Integrated Multiscale Optimization of Production and Distribution Operations in an Industrial Gas Supply Chain

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PRAXAIR

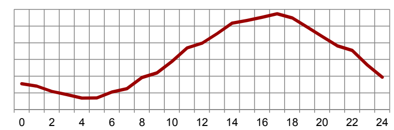
How do we effectively coordinate production and distribution operations in an industrial gas supply chain?

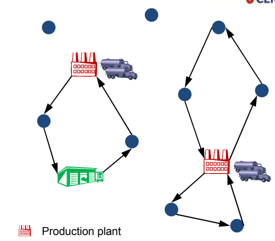
Air separation plant

FREE!
Air feed → LO2, LN2, LAr

Production cost = cost of electricity

Electricity prices are time-sensitive.





Production plant
Alternative source
Customer

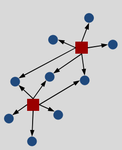
Distribution cost depends on the routing of the trucks

For optimal coordination, production and distribution have be optimized **simultaneously** by using an integrated model.

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

Supply Chain Level [1,2]

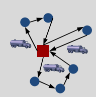
- Long-term strategic or tactical decisions
- Aggregate modeling of production and distribution

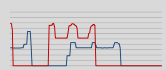


Conservative restrictions, no routing

Scheduling Level [3,4]

- Short-term operational decisions
- Detailed modeling of production and distribution





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

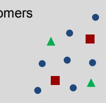
- Detailed production scheduling
- Improved computational performance due to simpler distribution model
- Yet still consider routing decisions

1. Jayaraman and Pirkul (2001)
2. Chen (2004)
3. Gupta et al. (2012)
4. Cóccola et al. (2013)

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

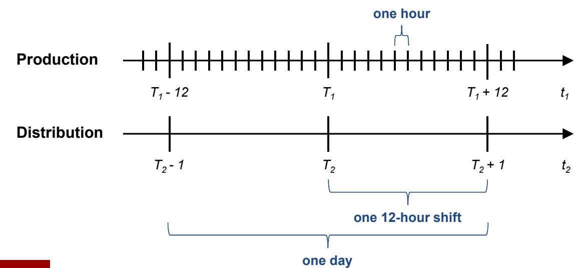
- Shipments from each plant to each customer
- Number of trucks in assignment to routes
- Amount of products required from alternative sources

Objective: Minimize total cost

Problem is formulated as a mixed-integer linear program (MILP) using two different time scales.

minimize total cost = production cost + distribution cost + purchasing cost

subject to
- production scheduling constraints
- distribution planning constraints
- constraints linking production and distribution
- initial conditions
- terminal constraints



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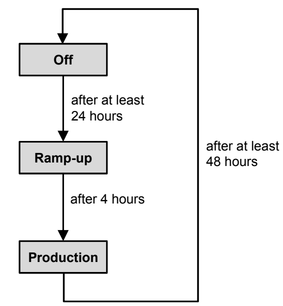
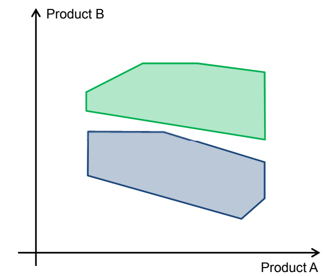
In the production scheduling model [1], a plant is represented by its operating modes.

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



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



1. Mitra et al. (2012)

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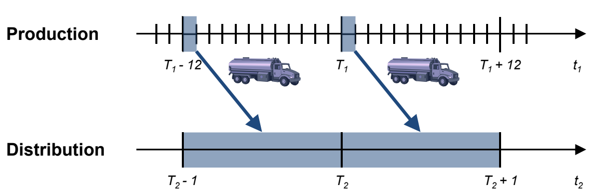
With two different time scales, distribution can be modeled without detailed vehicle routing.

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.

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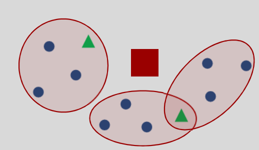
A customer clustering algorithm is used to reduce the number of potential routes.

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.

