Simulation, optimal management and infrastructure planning of gas transmission networks

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GANESO®: Overview of the project

GANESO®: Gas Network Simulation and Optimization

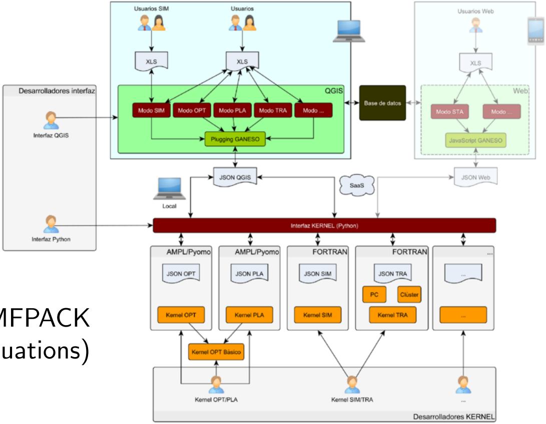
- Software developed by researchers at **USC**, **UDC** and **ITMATI** for **Reganosa Company**
- Ongoing collaboration that started in **2011**
- More than 15 researchers have participated so far

Main functionalities of **GANESO®**

- Steady-state simulation and optimization
- Transient simulation
  - Support to the injection of gases with different compositions
- Network planning and design under uncertainty
- Computation of tariffs for network access
- Database management for storing and handling scenarios
- User interface via QGIS
- Network visualizations via QGIS and Google Earth
- ...

GANESO® Software

- Programming languages:
  Python, FORTRAN
- Modeling languages:
  AMPL, Pyomo
- Database management:
  MySQL
- Auxiliary software:
  - **Mathematical libraries:** UMFPACK (to solve systems of linear equations)
  - **Optimization software:**
    Free and commercial solvers:
    - **Linear solvers:**
      CBC, Glop, LPSolve, Gurobi,. . .
    - **Nonlinear solvers:**
      ipopt, Knitro, snopt, minos,. . .
  - **Visualization:** QGIS, Google Earth
  - **Data input/output:** XLS, CSV, and JSON files



Stationary Simulation and Optimization

Gas transmission networks

Gas transmission networks

Gas transmission networks

Gas transmission networks

Graph Associated to a Gas Transport Network

The network is modeled as a **directed graph**

- **Edges** represent gas pipes and roads for tank trucks
- **Edges** connect **nodes**. **Nodes** can represent:
  - Entry points (supply nodes) such as international connections and regasification plants
  - Exit points (demand nodes) such as international connections and cities
  - Underground storage facilities
  - Suction and discharge points of a compressor station
  - Loading and unloading stations for tank trucks
  - Virtual interconnection points
  - Points where there are changes in the properties of a pipe (section, rugosity,. . .)

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  - Points where there are changes in the properties of a pipe (section, rugosity,. . .)
- The **Spanish High Pressure Network** has been modeled with around 500 edges and 500 nodes

Equations for the Model

Mathematical model

The equations/constraints of the simulation and optimization models are deduced from the following fundamental equations:

- **Navier-Stokes** equations for compressible flows:
  - Conservation of mass
  - Conservation of momentum
  - Conservation of energy
- **Constitutive laws**:
  - Law of friction for turbulent flows
  - State equation for real gases
  - Fourier's law for the heat flow

Ingredients of the Optimization Problem

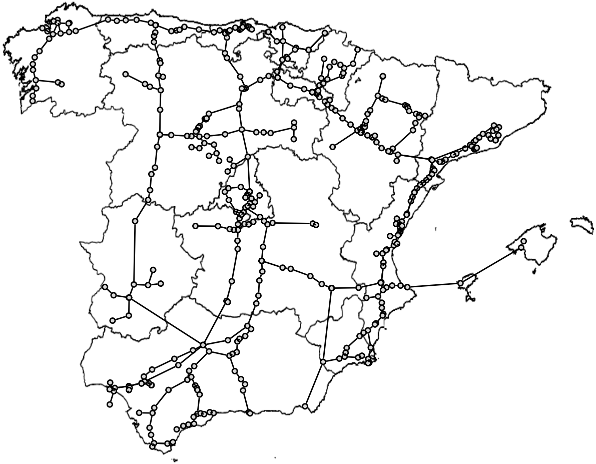
Determine a feasible gas flow configuration such that:

