Industrial applications of large-scale and distributed optimization

HYCON2 Workshop on Distributed Optimization in Large Networks and its Applications,
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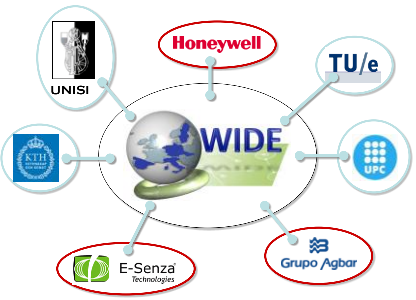
Automation and Control Solutions
ACS Global Laboratory Prague

Outline

- **Large-scale distributed networked systems**
- **Water distribution network optimization**
  - **Hierarchy**
  - **Control objectives & problem formulation**
  - **DMPC for transport layer**
- **Application with AGBAR Barcelona network**
  - **Benefit evaluation tool**
  - **Real-time closed loop DMPC demo**
    (EU FP7 WIDE project)
  - **Conclusions**



Large-scale Networked Systems

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Typical large-scale networked systems

- Water / gas distribution networks
- River cascade dams control
- Electricity distribution – current smart grid solutions are variations on presented methods
- Logistic problems (integer optimization)

Control solution

- Suitable for Model Predictive Control (MPC)
- **Translates to QP for linear dynamic process models**
- **Computation complexity grows quickly with problem size**

Water Network Control Center
AGBAR Barcelona

Water supply management

Water treatment layer

- Mechanical / chemical / biological water treatment
  - Different water quality
  - Different processing cost

Water transport layer

- Transport to storage tanks (water towers)
- Control of pumping stations and valves
  - Pumping cost
  - Periodic demand
  - Limited storage capacity

Water distribution layer

- Distribution to end users
  - Control of pressure reducing valves and booster pumps
  - Major losses occur here

Sewage water collection and treatment

- Similar hierarchy

Control technology (i)

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Water treatment layer

- Continuous process control methods
  - Large time constants
  - Large storage capacity
  - Cumulative constraints on availability

Water transport layer

- Networked control problem
  - Typical sampling interval 1 hour
  - Control / optimization horizon up to 1 week
    (need to capture periodic demand, varying electricity tariffs, varying production costs, impact on water quality (storage, ageing)
- Current solution
  - Heuristic control law with operator interventions
- Next generation solution
  - Large-scale spatially distributed control & optimization problem
  - Can be solved by distributed MPC
  - Complex optimization criteria embedded

} … this talk

Control technology (ii)

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Water distribution layer

- **Network control problem**
  - **Sampling period < 1 second (pressure control = stiff problem)**
- **Current solution**
  - **PLCs /mechanical PRVs with several preprogrammed pressure levels (day/night) in the distribution network feeding points (Pressure Reducing Valves)**
- **Next generation solution**
  - **Active pressure zone control**
    - Closed loop, multivariable solution
    - Flow / pressure sensor network
  - **Network monitoring and data reconciliation**
    - Introduction of smart sensors
  - **Leaking detection and failure recovery to minimize water losses**
    - Detect abrupt changes (bursts) as well as background losses (drift)
    - Bottom-up approach - pressure zone modeling
    - Top-down approach - balancing individual metered areas

Barcelona Water Distribution Network

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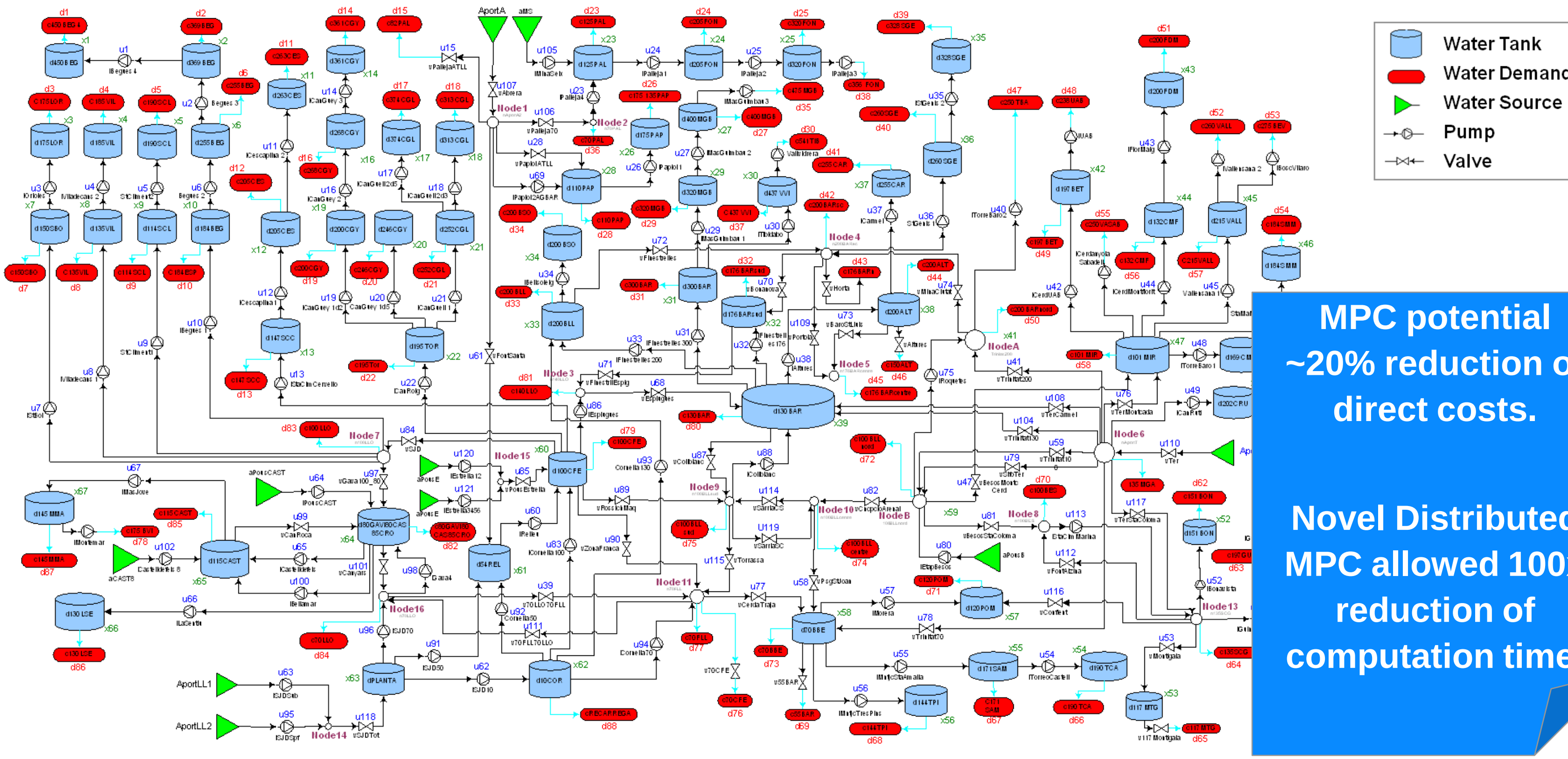

MPC potential ~20% reduction of direct costs.

Novel Distributed MPC allowed 100x reduction of computation time.

