Bridging the Gap Between Planning and Control:

A Multiscale MPC Cascade Approach

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Background and Motivations

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- ✓ Over the last 30+ years, process industries have made much progress in real-time control and optimization
  - ➢ Close to 10 thousand MPC controllers have been implemented in different industries.
    - ◆ Oil refining, petrochemical, pulp & paper, alumina – just to name a few
  - ➢ >100 plantwide optimization solutions have been implemented
    - ◆ The majority of them are for ethylene plants
  - ➢ Estimated benefits delivered: $10 billions ($5 billions by Honeywell)
- ✓ To broaden the reach of control, improvement opportunities exist:
  1) Solution Scalability:
  2) Solution Operability
  3) Real-time responsiveness (e.g., steady-state RTO)
- ✓ A multiscale MPC cascade solution will be proposed
  - ➢ The goal is to broaden the reach of control into a new class of unsolved problems, and more specifically, to bridge the gap between planning and control.

Cascade Control: MPC vs PID

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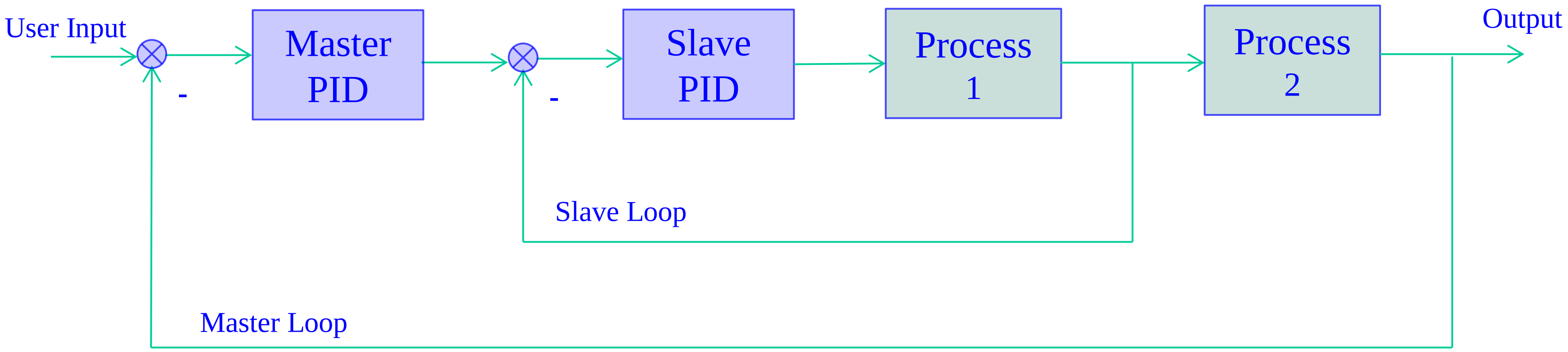

Cascade Control: MPC vs PID

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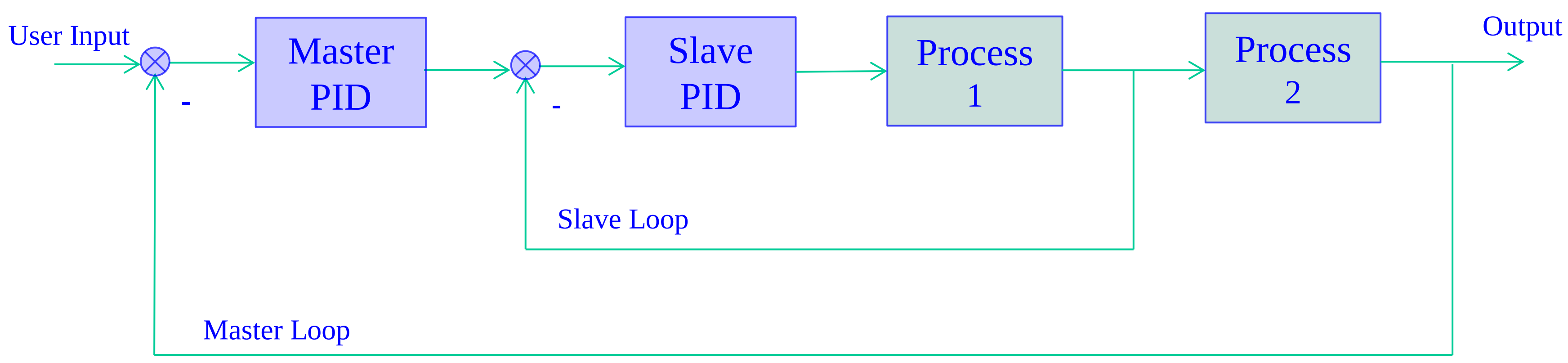