- Guarantee the security of supply
  - Meet demands at the consumption points
  - Gas pressure is kept within specified bounds
- Mass balance
- Pressure loss constraints

Available objective functions

- Minimize gas consumption at compressor stations
- Minimize boil-off gas at regasification plants
- Minimize **overall transport costs**:
  compressor stations + regasification plants + tank trucks
- Maximize network linepack
- Maximize/minimize exports of different zones
- Control bottlenecks

Network Flow Problem



Flow conservation constraints

$$\sum_{k \in A_i^{\text{ini}}} q_k - \sum_{k \in A_i^{\text{fin}}} q_k = c_i$$

$\forall i \in N^C$ demand nodes

$$0 \leq \sum_{k \in A_i^{\text{ini}}} q_k - \sum_{k \in A_i^{\text{fin}}} q_k \leq s_i$$

$\forall i \in N^S$ supply nodes

Box Constraints

$$\underline{q}_k \leq q_k \leq \bar{q}_k$$

$\forall k \in E$ flow bounds

$$\underline{p}_i^2 \leq {p_i}^2 \leq \bar{p}_i^2$$

$\forall i \in N$ pressure bounds

Variables of the problem

- Flow through each pipe
- Pressure at each node

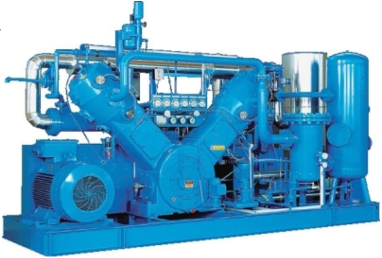
Pressure loss

Given a pipe between two nodes $k = (i, j) \in E^{st}$

- L_k: length of the pipe
- D_k: diameter of the pipe
- R: gas specific constant
- $\lambda(q_k)$: friction coefficient computed with **Colebrook** or **Weymouth**
- $Z(p_{m_k}, \theta_{m_k})$: compressibility factor computed with **AGA-8** or **SGERG-88**
  - p_{m_k}: average pressure in the pipe
  - θ_{m_k}: average temperature in the pipe
- h_i and h_j: height at nodes i and j

$$p_i{}^2 - p_j{}^2 = \frac{16 L_k \lambda(q_k)}{\pi^2 D_k{}^5} Z(p_{m_k}, \theta_{m_k}) R\theta_{m_k} |q_k| q_k + \frac{2g}{R\theta_{m_k}} \frac{p_i{}^2 + p_j{}^2}{2Z(p_{m_k}, \theta_{m_k})} (h_j - h_i)$$

As many nonlinear constraints as structural pipes



Increase the pressure

Let $k = (i, j) \in E^c$ be a compressor ($q_k \geq 0$)

$$p_i \leq p_j$$

being p_i the input pressure and p_j the output pressure.

Gas consumption at compressors

$$g_k = \frac{1}{LCV} \frac{1}{\varepsilon \xi \eta_k^*} \frac{\gamma}{\gamma - 1} Z\left(p_{m_k}, \theta_i\right) R\theta_i \left(\left(\frac{p_j}{p_i}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right) |q_k|,$$

- LCV: lower calorific value
- γ: adiabatic coefficient of the gas (ratio of the specific heats)
- ε and ξ: efficiency parameters of the compressor
- η_k^*: optimal isentropic efficiency (it actually depends on (q_k, p_i, p_j) and the **operating diagram constraints**)

Nonlinear Nonconvex Optimization Problem

Obj. Function: min $\sum_{k \in E^c} g_k$

Box Constraints

$\underline{p}_i^2 \leq {p_i}^2 \leq \bar{p}_i^2$ $\quad \forall i \in N$ pressure bounds

$\underline{q}_k \leq q_k \leq \bar{q}_k$ $\quad \forall k \in E$ flow bounds

Flow conservation constraints

$$\sum_{k \in A_i^{\text{ini}}} q_k - \sum_{k \in A_i^{\text{fin}}} q_k = c_i \qquad \forall i \in N^C \text{ flow conservation at demand nodes}$$

$$0 \leq \sum_{k \in A_i^{\text{ini}}} q_k - \sum_{k \in A_i^{\text{fin}}} q_k \leq s_i \qquad \forall i \in N^S \text{ flow conservation at supply nodes}$$