Network Size

- **70 tanks**
- **110 pumps/valves**
- **80 demands (disturbances)**
- **9 water sources**
- **1 hour sampling time**
- **24-48 step prediction**
- **5000 - 10000 variables**

Barcelona Water Distribution Network

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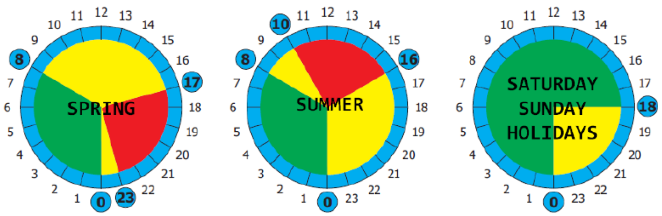
CONTROL OBJECTIVES

- **Satisfaction of water demand (avoid exceeding tank safety limits – range control)**
- **Minimization of operation costs**
- **Manipulated variables**
  - **pump flows**
  - **valve flows**
  - **water sources production**

Tank and pumping station

OPTIMIZATION POTENTIAL

- **Time varying electricity price during the day**
- **Different costs of water sources (rivers, wells, etc.)**
- **Multiple possible routes from sources to consumers**
- **Operation costs can be mainly reduced**
  - **Using network storage capacity by pumping in the periods of cheap electricity**
  - **Optimal routing of water from sources to tanks and blending**



Electricity price patters during different days

Barcelona Water Distribution Network

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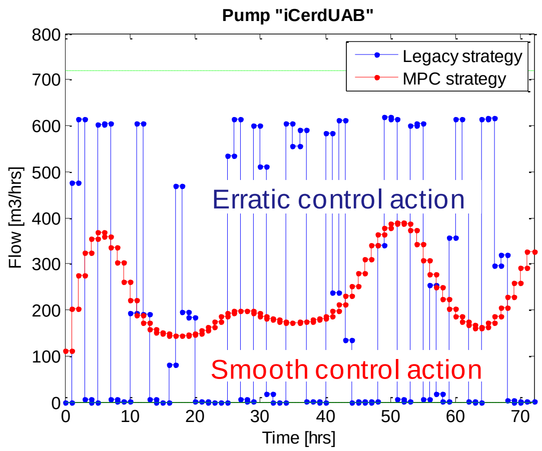
Indirect costs

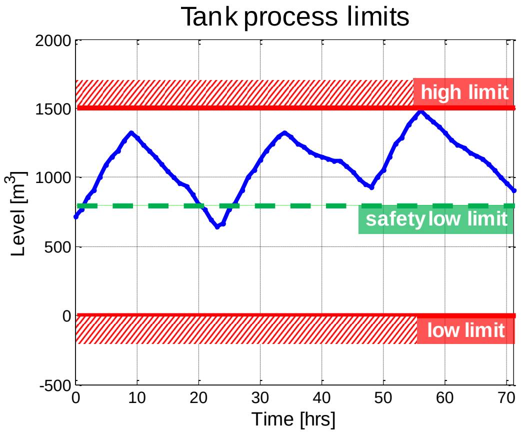
- **Reduction of large set point changes for pumps, valves and water sources:**
  - **Reducing pressure surges (leakage prevention)**
  - **Reducing equipment tear & wear**
- **Water ageing – long water storage degrades its quality and requires additional chlorination**



Smooth vs. erratic pump control action

Constraints

- **Hard constraints**
  - **Actuator limits & rate-of-change limits**
  - **Pumps, valves and water sources**
- **Soft constraints**
  - **tanks minimum safety limits**
- **Constraints are time variable (maintenance, failures)**



Soft safety limits

MPC problem formulation

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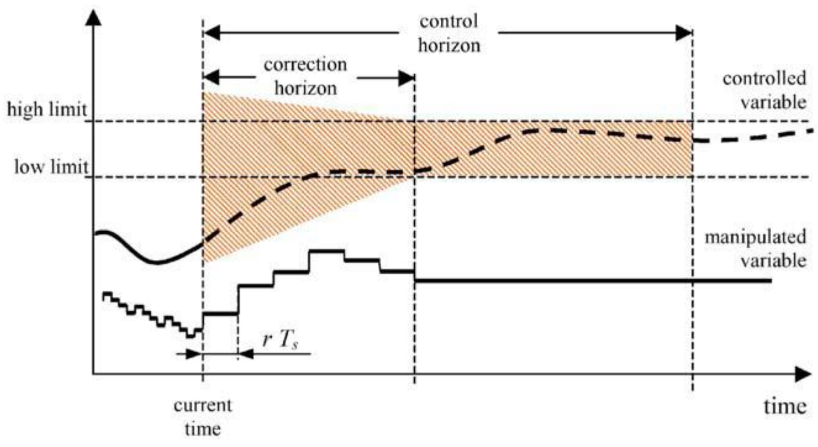
Basic MPC problem

- *K*-step ahead prediction horizon
- Reference tracking
- Hard constraints on MV, ΔMV
  (all constraints can be time varying)

$$\min_{u_1,\dots,u_K} \sum_{k=1}^{K} (y_k - r_k)^T Q_k (y_k - r_k) + \Delta u_k^T R_k \Delta u_k$$

$$u_L \le u_k \le u_H; \quad \Delta u_L \le \Delta u_{t+k} \le \Delta u_H$$



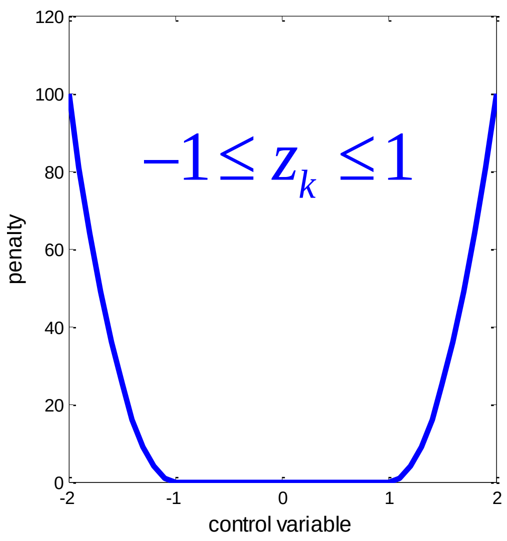
Range control concept

- Soft constraints on CVs
- Auxiliary variable z_k
- Additional degree of freedom for optimization

$$\min_{\substack{u_1,\dots,u_K \\ z_1,\dots,z_K}} \sum_{k=1}^{K} (y_k - z_k)^T Q_k (y_k - z_k) + \Delta u_k^T R_k \Delta u_k$$

$$u_L \le u_k \le u_H; \quad \Delta u_L \le \Delta u_{t+k} \le \Delta u_H$$

$$y_L \le z_k \le y_H$$



MPC problem formulation

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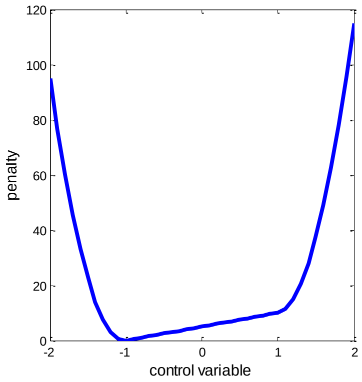

Additional “economic” cost terms (linear)

- Pumping cost – time varying electricity tarif
- Water sources cost
- Water aging / storage cost

$$\min_{\substack{u_1,\dots,u_K \\ z_1,\dots,z_K}} \sum_{k=1}^{K} (y_k - z_k)^T Q_k (y_k - z_k) + \Delta u_k^T R_k \Delta u_k + C_k^P u_k + C_k^W u_k + C_k^S (y_k - y_L)$$

$$u_L \le u_k \le u_H; \quad \Delta u_L \le \Delta u_k \le \Delta u_H$$

$$y_L \le z_k \le y_H$$

Optimization problem

- Use current state, control sequence $u_1, \dots, u_K$ and predicted disturbance sequence $d_1, \dots, d_K$ to calculate controlled variables $y_1, \dots, y_K$
- Substitute into criterion
- Resulting problem
  - (Large scale) quadratic programming
  - Can be solved in distributed way

