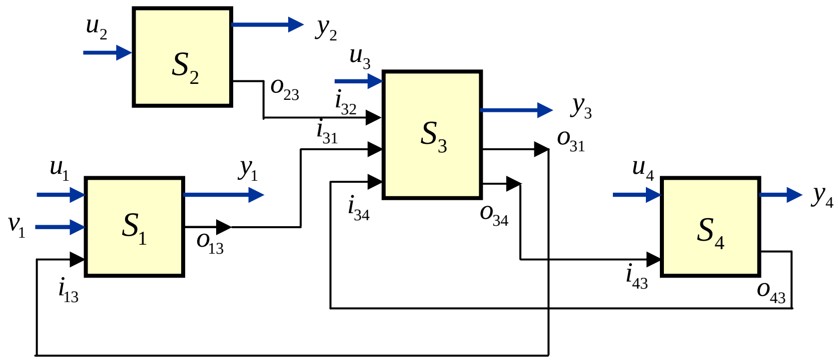
- **19 subsystems**
- **Local controllers communicate only with their neighbors**
- **Price coordination:** Projected Nesterov gradient method



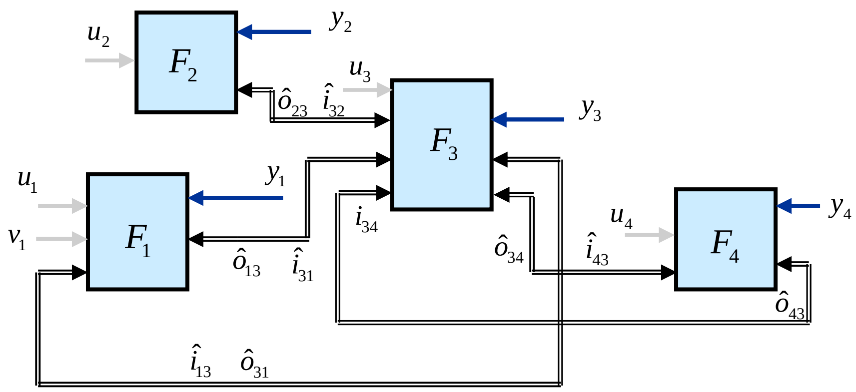


Distributed state estimation

- **Motivation:** replacing state measurements in output-feedback distributed control.

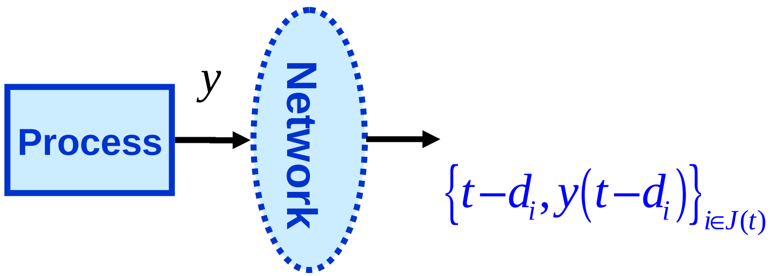


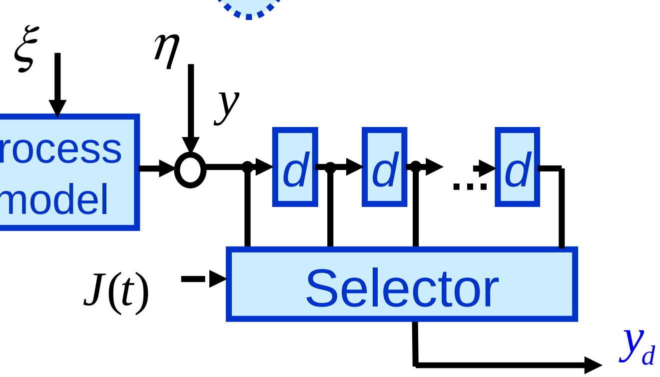
- **Proposed solution:** Kalman filter network
  - topology corresponding to the process interconnection map.
  - Small overlap in locally estimated variables.
  - Local agents know only a part of the overall model
  - Generally sub-optimal (relative to the centralized Kalman filter).
  - Re-configurability, robustness to changes in network topology.



