WIDE – WP5 Achievements

SEVENTH FRAMEWORK PROGRAMME

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Agenda

- Introduction
- Overview
- Concluding Remarks
- Discussion

WP5 Introduction

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WP5 Overview

- Proof of concept: water network
- Objectives
  - The role of WP5 is to validate the concepts developed in WP2, WP3 and WP4 on a large-scale water distribution system.
  - It will also serve to motivate and circumscribe the class of large-scale systems WP2, WP3 and WP4 will focus on, providing useful engineering inputs to the theoretical developments.
  - The concepts will be demonstrated in a software demonstration of the entire water network using a simulation environment based on MATLAB/SIMULINK and an experimental demonstration of part of the water network.
- Tasks
  - T5.1 Definition of the water network demonstration
  - T5.2 Dynamical model of the water network and model decomposition
  - T5.3 Control design for the water network
  - T5.4 Development of the water demo demonstrator
  - T5.4 Testing and evaluation of the solution

T5.1 Definition of the Water Network Demonstration

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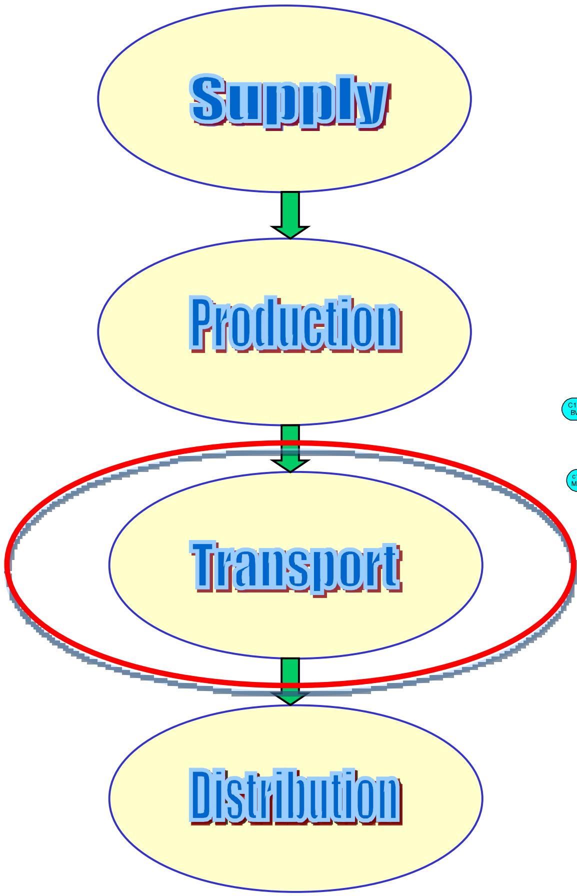
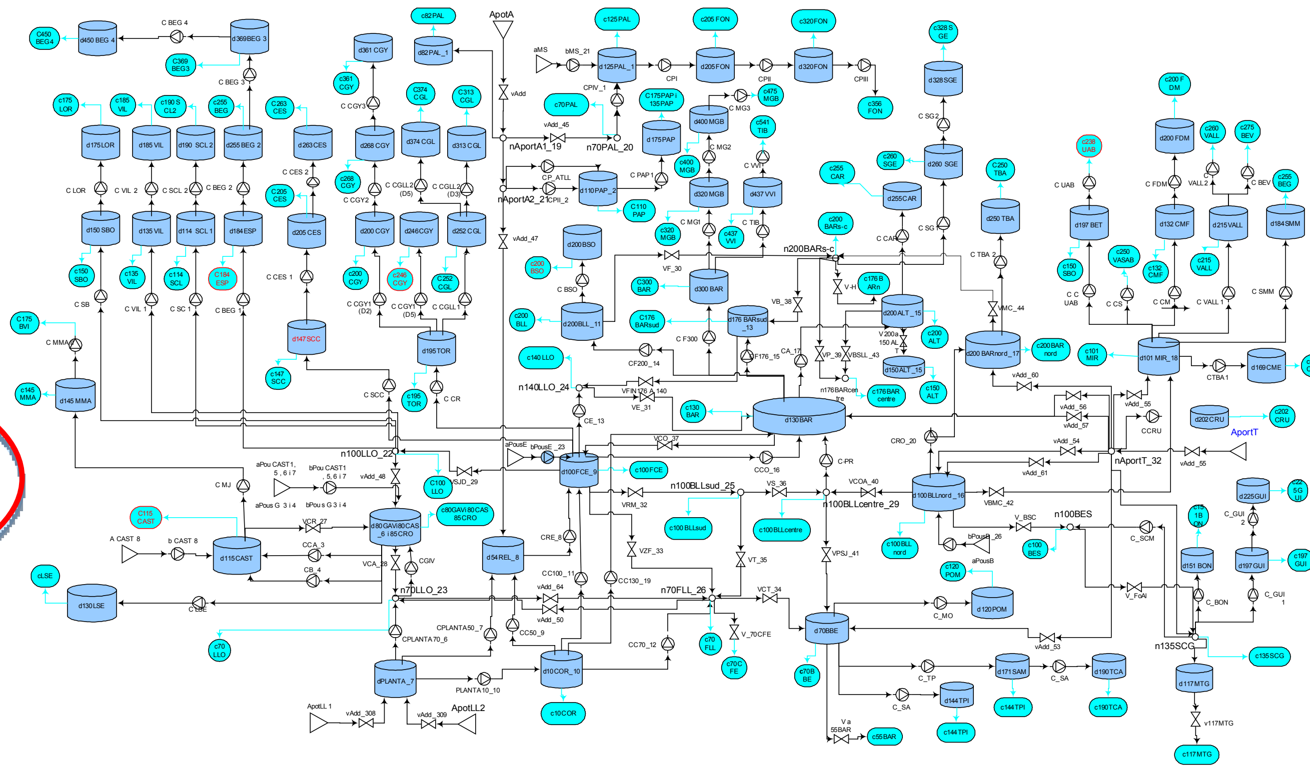
Pilot Definition

- Definition of Pilot 1: DMPC of the Barcelona Water Transprot Network
  - Definition of the part of Barcelona water network used to illustrate DMPC
  - Definition of the control problem
- Definition of Pilot 2: Wireless Control of Valve in Barcelona Water Network
  - Definition of the part of Barcelona water network used to illustrate wireless control
  - Definition of the control problem

