Refinery scheduling model and optimization method based on optimal process control

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Outlines

- Backgrounds
- Integrated framework based on optimal process control
  - Unit-specific scheduling model
  - Optimization strategy
- Summary

Backgrounds

- Global competition, increasing product demand and specification
- Wide use of advanced process control and optimization technology
  - Model predictive control to more steady unit operation and increasing ability to mitigate process disturbance
  - Real time optimization to get more profit, reduce energy use and pollution
  - Making scheduling optimization be possible to maintain orderly production.

Backgrounds

- Increasing attention in academia
  - CMU-Grossmann's group
  - Rutegers-Ierapetritou's group
  - HUST-Wenkai Li
  - Industrial Algorithms-Kelly
  - Zhejiang University-Rong's group

Backgrounds

- Industrial application
  - Aspen Orion
    - Blending optimization
    - Interactive scheduling and simulation validation platform
  - Honeywell Business FLEX
    - Due to the model issue, no wide and successful application report
  - **Process Scheduling Model is the main obstacle for application!**

Backgrounds

- Refinery is quite different from other processes
  - Varying operating conditions results in varying model

For distillation tower (Atmospheric and vacuum unit and product distillation of secondary processing units), adjacent distillates cover a common swing-cut, different operating modes result in different cut-points, distillate yields.

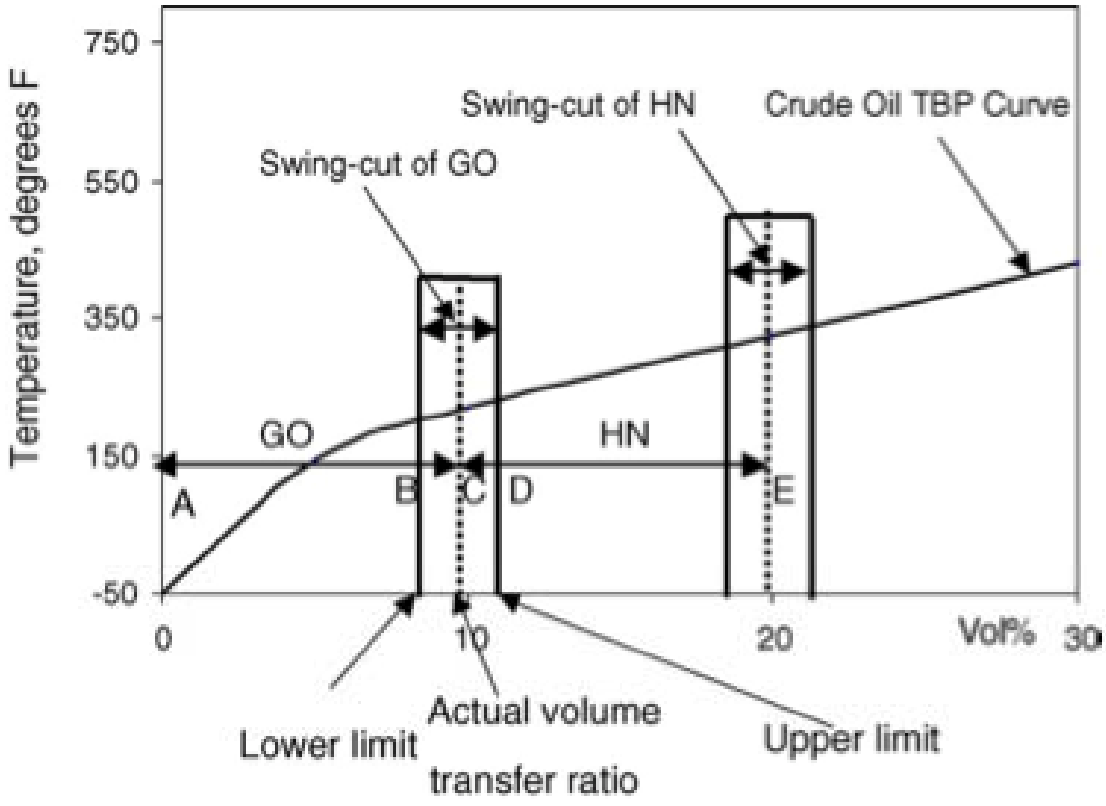
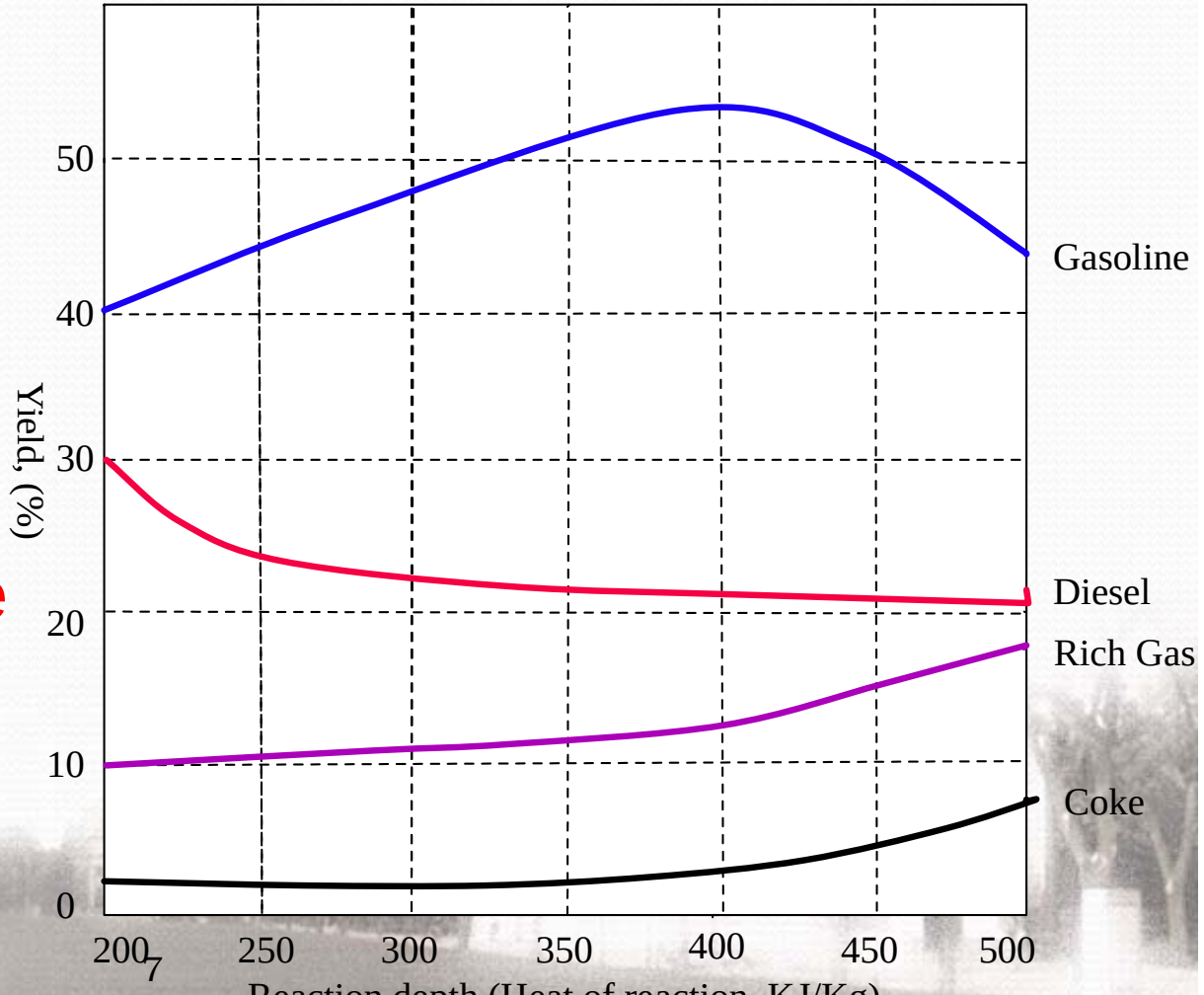


Figure 1 from *W. Li et al. Computers & Chemical Engineering* 29(2005) 2010-2028

Backgrounds

- Refinery is quite different from other processes
  - Varying operating conditions results in varying model

For cracking reaction of secondary processing units, e.g., FCCU(Fluid catalytic cracking unit), products distribution vary in terms of reaction depth with a degree of reaction heat or reaction temperature.