Gas loss constraints

$${p_i}^2 - {p_j}^2 = \frac{16 L_k \lambda(q_k)}{\pi^2 D_k^5} Z(p_{m_k}, T_m) R T_m |q_k| q_k + \frac{2g}{R T_m} \frac{{p_i}^2 + {p_j}^2}{2 Z(p_{m_k}, T_m)} (h_{in} - h_{out}) \quad \forall k \in E$$

Increase pressure in compressors

$p_i \leq p_j$ $\quad \forall k = (i,j) \in E^c$

Gas consumption constraints

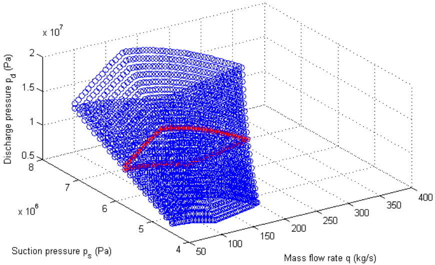
$$g_k = \frac{1}{e_h H^c} \frac{\gamma}{\gamma - 1} Z(p_m, T_{in}) R T_{in} \left(\left(\frac{p_j}{p_i}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right) q_k \quad \forall k = (i,j) \in E^c$$

Additional Network Elements

Pressure control valves (open/closed valves, ...)

- Freedom to decrease pressure in the direction of flow
- Suppose **pipe** $k = (i, j) \in E^{PCV}$: (BINARY VARIABLES)
  if $q_k > 0 \Rightarrow p_i \geq p_j$ if $q_k \leq 0 \Rightarrow p_i \leq p_j$

Operating diagrams in compressors

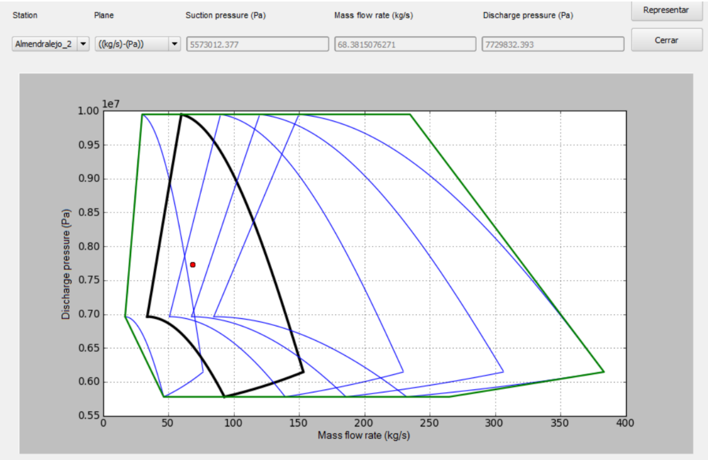


Boil-off costs

- Operation of a **regasification plant**.
- BINARY VARIABLES: whether is supplying gas.

Operational Ranges at Compressor Stations

- GANESO® delivers solutions in which compressor stations work in **feasible** and **efficient** regimes
- The user can check the point of operation of each compressor station



GANESO® Algorithms for steady-state simulation and optimization

Mathematical Modeling

- As the pipe length is much larger than the area of its cross-section we can use a 1D model
- We **integrate the 3D equations** on the pipe cross-section to obtain a stationary 1D model

Simulation

- Resolution of systems of nonlinear equations relying on **Newton-like numeric methods for nonlinear equations**

Optimization

- Custom-made implementation of a **Sequential Linear Programming algorithm**
- Custom-made implementation of a hybrid algorithm combining **Control Theory** (simulator) and **Sequential Linear Programming**
- Use of state of the art **nonlinear solvers** via algebraic modeling languages AMPL and Pyomo (Ipopt, Knitro,. . .)