Test Pilot 1: Demo of DMPC in the Barcelona Network

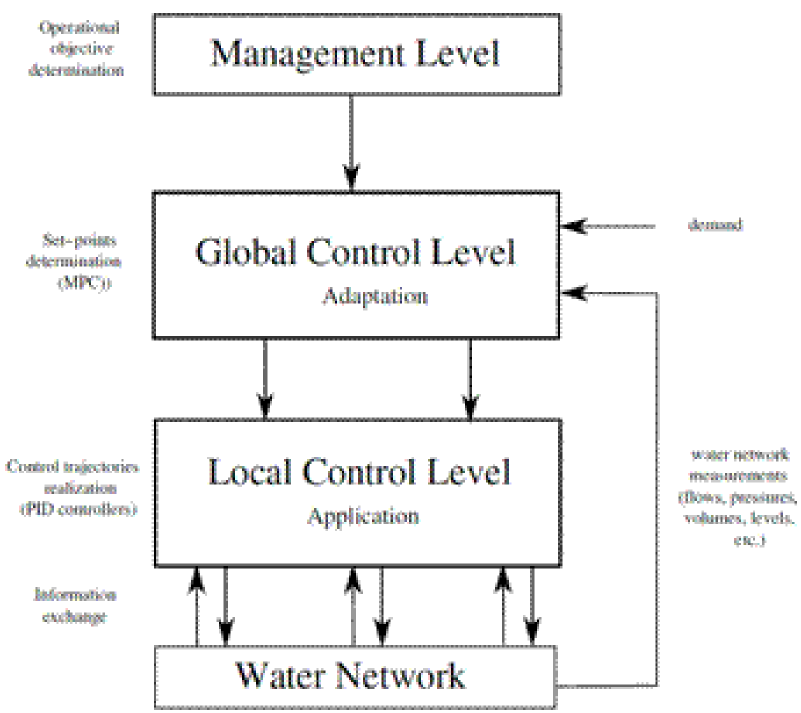
Transport Water Network

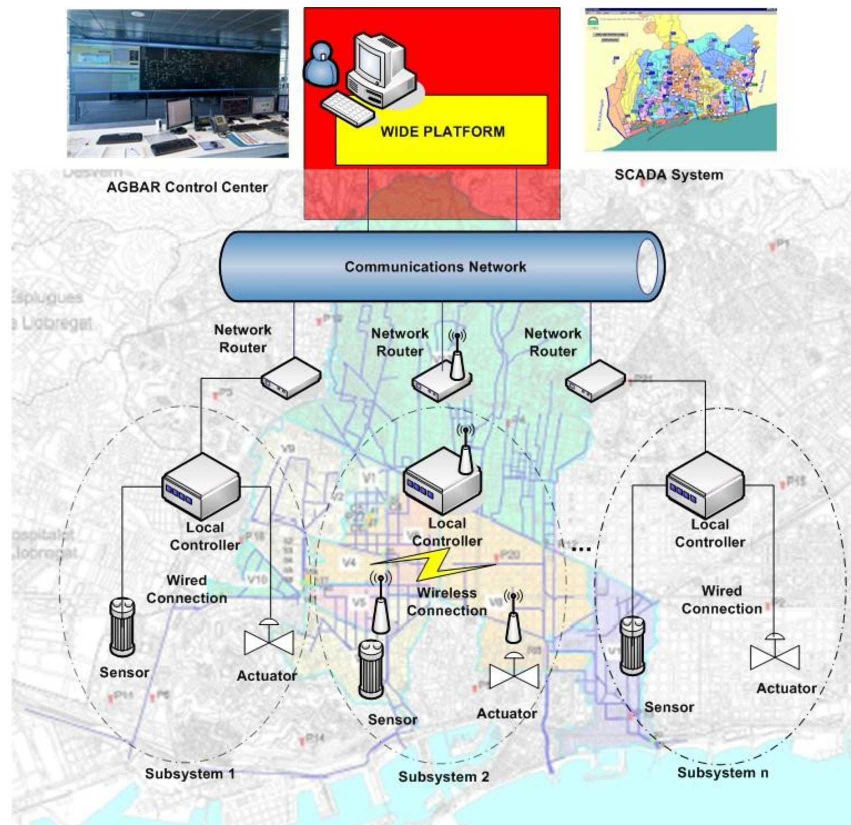




Test Pilot 1: Demo of DMPC in the Barcelona Network

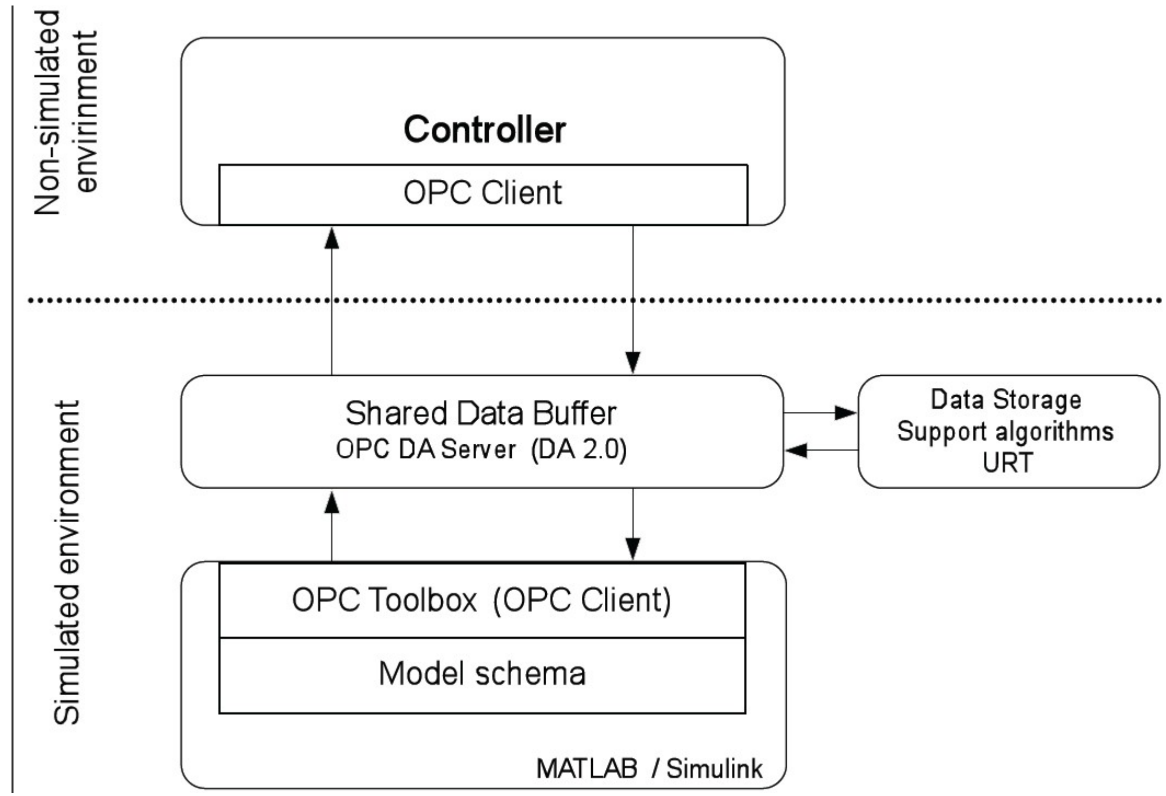
Supervisory MPC Control Architecture





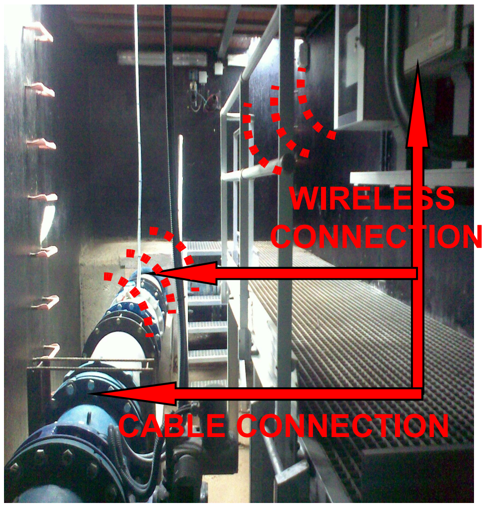
Test Pilot 1: Demo of DMPC in the Barcelona Network

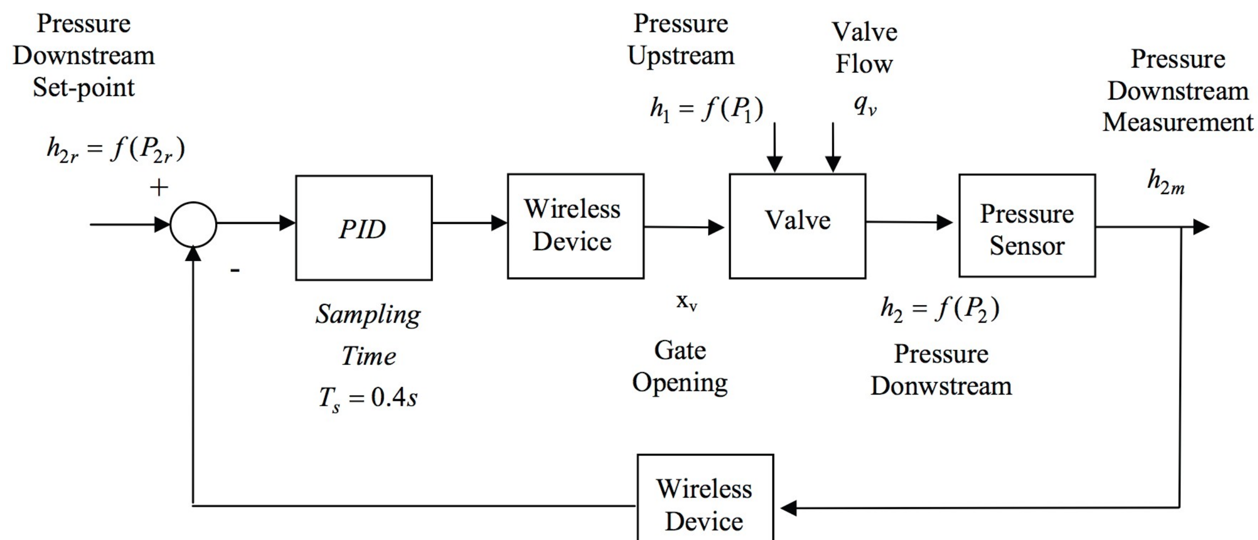
Interface Simulator/DMPC Controller



Test Pilot 2: Demo of Wireless Control Functionalities

Closed-loop Control of a Valve at the Regulatory Level





• The overall idea is to check the use of wireless connection between the sensors and the remote station.

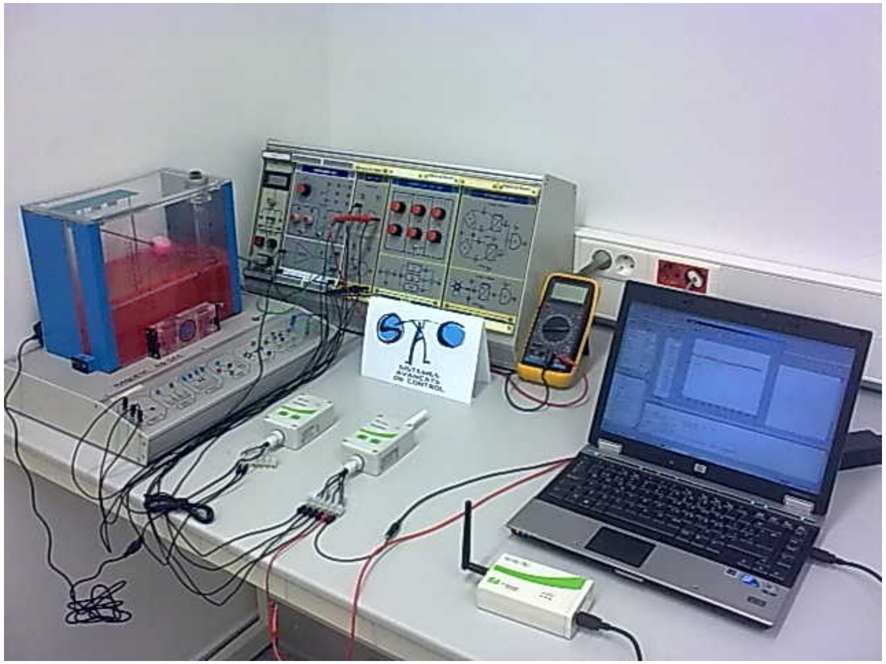
• Each signal will be doubled (cable connection and wireless connection) as a protection to the overall control system. Both sets of data will be compared and contrasted afterwards.

• Double aim: a) Transference of information through wireless.
b) Operational feasibility/constraints regarding the overall valve control (delays, etc.)

Test Pilot 2: Demo of Wireless Control Functionalities

Phase 1: Lab Test

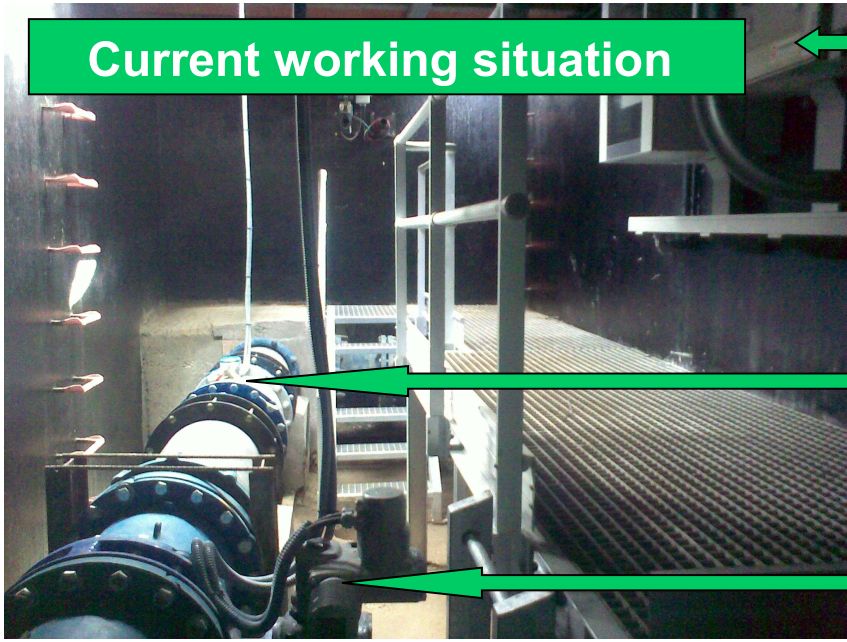
AGBAR Labs



UPC Labs

Test Pilot 2: Demo of Wireless Control Functionalities

Phase 2: Real Test



Remote station

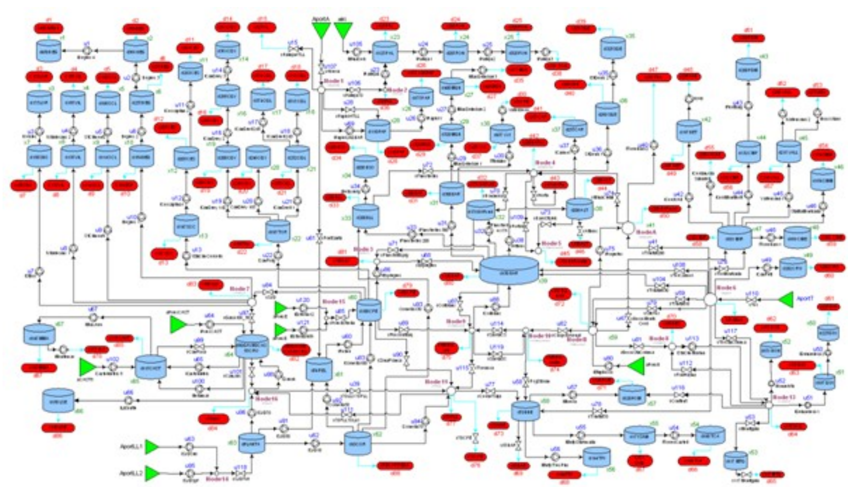
Flow / pressure meters

Valve and Servomotor

- Pressure and flow data are stored every 0.4 s in the remote station.
- Input data + desired pressure downstream→ the PID controller in the remote station changes valve position.
- The remote station sends flow and pressure data every 4-5 s to the Control Centre.
- Set points of pressure or flow can be sent from the Control Centre to the remote station when necessary.
- Alarms due to values out of the acceptable range also pop up at the alarms panel in the Control Centre.

Demonstration Objectives

- **Demonstrate the benefits of distributed MPC by comparing overall costs for legacy and distributed MPC control strategies.**
- **Demonstrate the ability of the proposed distributed MPC solution to replace the legacy control in multiple steps.**
  - In each step, the APC will be implemented on a selected network part only.
  - Important for practical application and advanced process control life cycle; standard requirement by process operators.
  - Demonstrating the ability of APC to work with some controllers switched to a backup strategy based on the legacy control
- **Demonstrate control over wireless network on the lowest control level.**
  - Robust algorithms assuming communication delays, packet dropouts, etc. will be demonstrated on flow or tank level control with wireless sensors and actuators.