Approach: dual decomposition

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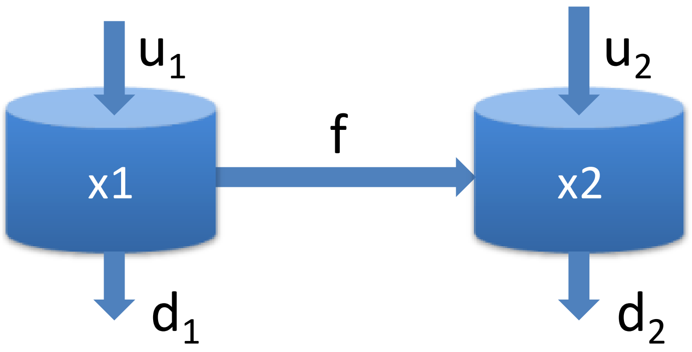
Distributed MPC problem

$$\min_{u_1,u_2,f} J(u_1,u_2,f) = \min_{u_1,f} J_1(u_1,f) + \min_{u_2,f} J_2(u_2,f)$$

$$\underline{u}_i \le u_i \le \overline{u}_i,\ \underline{f} \le f \le \overline{f},\ \underline{x}_i \le x_i \le \overline{x}_i$$



Duplicating complicating variable *f*

$$\min_{u_1,u_2,f_1,f_2} J_1(u_1,f_1) + J_2(u_2,f_2) \qquad \text{s.t.} \qquad f_1 = f_2$$

Lagrangian

$$L(u_1,u_2,f_1,f_2,\lambda) = J_1(u_1,f_1) + J_2(u_2,f_2) + \lambda^T(f_1 - f_2)$$

Dual function

$$g(\lambda) = \min_{u_1,u_2,f_1,f_2} L(u_1,u_2,f_1,f_2,\lambda) = g_1(\lambda) + g_2(\lambda)$$

can be separated

$$g_1(\lambda) = \min_{u_1,f_1} J_1(u_1,f_1) + \lambda^T f_1$$

$$g_2(\lambda) = \min_{u_2,f_2} J_2(u_2,f_2) - \lambda^T f_2$$

Optimal solution (saddle point theorem) – "shadow price"

$$\lambda^* = \arg\max_{\lambda} g(\lambda)$$

Two Tanks Example

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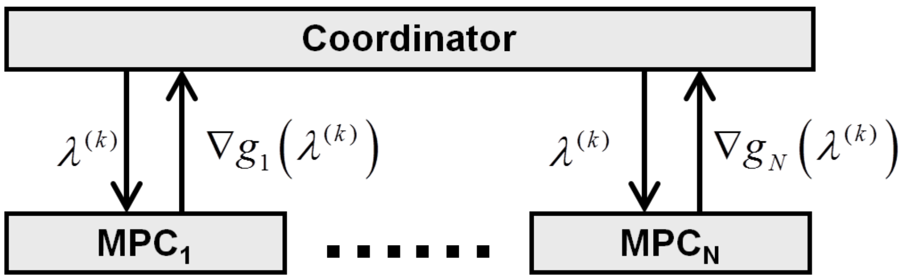
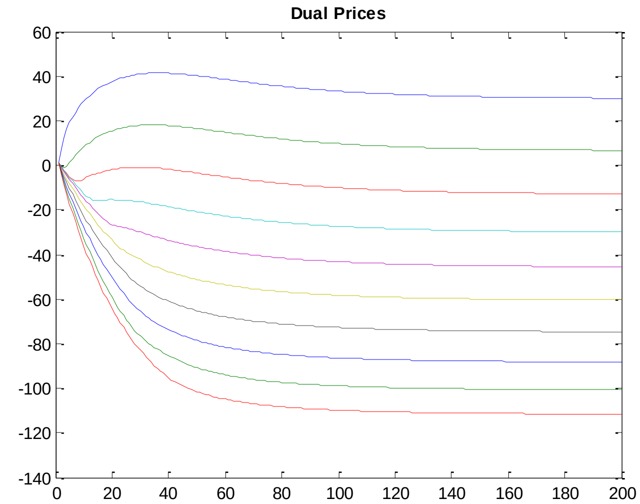
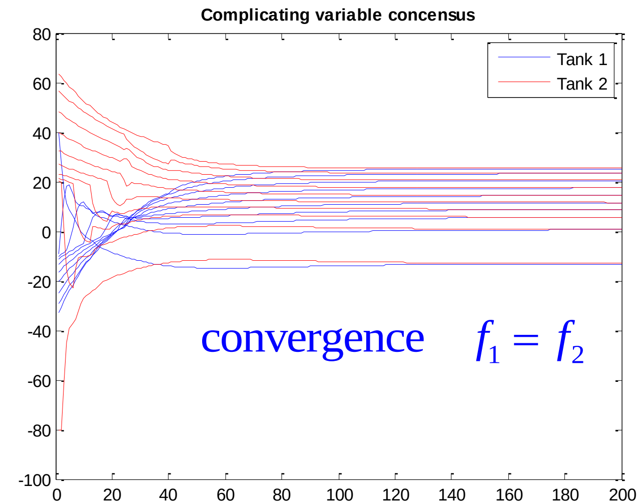
Maximizing dual function (grad. method)

$$\lambda^{(k+1)} = \lambda^{(k)} + \alpha^{(k)} \left(\frac{\partial g_1}{\partial \lambda} + \frac{\partial g_2}{\partial \lambda} \right) \Bigg|_k \quad \frac{\partial g_1}{\partial \lambda}\Bigg|_k = f_1^{(k)*} \quad \frac{\partial g_2}{\partial \lambda}\Bigg|_k = -f_2^{(k)*}$$







- **MPC control horizon *K* = 20**
- **Simple gradient method**
  - **High number of iteration (~ 200)**
- **Large improvement**
  - **Nesterov accelerated gradient method**
  - **Still too many iterations for Barcelona sized network**

Price coordination

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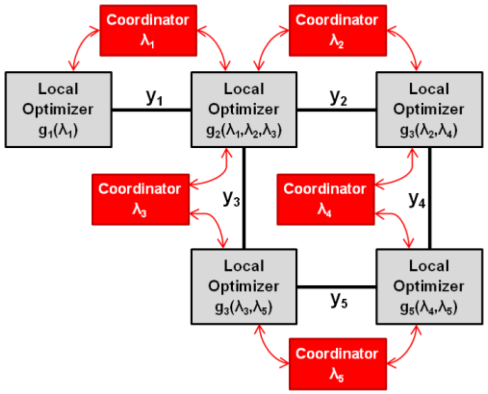
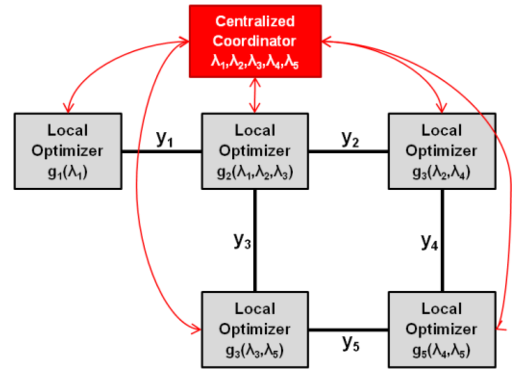
$$\max_{\lambda} g(\lambda), \qquad g(\lambda) = \sum_i g_i(\lambda)$$