Case Study in the Spanish High Pressure Network

Running GANESO® on a feasible flow configuration reported by Spanish TSM

Scenario

- Spanish High Pressure Gas Network
- Work day of January with low demand

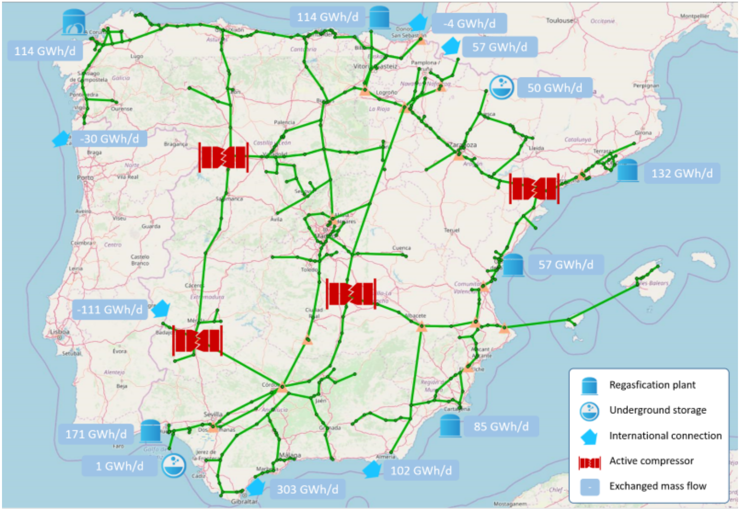
Optimization premises

- Flows at **International connections** and **underground facilities** are taken as **fixed** inputs
- The optimizer has freedom to choose the distribution of flow among the **regasification plants**
- The optimizer has freedom to choose how to use **compressor stations**, **PCVs** and **FCVs**.
- The goal is to minimize the cost associated to the **gas consumption** at compressor stations.

Case Study in the Spanish High Pressure Network

Running GANESO® on a feasible flow configuration reported by Spanish TSM

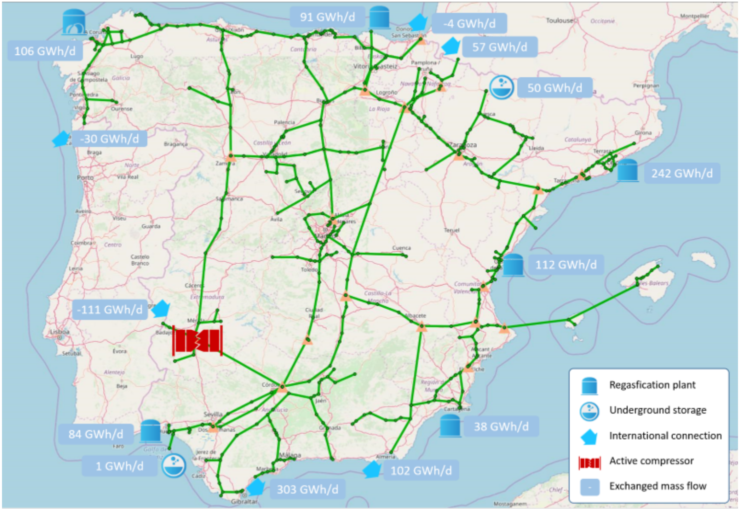
Operation obtained from TSM reports (on security of supply)



Case Study in the Spanish High Pressure Network

Running GANESO® on a feasible flow configuration reported by Spanish TSM

Operation optimized with GANESO®



Case Study in the Spanish High Pressure Network

Running GANESO® on a feasible flow configuration reported by Spanish TSM

Distribution of flow in the plants

[GWh/d]	TSM	Optim.
Barcelona	131.8	241.6
Bilbao	113.9	90.7
Cartagena	85.4	38.2
Huelva	170.8	83.6
Reganosa	114.2	106.4
Sagunto	56.9	112.3

Before vs. After

From South Cartagena + Huelva	**From North** Reganosa + Barcelona + Bilbao
-134.3 GWh/d	+78.9 GWh/d

Compression costs in stations

[GWh/d]	TSM	Optim
Alcazar	0.29	-
Almendralejo	0.27	0.16
Tivisa	0.22	-
Zamora	0.15	-
TOTAL	0.93	0.16

- **GANESO®** has optimized
  1. the distribution of flow among the regasification plants
  2. the use of compressor stations
- Based on this management, the cost would be **17%** of the usual one
- Execution takes less than **5 minutes** on a desktop computer

