Optimal retrofit of a heat recovery network at a pulp and paper mill for minimizing energy and water consumption

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Team Composition

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And a bunch of fancy supporters!

Problem Statement

Goal: improve energy efficiency and water management in a pulp and paper mill.

Two main existing parts:

1. Water Tank Network (WTN);
2. Heat Exchanger Network (HEN).

Specific objective: minimize investment and operation costs:

1. minimize water consumption;
2. minimize energy requirements.

$\Rightarrow$ Coupling WTN and HEN is a way to achieve this.

Assumptions

- Steady state operation.
- One contaminant, waste treatment is not taken into account.
- Fixed cost coefficients.
- Water sources at fixed temperature.

Problem Formulation

Considered problem is retrofit, i.e.

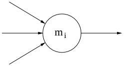
1. architecture modifications/additions;
2. modification of operating conditions.

As a consequence, the resulting problem, if expressed as a mathematical program, is a MINLP (Mixed Integer Nonlinear Program).

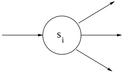
Integer (binary) variables encode all possible process network configurations.

Examples of network elements:

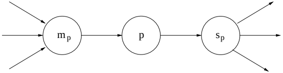
Mixer



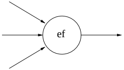
Splitter



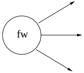
Process



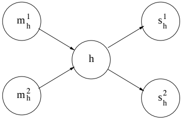
Effluent



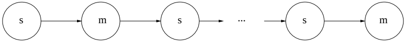
Fresh Water



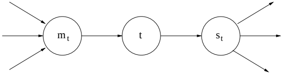
Heat Exchangers



Hot Stream



Tanks



Integer Part (2)

This formulation allows to represent both Water Allocation Network (WAN) and Heat Exchanger Network (HEN) and their interconnections within one superstructure.

Continuous Part

Continuous variables represent *temperatures*, *flowrates* and concentration of *contaminant*.

Structural Rules

Some situations are technically forbidden. These are expressed as constraints on possible connections as:

- you cannot directly connect the freshwater splitter to the effluent mixer;
- fixed hot streams can only be connected to heat exchangers;
- you cannot connect two hot streams to the same heat exchanger;
- ...

Physical Constraints

There are also physical constraints to take into account:

- water and contaminants mass balance;
- energy (heat) balance;
- efficiency conditions over water streams;
- contaminant concentration threshold for units;
- ...

Objective function

The objective function is composed of the sum of the following three terms :

1. investment costs;
2. water cost;
3. energy cost.

Solving the Problem (overview)

1. Current engineering practice (heuristics and enumeration).
2. ”Exact” approach (solve MINLP).
3. Hybrid approaches (NLP + ”metaheuristics” + engineering heuristics).

Current Engineering Practice

- Heuristics, heuristics, heuristics
- Direct enumeration
- Simple mathematical programming (e.g., separate HEN and WAN, disallow new units)
  1. Solve MILP and NLP sequentially:
     a. Initialize.
     b. Do NLP.
     c. Freeze some variables to make the problems linear. Do MILP.
     d. Rinse, wash, repeat until (hopefully) problem solved. (Note that the NLP and MILP problems can be different each time they come.)

     Main issue: Does this converge? If so, is the solution useful?
  2. You make it so simple (e.g., only continuous variables) that it's useless for applications.

Exact Solutions

- Consider coupled HEN and WAN (i.e., attempt to solve full MINLP problem).
- To do this, try known cookbook solvers, e.g., BARON (commercial) and BONMIN (open-source) that are available on NEOS server.
- Open-source $\Rightarrow$ can go into the guts of the program and make appropriate adjustments.

Hybrid Methods

- Hybrid approach = NLP + ”Metaheuristics” + engineering heuristics
- Metaheuristics = your favorite learning algorithm (e.g., simulated annealing, genetic algorithms, etc.)
- To be efficient, the space exploration phase of metaheuristics should rely on some metric to measure the difference between graphs. (We adapt one motivated by similar engineering problems in the literature.)
  - Fixing all binary variables is equivalent to specifying a particular graph (i.e., network layout).
  - Consider all admissible modifications (or ”moves”) on such a graph (e.g., add/remove a heat exchanger).
  - For each move, associate a weight. Distance between two graphs = minimal sum of weights for sequences of moves going from one graph to the other.

Hybrid Methods (2)

- We can incorporate existing engineering heuristics when setting the weights or use them when selecting small and big steps. (Note: yields not only practical algorithms that improve on existing techniques but also interesting mathematics.)
- Also use a standard NLP solver for local (descent) search.

Big Picture/Conclusions

- Although attempting to design optimal HEN and WAN simultaneously (i.e., without artificially thinking of them as separate objects) is a very difficult problem, a combined use of mathematical programming, metaheuristics, and existing engineering heuristics has the potential to be helpful in practice and lead to interesting mathematics.
- Our design of course must be tested on both benchmark examples and real data in order to refine these ideas further.
- MINLP is an emerging, exciting, and very promising field with numerous potential applications in many areas of industry and basic science.

Future Work and Possible Extensions

- Relax some (many?) assumptions:
  - consider more than one contaminant, and their treatment;
  - stochastic behavior of source water temperature (seasonal);
  - ...
- Model improvement:
  - generalize cost function (refine cost function components);
  - heat loss (e.g., in pipes);
  - robustness;
  - control and dynamical aspects;
  - environmental and practical constraints;
- Numerical experimentation:
  - do tests on real networks and benchmark networks;
  - explore alternative solution strategies
- ...