LOCAL (distributed)

- **Gradient method exploiting problem structure (components computed locally)**
- $$\frac{\partial g}{\partial \lambda_3} = \frac{\partial g_2}{\partial \lambda_3} + \frac{\partial g_3}{\partial \lambda_3}$$
- **Computing derivatives requires to solve local sub-problems for given *λ***

$$\left.\frac{\partial g_i}{\partial \lambda}\right|_k = f_i^{(k)*}$$

CENTRALIZED

- **Captures the multivariable problem (interactions between λ_i)**
- **Significantly improved convergence**
  - **Newton type methods**
  - **Quasi-Newton type methods**
  - **Structure: local optimizers provide components of Hessian**
- **Requires centralized communication**
- **Coordinator computation complexity**

Parametric price coordination

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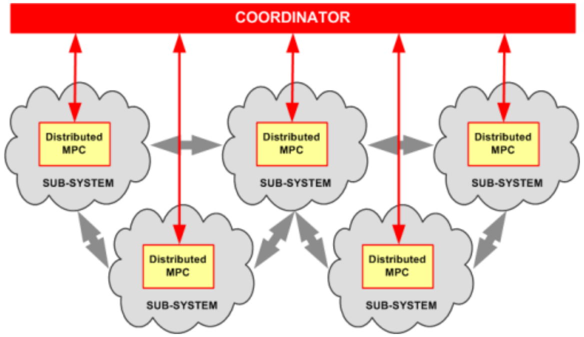
- **For LQ problem, local dual functions are piece-wise quadratic on polytopic regions**
- **Local controllers provide quadratic parameters valid in current polytopic region**



$$g_i(\lambda) = \lambda^T A_i \lambda + b_i^T \lambda + c_i \quad s.t. \quad \lambda \in P_i$$

- **Optimal local solution is affine in current region**

$$\begin{bmatrix} x_i^*(\lambda) \\ f_i^*(\lambda) \end{bmatrix} = F_i \lambda + g_i \quad \text{for} \quad H_i \lambda \le k_i$$

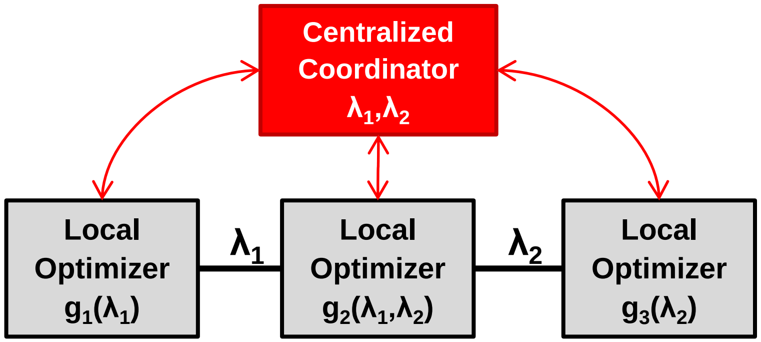
- **Optimal dual solution can be obtained in single step if feasible**

$$\nabla^2 g(\lambda_k) v_k = -\nabla g(\lambda_k) \quad \text{such that} \quad \lambda_k + v_k \in \bigcap P_i$$

otherwise use damped Levenberg-Marquardt

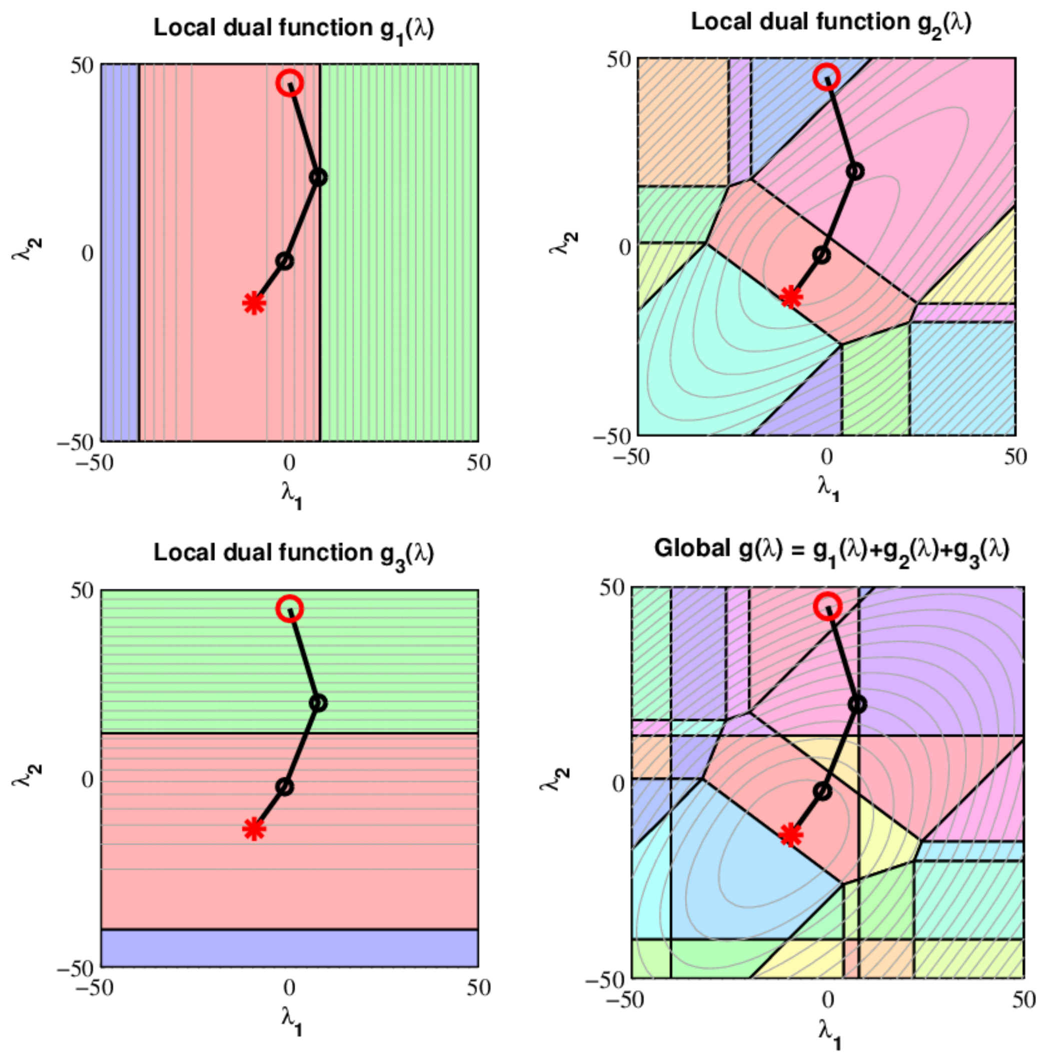
$$\left(\varepsilon I + \nabla^2 g(\lambda_k)\right) v_k = -\nabla g(\lambda_k)$$

Parametric coordination – example



$$g(\lambda) = g_1(\lambda) + g_2(\lambda) + g_3(\lambda)$$

$$\max_{\lambda} g(\lambda)$$



- **Illustration of the local dual functions composition**

- **Coordinator can use this fact to improve convergence and reduce communication load**