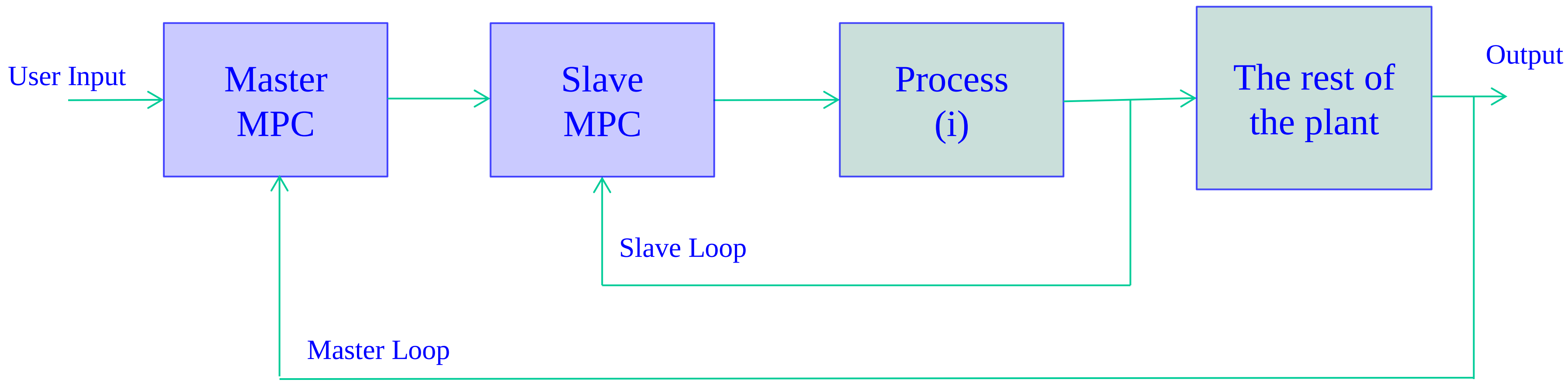

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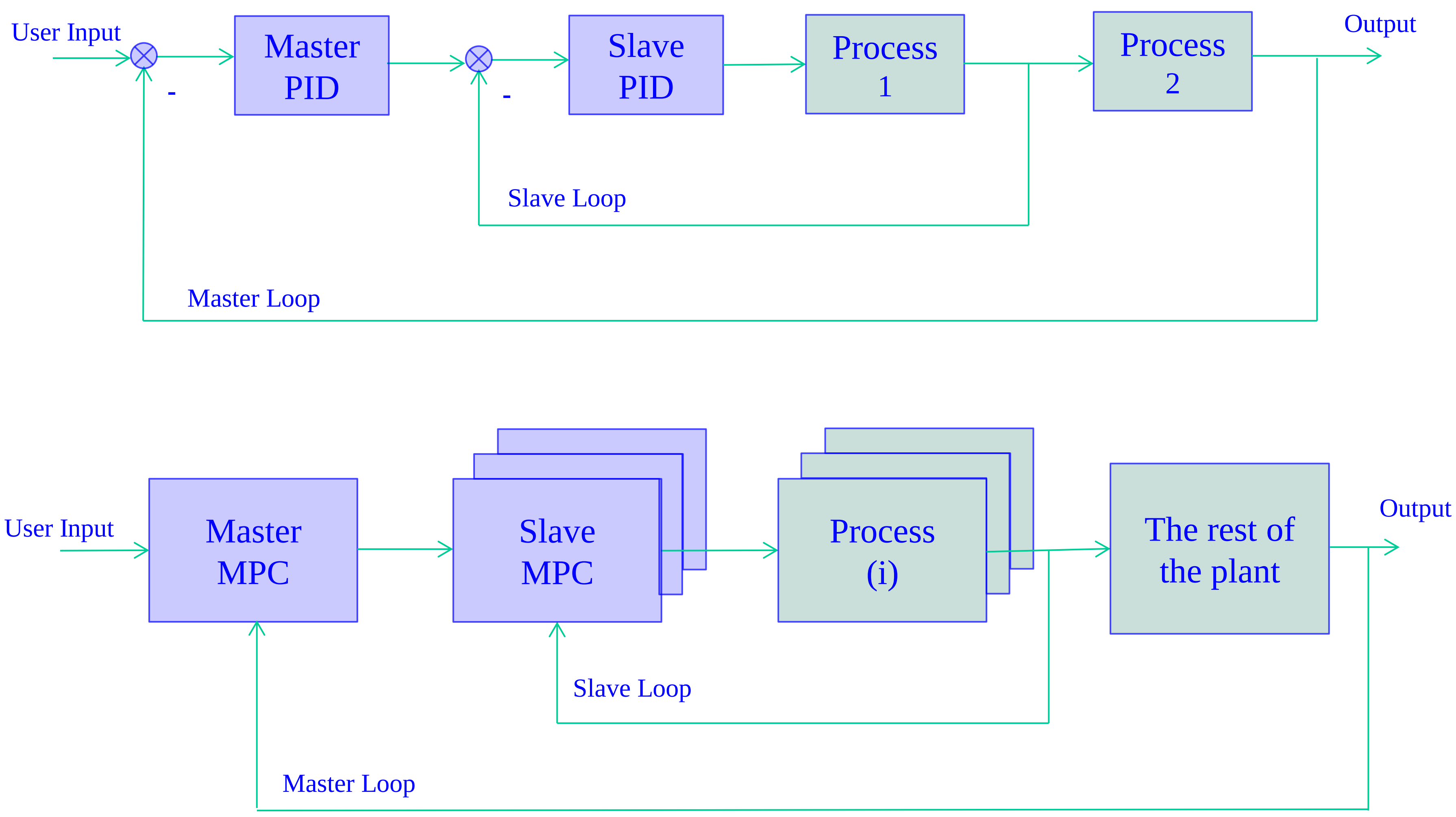