Injection of gases with different qualities

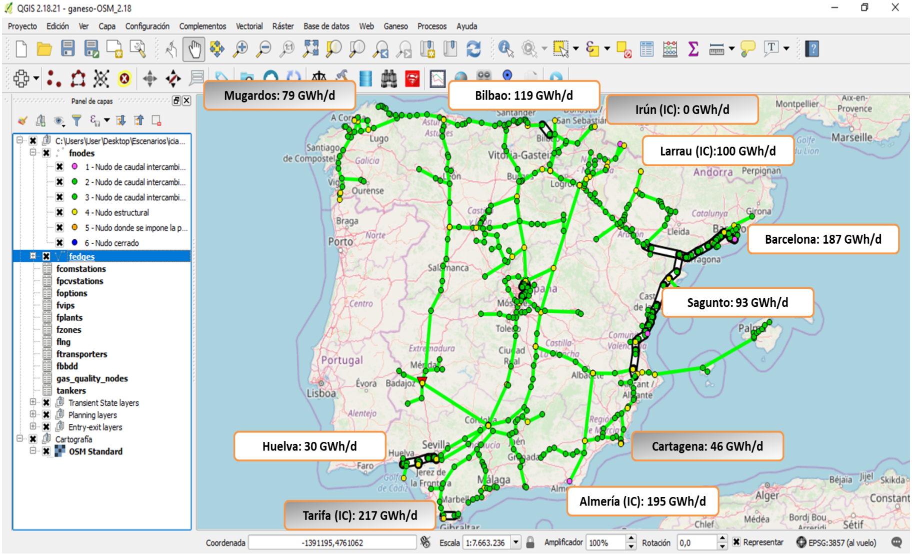
- The injection of gases with **different qualities** in the network has a big impact in the equations of the model
- Some parameters depend **drastically** on the **gas composition**:
  - $R = \frac{\mathcal{R}}{M}$: gas specific constant, where $\mathcal{R} = 8.31434$ [kJ/(kmol K)] is the universal gas constant and M the **molar mass** of the gas [kg/kmol].
  - $Z(p_{m_k}, \theta_{m_k})$: compressibility factor
- Further, the **customers usually demand** a certain amount of **energy**, but depending on the gas composition the mass flow needed to satisfy it changes
- The following constraints are incorporated:
  - **Calorific value propagation** (pooling constraints)
  - **Flow conservation** constraint in terms of **energy**

Case Study: Maximize the injection of H_2

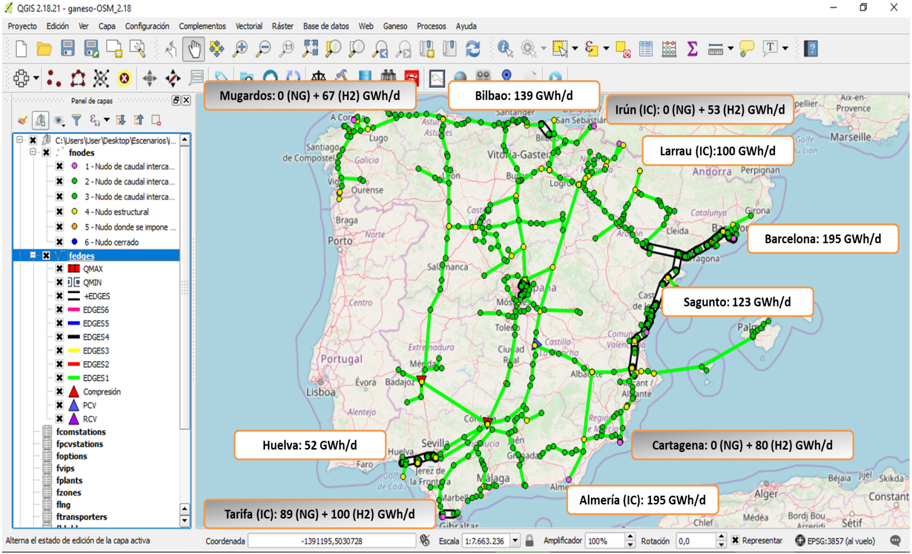
- Real instance of the **Spanish gas transmission network**
  - Minimize the **gas consumption** at compressors
  - The optimizer has **freedom** to choose the distribution of flow among the **regasification plants**
  - The optimizer consider as **controllable** elements the **compressor stations** and **PCVs**
  - **Work** day of **January** with low demand (1065 GWh/d)
- We consider two case studies:
  - **Case A**: conventional **natural gas** through entry points
  - **Case B**: maximize the injection of **Hydrogen** through 4 entry points: Mugardos (North-West), Irún (North), Cartagena (East) and Tarifa (South)