Backgrounds

- Refinery is quite different from other processes
  - Feed dependent
    - Varying feed crude results in varying product profile

    For Atmospheric and vacuum unit, varying crude

    → varying TBP(True Boiling Point)

    → varying yield model

    - For secondary processing units, varying crude

    → varying C-H composition

    → varying cracking performance

    → varying yield model and operating cost model

Backgrounds

- Refinery is quite different from other processes
  - Real-time of the schedules
    - When confronted with product demand change or unit failure(*e.g. exterior heat-removing system fault in the regenerator of FCC unit*), the schedules should **quickly respond** to this situation.
    - However, process dynamics always exists, which also are hardly included in scheduling model due to its schedule dependence.

Backgrounds

- Under current treatment, unit-wide process control is isolated with the plant-wide scheduling optimization
  - Unsatisfactory plant-wide schedules result in the frequent changes of unit operation or feed composition

  → unit-wide processes are difficulty to stable

  → unit-wide APC(advanced process control) can not work well

  → can not realize the demanded schedule in actual

  → can not get satisfactory scheduling model

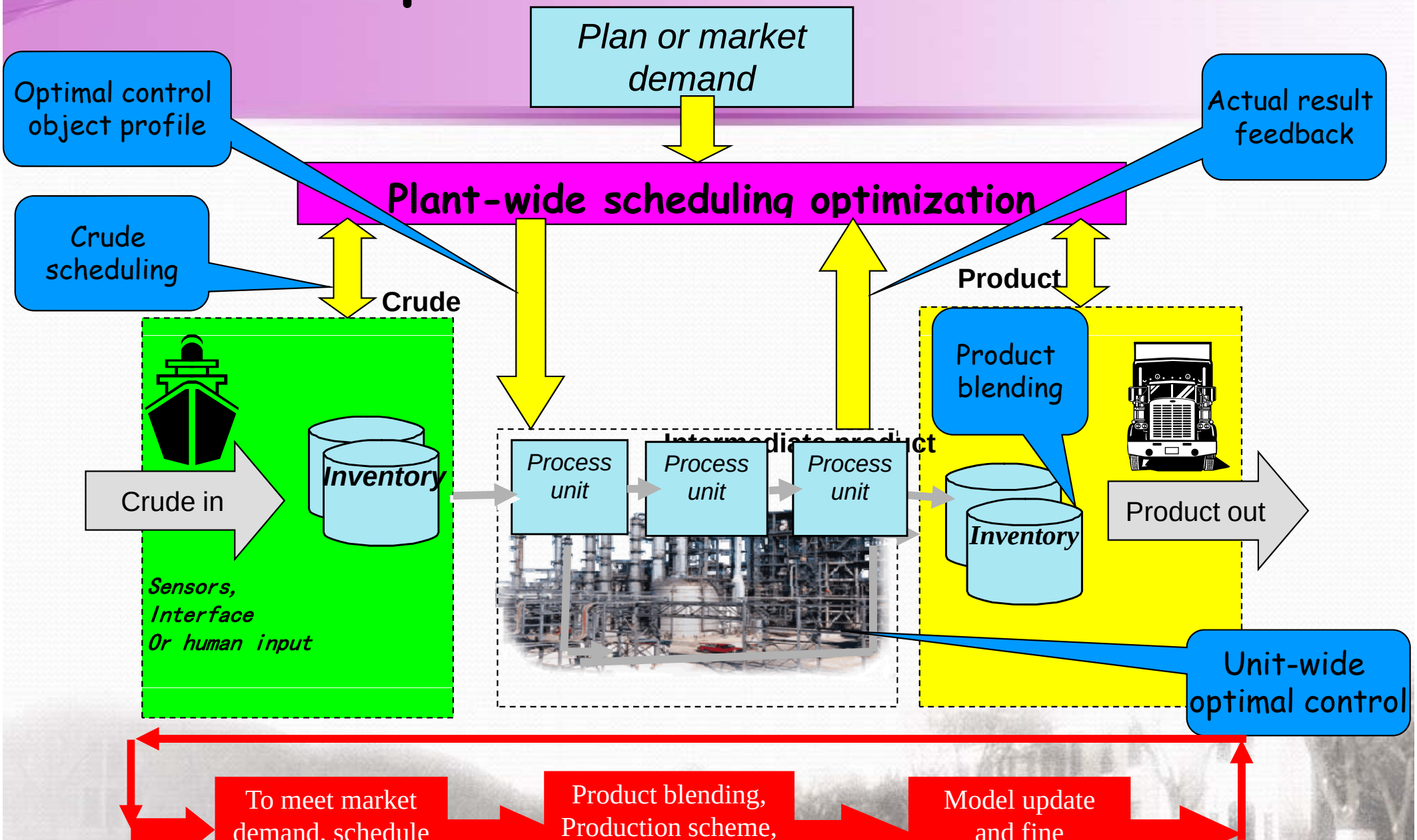
  → can not realize plant-wide schedules well again.

Backgrounds

- Focusing on scheduling optimization, regardless of unit-wide process control, can not well handle the scheduling issue
- It is challenging for refinery scheduling optimization

Then, a integrate solution strategy for APC and scheduling is proposed.