Parametric coordination – example

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- **Local controllers return quadratic parameters and their polytopic validity region around given price vector (local solution)**

$$g_i(\lambda) = \lambda^T A_i \lambda + b_i^T \lambda + c_i$$

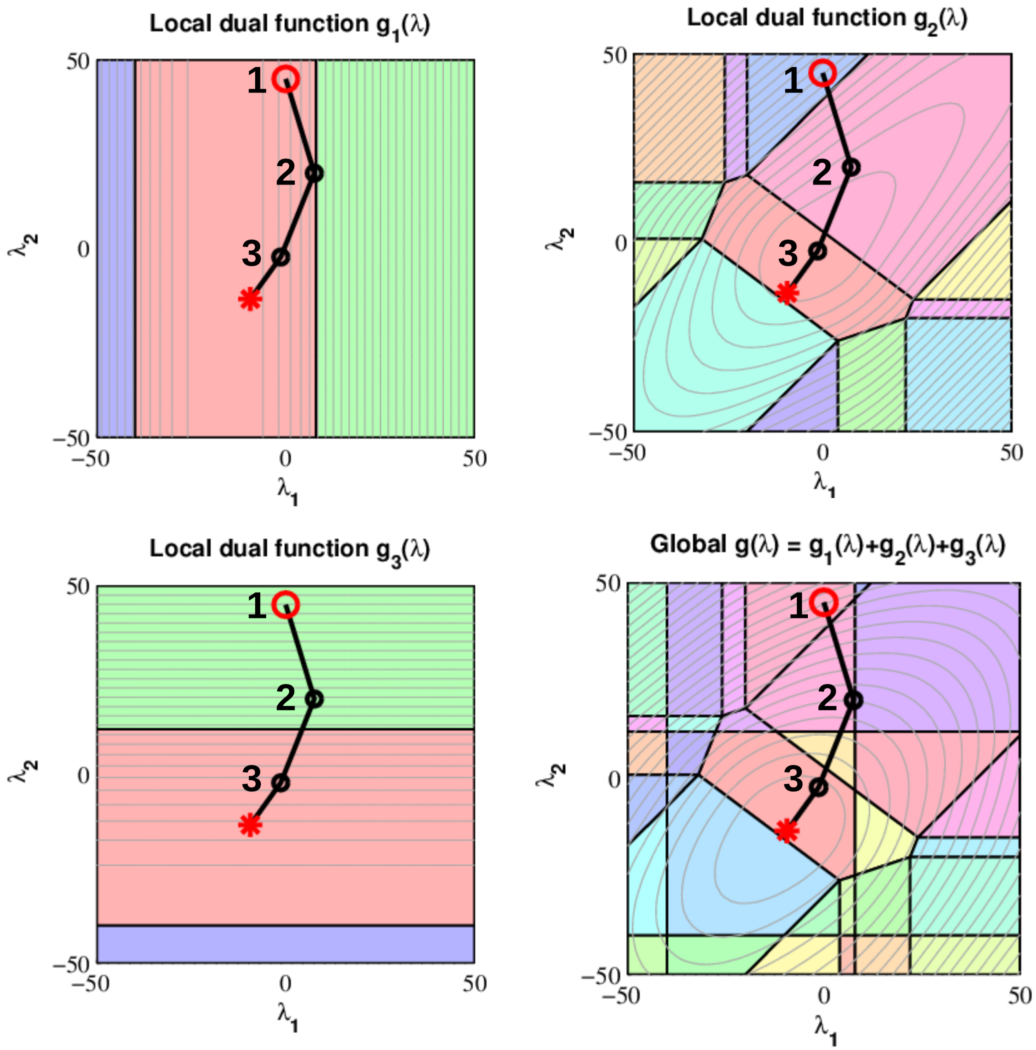
such that $\lambda \in P_i$

i.e. $H_i \lambda \le k_i$

- **Local solutions are kept between iterations**
  - **Recalculation required only if invalidated by shadow price update**

$$\lambda^{(k+1)} \notin P_i$$

- **Coordination process**
  - **Newton method with Levenberg-Marquardt damping**
  - **Switching on region borders not efficient**



DMPC Results on Barcelona Network

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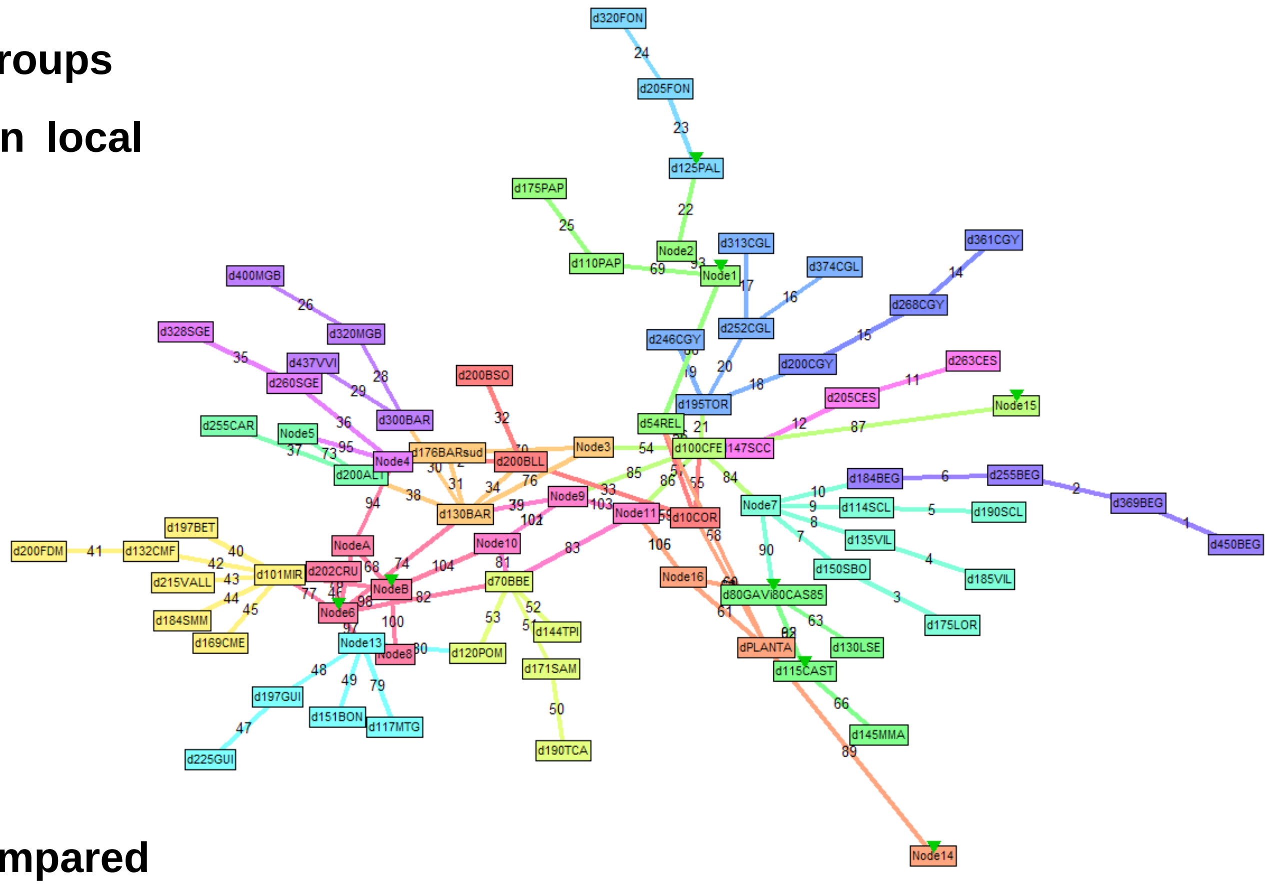
- Network separated to 20 groups
  - Each group has its own local MPC controller
  - APC can be on/off



