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AIR LIQUIDE

Production-Distribution Coordination of Industrial Gases Supply-chains

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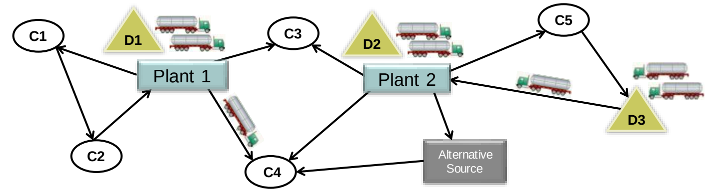
Background and Motivation

Industrial Gases Supply-Chain

- Multiple Plants and Depots (located or not at plants)
- Multiple Products *(LIN, LOX etc.)* and Product Grades
- Over-the-fence, call-in and distributed customers *(some shared customers)*
- Storage facilities at production sites and customer locations

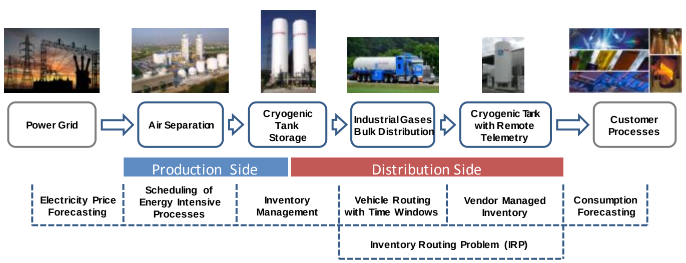


Goal

To quantify and access the savings associated with the
Production-Distribution Coordination at Operational Level
using an approximate model

Background and Motivation

Production and Distribution of Liquefied Industrial Gases



Alternatives to reduce Distribution Side complexity:

- **Planed Delivery Forecast:**
  Amount of product delivered to customers given for each time interval.
- **Full Inventory Routing Problem:**
  No assumption on distribution side. The model determines when and how much product to deliver to each customer such that customer inventory constraints hold.

Problem Statement and Main Assumptions

Given

- Plants, Products, Operating Modes and Production Limits
- Daily Electricity Prices (off-peak and peak)
- Customers and their demand/consumption profiles
- Max/Min inventory at production sites and customer locations
- Alternative sources and product availabilities
- Depots, Truck availabilities and capacities, Distances
- Fixed Planning Horizon (usually 1-2 weeks)

Decisions in each time period t

- Modes and production rates at each plant
- Inventory level at customer location and plants
- How much product to be delivered to each customer through which route

Objective Function

- Minimize total production and distribution cost over planning horizon

Main Assumptions – Distribution Side

- Two time periods per day (peak and off-peak) are considered
- Trucks do not visit more than 4 customers in a single delivery

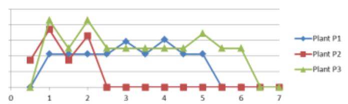
Mathematical Model (MILP)

Objective **Minimize total Production and Distribution Cost**

Constraints on Production Side

Production Cost = Fixed Start-up cost
+ Variable production cost

- **Min/Max Production Capacity Constraints in each mode of operation**
- **Logic Constraints for switching between various modes of operation**
- **Max/Min Inventory limits at the production sites**
- **Plant Inventory Balance Constraints**
- **Demand satisfaction for pick-up customers**
- **Ad Hoc Production Models**
  To account for specific equipment configurations and production modes.



Main binary variables
mode selection
B_{pmt}

Mathematical Model (MILP)

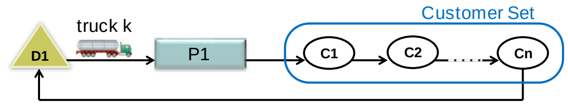
Constraints on Distribution Side

Distribution Cost = Cost of deliveries by trucks
+ purchases from competitors

- **Max/Min Inventory limits at the customer locations**
- **Customer Inventory Balance Constraints**
- **Truck Capacity constraints**
- **Material balance constraints for product pick-up and delivery points**
- **Max product purchase limit from alternative sources**

Main binary variables
truck-customers association
y_{kst}
truck-source association
Y_{kpt}

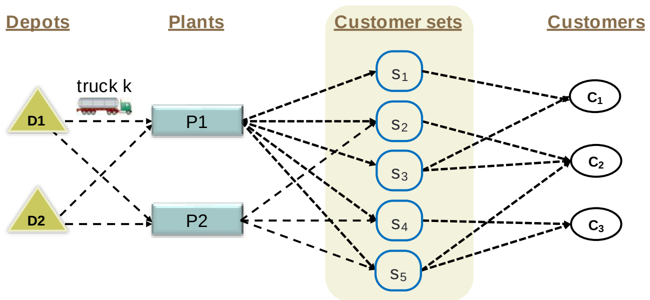
Route = Depot + Plant + Customers



Route Generation Algorithm developed to obtain alternative routes for truck distribution.