(%)	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	H_2	CV (MJ/kg)
Natural gas	88.72	7.81	2.72	0.73	0.02	-	55.04
Hydrogen	-	-	-	-	-	100	141.79

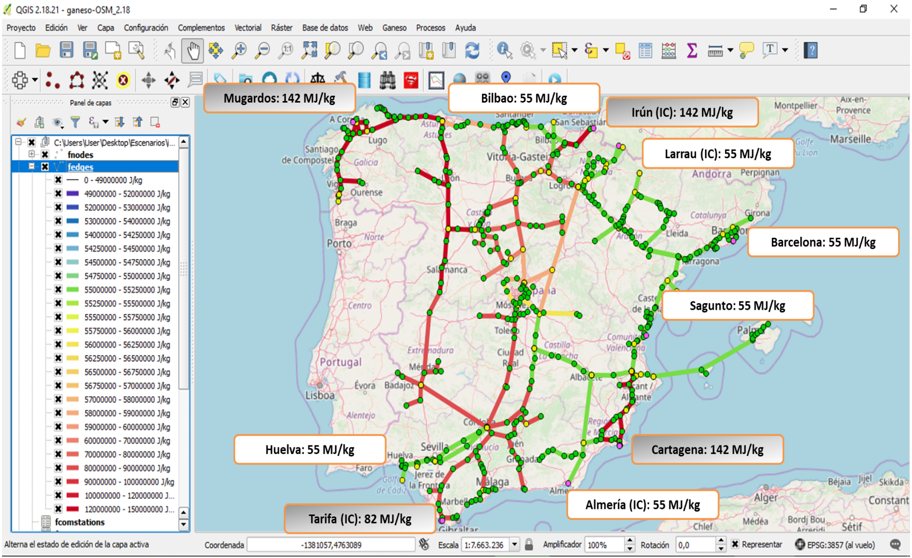
Case A: natural gas injection



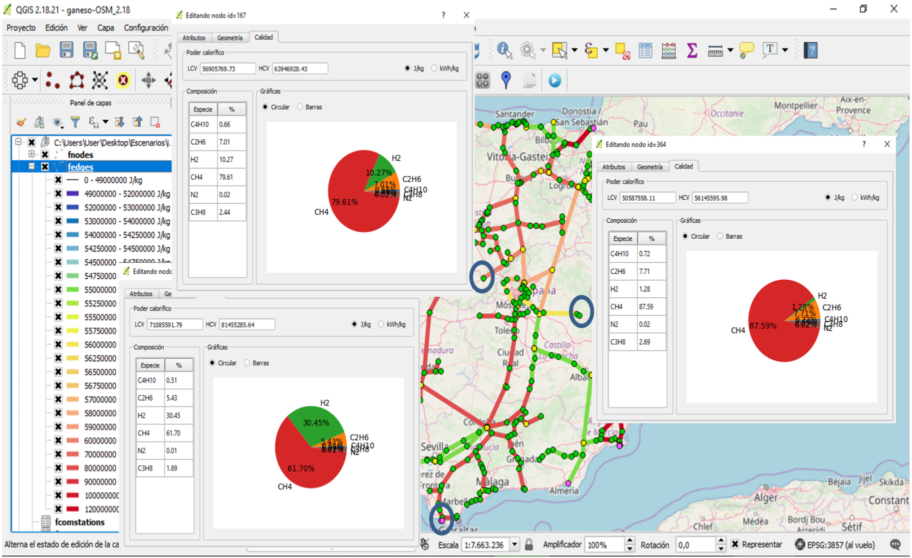
Case B: maximize H_2 injection



Case study B: maximize H_2 injection (CV propagation)



Case study B: maximize H_2 injection (Gas composition)