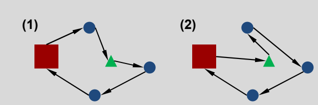
Clustering of Customers



Each cluster corresponds to one route, i.e. all locations in the cluster can be visited on one trip.

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.

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Case Study

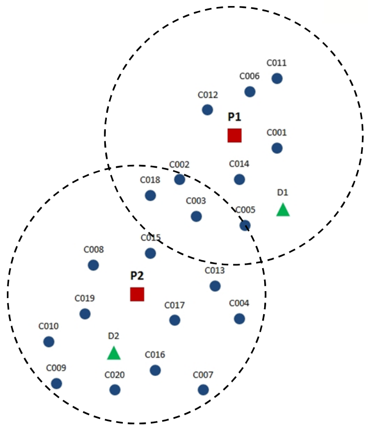
Problem Specifications

- 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

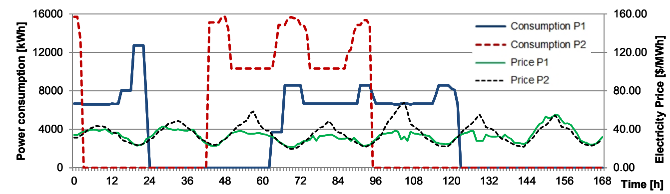
Solved in 17 minutes [1]



1. Using CPLEX 12.5 in GAMS 24 under Windows 7 on an Intel i7-2600 (3.40 GHz) with 8 processors and 8 GB RAM, 1% gap

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

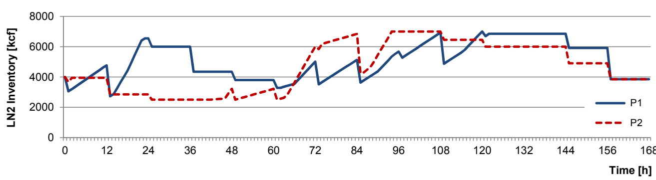
Total Cost	$ 108,413

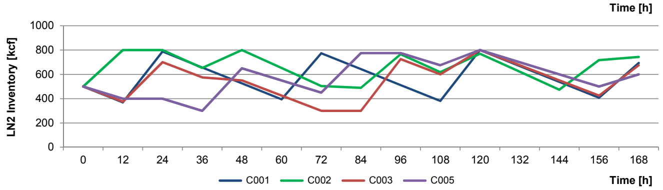


- Electricity consumption profiles follow electricity price fluctuations
- Solution suggests multiple shutdowns
- Vast majority of shared demand is satisfied by plant P1

Coordination of production and distribution strongly depends on the inventory capacities.

Inventory level profile for liquid nitrogen at the production plants and some of the customers:



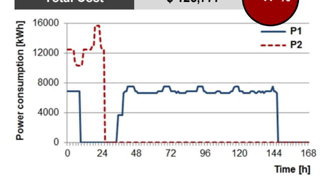


Sequential optimization results in inefficiencies.

Production First Strategy

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

Total Cost	$ 126,777	+ 17 %

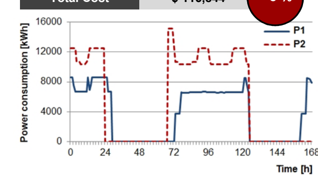


- **Solved in 12 s**
- Insufficient production at plant P2
- Shortage compensated by expense purchases

Distribution First Strategy

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

Total Cost	$ 116,844	+ 8 %

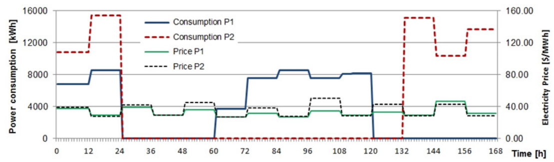


- **Solved in 130 s**
- Inflexible production
- Reduced capability of adjusting to price changes

Significant cost savings through integrated approach

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**.

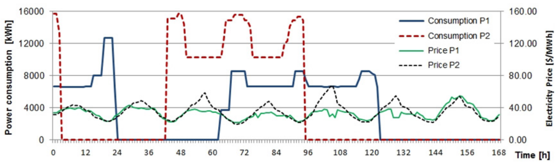


Aggregate Model

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

Detailed production scheduling results in cost savings due to higher level of flexibility.

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