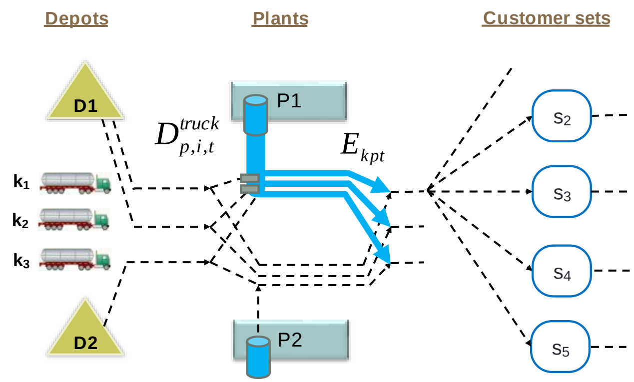
Supply-chain Example

Definition of Customer Sets:



Supply-chain Example

Meaning of continuous variables to transfer products from plants to customers:



Supply-chain Example

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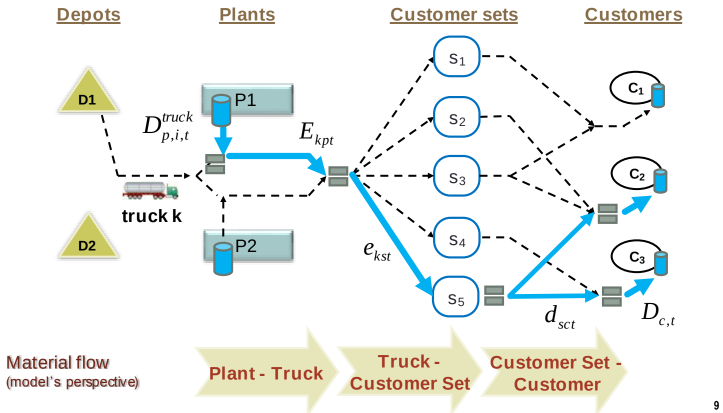


Industrial Size Test Case

- 4 Plants / Depots
- 2 products (LIN, LOX)
- 2-4 production modes for each plant
- 2 alternative sources
- 258 customers
- 14 time periods (peak and off-peak)
- 37 trucks (25 for LIN, 12 for LOX)
- Min/max inventory, distances, electricity prices, truck deliveries, etc.

6 sources → 3126 possible routes ← 521 customer sets

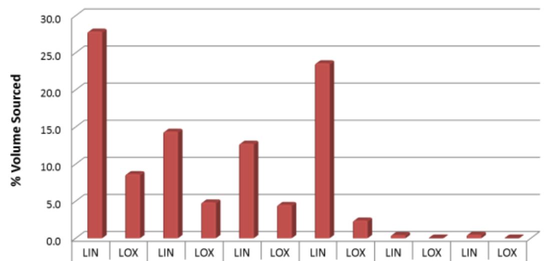
Model Size	Binary variables	18,378
	Continuous variables	26,241
	Constraints	27,101
CPU results	Time	**79 s**
	Nodes	**1,632**
	Relative gap	**0.1%**

Good solutions found in few CPU sec.!!!

Models implemented with GAMS
CPU results obtained with solver CPLEX 12.3

Industrial Size Test Case

Results are compared with **historical data** by fixing **volume sourced** from each plant.



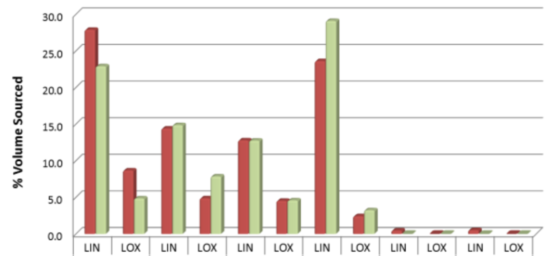
	Plant 1 LIN	Plant 1 LOX	Plant 2 LIN	Plant 2 LOX	Plant 3 LIN	Plant 3 LOX	Plant 4 LIN	Plant 4 LOX	Alt 1 LIN	Alt 1 LOX	Alt 2 LIN	Alt 2 LOX
Historical data	27.9	8.7	14.4	4.9	12.8	4.5	23.6	2.4	0.4	-	0.5	-

Historical Model:

- Volume sourced is fixed to historical data.
- Production and distribution subproblems do not need to be solved simultaneously.
- Production subproblems can be solved for each plant.

Industrial Size Test Case – Results

Comparison of volume sourced: ***optimal model solution*** vs ***historical data***.

