Optimal Scheduling of Refinery Crude-Oil Operations

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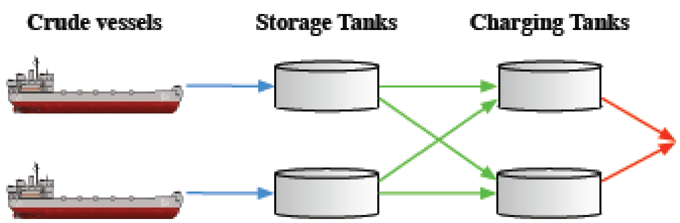
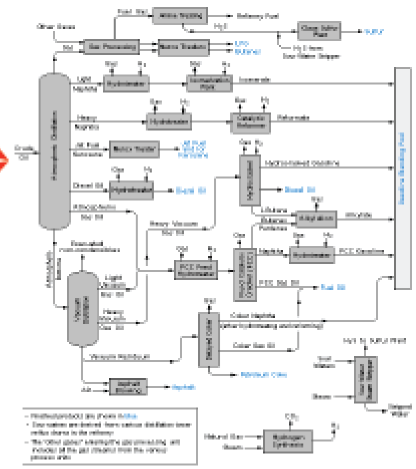
Integration of planning and scheduling in oil refineries

- Planning/Scheduling in oil refineries and in batch/continuous production plant are different !
- In oil refineries crude-oil scheduling and planning problems are 2 distinct problems connected by the CDUs (crude distillation targets)

- The economic data is only included in the planning level
- In practice, the crude-oil scheduling is mostly a feasibility problem





- Objective: $\max V_P^T x_S - V_C^T y_F$

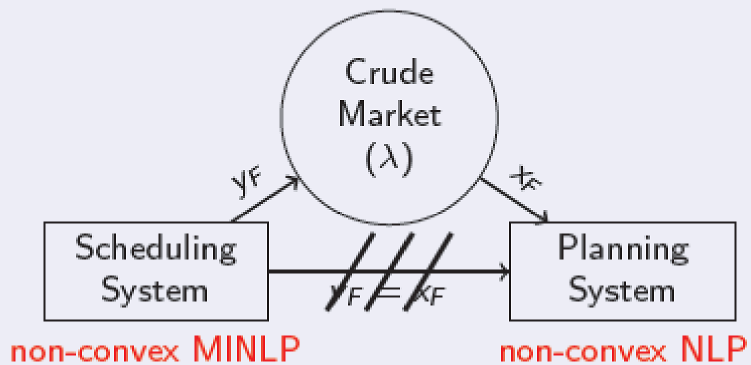
sales revenue

distilled crude-oil replacement cost

Lagrangian decomposition approach

Integration guidelines

- Form a Lagrangian relaxation $(P_R(\lambda))$ of the full-space problem (P):
  - Relax the complicating CDU feedstock constraint: $y_F = x_F$
  - Penalize the violation of this constraint with Lagrange multiplier $\lambda \in \mathbb{R}$

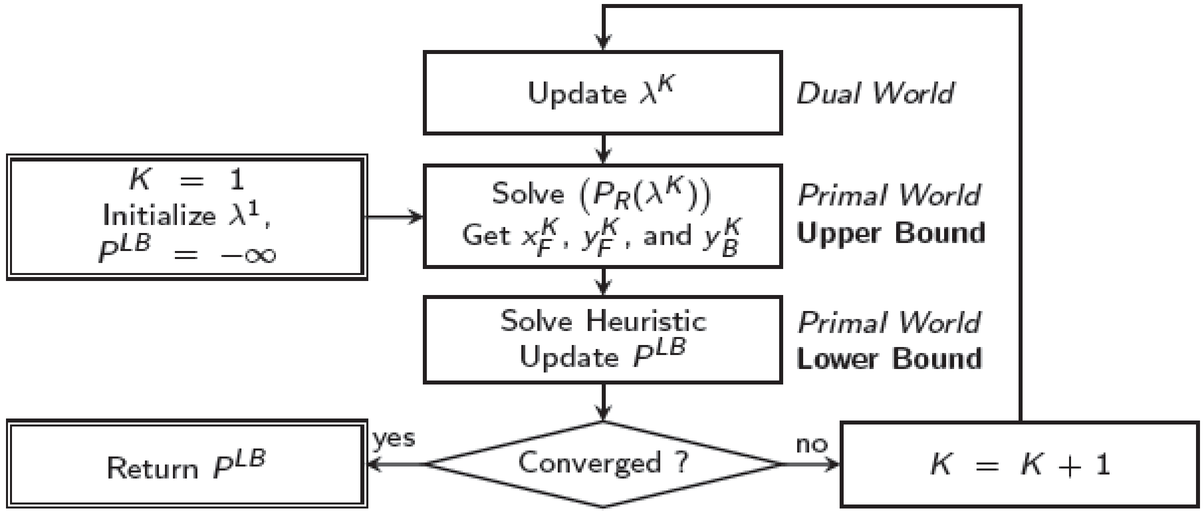


- Solve the Lagrangian dual problem (P_D) (upper bound):

$$\min_{\lambda} v\left(P_R(\lambda)\right)$$

- Meanwhile, generate heuristic feasible solutions (lower bound)

