Dynamic Optimization in Gas Pipeline Networks

EWO MEETING, Spring 2012

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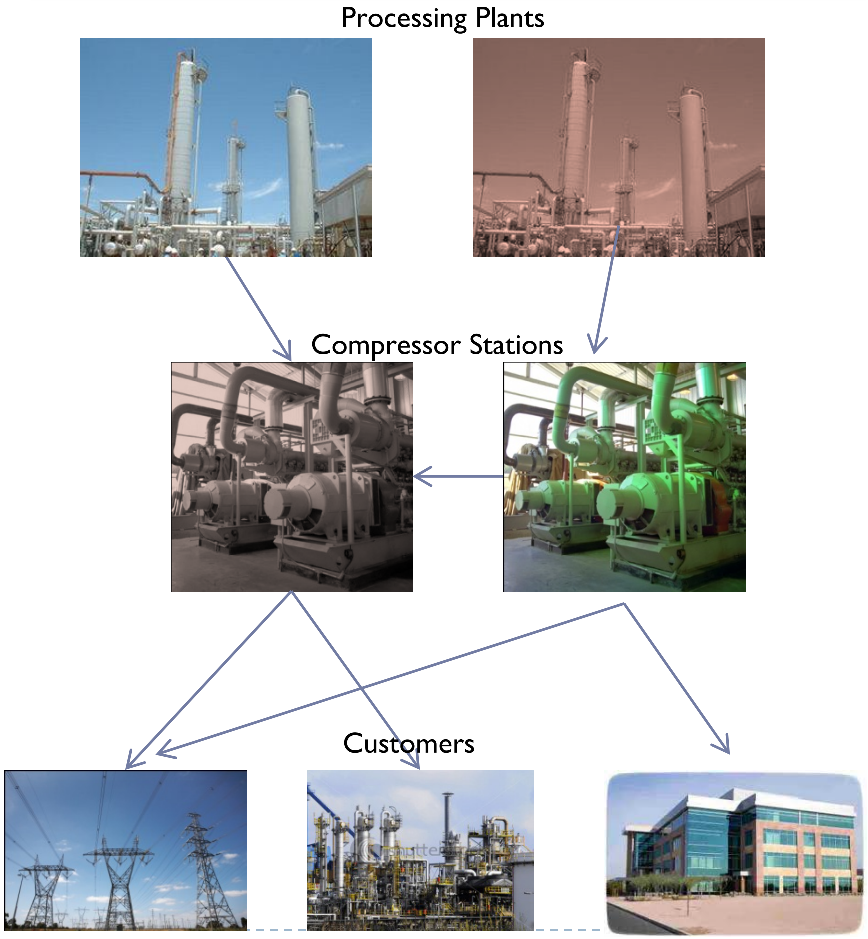
Project Background

- Collaboration with Cognizant (Invensys).
- Dynamic Optimization of Gas Pipeline Networks
  - First principles model developed in Baumrucker & Biegler (2010), moved into a GUI-based ROMeo platform.
    - ROMeo: Rigorous On-line Modeling and Equation-based Optimization
  - Model will provide a case study for ROMeo's dynamic optimization capabilities using the OPERA SQP solver.
  - Generate scenarios and verify results.

Gas Transmission Pipeline Networks

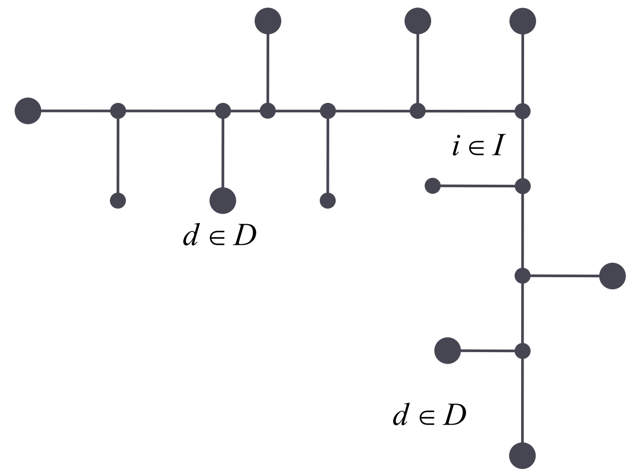
Interconnected network of suppliers, consumers and compressor stations



- **Suppliers**: Continuous flow of gas into network.
- **Customers**: Chemical industries, Power plants, Residential/commercial heating: Flow demands must be satisfied at a contract pressure.
- **Compressor Stations**: Compression of gas to compensate for frictional loss.
- Optimization Scope – Decide on optimal operating points by minimizing the operating cost of compressors s.t.,
  - satisfying time varying gas demands,
  - contract pressures, and
  - physical constraints.