Kalman filter for systems with communication delays 1

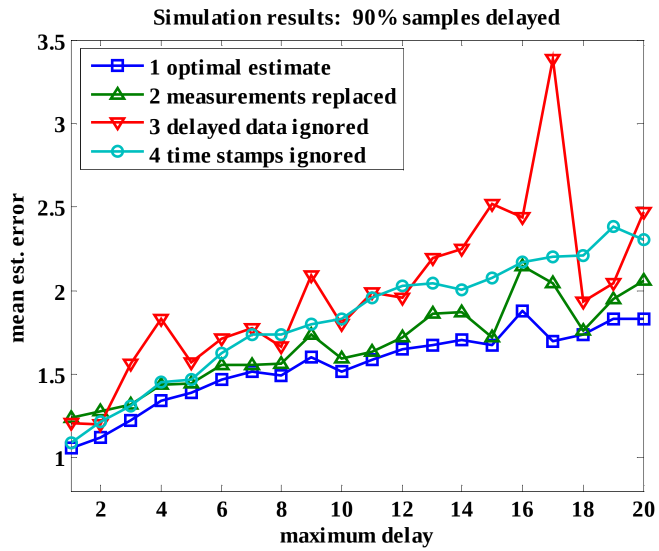
- **Process data transmitted over the network**
  - Delayed and lost packets.
- **Assumptions**
  - Delays in integer multiples of sampling intervals
  - Data transmitted with the time stamps.
- **Optimal estimator** – time varying Kalman filter for system augmented by a chain of delays
  - Finite length; longer delays → lost data
  - Samples may arrive out of order, with several different time-stamps at a time.
- **New implementation of KF for this class of systems** – lower computational demand
  - A set of pre-computed gains
  - Recasting Riccati eqn into a dynamical equation of a reduced-rank matrix factor

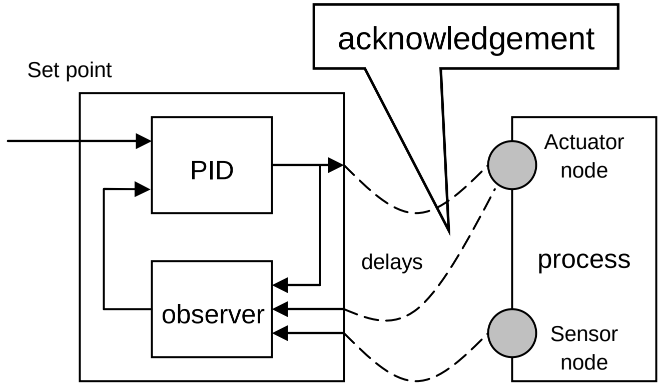




Kalman filter for systems with communication delays 2

- ***Time-varying Kalman*** filter
  - computationally expensive for DCS
- Proposed **suboptimal solution**:
  - Missing values are replaced by estimates.
  - When the missing value arrives, the effect of value replacement is removed and the optimality recovered.
- A generalization:
  - Estimator is optimal when less then N samples is missing.
  - Pre-computed gains for each combination of missing samples
- On-line computational complexity
  - moderate increase relative to asymptotic KF





Higher-level RTO

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Higher – level RTO

- **Objectives**
  - ***Framework for robust integrated plant-wide control and optimization***
- **Going beyond the classical steady-state economic optimizer paradigm**.
  - Optimizer computes optimal set-points/steady state targets.
  - Subordinate MPC is responsible for achieving these targets.
- ***Dynamic optimizer*** is needed for better responsiveness to demands
  - Transitions is costly and/or result in off-specs products
  - Significant delays, storages and recycle loops between units controlled by MPC.
- **Issues**
  - Stability and robustness of the interlayer integration considering feedback spanning several layers.
  - Uncertainty handling in the hierarchical framework and worst case control.
  - Integrating a centralized hybrid MPC – optimizer (higher level) and decentralized linear MPC (lower level).