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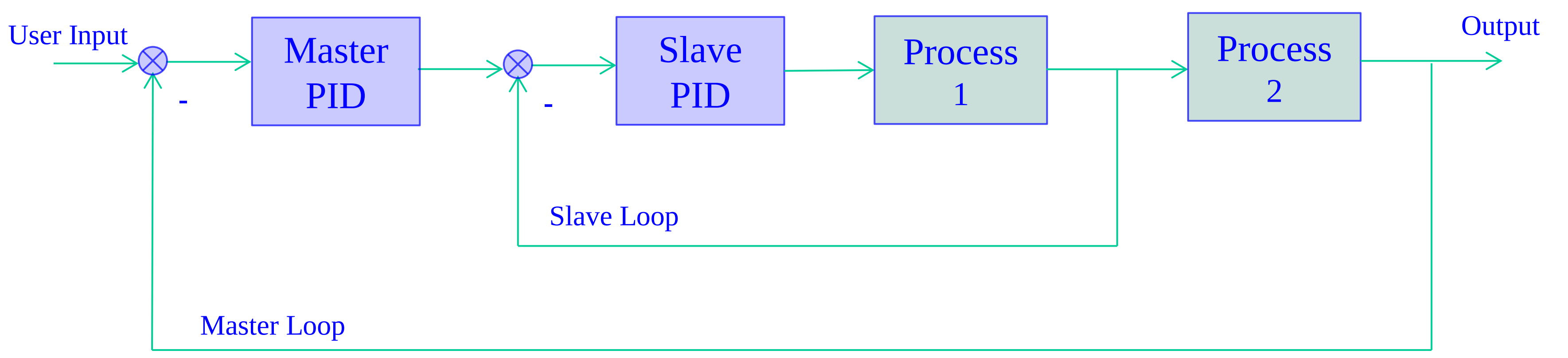