Integrated framework based on optimal process control



Part I: Unit-specific scheduling model

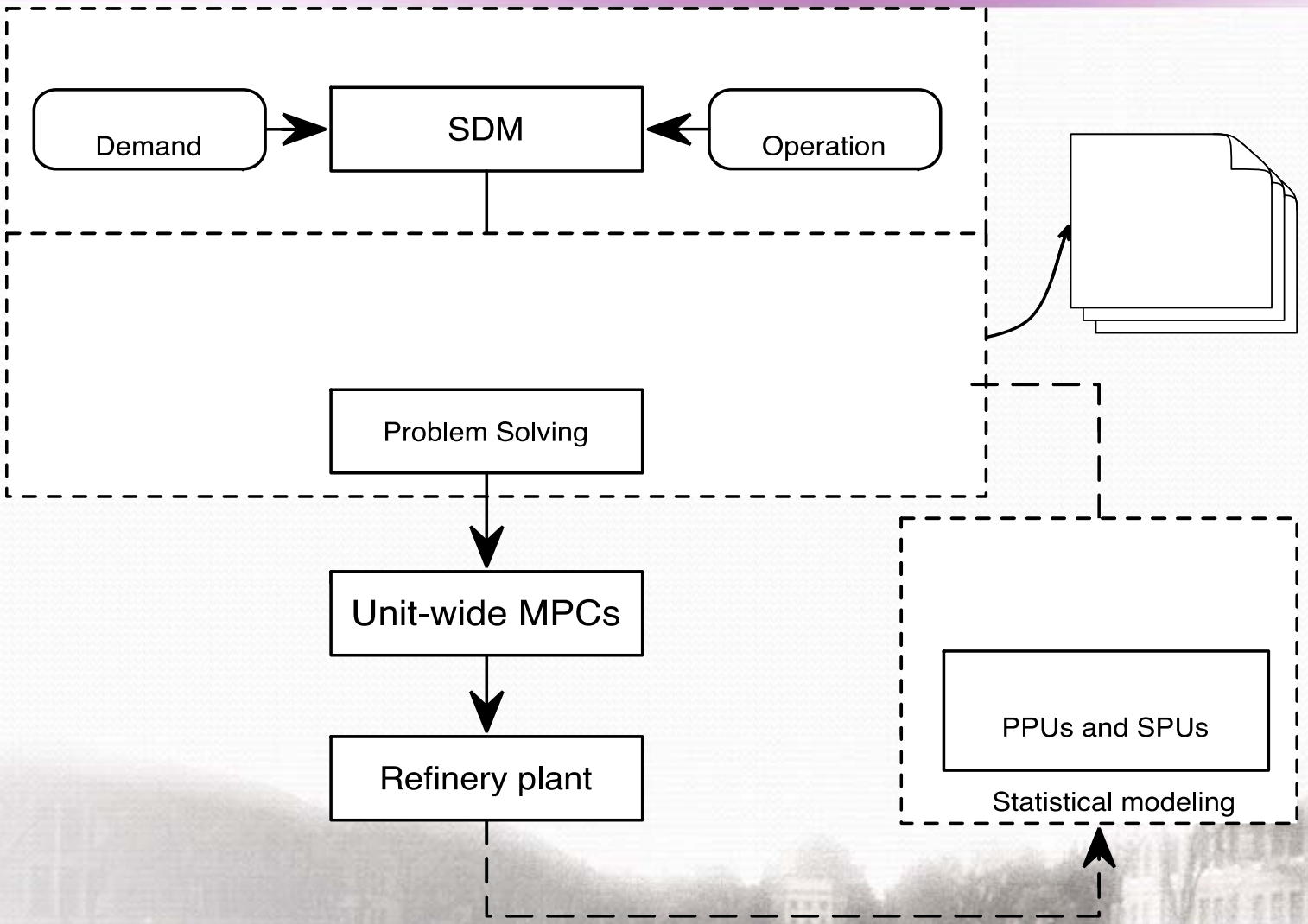


Figure 2 Integrated framework

Part I: Unit-specific scheduling model

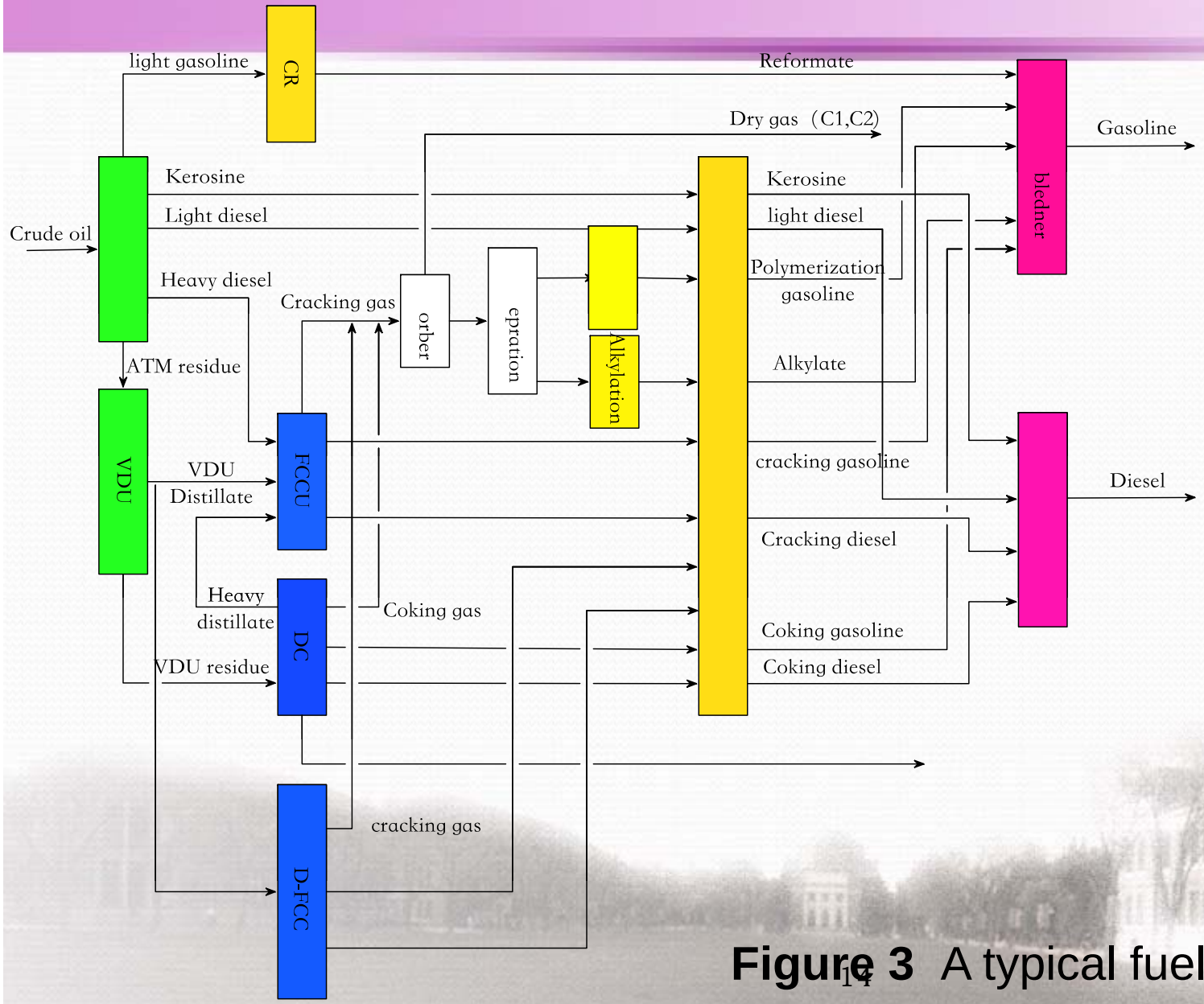


Figure 3 A typical fuel oil-oriented refinery

Part I: Unit-specific scheduling model

- Unit-specific model structure
  - Crude oil blending process
  - Primary Processing Units (PPUs)
    - CDU
  - Secondary Processing Units (SPUs)
    - FCCU, Delayed coking, Hydro-cracking, et al.
  - Hydro-Upgrading Processing Units (HUPUs)
    - Hydro-treatment, Hydro-desulfurization, et al.
  - Product oil blending process