Pipeline modeling

- **Pipeline Arcs:** PDE's to describe pressure driven flow in a pipe: $p(z,t)$ and $q(z,t)$



Momentum Balance: $$\frac{\partial p}{\partial z} + \frac{f}{2}\frac{RT}{M_w D A^2}\frac{q|q|}{p} = 0$$

Material Balance: $$\frac{\partial q}{\partial z} + \frac{\partial p}{\partial t}\frac{M_w A}{ZRT} = 0$$

Network Inventory: $$A\int_0^L p(z)dz = Z\frac{m}{M_w}RT$$

- Node equations
  - Flow balance: no accumulation at nodes.
  - Pressure balance: pressure at a node is equal to the pressure either into or out of the connected arc.
- Compressor equation: $Power_{s,t} = q_{s,t}^{Supply}\frac{C_p T_{ref}}{\eta}\left[\left(\frac{P_{s,t}}{P_{inlet}}\right)^{(\gamma-1)/\gamma} - 1\right] \quad \forall s \in S, t \in T$
- Colebrook-White turbulent friction factor
- Flow reversals through smoothing

SET DEFINITIONS

I	Arcs (pipe segments)
J	Nodes (intersection)
$K = \{in, out\}$	End-points of the pipe
S	Suppliers in network
D	Demands in network
$T = \{0, \ldots, t_f\}$	Time points

B.T. Baumrucker and L.T. Biegler, MPEC strategies for cost optimization of pipeline operations, Computers & Chemical Engineering, 34 (2010), 900-913.

Dynamic Optimization Formulation

- Formulation (NLP):

$$\begin{aligned} &\min \quad \text{Compression energy} \\ &s.t. \quad \text{Discretized dynamic pipeline model} \\ &\qquad\; \textit{Physical} \text{ Constraints} \\ &\qquad\; \textit{Terminal} \text{ Constraint} \end{aligned}$$

Term	Meaning
States	Pipeline Inventory
Inputs (MV)	Supplier flow rates
Parameters	Forecast of future demand

- Objective function (Energy minimization):

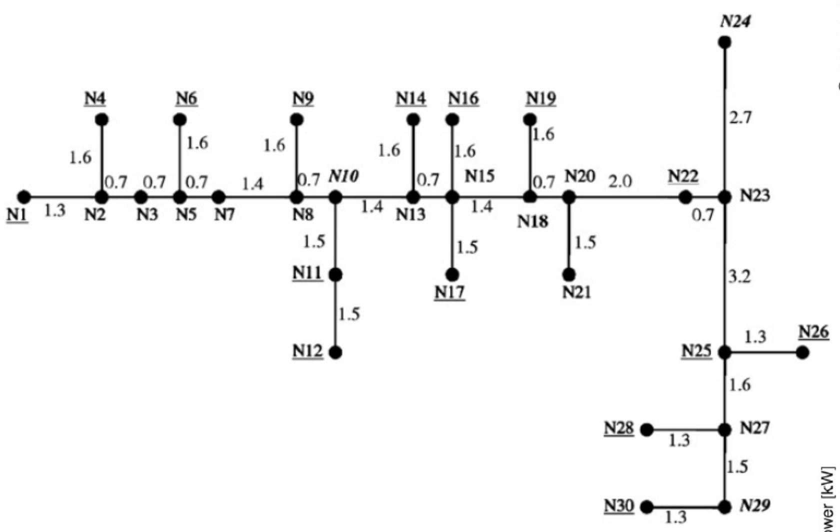
$$J(t_0) = \underbrace{\sum_{s \in S} \int_{t=t_0}^{t=t_0+T_P} Power_{s,t} dt}_{\text{Total Energy}} + \underbrace{\rho \sum_{s \in S} \sum_{t \in T \setminus \{t_0\}} (Power_{s,t} - Power_{s,t-1})^2}_{\text{Smoothing term}}$$