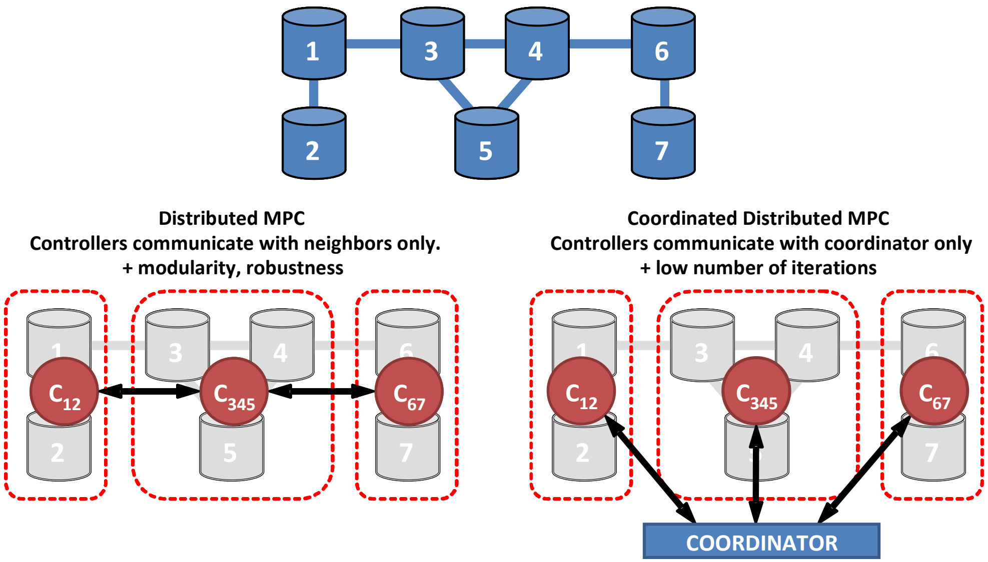


Benefit Demonstration

- **As a baseline, the price of the current PID-based control strategy will be evaluated from 3 days historical process data.**
- **Two distributed advanced control strategies will be evaluated:**
  - Distributed MPC with the central coordinator
  - Distributed MPC without the central coordinator
  - In either case, local MPC controllers will control groups of tanks.
- **All strategies will use identical initial tank level settings and demand data.**

- **Demonstration Scale:**
  - Full model of the Barcelona Water network
- **Demonstration Platform**
  - MATLAB/Simulink

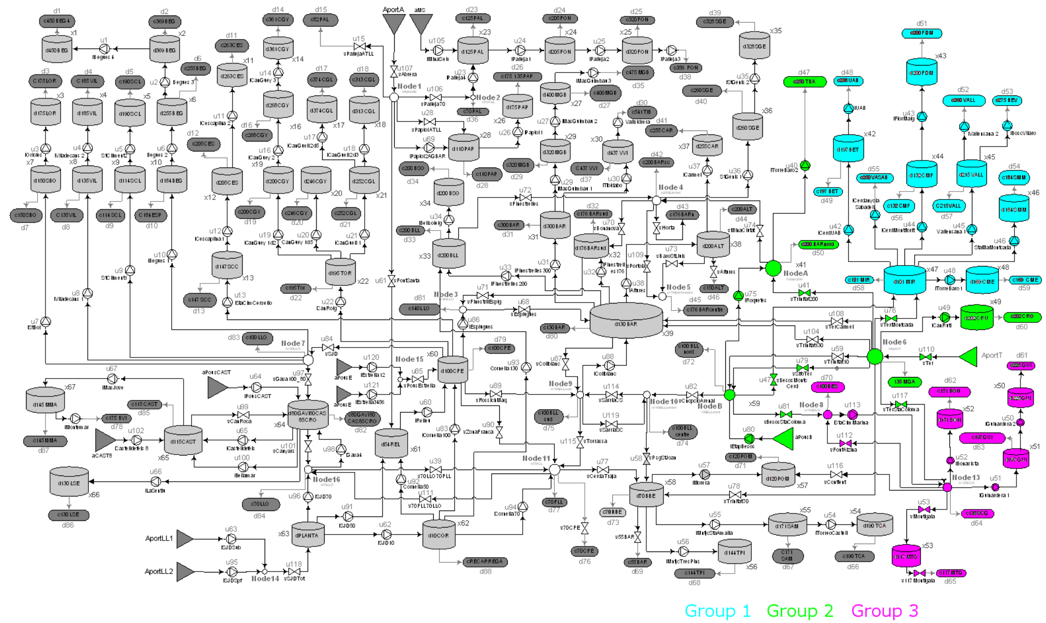
Water network for the demonstration of the different distributedcontrol strategies



Sequential Replacement of Legacy Control

- **Replacement of legacy control in successive steps.**
- **Demonstration will be done on a part of the network model.**
- **The part of the network is divided into 3 groups of tanks**
  - At the beginning, the network section under consideration is controlled by the *PID-based legacy control.*
  - Nominal trajectories are pre-computed for all flows.
- **Group #1 is switched to advanced control while the rest is controlled by the legacy control strategy.**
- **Groups #2 and #3 are sequentially switched from the legacy to the advanced control.**
- **Simulated communication failures can test switching from the advanced to legacy control used as a back-up.**

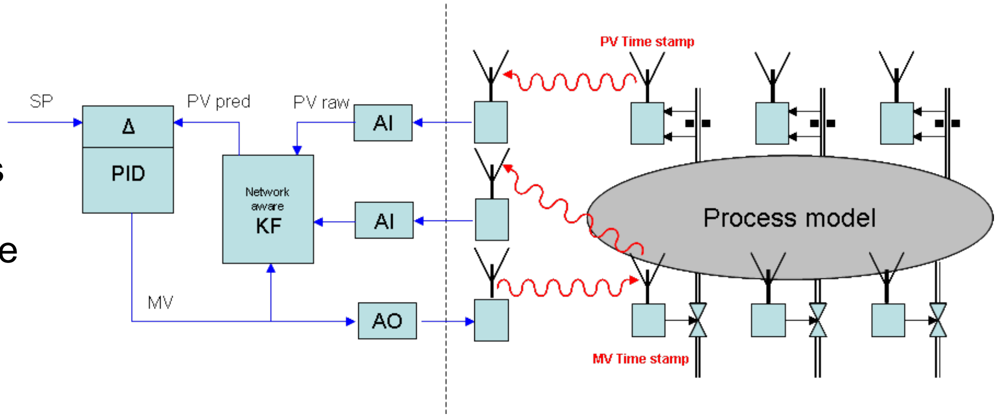
- **Demonstration scale**
  - Part of the network
- Demonstration platforms
  - Model – Simulink
  - Backup control and backup/APC switching: Simulink, using blocks emulating Honeywell Experion DCS
  - Advanced Control – Honeywell URT platform communicating with Simulink over the OPC bridge



Wireless Control

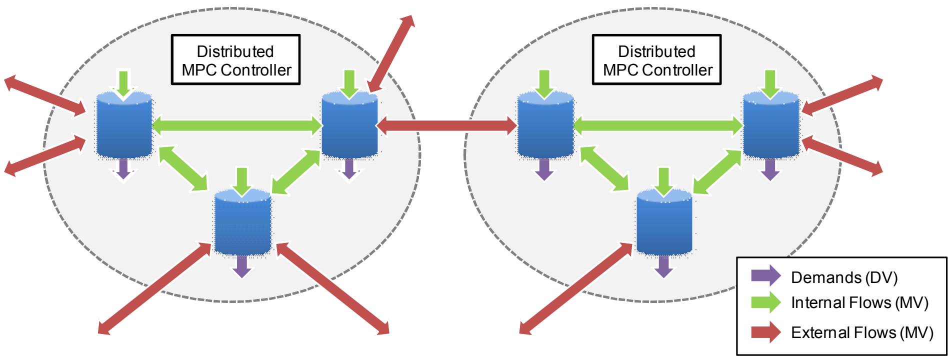
- **Applied to the base control layer with fast sampling (1 second)**
  - Network effects will not show up at the advanced control layer with sampling interval 1 hour.
- **Demonstrating Integration of WSN and DCS.**
- **PID controller will be given, in place of raw measurement, a process value estimated by a network-aware Kalman filter.**
  - Kalman filter will receive measurement data from the network with time stamps provided by the sensor.
  - Kalman filter will further receive time stamps of manipulated variables provided by the actuator, to account for network delays in the MV channel.
- **Network delays and data losses will be simulated using network models developed in WP2.**

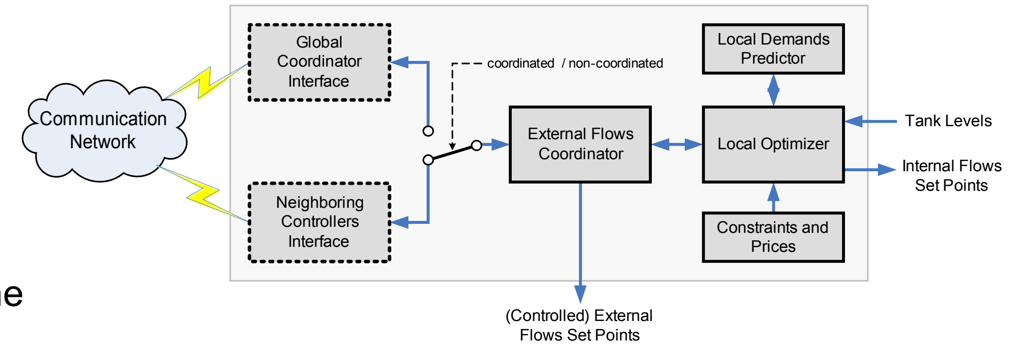
- **Demonstration scale**
  - Single flow/tank level controller
- **Demonstration platform**
  - Simulink
  - Real Site



Distributed MPC

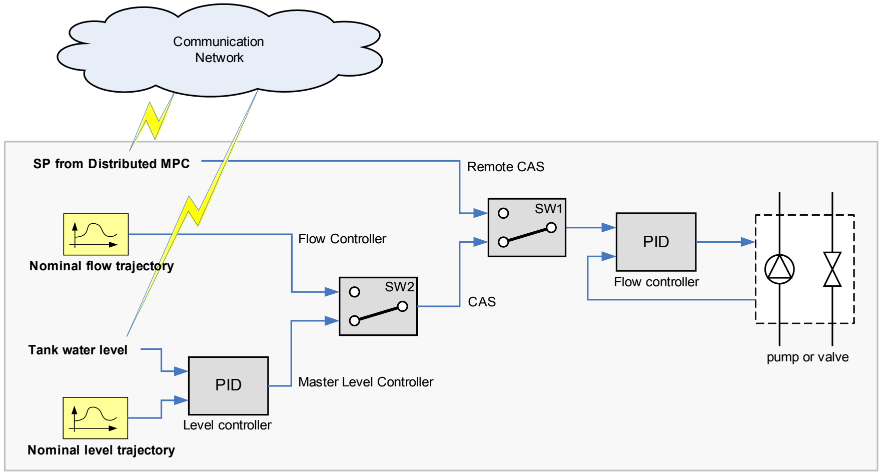
- **Local controller controls water level for a group of tanks by defining set-points of internal flows**
  - Internal flows – between tanks of the same group, controlled by PID controllers at the DCS level
  - External flows – between tanks of different groups. Determined by a consensus negotiated between neighboring controllers.
  - Set-point for an external flows is imposed by the predefined controller
- **The implementation of the local controller allows its use in 2 strategies**
  - With a global coordinator defining shadow prices of external flows
  - Without a global coordinator: shadow prices are defined locally by one of the neighboring controllers





Backup Strategy

- **Legacy PID-based solution guarantees operational safety, and a baseline operation.**
- **Required as a back-up control strategy with advanced control**
- **Back-up control uses pre-computed nominal flow/level trajectories.**
- **Flow controllers either**
  - follow nominal flow trajectories
  - track flow trajectories of the master level controller.
- **Master level controller (one per tank)**
  - Tracks the nominal level trajectory
  - Typically controls the inflow with largest capacity for the tank.
- **Advanced control (MPC), if available, provides set-points for flow controllers**