Part I: Unit-specific scheduling model

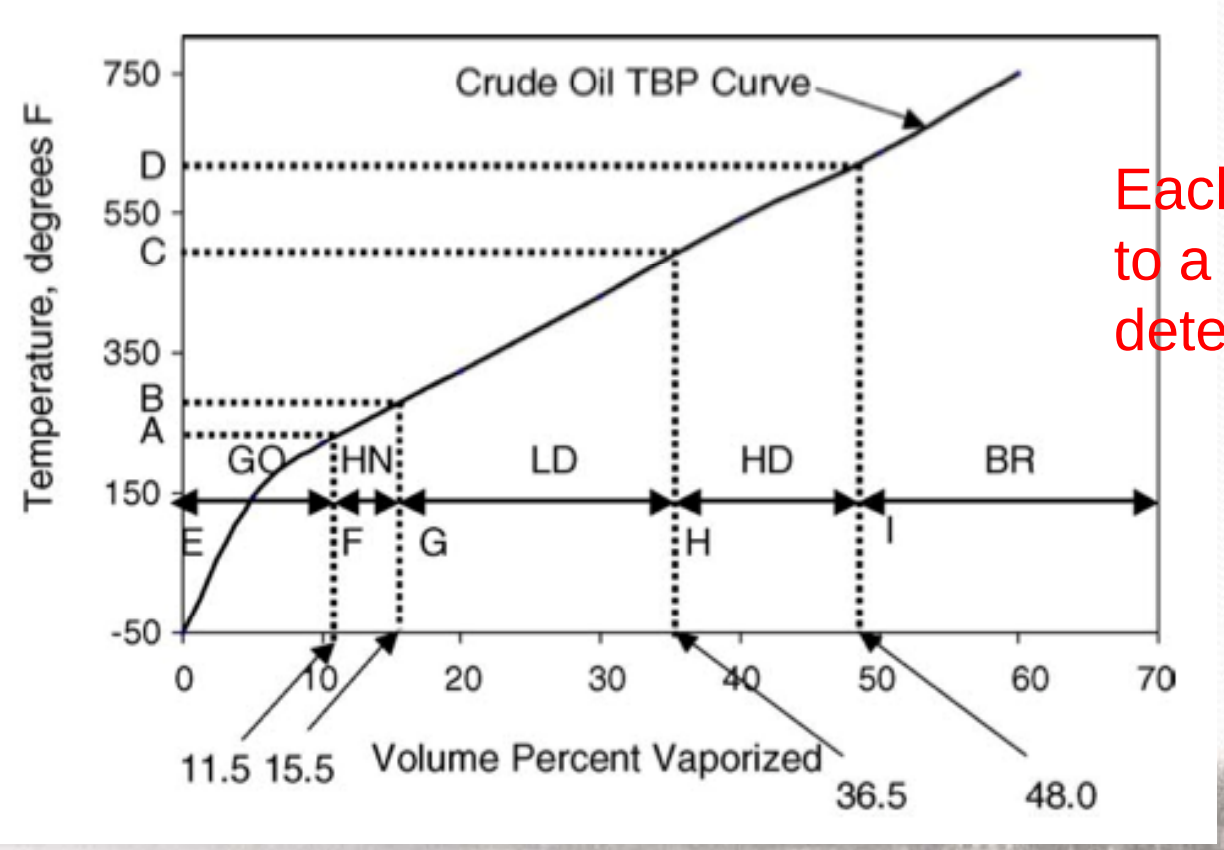
- With optimal process control, the unit is operated in several optimal operating modes
  - PPUs-CDU: *gasoline maximizing mode*
    light diesel maximizing mode
    heavy diesel maximizing mode
  - SPUs-FCCU: *gasoline maximizing mode*
    diesel maximizing mode
    total light oil maximizing mode

Part I: Unit-specific scheduling model

- multi- process scheduling model under optimal modes to represent operating conditions
  - Operational modes → concrete model → containable schedules
  - Finite optimal modes → making multi-model be reasonable

Part I: Unit-specific scheduling model

- For PPUs
  - TBP curve + Multi-cut points (Multi-modes)



Each set of cut points corresponds to a certain operating mode determined by unit optimal control

Figure 2 from *W. Li et al. Computers & Chemical Engineering* 29(2005) 2010-2028

Part I: Unit-specific scheduling model

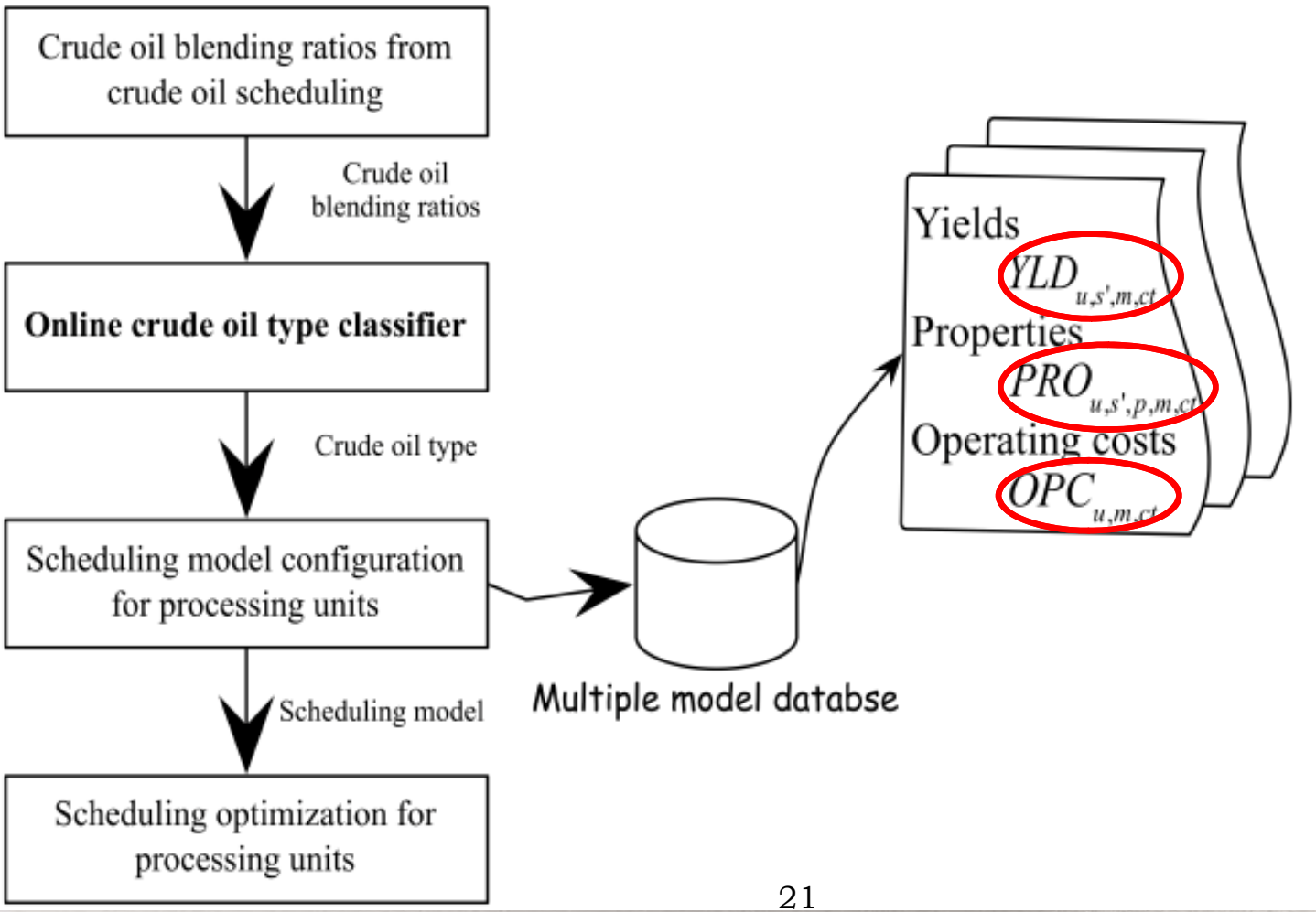
- **For SPUs**
  - Including reactions, such as cracking
    - Different feeds with similar TBPs exhibit quite different product profile TBP-based model can not reflect the feed changes.
    - Distillate oil assay is not included in routine test by refinery laboratory

Part I: Unit-specific scheduling model

- Feeds of SPUs are heavy distillates drawn from PPUs
  - There is little influence on SPUs under PPUs' operation adjustment, because PPUs' operation only change its light distillates profile
- Same hydrocarbon group has similar reaction property
  - Naphthene
  - Paraffin
  - Aromatics
  - Olefins, et al.