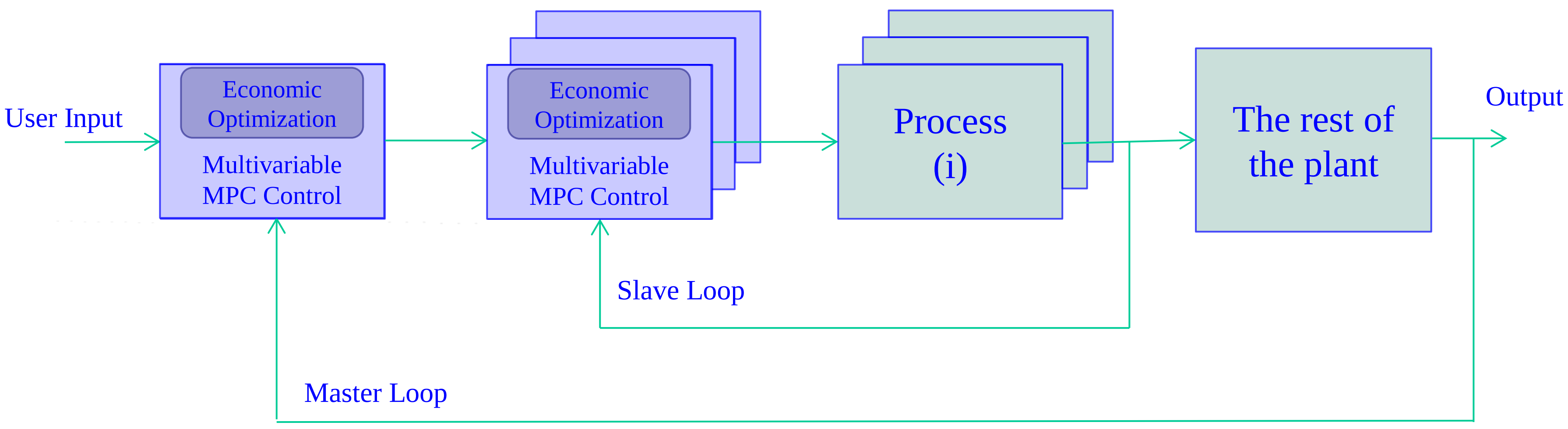
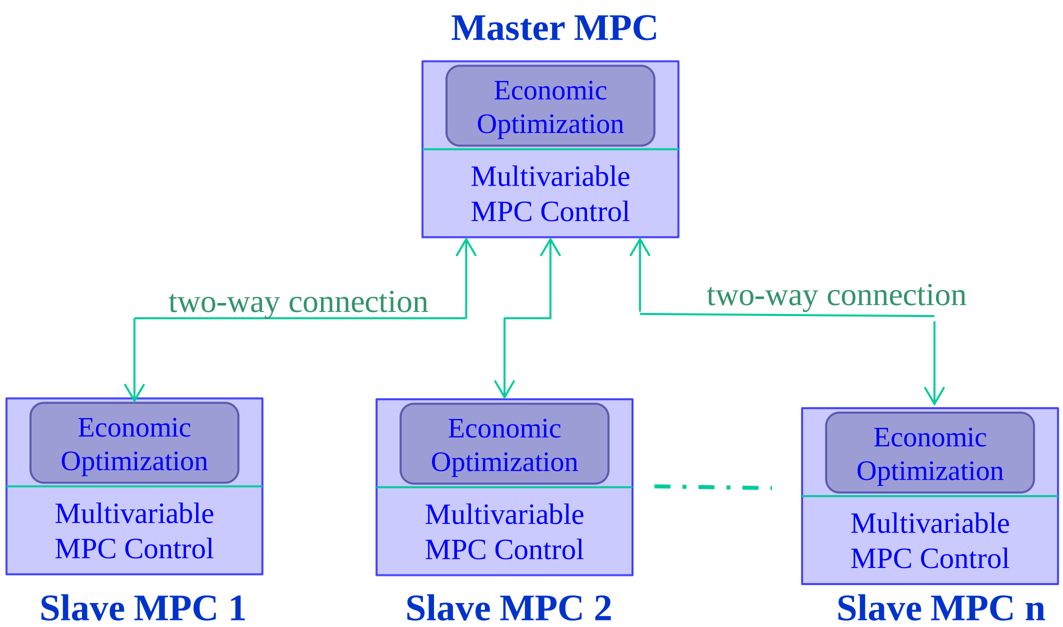
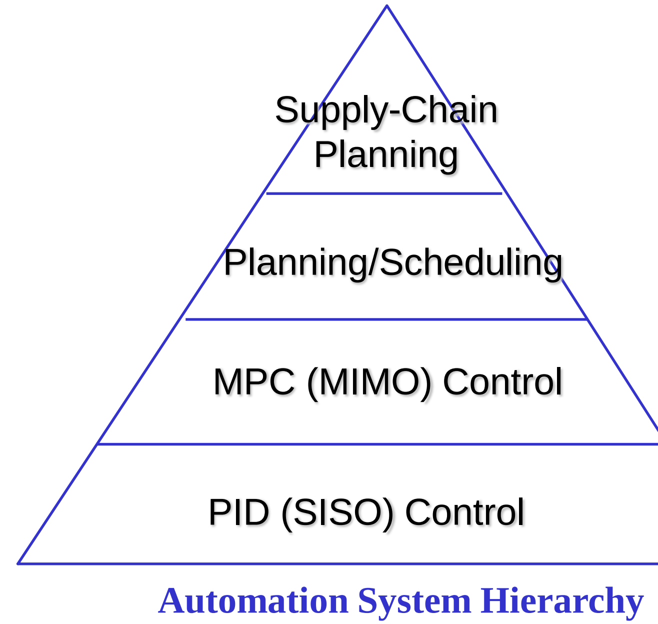