Transient Simulation

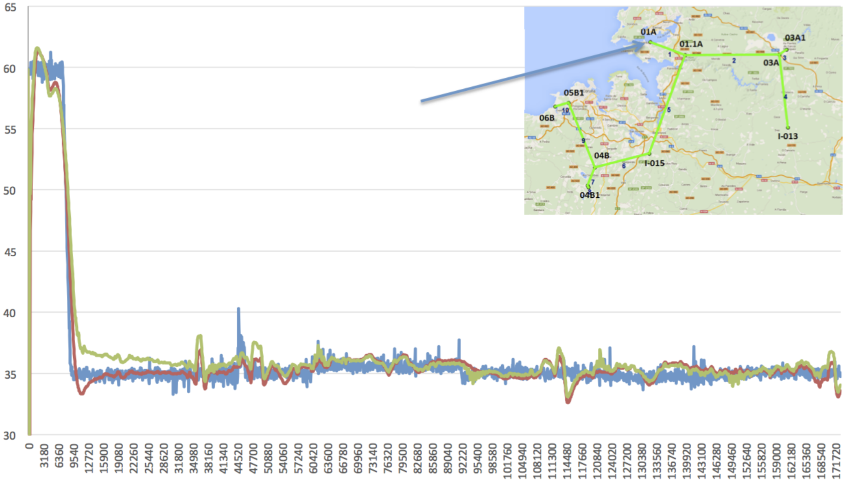
Transient Simulation

- Physical Equations:
  - **Navier-Stokes** equations for compressible flows:
    - Conservation of mass, conservation of momentum, conservation of energy
  - **Constitutive laws**:
    - Law of friction for turbulent flows, equations of state for real gases

- Mathematical modeling:
  - Again, we **integrate 3D equations** to obtain a **<u>transient</u> 1D model**
  - Obtaining **1D compressible Euler** equations with source terms:
    - Friction, variable height along the pipeline, heat exchange with the exterior
  - Modeling junctions of several pipes requires additional mathematical tools
  - Allowing for heterogeneous gases also requires additional tools

- Numerical methods:
  - **Standard methods** such as Euler explicit for time discretization and finite volume methods for space discretization **cannot be applied** in the presence of source terms
  - Need to use **Euler explicit methods enhanced with well-balanced schemes** (discretization of source terms needs some upwinding)

Transient Simulation: Numerical Results



Mass flow rate at node 01A

- **Blue**. Real measurement
- **Red**. Simulation with a homogeneous gas model
- **Green**. Simulation with a heterogeneous gas model

Network Design and Infrastructure Planning

Network Design and Infrastructure Planning under Uncertainty

- Decisions regarding network design and network expansions
- Long-term planning under uncertainty to prioritize infrastructures
- **Multistage optimization problem**
- **Stochastic programming problem**

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Sources of uncertainty: Gas demand – Gas prices – Infrastructure costs

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Sources of uncertainty: Gas demand – Gas prices – Infrastructure costs

Main costs involved in the multistage problem

- Operational costs in each period:gas consumption at compressor stations, boil-off gas, tank trucks,. . .
- Costs for unmet demand (if any) in each period
- Costs of building infrastructures

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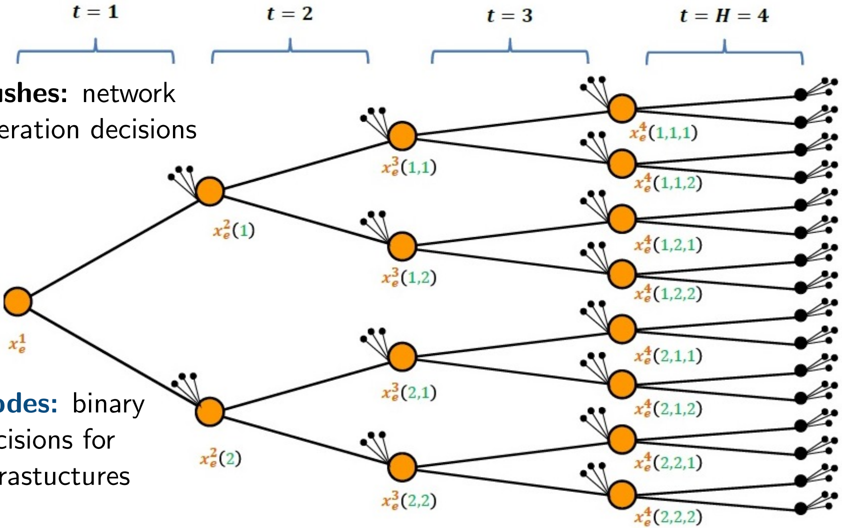
Main approaches