Part I: Unit-specific scheduling model

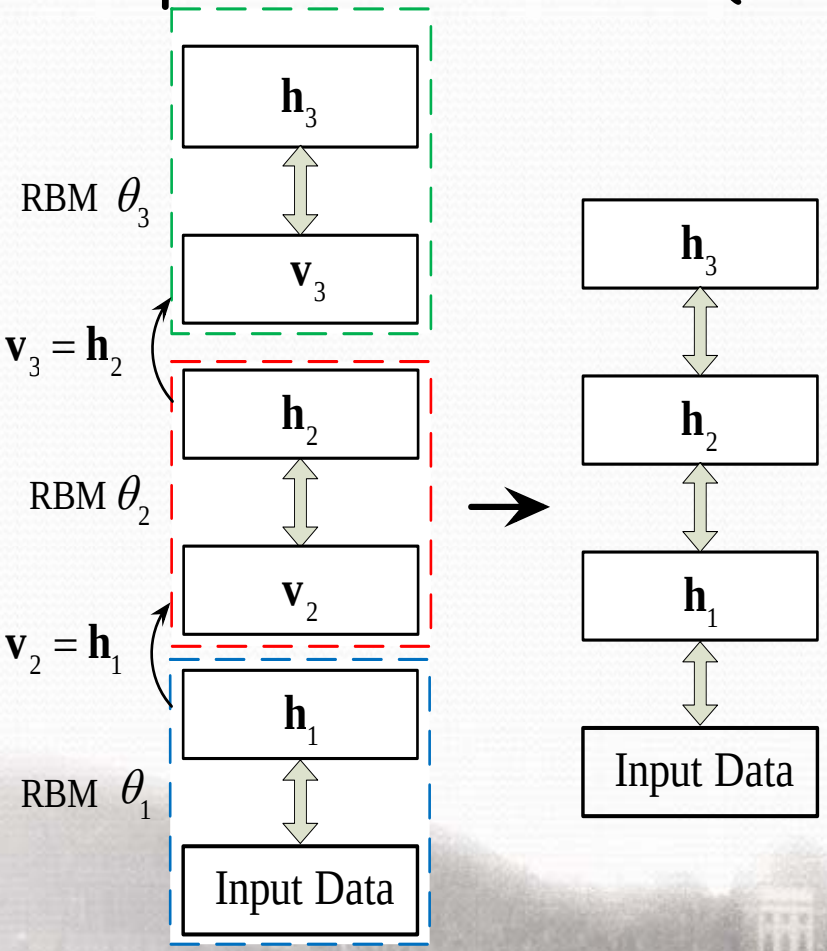
- Multi-model based on crude oil classifier



Unit-Operation-Feed Type Specific Multi-Model structure

Part I: Unit-specific scheduling model

- Deep belief network (DBN) is introduced



Restricted Boltzmann Machines

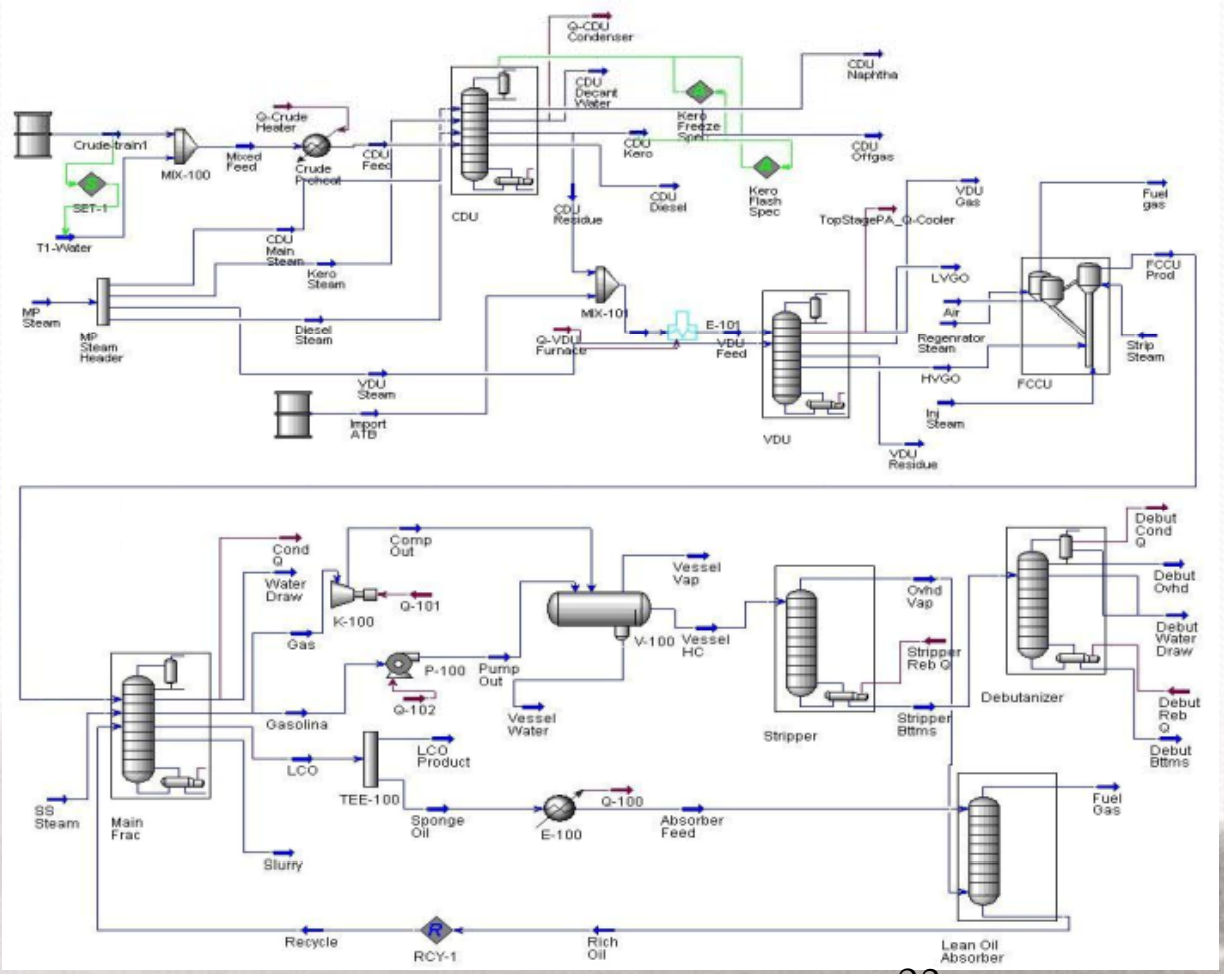
Deep Belief Network

Deep layers structure, formed by stacking a series of *restricted Boltzmann machines* (RBMs) on top of each other

Each RBM is a *bi-directional probabilistic model*

Part I: Unit-specific scheduling model

- Petro-SIM simulation based case study



Part I: Unit-specific scheduling model

RMSE of type-specific models.