- **In the case of a level control on a tank being in the back-up mode due to the communication failure, MPC can still control other tanks**
  - **Manipulated variable in the back-up mode can be treated as a disturbance by MPC**

T5.2 Dynamical model of the water network and model decomposition

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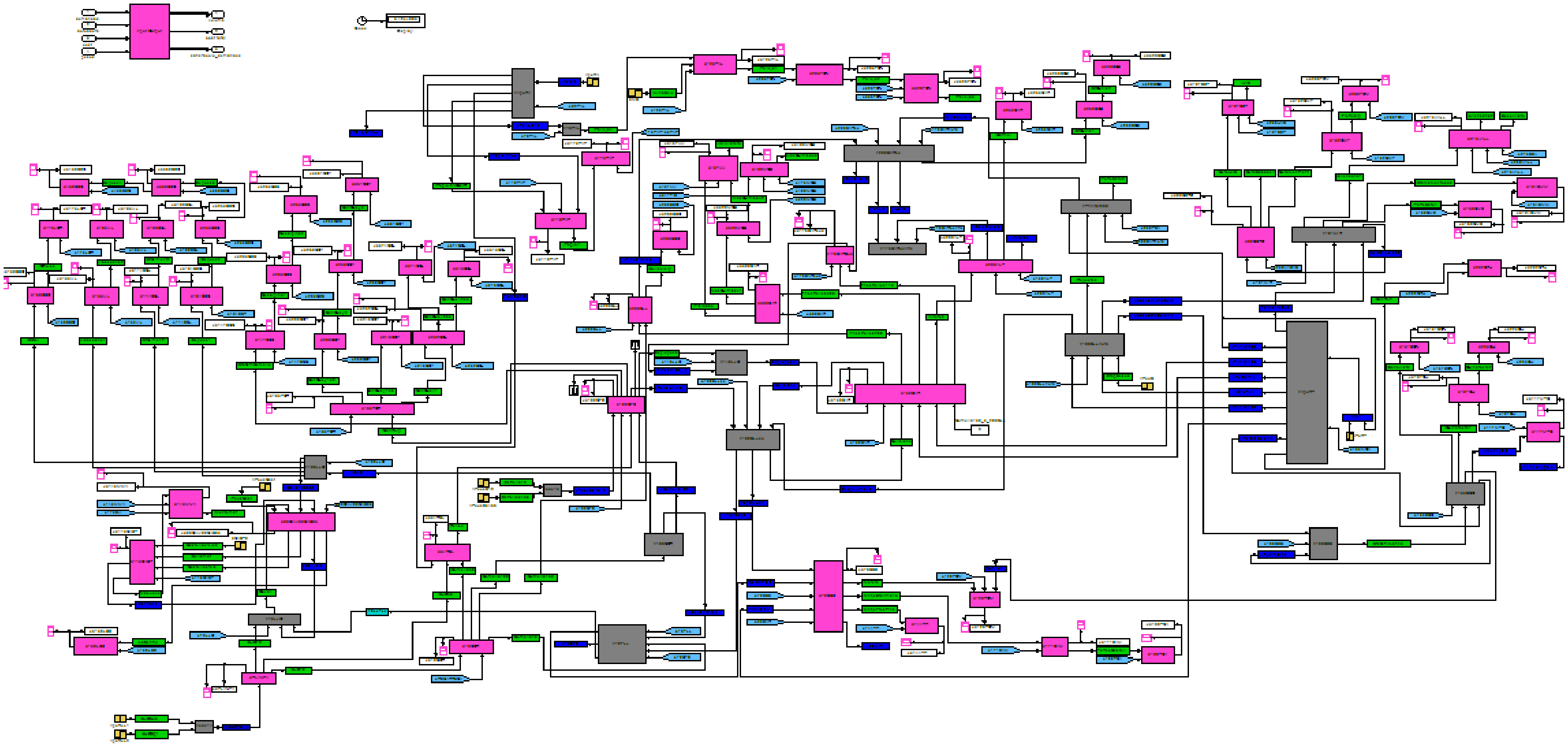
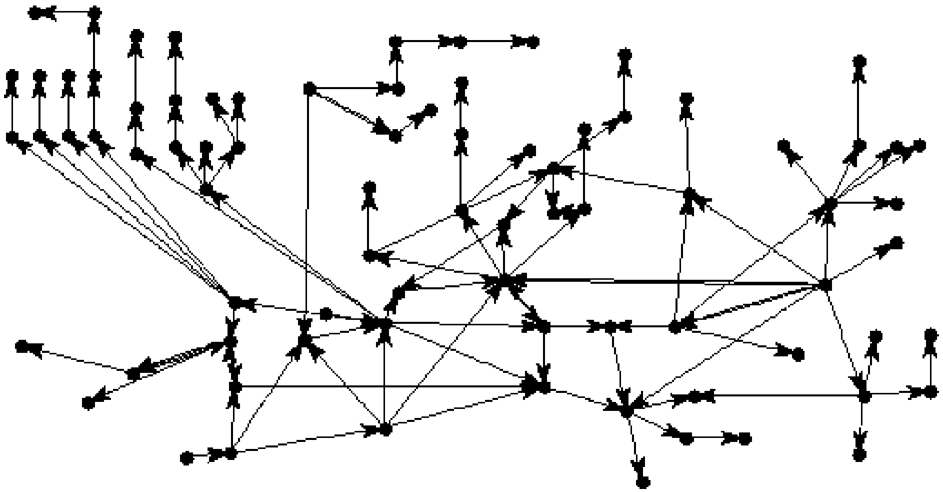
Network Model

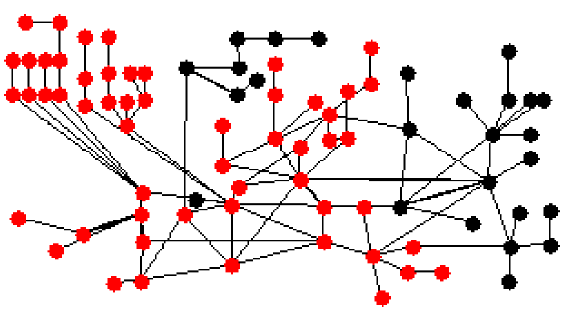


- 121 control variables
- 67 system states (tank volumes)
- 88 perturbations (water demands)
- 15 additional constrains (related to the nodes equalities)
- Matlab implementation

Graph Analysis



Abast font Llobregat



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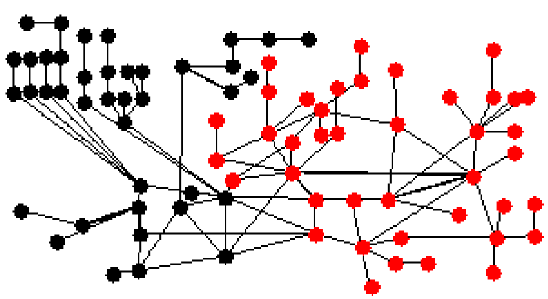

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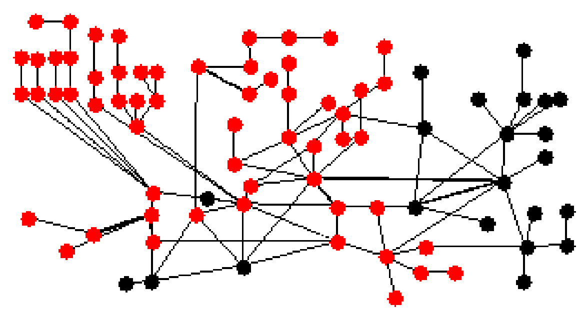
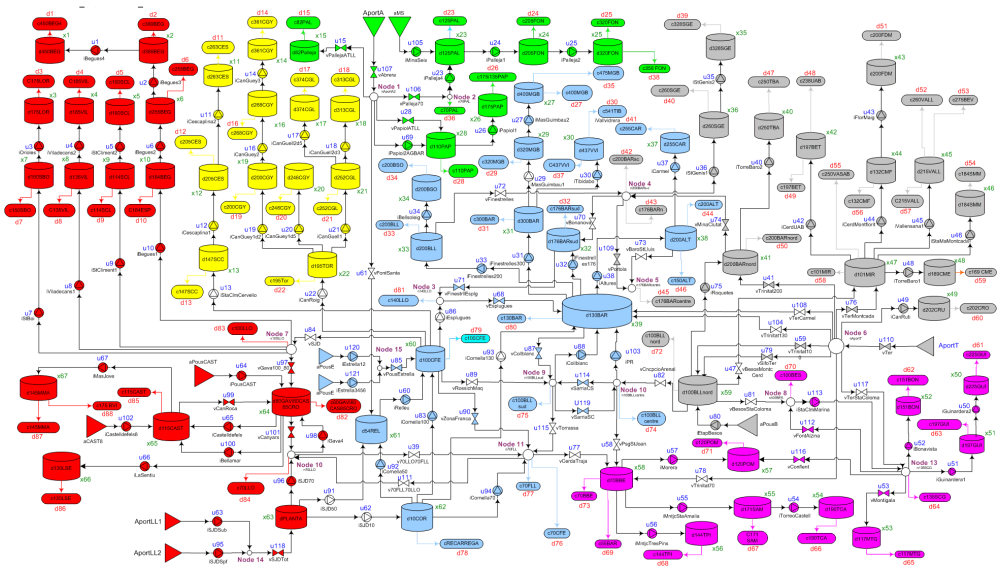
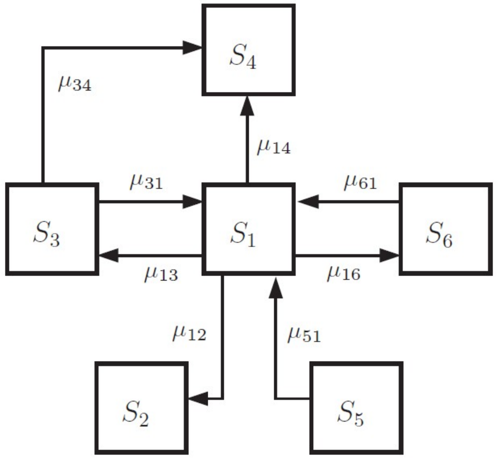


Subsystem Decomposition using Graph Partitioning

PROPOSED SOLUTION – Graph Partitioning Algorithm

- **Novel algorithm for automatic LSS subsytem decomposition based on a graph partitioning approach**
- **Step 0: Graph representation of the LSS system**
- **Step 1: Subsystem decompostion based on identifyng loosely coupled subsystems using graph theory**
- **Step 2: Solution refinement using some auxiliary**