Proposed Multiscale MPC Cascade





- 1-to-n MPC cascade – One Master MPC and multiple Slave MPCs
- The Master MPC employs a dynamic model which can be, at user's discretion, a coarser-scale model
  - e.g., similar to the scale-level of a planning model
- The Slave MPCs employs a dynamic model which can be a finer-scale one

- If Slave MPCs are deployed at every process unit, then the Master MPC can solve the plantwide production control problem dynamically and in closed loop
  - Currently, a steady-state version of this problem is controlled by planning solutions in open-loop

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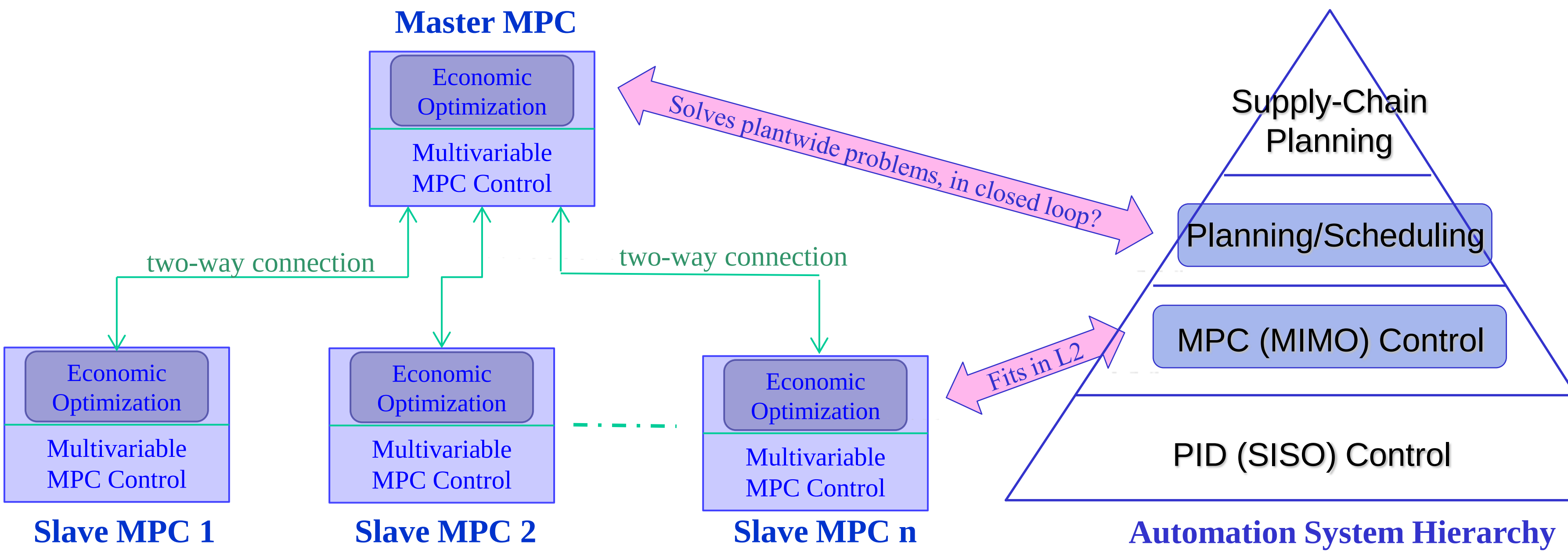