Lagrangian algorithm



- The iterative primal-dual algorithm is composed of 3 main steps:
  - The Lagrange multipliers λ are updated by solving a hybrid dual problem
  - The relaxed full-space problem is solved
  - The original full-space problem is solved with fixed binary decisions from the solution of the relaxed problem (i.e. from the solution of the scheduling subproblem)

- Convergence based on the Lagrangian gap and dual gap

Hybrid Lagrangian dual problem

- The Lagrange multipliers λ are updated by solving the following hybrid LP dual problem $(\hat{P}_D^{K+1})$:

$$
\begin{aligned}
\min \quad & \eta \\
\text{s.t.} \quad & \eta \geq V_P^T x_S^k - V_C^T y_F^k + \lambda^T (y_F^k - x_F^k) \qquad \forall k = 1 \dots K \\
& \lambda = \lambda^K + \alpha \frac{v(P_D) - v(P_R(\lambda^K))}{\left|\left|y_F^K - x_F^K\right|\right|^2} (y_F^K - x_F^K) + \delta \\
& \eta \in \mathbb{R}, \lambda \in \mathbb{R}^{|F|} \\
& \alpha \in]-\infty, \overline{\alpha}], \delta \in [-\overline{\delta}, \overline{\delta}]^{|F|}
\end{aligned}
$$

- It is based on the following concepts:
  - Cutting planes $\rightarrow$ objective value of current vertex solution for all λs
  - Subgradient step $\rightarrow$ steepest descent direction from current solution
  - Trust-region $\rightarrow$ deviation from subgradient
    - solves convergence issues of pure subgradient method
    - helps with stability for nonlinear problems

Hybrid Lagrangian dual problem

$$
\begin{aligned}
\min \quad & \eta \\
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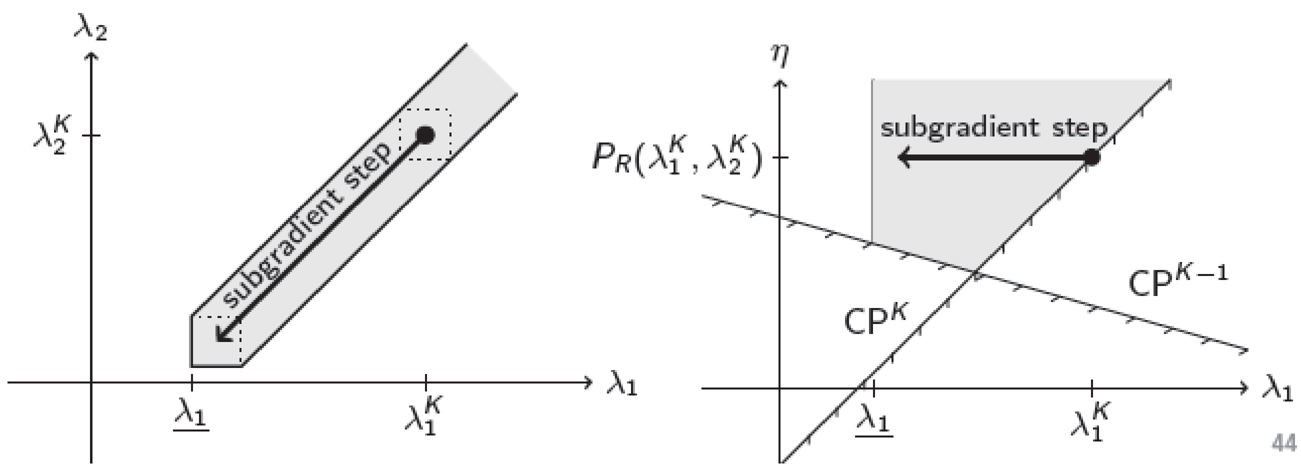

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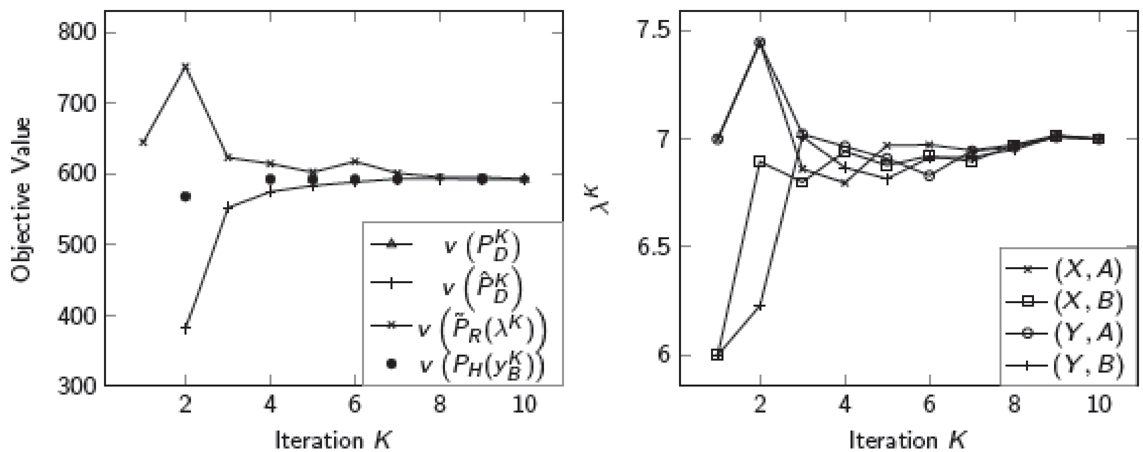
Numerical illustration: small case-study