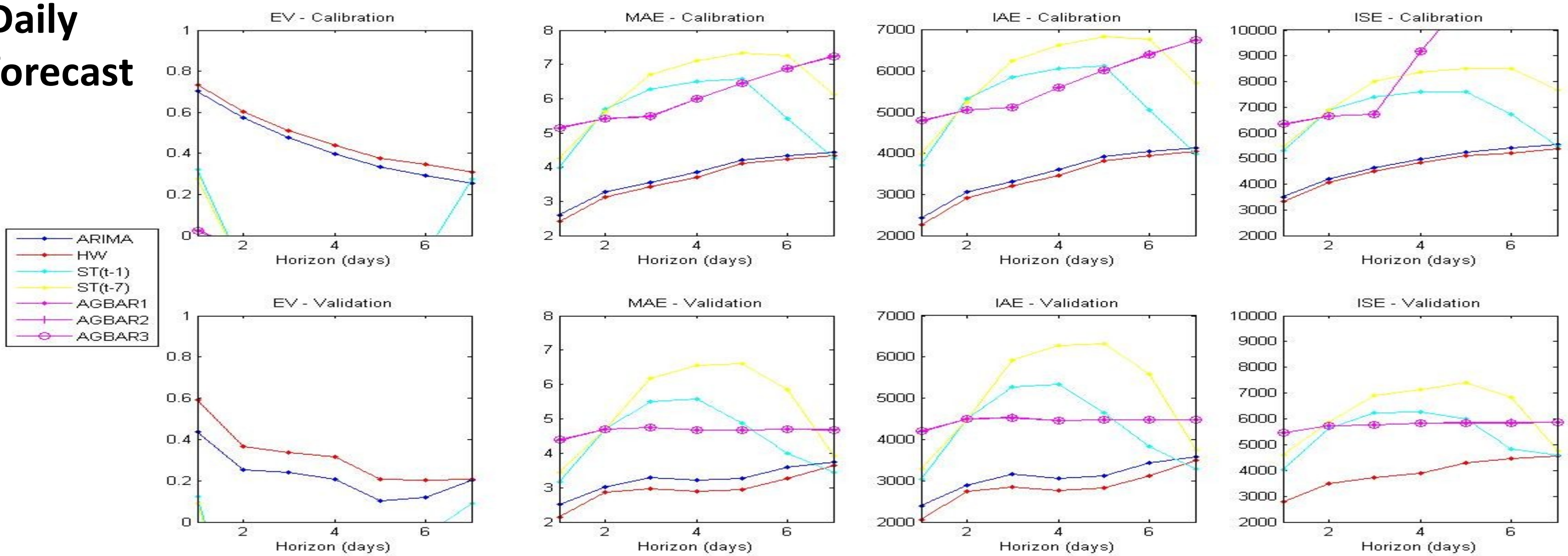
SUBSYSTEM	Tanks	Actuators	Demands	Nodes
1	13	36	20	5
2	11	11	11	0
3	13	22	20	3
4	9	16	12	2
5	6	10	8	2
6	15	26	17	3
Total	67	121	88	15

PUBLICATIONS

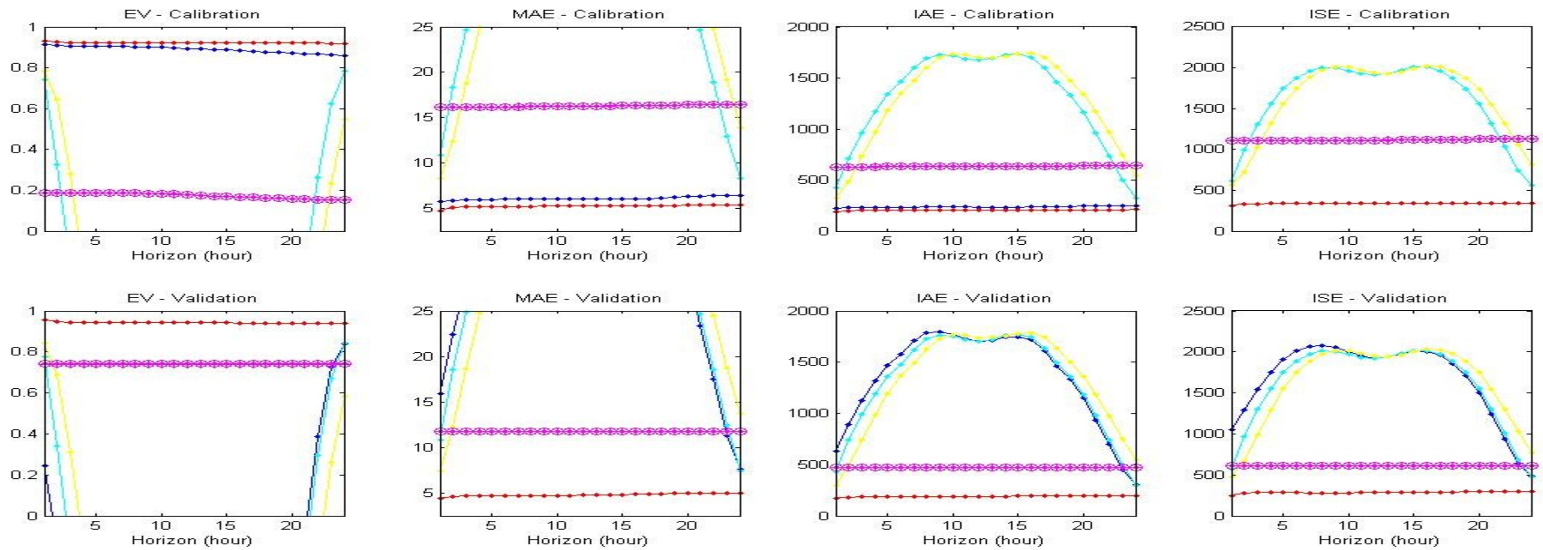
Paper submitted to IFAC World Congress 2011 and Journal of Process Control

Demand Forecast Time Series Model

Daily forecast

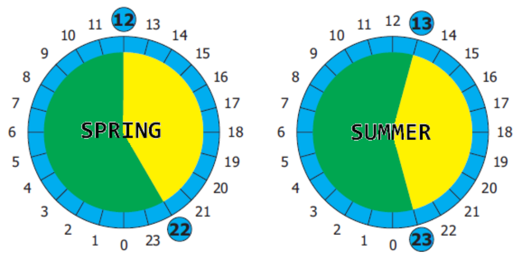


Hourly forecast

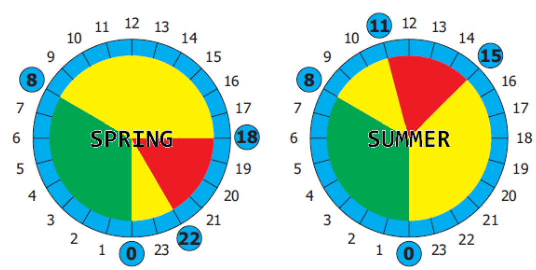


Electricity Cost Model

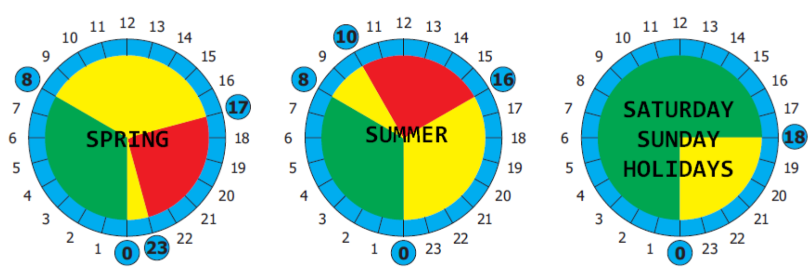
TIME TABLE: 1.0, 2.0.1, 2.0.2, 2.0.3, 3.0.1



TIME TABLE: 3.0.2

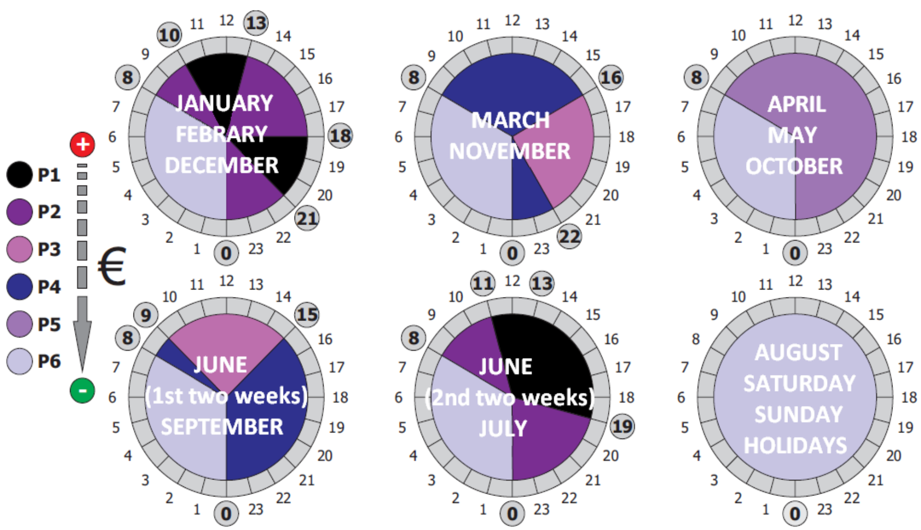


TIME TABLE: 3.1 < 450 KWh



- An electricity cost model that takes into account the price of electricity depending on the day, hour and period of the year has been developed and taken into account in the MPC formulation.

METHOD 6 PERIODS



T5.3 Control design for the water network

MPC Objective Function Formulation

1. Energy/Production Costs

$$FCP = \sum_i \left[a_i \sum_{k=0}^{N-1} \left(\Delta t \cdot q_i(k) \cdot C_i \right) \right]$$

2. Operation-safety Costs

$$FCS = \sum_j \left[c_j \frac{1}{N} \sum_{k=0}^{N-1} \left(\frac{V_{\sec,j} - V_j(k)}{V_{\sec,j}} \right) \right]$$

3. Stability Costs

$$FCE = \sum_j \left[d_j \frac{1}{N} \sum_{k=0}^{N-1} \left(\frac{q_j(k) - q_j(k-1)}{q_{\max,j}} \right)^2 \right]$$

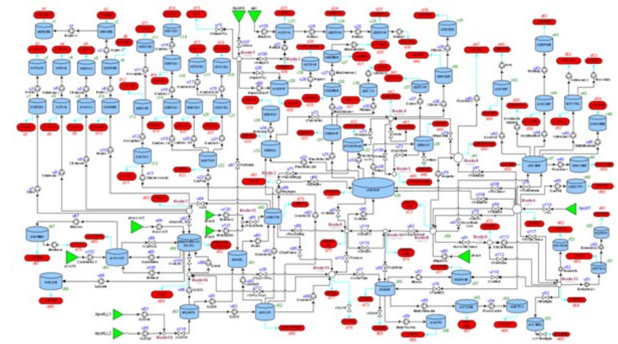
Distributed MPC

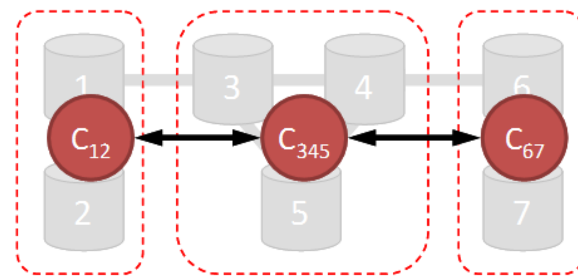
SOLVED PROBLEM

- **Design of Distributed MPC for truly large scale systems**
- **Class of target systems (Barcelona WN):**
  - **Centralized optimization problem impossible to solve due to high number of variables (~5000) and constraints (~10000)**
  - **Long sampling period (1 hrs) → iterative solution with nearly optimal performance**
- **Two controller types:**
  - **WITH Central Coordination – fast coordination, useful also for large scale optimization on a single computer**
  - **WITHOUT Central Coordination – local controllers coordinate flows between neighbors only (modular architecture)**

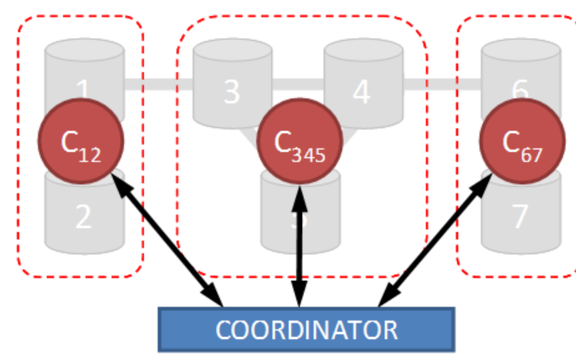
STATE OF THE ART

- **Well known methods based on dual decompositions; however, with problematic speed of convergence**
- **No application of MPC to full-scale water distribution network**
- **LS system partitioning algorithms for DMPC are missing**