Constraints:

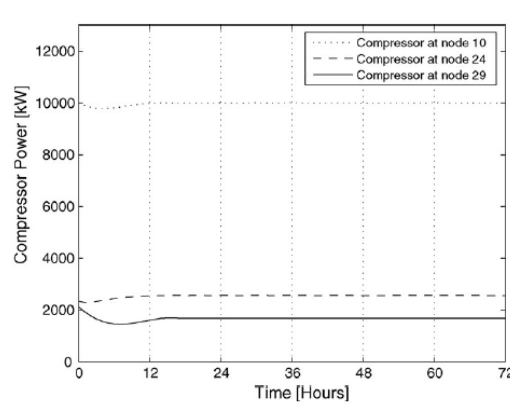
- **Delivery points:** Contract pressures should be satisfied.
- **Supplier points**: Compressor limits on minimum & maximum discharge, pressures and work.
- **Linepack/Inventory targets:** Restoring sustainable gas pipeline inventory and pressure.

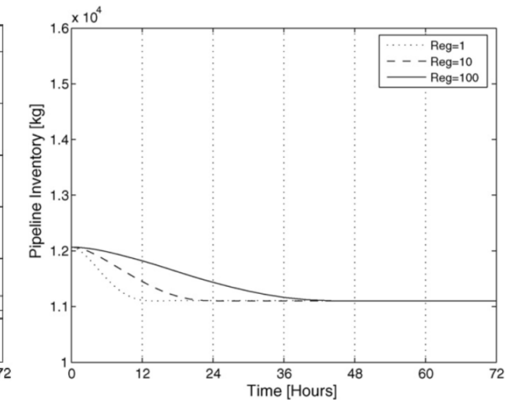
$$\sum_i mass_{i,t_f} \geq \sum_i mass_{i,0}$$

Case Studies on the Praxair Network

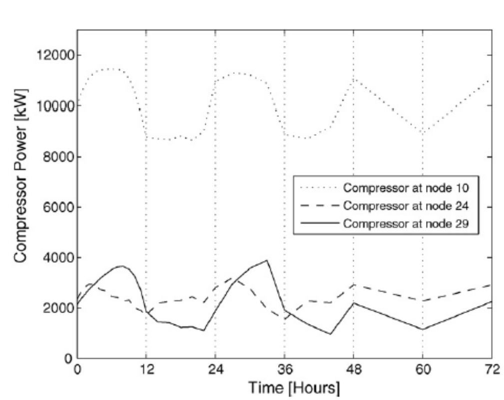


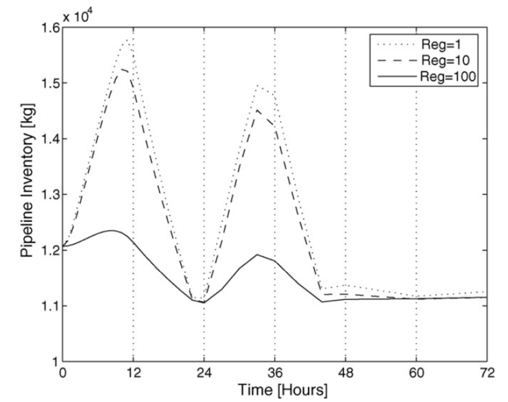
- Energy minimization:





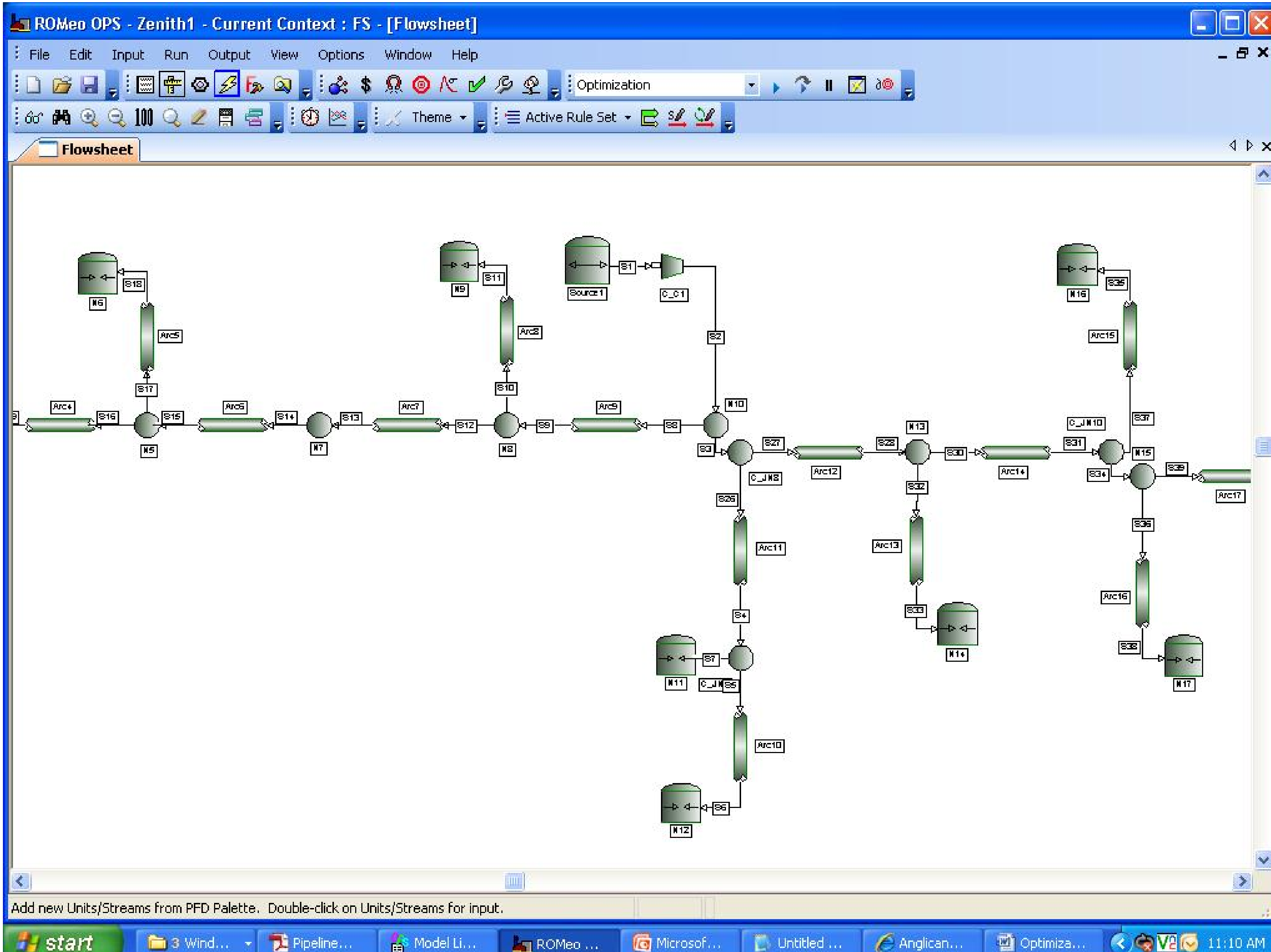
- Time of day pricing:





Zhu, G.-Y., Henson, M. A., & Megan, L. (2001). Dynamic modeling and linear model predictive control of gas pipeline networks. Journal of Process Control, 11, 129–148.

Flowsheet representation in ROMeo



Collaborative Efforts

- Pipeline model built in ROMeo.
- Allows user to add Pipe Segments, Sinks, Sources, Compressors and Nodes.
- First principles models from Baumrucker & Biegler, embedded into ROMeo.
- Results validated against PIPEPHASE: steady-state pipeline simulator (Invensys)
- Dynamic Optimization case studies compare well against results published in Baumrucker & Biegler.
- Future interest in dynamic optimization: Water Pipeline Networks, PSA.

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