- Crude-oil operations scheduling problem COSP1
  - MOS time representation with 7 priority-slots
- Refinery planning problem expressed as a pooling problem
  - 1 CDU (2 operating modes), 4 intermediate pools, and 4 final products
  - Solved with BARON in order to provide rigorous upper bounds
- The number of Lagrange multipliers is 4 (2 crudes and 2 CDU modes)

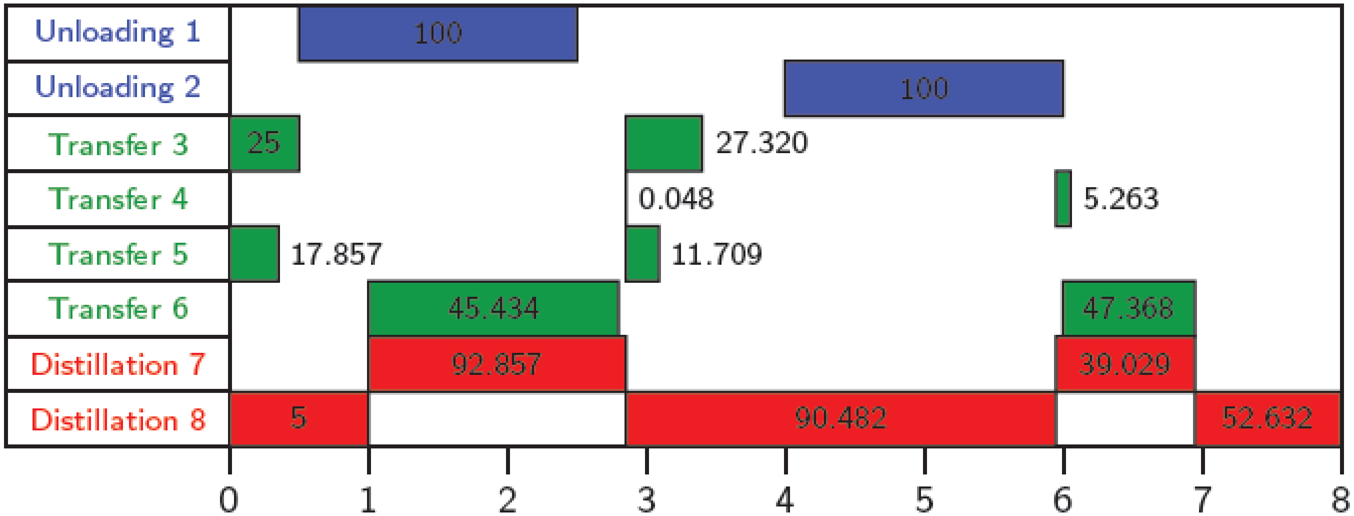


(a) Iteration objective values (b) Lagrange multiplier updates

- Fast and stable convergence in 100s (10 iteration) with 0% dual gap

Numerical illustration: small case-study solution

- Optimal solution schedule:



- Optimal aggregated blend compositions:

	Blend 1 / Dist. 7	Blend 2 / Dist. 8
Crude A	92.320	15.311
Crude B	39.566	132.803

Numerical illustration: larger refinery problem

- Crude-oil operations scheduling problem COSP3
  - MOS time representation with 6 priority-slots
- Refinery planning problem based on CDU fitting model expressed as an artificial neural network (Gueddar and Dua, 2010)
  - 1 CDU (3 operating modes), 5 final products
  - Solved to local optimality with CONOPT
- The number of Lagrange multipliers is 21 (7 crudes and 3 CDU modes)

(a) Comparative performance of several MINLP algorithms

MINLP Solver	Objective Value	CPU Time
Proposed	250.989	1,045s
Sequential	116.814	46s
DICOPT	—	+3,600s
AlphaECP	—	+3,600s
SBB	—	+3,600s

(b) Optimal blend composition

Crude	Mode 1	Mode 2	Mode 3
A	0.164	49.480	
B		33.293	16.707
C		50.000	
D	0.066	19.792	
E	3.500	55.943	2.982
F			50.000
G	9.480		

- Convergence in less than 20 iterations, more than 80% of CPU time is spent on solving the crude-oil scheduling problem

Conclusions

- A general integration approach for refinery planning and crude-oil scheduling problems
  - Based on a Lagrangian decomposition of the full-space problem
- A new hybrid dual algorithm for optimizing the Lagrange multipliers
  - Based on cutting planes and a subgradient-based trust-region
  - Two parameters only:
    - maximum step size
    - maximum deviation from the subgradient step