- **U1: Multideterministic solver:**
  Execution and analysis of a battery of different (plausible) multistage scenarios
- **U2: Stochastic programming solver:**
  If probabilities are known for the different scenarios, joint analysis of the optimization problem under uncertainty with tools from stochastic programming

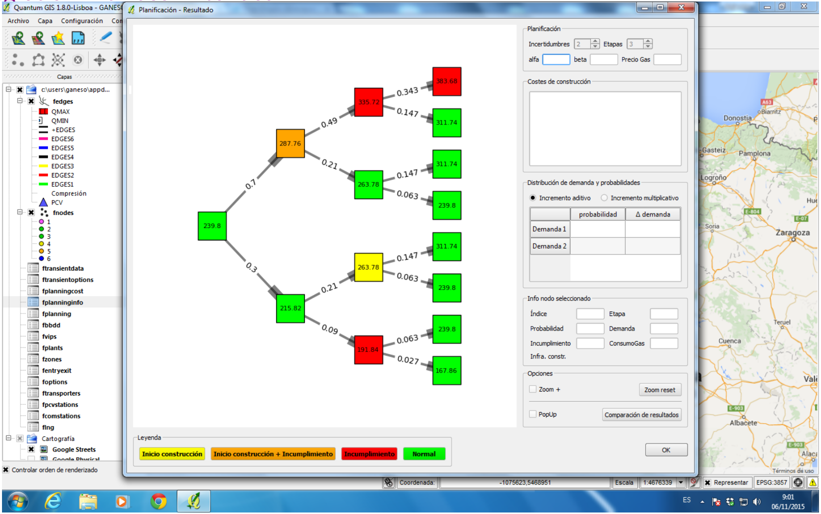
Tree Representation of a Multistage Problem under Uncertainty



- **Bushes:** network operation decisions
- **Nodes:** binary decisions for infrastructures
- **U1:** Scenarios, paths from the root to the end, are solved independently
- **U2:** The whole tree is solved at once: **Large optimization problem**

Network Design and Infrastructure Planning under Uncertainty

Integration with user interface



Network Design and Infrastructure Planning under Uncertainty

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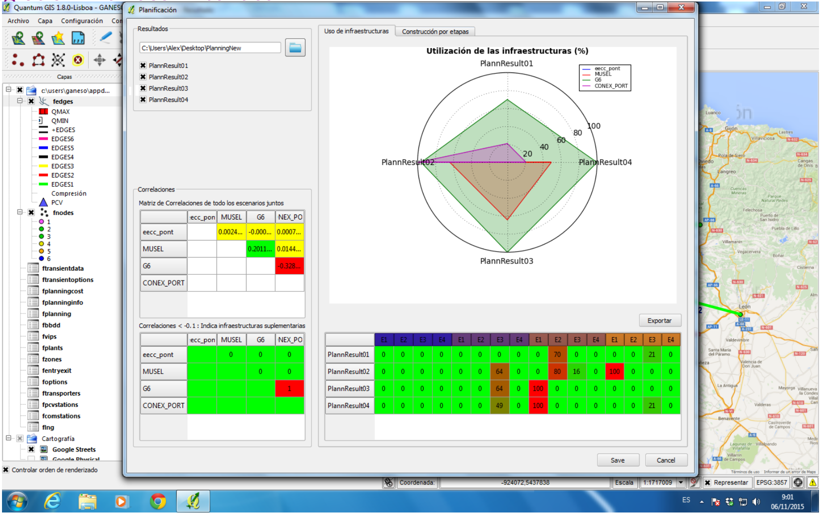

Ongoing work

Ongoing work

- The development and validation of the **physical parameters for hydrogen** enriched natural gas
  - For example, we are considering the use of **Papay equation** for the approximation of compressibility factor
- Extent the network **planning module** to include the injection of heterogeneous gases
- The development of mathematical models and algorithms to **combine electrical and gas transmission networks** (e.g, power to gas)

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