How do we effectively coordinate production and distribution operations in an industrial gas supply chain?

We propose a multiscale approach to mitigate downsides of traditional integrated frameworks.

Supply Chain Level 1, 2
- Long-term strategic or tactical decisions
- Aggregate modeling of production and distribution

Scheduling Level 3, 4
- Short-term operational decisions
- Detailed modeling of production and distribution

Conservative restrictions, no routing

Computationally intractable

Need to find good trade-off between level of detail in the model and problem size.

Multiscale Optimization
- Operational decisions on the production side
- Tactical decisions on the distribution side
- Detailed production scheduling
- Improved computational performance due to simpler distribution model
- Yet still consider routing decisions

Problem Statement
Given
- Network of production plants, alternative sources, and customers
- Operating mode information for each plant
- Tank sizes at plants and customer sites, truck capacities
- Customer demand, distribution costs, purchasing costs
- Deterministic forecast of hourly changing electricity prices

Production
- Operational decisions
  - Amount of products to produce
  - Amount of products to store
  - Operational settings for the plants to achieve required production rates

Distribution
- Tactical decisions
  - Shipments from each plant to each customer
  - Number of trucks in assignment to routes
  - Amount of products required from alternative sources

Objective: Minimize total cost
Problem is formulated as a mixed-integer linear program (MILP) using two different time scales.

\[
\begin{align*}
\text{minimize} & \quad \text{total cost} = \text{production cost} + \text{distribution cost} + \text{purchasing cost} \\
\text{subject to} & \quad \text{production scheduling constraints} \\
& \quad \text{distribution planning constraints} \\
& \quad \text{constraints linking production and distribution} \\
& \quad \text{initial conditions} \\
& \quad \text{terminal constraints}
\end{align*}
\]

With two different time scales, distribution can be modeled without detailed vehicle routing.

Main Assumption: Every trip is completed within one shift.

- Shipments are loaded onto the trucks during the first hour of each shift.
- All trucks return to their assigned plants at the end of each shift.

Only need to know the conditions at the beginning and the end of each shift. Size and combinatorial complexity of the problem are significantly reduced.

In the production scheduling model, a plant is represented by its operating modes.

- Plant can switch between operating modes
- Constraints on transitions are imposed

Each mode is characterized by its feasible region in the product space.

A customer clustering algorithm is used to reduce the number of potential routes.

The number of possible routes increases exponentially with the number of customers. To reduce the computational burden, we only consider a subset of all possible routes. These routes are generated by a clustering algorithm.

Sequence-Independent Routes

Transportation cost depends on the order in which the locations are visited, i.e. (1) ≠ (2).

Due to clustering, customers on each route are close to each other. Thus, we neglect the sequence-dependent cost difference and consider all possible sequences as one route.
Case Study

Problem Specifications
- 2 production plants
- 2 alternative sources
- 20 customers
- 25 potential routes
- 1 week time horizon
- 168 production time periods
- 14 distribution time periods

MILP Model Size
- 20,010 constraints
- 47,748 continuous variables
- 6,486 discrete variables

Solved in 17 minutes

Results show the effect of simultaneous optimization of production and distribution.

Sequential optimization results in inefficiencies.

Production First Strategy
1. Solve production scheduling problem with aggregated customer demand
2. Solve distribution planning problem with fixed production rates

Distribution First Strategy
1. Solve distribution planning problem with plants solely characterized by conservative capacities
2. Solve production scheduling problem with fixed shipments

Inventory level profile for liquid nitrogen at the production plants and some of the customers:
What if we simplify production scheduling with an aggregate model?

Aggregate model uses a more coarse time discretization with electricity prices averaged over 12 hours.

12-hour time discretization
Solved in 12 s
$112,545

Detailed model
1-hour time discretization
Solved in 1,030 s
$108,413
4 % savings

Conclusions & Perspectives

Main Insights

- Two main advantages of the proposed multiscale model:
  1. Detailed production model considers time-sensitive electricity prices
  2. Distribution model simplified while still considering routing decisions
- Integrated optimization outperforms sequential approaches, i.e. it can result in large economic benefits
- Detailed production scheduling allows better use of plant flexibility

Future Work

- Apply proposed framework to a large-scale real-world case
- Improve route generation procedure
- Explore the use of decomposition techniques
- Consider uncertainty in the model