- Coordination methods compared
  - Centralized MPC
  - Distributed MPC / L-BFGS coordination
  - Distributed MPC / Parametric coordination

DMPC Results on Barcelona Network

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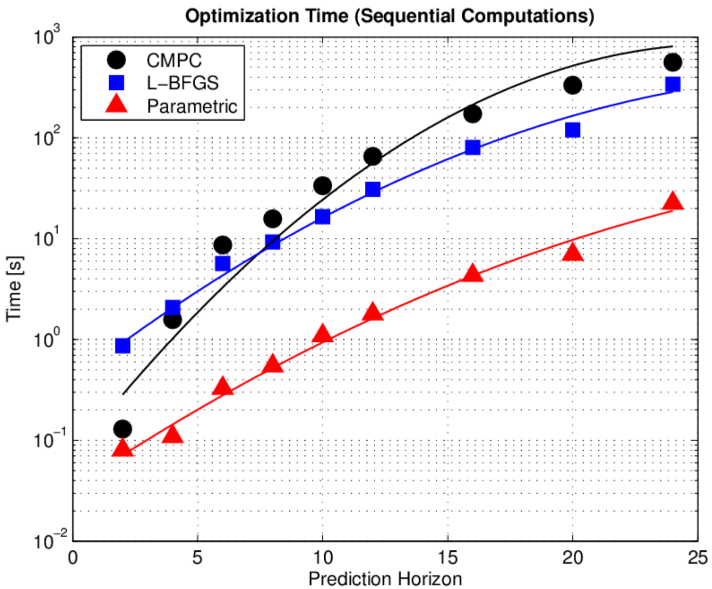

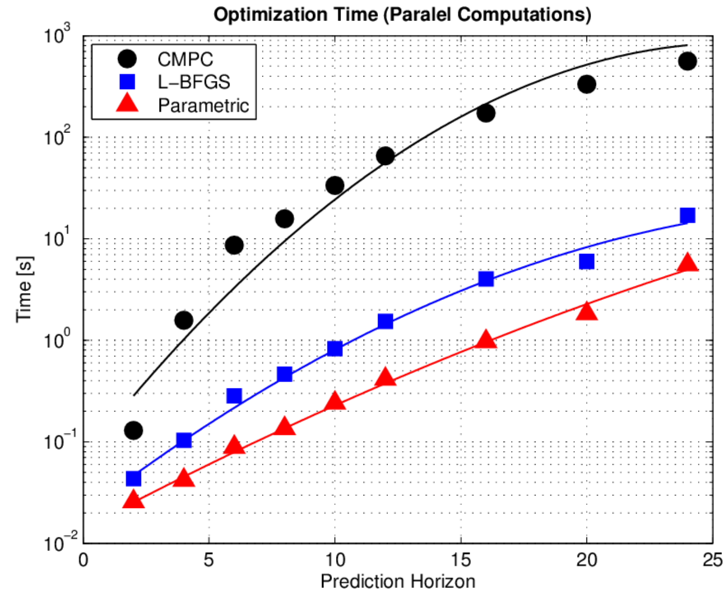

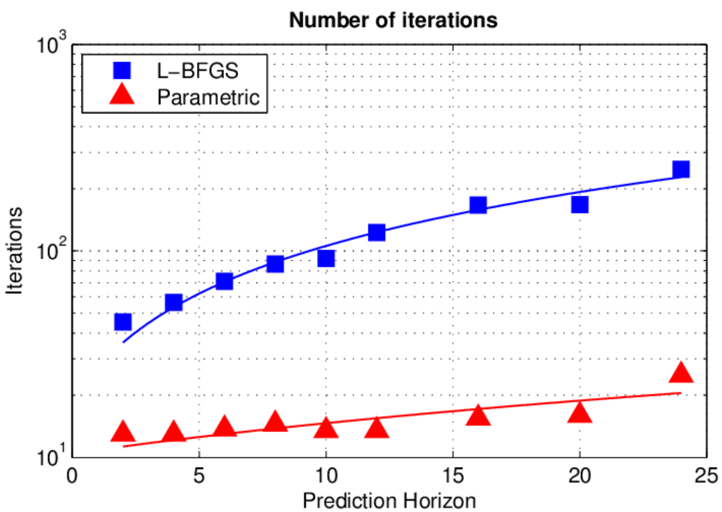

Summary

- **~10x reduction in a number of iterations (compared to Quasi-Newton L-BFGS)**
- **Only ~25% of local problems are recalculated in each iteration**
- **~100x faster than centralized MPC**
  ~10x faster than L-BFGS

DMPC Modularity (topology changes)

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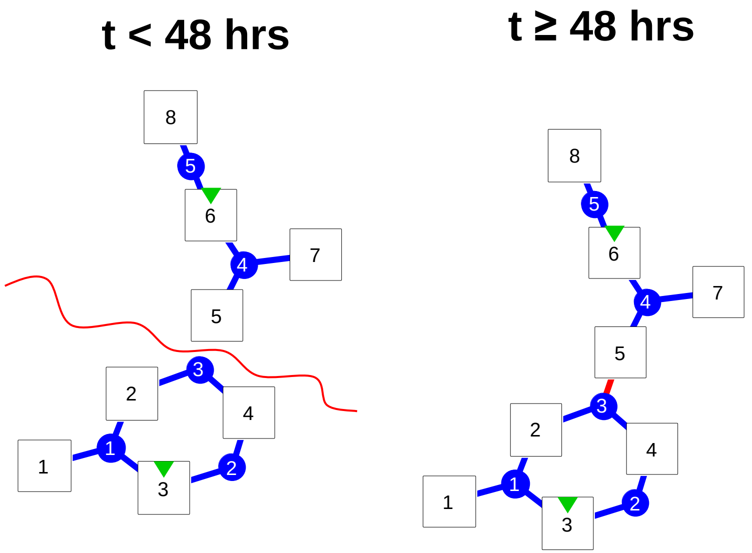
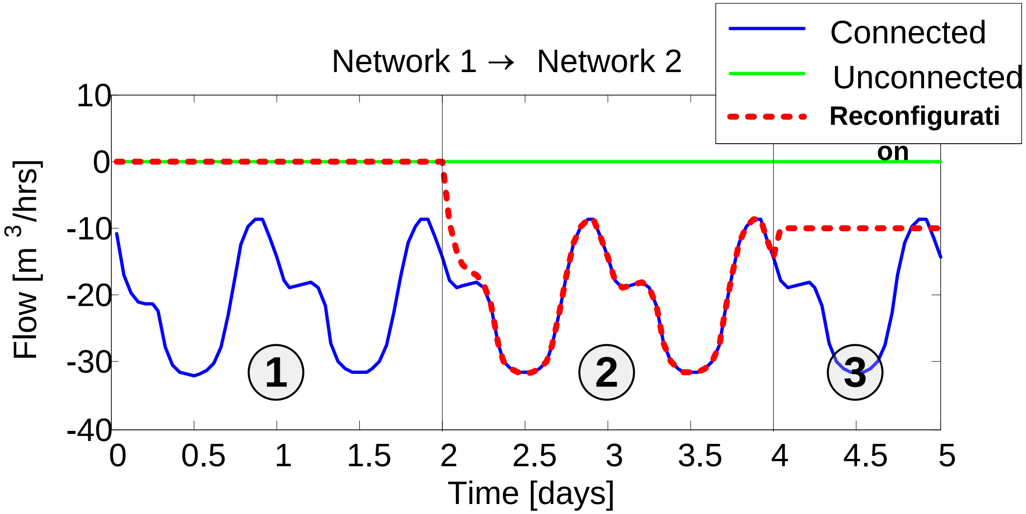
Decentralized control based on Dual Decomposition allows simple changes in network configuration without any global adjustments while preserving centralized MPC optimality:

1. **t<48 networks are unconnected**
2. **t=48 networks are connected**
3. **t≥96 connecting pump is switched to MAN**





Blue line – optimal control of connected networks on the whole interval

Green line – optimal control of unconnected networks on the whole interval

Implementation: Benefits Evaluation Tool

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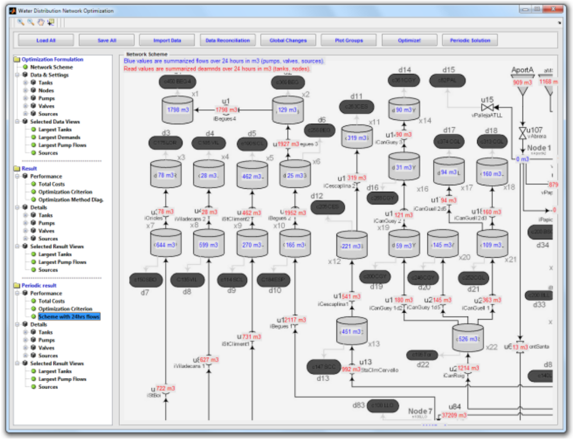
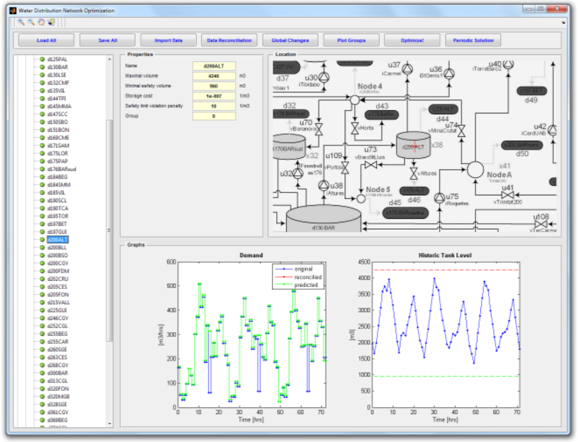
Off-line tool with GUI (in Matlab)

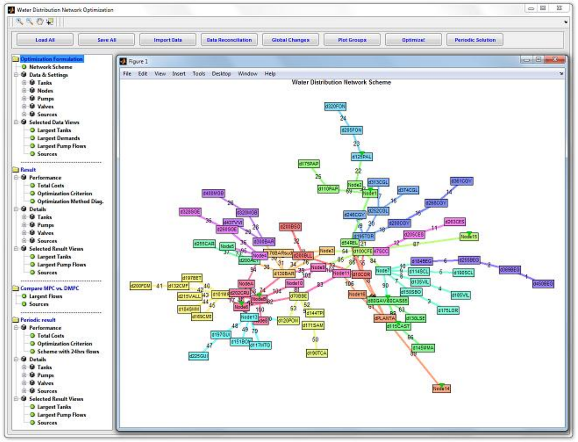
- Building water network topology
- Setting process limits and prices
- Importing historic data (with reconciliation)
- Performing optimization
- Comparing flow and tank level trajectories between historic data and MPC strategy
- Evaluating benefits (pumping and water costs)



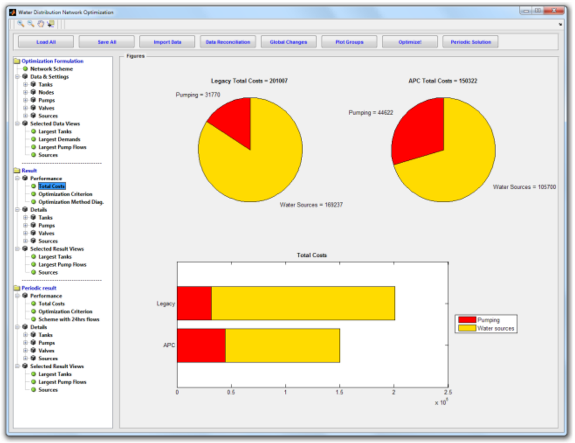
Network topology



Network object details view



Network separation to groups



Costs evaluation

Achievable Benefits

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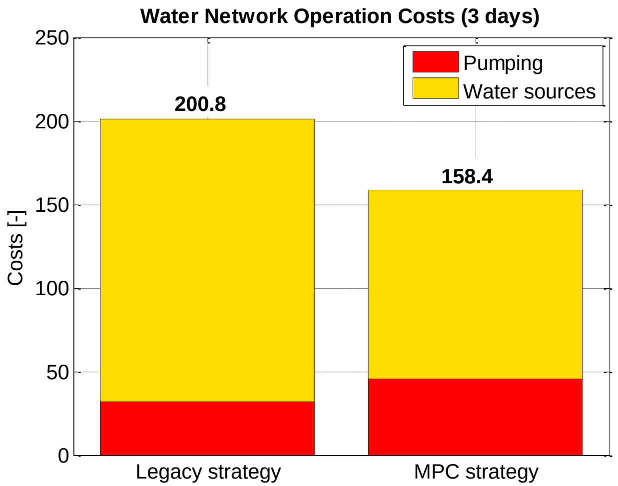
Based on historical data set

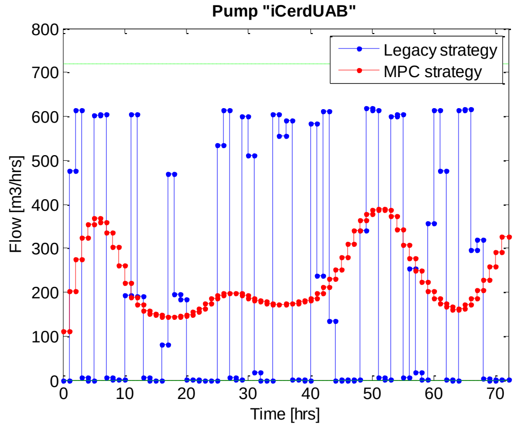
- ~20% direct cost savings
  - Increased pumping cost
  - Reduced cost of water treatment
  - Periodic operation enforced

- Indirect savings
  - smooth MV's operation / source loading
  - leakage prevention by small pressure surges
  - reduced equipment wear & tear

Operation costs comparison



Indirect benefits (calm control actions)



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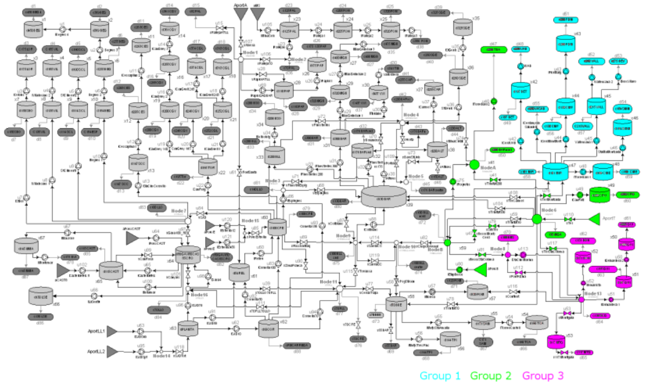
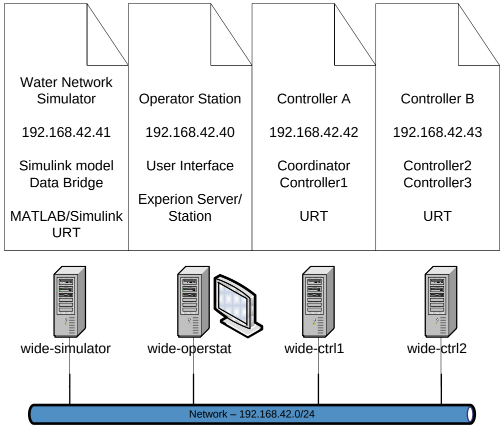
Implementation: Real-time DMPC Demo