Type	Model I			Model II			Model III			Model IV		
	YLD	RON	SUL	YLD	RON	SUL	YLD	RON	SUL	YLD	RON	SUL
1	**0.77**	**1.24**	**2.97**	1.43	38.14	16.98	2.92	23.98	23.83	1.92	16.21	16.69
2	1.21	22.61	27.35	**0.88**	**1.90**	**2.38**	1.73	13.61	19.42	1.97	20.08	24.71
3	1.68	18.95	16.37	1.71	8.46	22.03	**0.69**	**1.39**	**1.36**	1.36	17.65	19.22
4	1.79	15.28	19.71	1.94	25.91	25.69	2.41	29.72	17.81	**0.47**	**1.84**	**2.87**

- It is necessary and reasonable for classification

Part I: Unit-specific scheduling model

For a 5-days future demand scheduling case, comparisons between *multi-model method based on DBN classification* and *one model method without classification* are done

Optimized profit in Chinese Yuan.

	Without classification	DBN based classifier
Accounted profit of FCCU	1,237,060.1	**1,460,226.8**
Computed overall profit	4,027,552.3	**4,572,077.4**

- This result again confirms the need of performing crude oil classification for SPUs' scheduling model, from the profit point of view

Part I: Unit-specific scheduling model

- HUPUs
  - To upgrade the component oil for blending clean fuel(e.g. remove Sulfur, heavy metal, improve Octane number)
    - The outlets are directly fed as component oil to blend fuel
    - To precisely describe them is important for refinery profit
  - Continuous operation → continuous process scheduling model

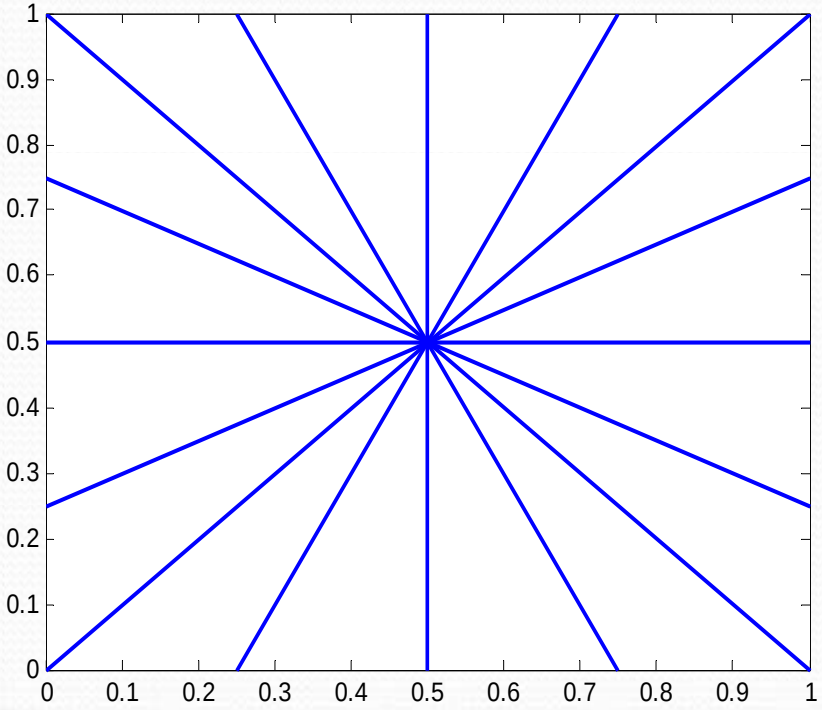
Part I: Unit-specific scheduling model

- Strong nonlinearity
  - Decision variable: outlet property variation
  - Dependent variable: yield/operating cost
  - Hard to solve if nonlinear model is built.
- Piecewise linear model is adopted [1], MINLP is transformed into MILP
  - High precision
  - Nonlinearity in global
  - Linearity in local

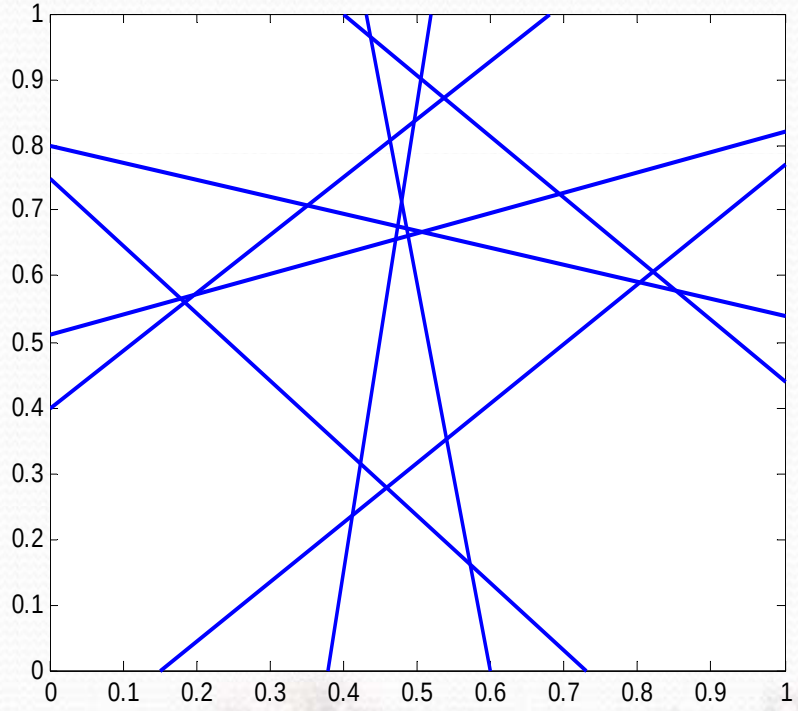
[1] Submitted to *Computers & Chemical Engineering*,(Second round review)