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A Refinery-wide Control Problem: JIT manufacturing

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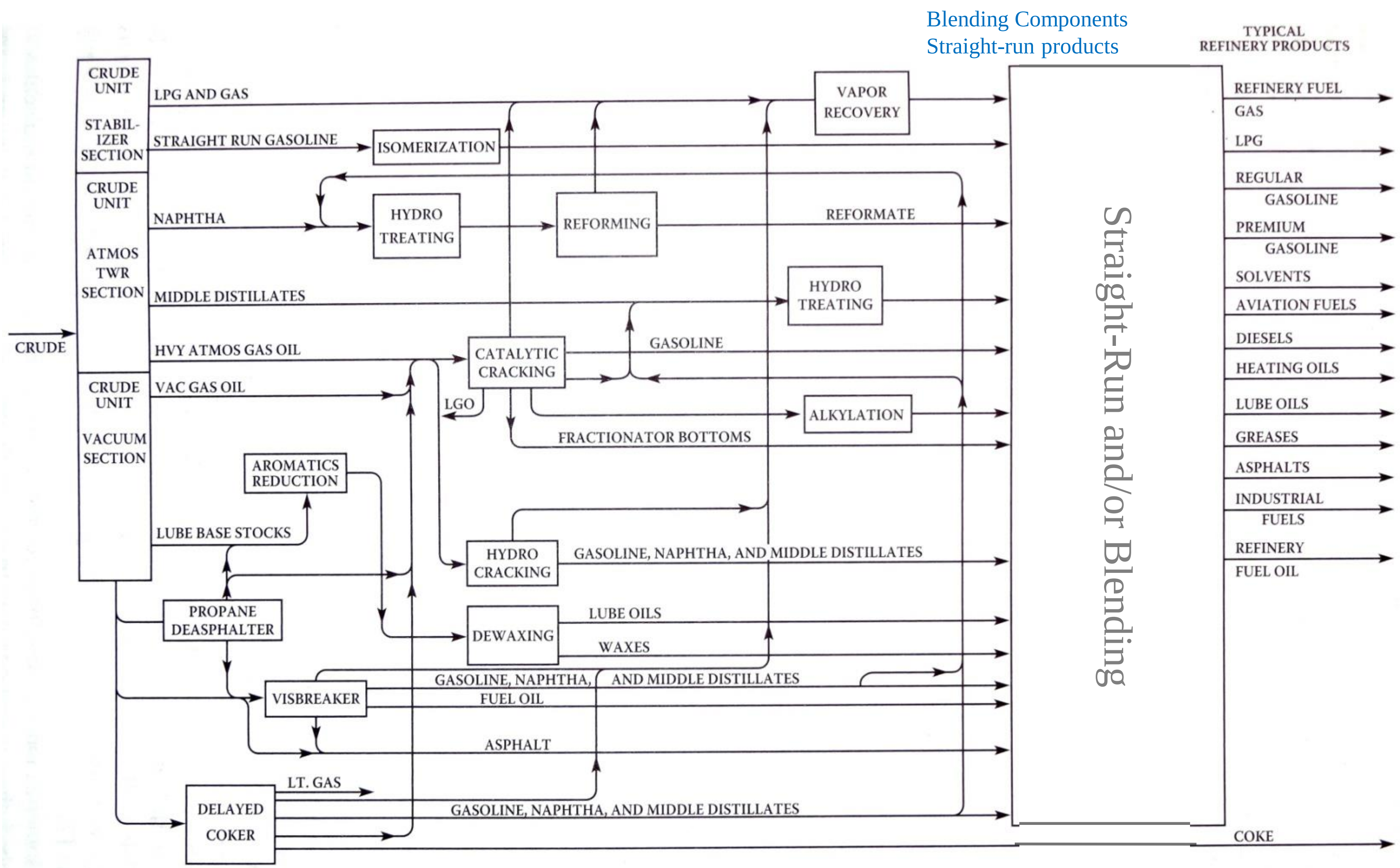