Distributed MPC

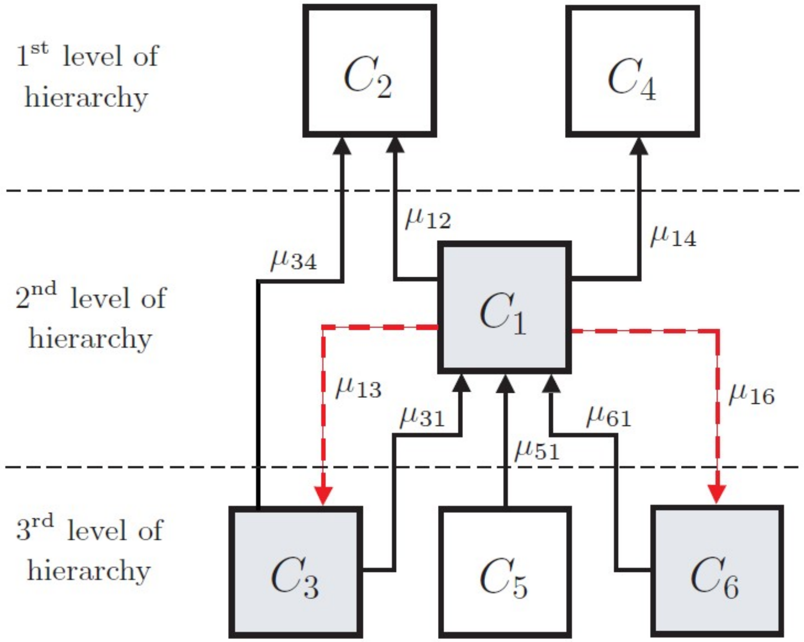


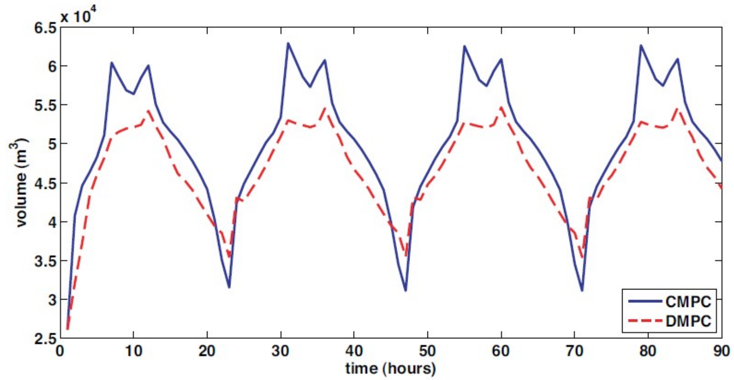
Coordinated Distributed MPC

Hierachical Decentralized MPC

PROPOSED SOLUTION - Decentralized MPC

- **A hierarchy of a local MPC controllers (one per each subsystem) is designed.**
- **Only one optimization per MPC controller is necessa Coordination is established thanks to t unidirectional flow of shared variables.**



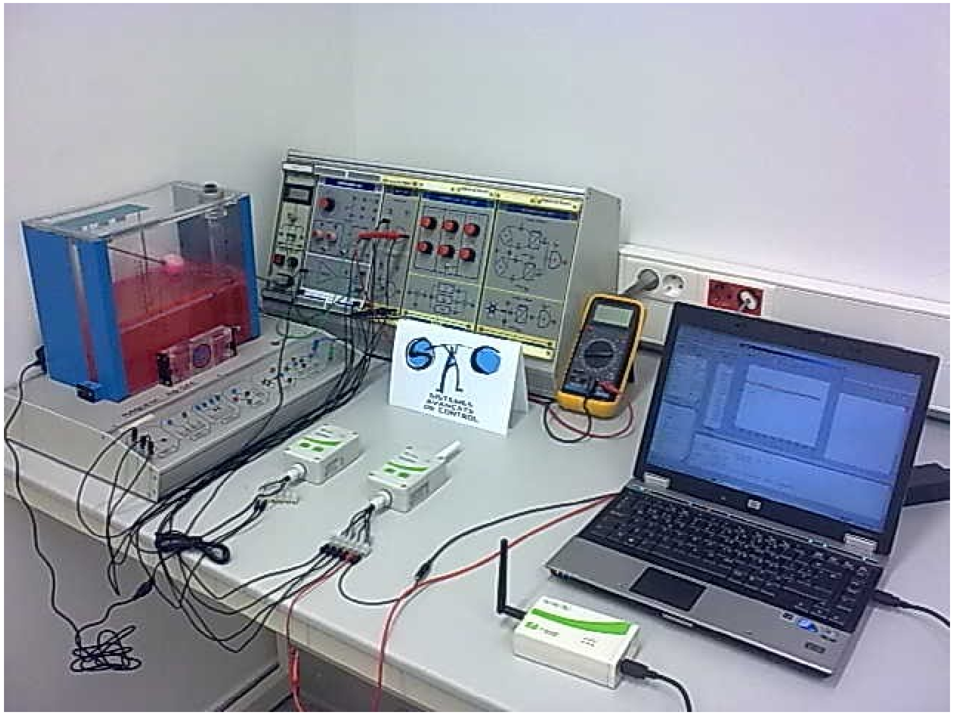


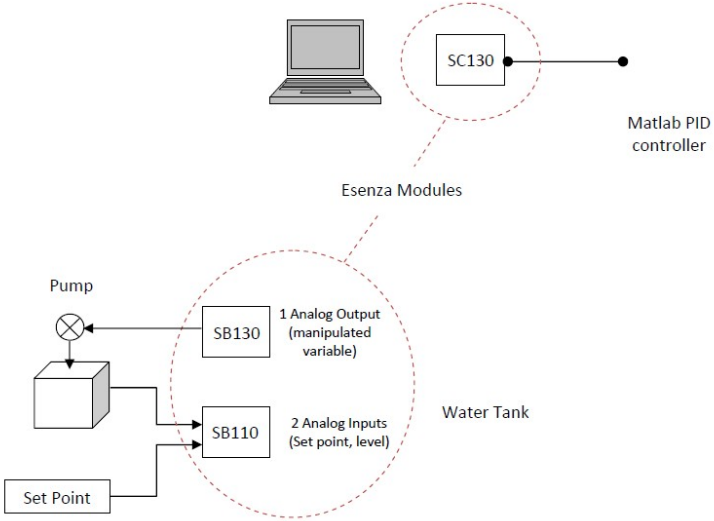
INDEX	Scenario 1 CMPC	Scenario 1 DMPC	Scenario 2 CMPC	Scenario 2 DMPC
Water Cost	138.37	189.45	137.05	188.81
Electric Cost	92.73	68.44	87.43	69.91
Total Cost	231.10	257.89	224.48	258.72
CPU time	1143	537	1127	560

PUBLICATIONS

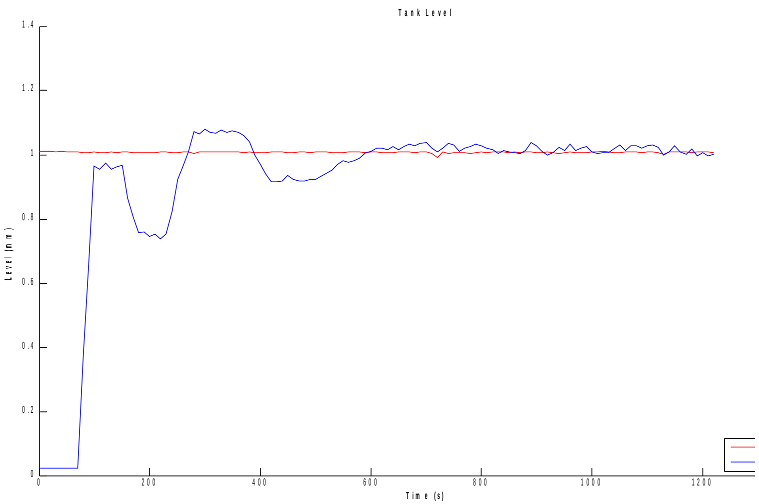
Papers presented at ACC'10, LSS'10 and submitted to IEEE Journal

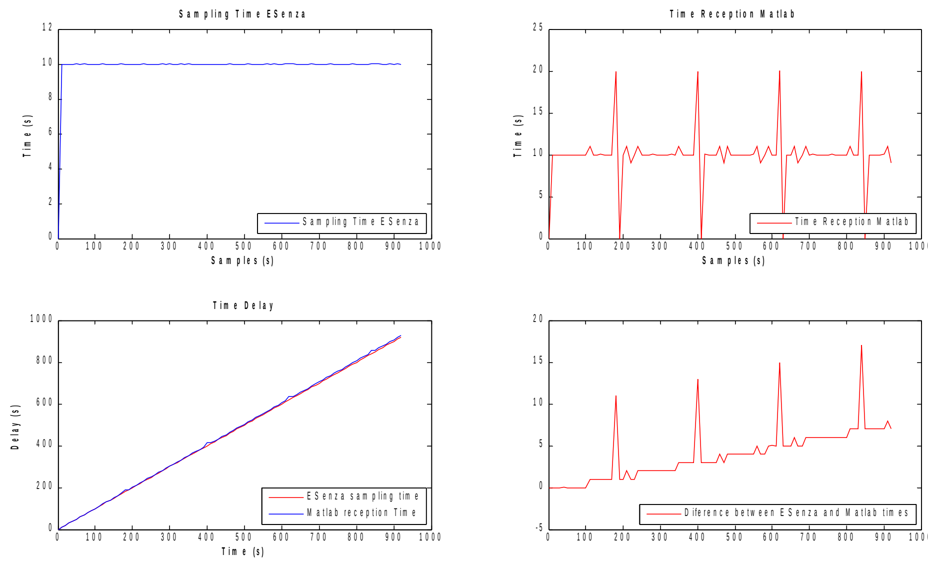
Wireless PID Control in Lab Environment (1)





Wireless PID Control in Lab Environment (2)