Part I: Unit-specific scheduling model

- Curse of partitions



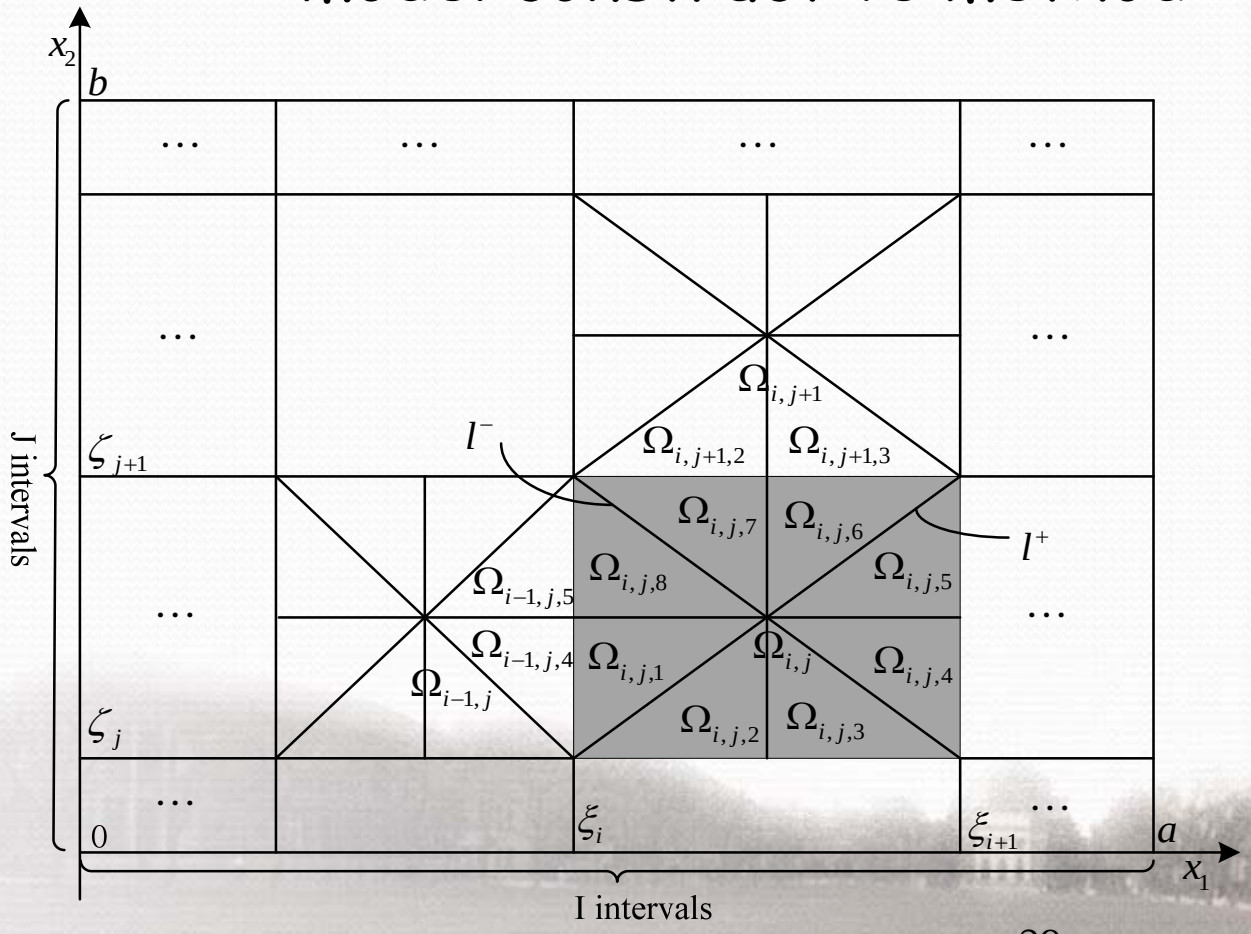
Initial partition



Final partition

Part I: Unit-specific scheduling model

- An improved simplicial partition strategy and PWL model constructive method

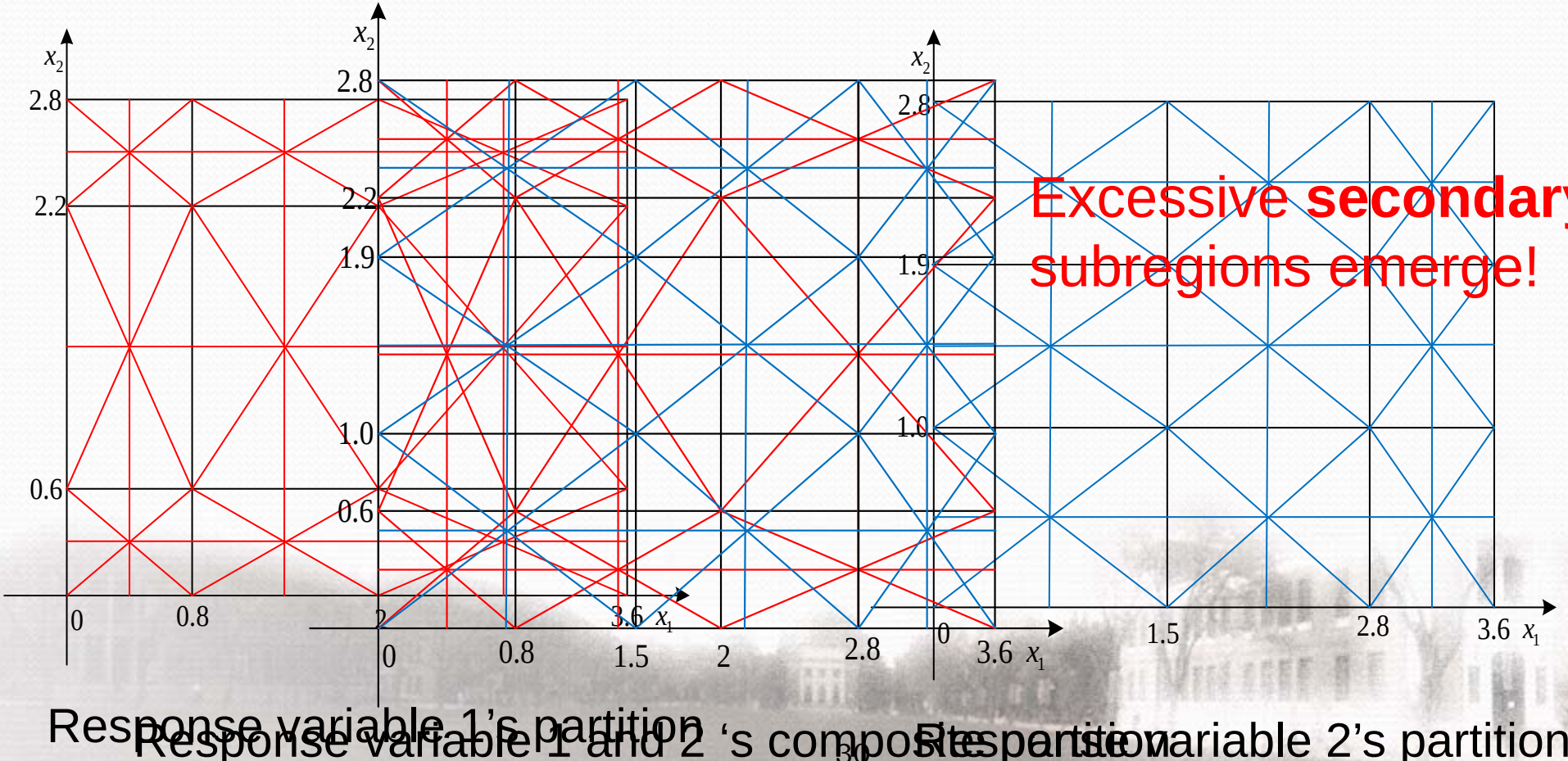


By Introducing alterable intervals, improves representation capability

More details, refer to *ISA Transactions, 2014, online*

Part I: Unit-specific scheduling model

- But, if two or more response variables to be approximated in one optimization issue, then,



Response variable 1's partition

Response variable 1 and 2 's composite partition

Response variable 2's partition

Part I: Unit-specific scheduling model

- Unified simplicial partition strategy
  - For the response variables *in terms of the same decision variables*, constraining them with the same partition

Precision Comparisons of two modeling methods in terms of RSSE.

Unit	Separate CPWL		multi-CPWL	
	Yield Model	Operating cost Model	Yield Model	Operating cost Model
Catalytic reformer	0.0739	0.0843	0.0873	0.0921
Diesel hydrotreater	0.0862	0.0801	0.0903	0.0872
Gasoline hydrodesulphurization	0.0735	0.0869	0.0798	0.0903
Gasoline etherification	0.0720	0.0797	0.0731	0.0815

Compared with separate CPWL, there is little precision loss for multi-CPWL

Part I: Unit-specific scheduling model

More importantly, the ***partitions complexity*** is largely decreased.

Comparisons of two methods in terms of the final subregions.

	Catalytic reformer	Diesel hydrotreater	Gasoline hydrodesulphurization	Gasoline etherification
Multi-CPWL	**72**	**48**	**24**	**48**
Separate CPWL	**464**	**382**	**344**	**426**

This facilitates the subsequent model-based scheduling optimization! ***Less computation time, but more profit gains!***

Optimization results comparisons.