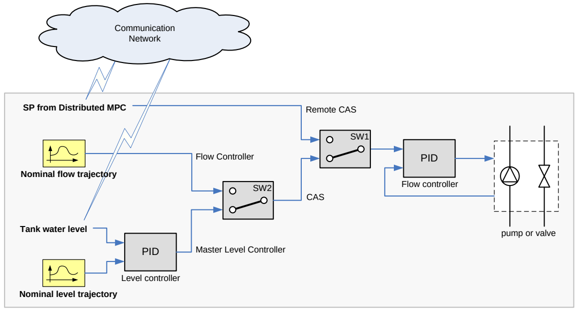
- **Complete control solution on 3 selected areas of Barcelona Water Network**
  - **Algorithms implemented in C++ for Honeywell Unified Real Time (URT) platform – infrastructure for implementing advanced process control (power plants, chemical processes)**
  - **Design of basic control layer and backup control strategy (industrial Experion PIDs)**
  - **Operator panels (industrial Experion HMIweb)**
- **Demonstrates project life cycle - the ability of distributed MPC to replace legacy control in multiple steps for smooth transition between legacy and advanced control strategy**
- **Water network is simulated – hidden for control layer by standard OPC connectivity**
- **Areas controlled by 3 distributed MPC controllers**



3 selected areas of Barcelona network



Control configuration on 4 computers



Flow controller with backup control

Implementation: Real-time DMPC Demo

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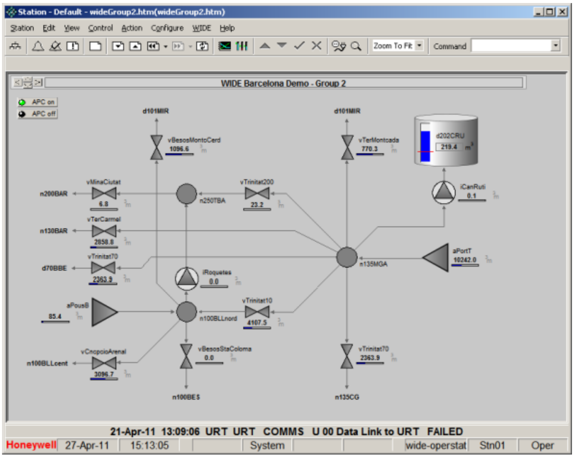
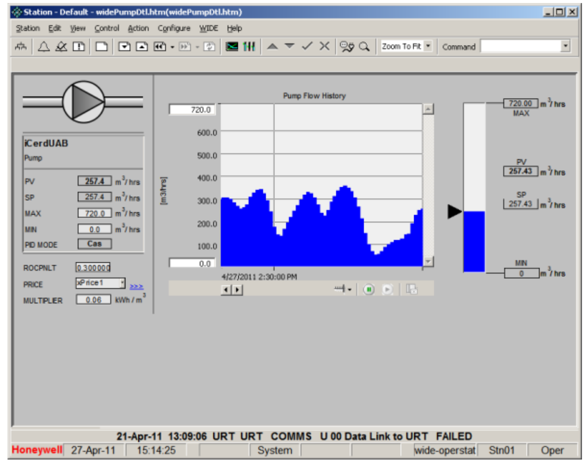
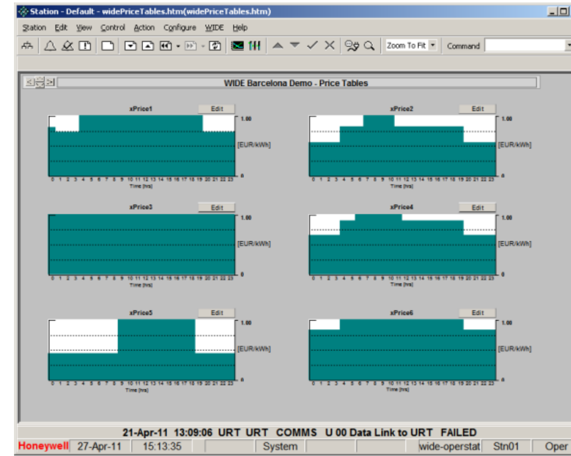


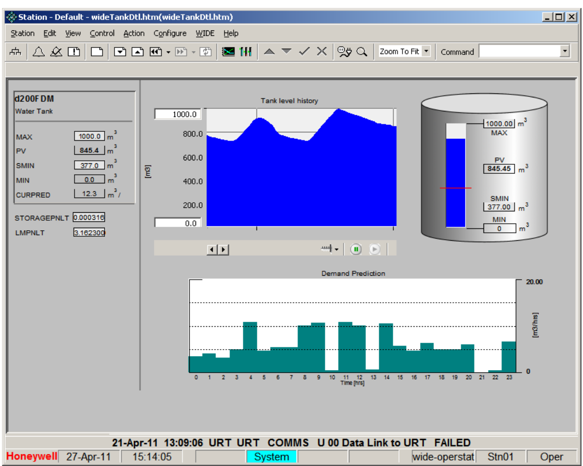
Network part detail



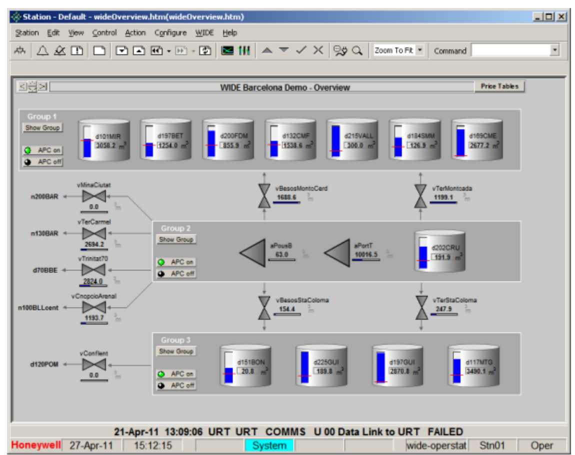
Pump details and history



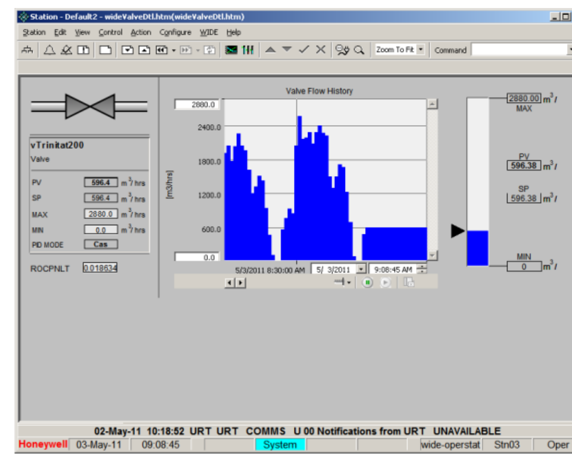
Electricity price patterns definitions



Tank details and history



Overview



Valve details and history

Conclusions

Honeywell

- Distributed optimization is a strong framework for challenging size problems
- Distributed implementation of MPC is straightforward
- MPC-like sparse QP problems can be coordinated very efficiently
- Solution based on DMPC is mature for real applications