T5.4 Development of the water demo demonstrator

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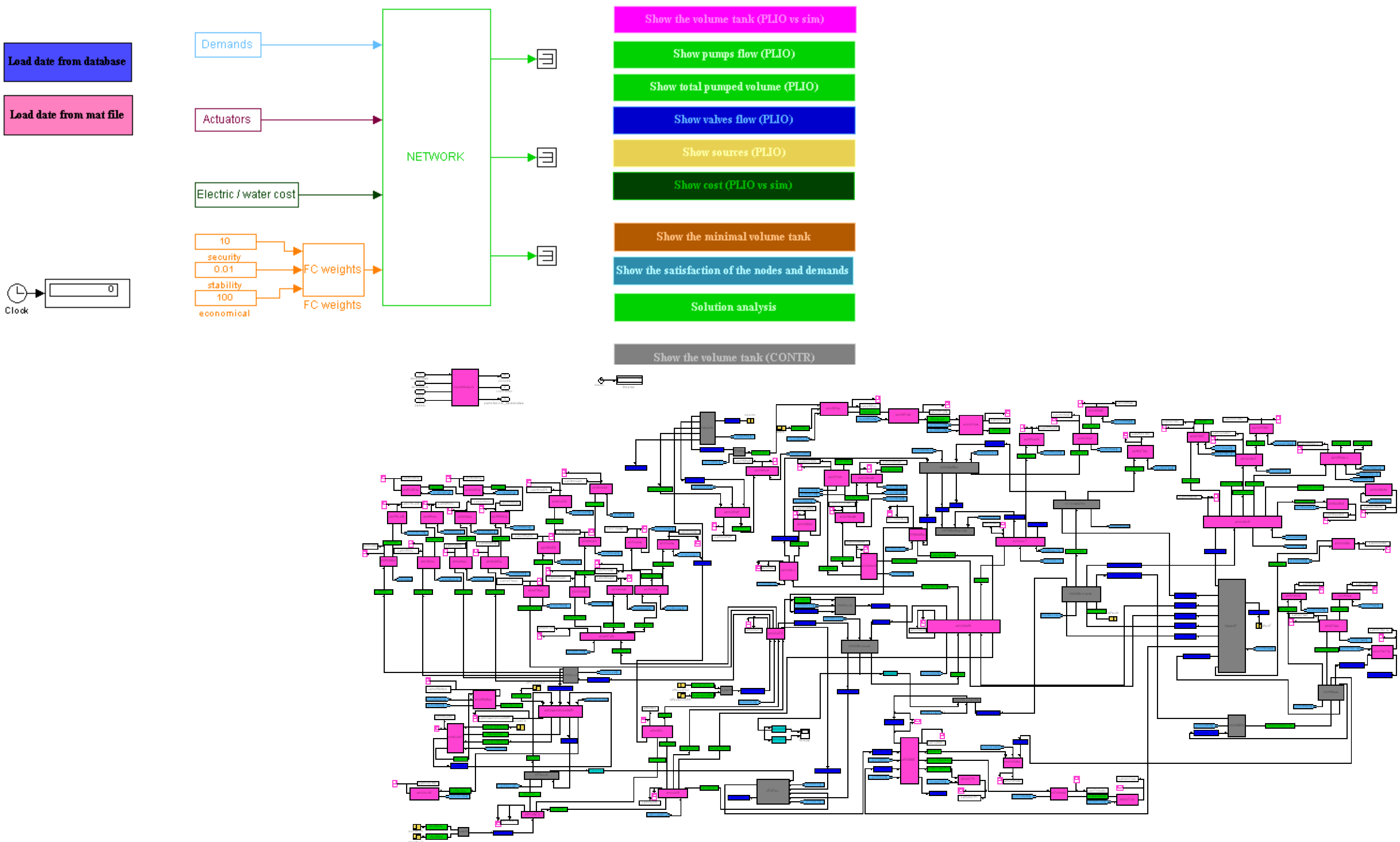
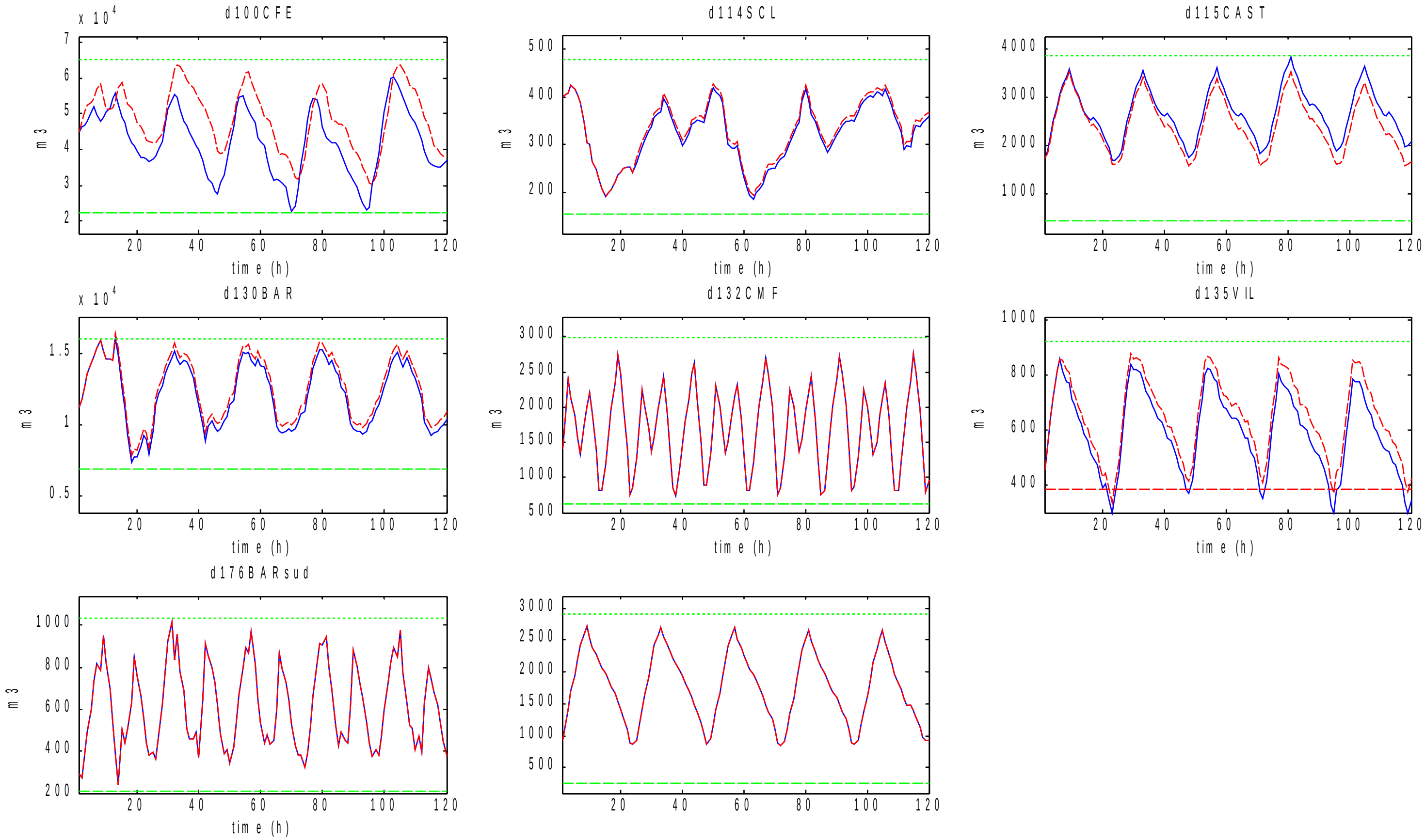
Network Simulator

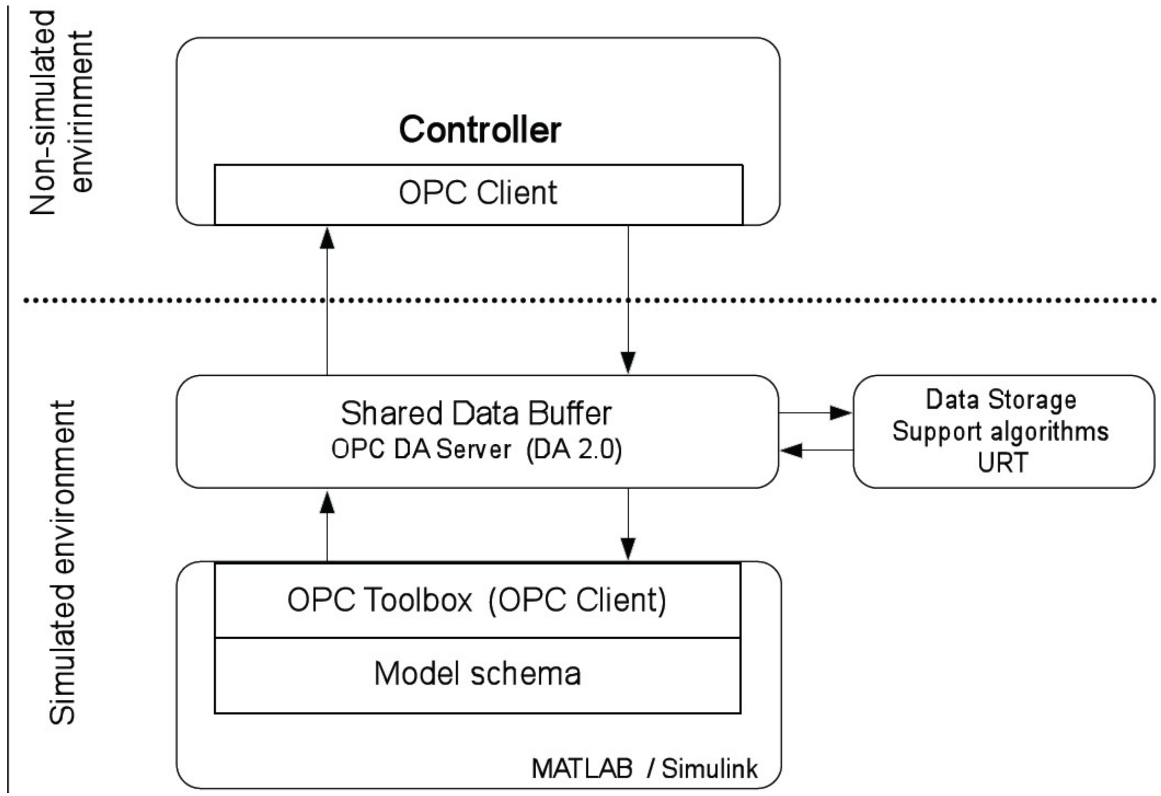


Network Simulator Validation

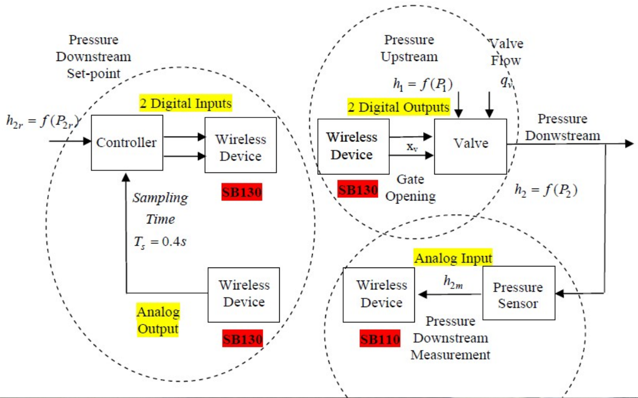
- **Simulated volume (blue) compared to real volume (red) for some tanks**