Model	CPU time/s	Computed Profit/Yuan
Multi-CPWL	**2,631**	**4,365,271**
Separate CPWL (Zhu et al., 2011)	**44,710**	**4,182,936**

Part I: Unit-specific scheduling model

- Local linear model can be described in analytical formulation
- Take **feed and unit operation** into consideration under optimal process control
- **Unit-specific** model structure
- Maintains a simpler **MILP problem** for refinery scheduling optimization

Part II: optimization strategy

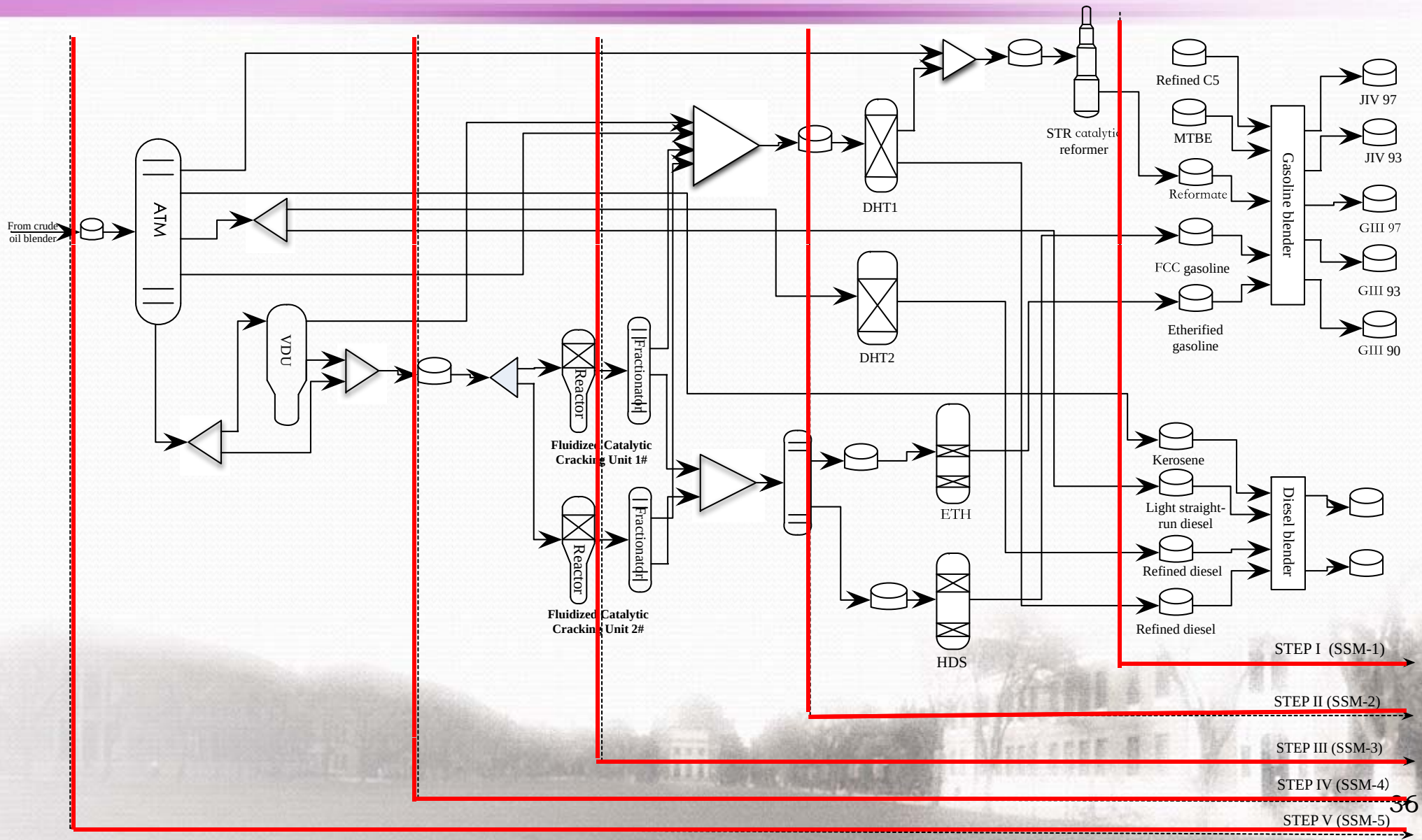
- Process dynamics
  - Common for industrial application, especially refinery
  - Due to real-time of the schedule, the process dynamics caused by schedules should be finely considered.
  - Different schedules result in different process dynamics and operating cost
  - Process dynamics are hard to be modeled in scheduling precisely

Part II: optimization strategy

- Step-wise decision making strategy[2]
  - It is easier to realize for schedules only adjusting downstream units than upstream units, or even the whole refinery

[2]Submitted to *Industrial & Engineering Chemistry Research*,(Second round review)

Part II: optimization strategy



Part II: optimization strategy

- Advantages
  - Decrease schedules' process dynamics

Items	Traditional solving	Our strategy
Computed profit (Yuan)	71,857,033	68,290,076
Process dynamic time (minutes)	**3761**	**536**
Solving time (s)	2735.8	341.5
Equality constraints number	13068	1896
Inequality constraints number	3960	1788
Continuous variables number	11304	2280
Discrete variables number	612	174

Part II: optimization strategy

- Make the resulted schedule more applicable, easier to be realized

Comparison results are obtained by Implementing the resulted schedules in simulation platform realized by *UniSim Operations*

Gasoline		Traditional solving / t		Our strategy / t	
		Available	Difference	Available	Difference
JIV 97	First batch	1901.7	-298.3	2214.8	14.8
	Second batch	2003.1	-396.9	2458.2	58.2
	Third batch	2133.5	-366.5	2510.7	10.7
JIV 93	First batch	1823.0	-177	2274.4	274.4
	Second batch	1897.8	-202.2	2150.7	50.7
	Third batch	2016.5	-133.5	2158.0	8.0
GIII 97	First batch	1620.7	-179.3	1957.6	157.6
	Second batch	1699.3	-200.7	1987.4	87.4
	Third batch	1785.9	-164.1	1976.8	26.8
GIII 93	First batch	1105.8	-94.2	1351.2	151.2
	Second batch	972.4	-27.6	1032.8	32.8
	Third batch	1073.9	-76.1	1210.1	60.1
GIII 90	First batch	1027.1	27.1	1109.2	9.2
	Second batch	810.3	10.3	841.6	41.6
	Third batch	842.5	-7.5	869.2	19.2

Summary

- Process model is the key for refinery scheduling optimization, and the main obstacle for industrial application
  - Based on unit-wide optimal control, we developed the multi-modes based process multi-scheduling model
  - Unit-specific model well grasp the refinery process characters and holds a simple model structure
  - Piecewise linear scheduling model for HUPUs preserves the whole scheduling problem an easy-to-solve MILP

Summary

- Multi-model based on crude oil classifier to
- Step-wise decision making strategy considers the process dynamics issue, makes schedules more applicable

More information

- Xiaoyong Gao, Chao Shang, Yongheng Jiang, Dexian Huang, Tao Chen. Refinery scheduling with varying crude: a deep belief network classification and multi-model approach. *AIChE Journal*, 2014, 60(7): 2525-2532.
- Xiaoyong Gao, Yongheng Jiang, Dexian Huang, Zhihua Xiong. A novel high level canonical piecewise linear model based on simplicial partition and its application. *ISA Transactions*, 2014. (Online)



Many thanks!