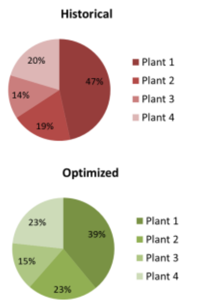


	Plant 1 LIN	Plant 1 LOX	Plant 2 LIN	Plant 2 LOX	Plant 3 LIN	Plant 3 LOX	Plant 4 LIN	Plant 4 LOX	Alt 1 LIN	Alt 1 LOX	Alt 2 LIN	Alt 2 LOX
Historical data	27.9	8.7	14.4	4.9	12.8	4.5	23.6	2.4	0.4	-	0.5	-
Model - optimized	22.9	4.8	14.8	7.8	12.7	4.6	29.1	3.2	-	-	-	-

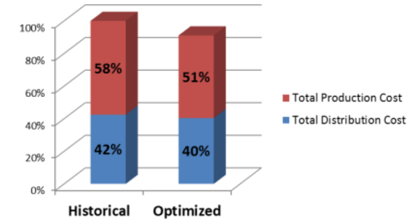
Optimal solution shifts production and distribution from plant P_1 to plant P_4, mainly due to lower electricity costs at P_4

Industrial Size Test Case – Results

Production cost % for each plant



Percentage of Total Historical Cost

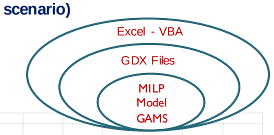


$$\text{Savings} = \frac{[\text{Amount saved}]}{[\text{Historical model total}]} = 9\% \text{ per week}$$

Improved Route Generation Algorithm

Main Features:

- Exact distances among plants, depots, & customers obtained by GIS software.
- Route distances calculated using TSP method.
- Multiple parameters for each plant and product.
- Added routes to import product to plants (shut-down scenario)
- Alternative sort criteria to rank potential routes:
  - Distance (miles)
  - Logistics Ratio ($ / volume delivered)



Route Generation Parameters

RG_Parameters	p1 i1	p1 i2	p2 i1	p2 i2	p3 i1	p3 i2	p4 i1	p4 i2	comp1 i1	comp1 i2	comp2 i1	comp2 i2	comp3 i1
Generate routes for this plant/product	x	x	x	x	x	x	x	x	x	x	x	x	x
Include all one-customer routes	no	no	no	no	no	no	no	no	no	no	no	no	no
Maximum customers visited	3	3	3	3	3	3	3	3	2	2	2	2	2
Maximum distance	400	400	400	400	500	500	500	500	500	500	500	500	500
Minimum filling ratio	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
Maximum total routes	50	50	50	50	50	50	50	50	50	50	50	50	50
Minimum routes per customer	1	1	1	1	1	1	1	1	1	1	1	1	1
Limit routes per customer (0 = none)	2	2	2	2	2	2	2	2	2	2	2	2	2

Sort routes by: Cost / Volume delivered ($ / kscf)

Generate Routes

Add routes to plants (fake customers): yes

Improved Route Generation Algorithm

Progress Status, Statistics and Detailed Results

Progress			Statistics								
Iteration	Plant	-	p1	p1	p2	p2	p3	p3	p4	p4	comp1
	Product	-	i1	i2	i1	i2	i1	i2	i1	i2	i1
	Stage	all done	done	done	done	done	done	done	done	done	done
	Index	-	3475	39	2695	44	538	98	1265	39	51
Routes	Created	-	3839	39	3243	44	538	98	1265	39	206
	Branched	-	3839	39	3057	44	538	98	1265	39	205
	Selected	918	**103**	**20**	**122**	**20**	**62**	**35**	**88**	**23**	**50**
	Postponed	-	4759	0	4146	0	240	0	886	0	0
Visits	Required	-	294	44	298	46	172	56	282	40	100
	Pending	-	0	2	0	2	2	0	2	2	0

Plant p1 - Product i1

Route	Sort value	Distance	Fill ratio	C1	C2	C3
r1	0.0589686	38.624435	0.984962	u402		
r2	0.0633705	42.141396	1	u115		
r3	0.0636135	42.302952	1	u115	u116	
r4	0.0869378	57.813618	1	u373		
r5	0.092019	61.192635	1	u125		
r6	0.0943924	62.77092	1	u452		
	0.0955977	63.572487	1	u116	u452	
	0.0956258	63.591129	1	u115	u452	
	0.0958687	63.752686	1	u115	u116	u452
r7	0.1006547	66.935349	1	u13		

Plant p1 - Product i2

Route	Sort value	Distance	Fill ratio	C1	C2	C3
r104	0.13867	76.26834	1	u501		
r105	0.187541	103.1476	1	u249		
r106	0.219706	120.8381	1	u35	u249	
r107	0.223672	123.0197	1	u249	u501	
r108	0.245995	135.2974	1	u170		
r109	0.256897	141.2936	1	u170	u243	
r110	0.276793	152.2359	1	u169		
r111	0.279369	153.6527	1	u169	u170	u243
	0.280803	154.4418	1	u169	u243	
r112	0.283402	155.871	1	u169	u170	

Conclusions and Future Work

Conclusions

- Proposed Simultaneous Production-Distribution MILP Model for optimal operational planning of industrial gases supply-chain
  - Multiple products, plants and depots
  - Route generation algorithm
  - Ad hoc production models
- Selection of routes is a critical aspect to reduce the total cost of production and distribution.
- Good quality solutions for industrial size examples obtained in short CPU times.
- **Significant potential savings due to better coordination of production and distribution.**

Future work

- Uncertain behavior analysis (electricity prices & customer demands)
  - Stochastic optimization
  - Robust optimization