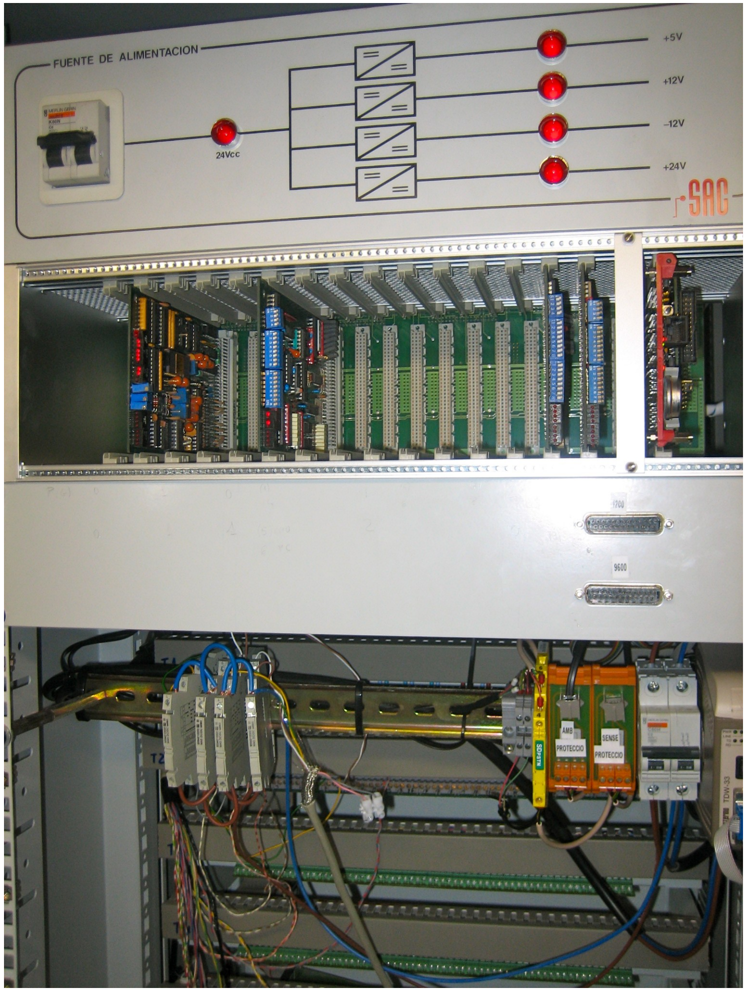


Interface Simulator/DMPC Controller

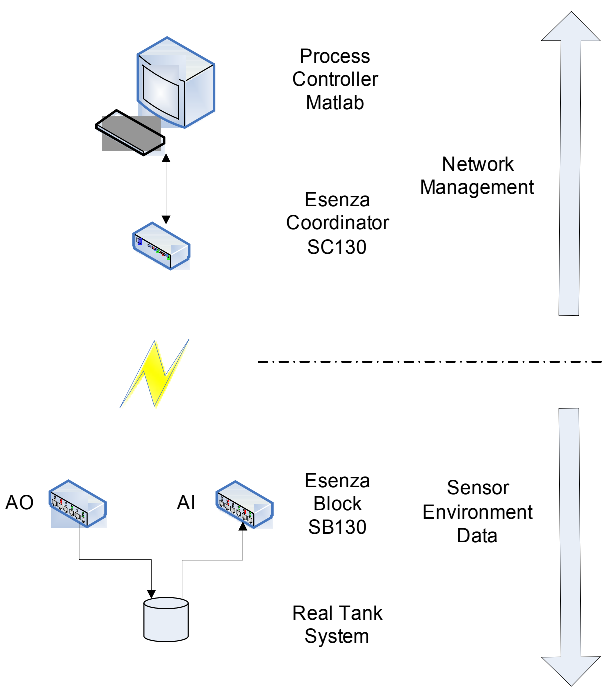


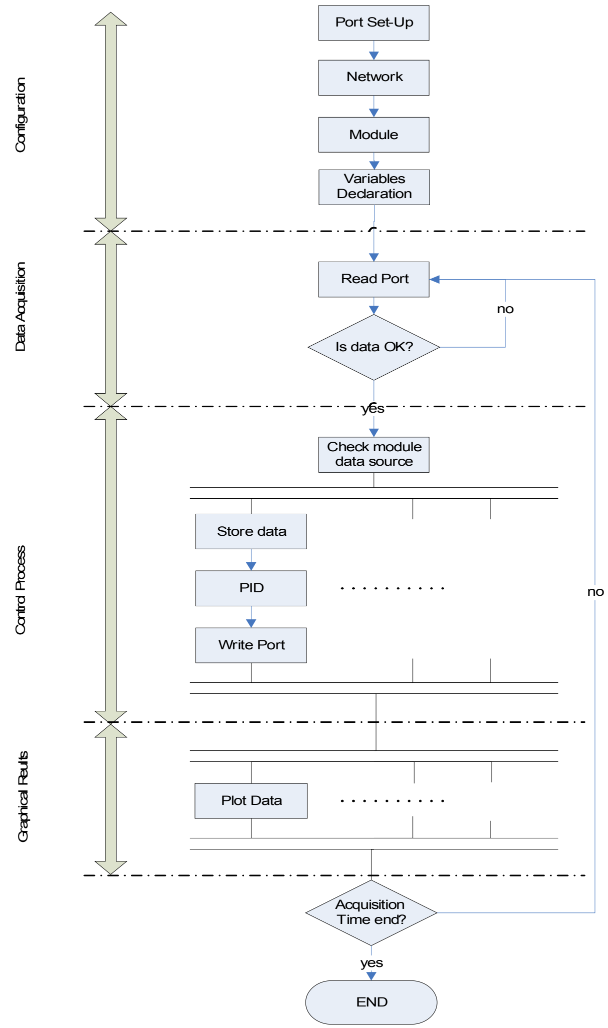
Electrical and Software Interfaces for Wireless Test





MATLAB Toolbox for E-Senza Wireless Devices





T5.5 Testing and evaluation

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Centralized MPC Results

- Centralized MPC Control of Barcelona water network has been implemented by means of PLIO tool.

- To test and adjust the MPC controller some different scenarios have been studied. Parameters to take into account in the calibration of the model are:
  - Initial and security levels in tanks
  - Objective function weights: economical, safety and maintenance factors.
  - Working with different sources operation:
    - Llobregat source set at constant flow (Scenario 1)
    - Fixed sources at real flow (Scenario 2)
    - Source optimization. The optimizer calculates the flow for each time step inside the operational limits of each source (Scenario 3)

Centralized MPC: Scenario 1 (1)

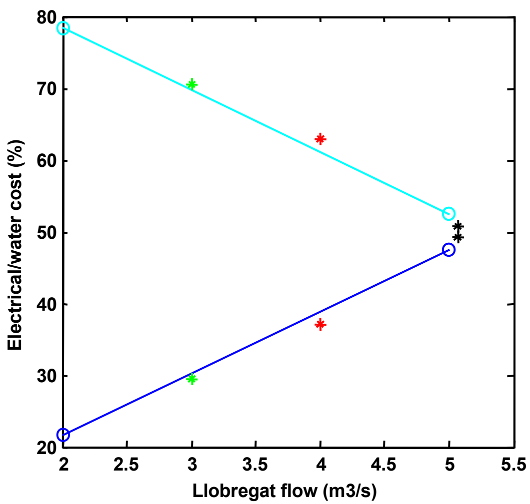
Scenario 1: Llobregat source set at constant flow

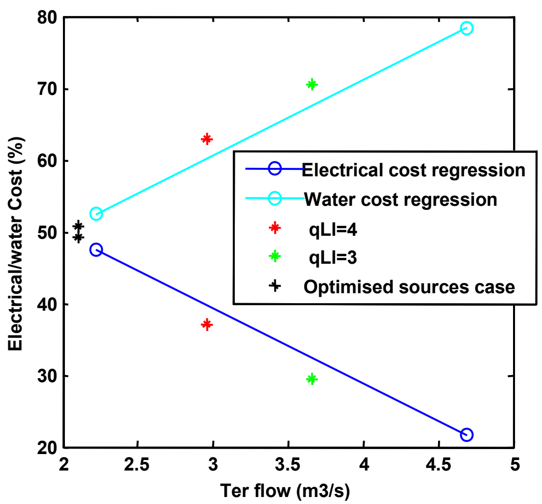
	Flow(m^3/s)	
	Case 1	Case 2
Llobregat surface source	3	0
Llobregat underground source	2	2

- Barcelona's average input flow is about 7.5 m3/s.
- In case 1 an important part of the total demand is taken from Llobregat.
- In case 2 only a 25% of the total demand is taken from Llobregat. It is expected that an important part of the network consumption is going to be taken from Ter.
- These two scenarios are interesting from the point of view of the behaviour of the economical cost.

Centralized MPC: Scenario 1 (2)

- Conclusions
  - It exists a strong and linear dependency between economical cost and the operation of this two sources.
  - In order to reduce the total cost it is necessary to maximise the quantity of water taken from Llobregat.





Case 1

	Electrical cost	Water cost	Total cost
Day 1	52,42	47,58	100,00
Day 2	46,65	53,35	100,00
Day 3	48,10	51,90	100,00
Day 4	47,57	52,43	100,00

Case 2

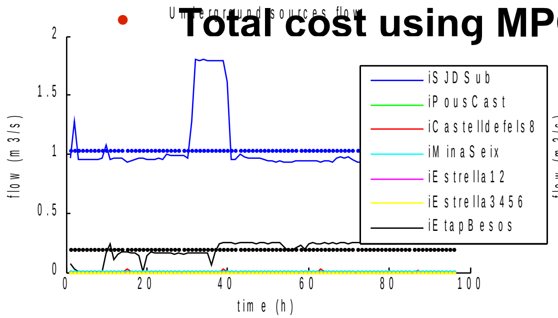
	Electrical cost	Water cost	Total cost
Day 1	-50,27	+91,34	+17,11
Day 2	-47,94	+72,77	+16,47
Day 3	-48,37	+78,27	+17,36
Day 4	-47,67	+71,06	+14,58

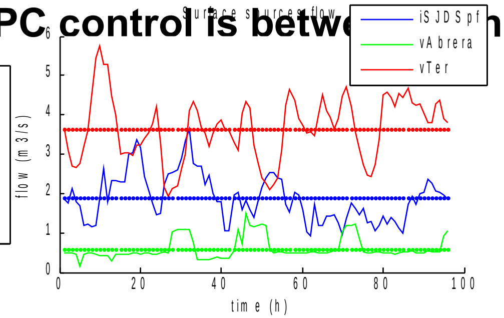
Increase/decrease % in comparison to case 1

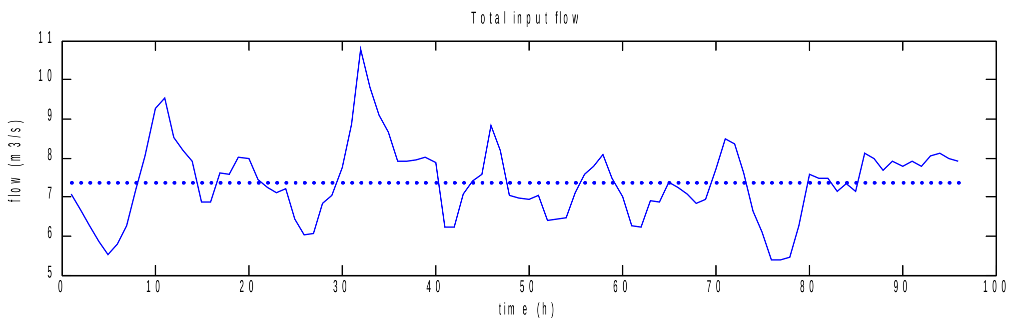
Centralized MPC: Scenario 2

Scenario 2: Sources set at real flow

- Sources flow is imposed by using real data obtained from AGBAR historical database.
- It is an interesting case study in order to compare centralised MPC control and current control applied regarding to transportation cost.
- It is a previous step before comparing centralised and decentralised MPC control.
- Important improvement in electrical cost, which represents between 10% and the 25 % of the real operation cost.
- Total cost using MPC control is betwe… nd 8 % lower than the real one.







Current control

	Electrical cost	Water cost	Total cost
23/07/2007	33,13	66,87	100,00
24/07/2007	34,66	65,34	100,00
25/07/2007	32,00	68,00	100,00
26/07/2007	31,29	68,71	100,00

MPC

	Electrical cost	Water cost	Total cost
23/07/2007	-23,27	+0,00	-7,71
24/07/2007	-10,56	+0,00	-3,66
25/07/2007	-20,61	+0,00	-6,59
26/07/2007	-18,58	+0,00	-5,81

Increase/decrease % in comparison to current control

Centralized MPC: Scenario 3 (1)

Scenario 3: Flow optimization

- **In this case electrical and water costs are minimised, so it is expected a higher improvement in the total cost referring to the scenario with fixed sources.**
- **Taking into account results obtained in the first case study (constant fixed flow in Llobregat source) a solution with maximum average flow from Llobregat source is expected.**
- **In the optimization results shown the term that guarantees stability in control elements (pumps and valves) is on.**
- **Underground sources' water cost is penalized to avoid its over-exploitation.**

Centralized MPC: Scenario 3 (2)

- Big water cost savings, between 30% and 50 %.
- Electrical cost has increased regarding to current control case ([+18,+27]%) and MPC case with fixed sources ([+27,+60]%).
- Total cost has decreased between 13% and 22 % regarding to MPC results obtained with fixed sources.
- Sources flow distribution is the expected one. Llobregat's source flow is maximized.

Current control

	Electrical cost	Water cost	Total cost
23/07/2007	33,13	66,87	100,00
24/07/2007	34,66	65,34	100,00
25/07/2007	32,00	68,00	100,00
26/07/2007	31,29	68,71	100,00

MPC improvement in comparison to current control case

	Electrical cost	Water cost	Total cost
23/07/2007	18,92	-50,70	-27,63
24/07/2007	14,04	-32,56	-16,41
25/07/2007	26,29	-43,91	-21,45
26/07/2007	26,09	-44,43	-22,36

MPC improvement in comparison to fixed sources to real flow case (Scenario 2)

	Electrical cost	Water cost	Total cost
23/07/2007	54,99	-50,70	-21,59
24/07/2007	27,51	-32,56	-13,23
25/07/2007	59,08	-43,91	-15,91
26/07/2007	54,86	-44,43	-17,57