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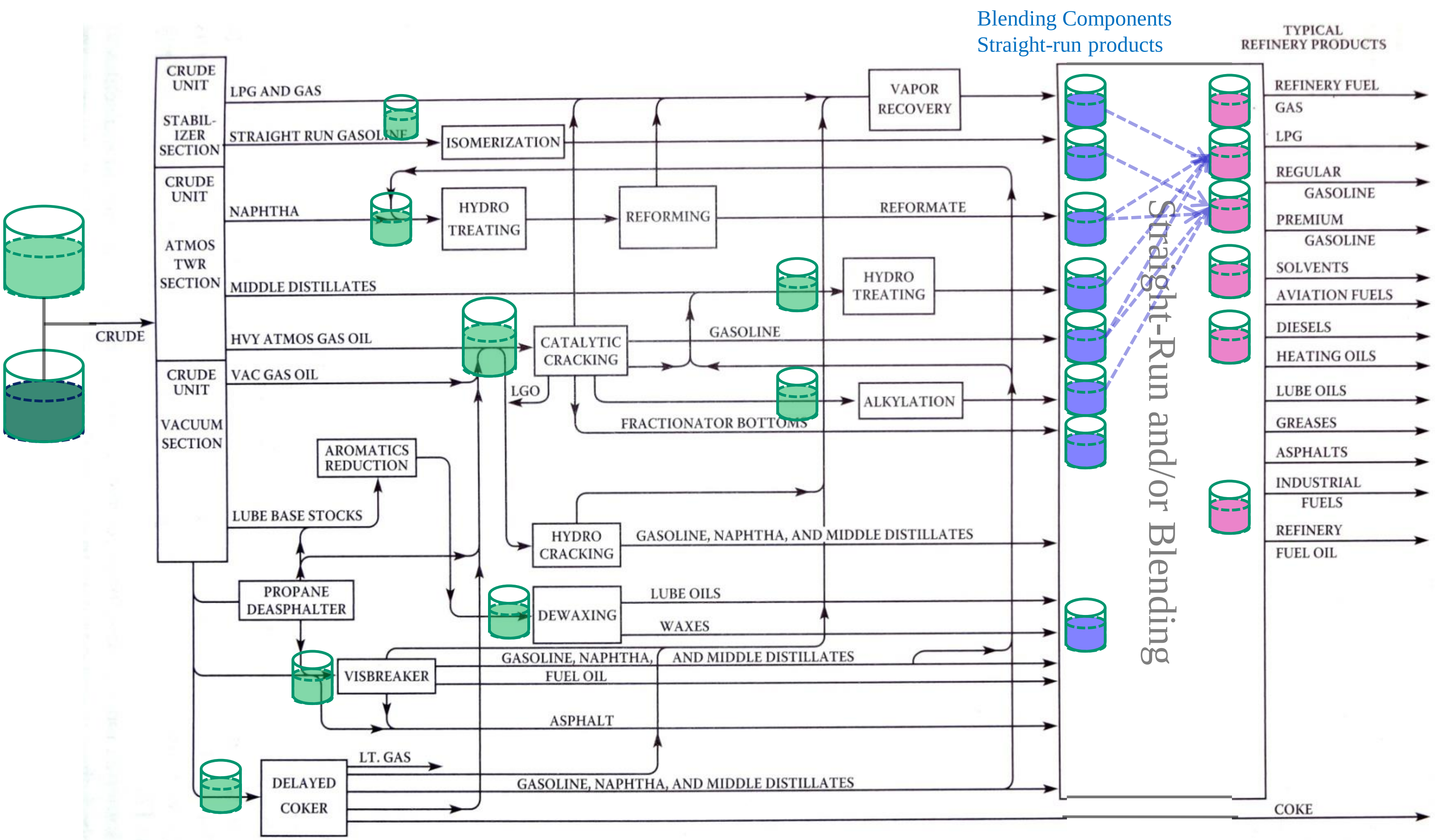

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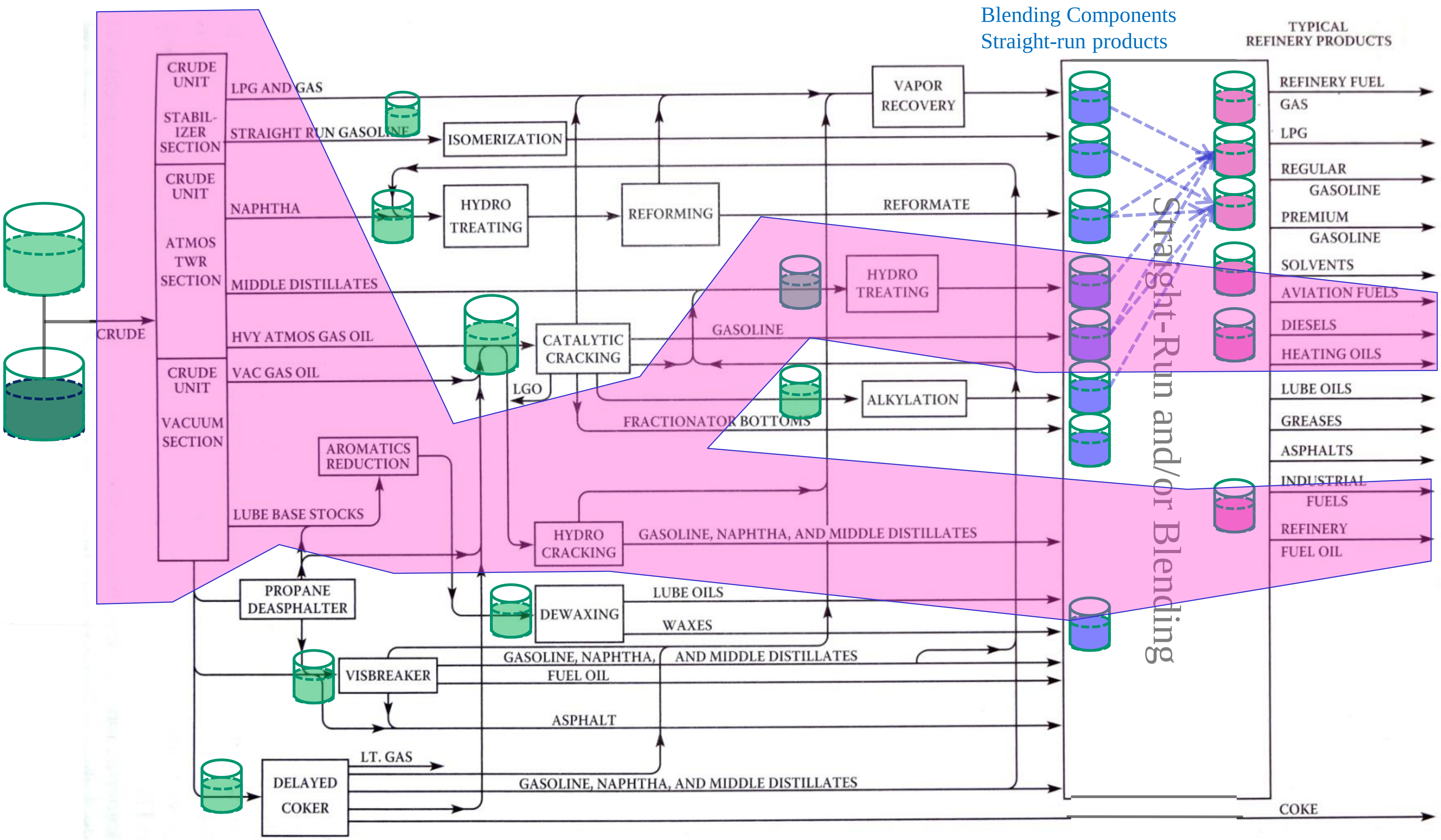

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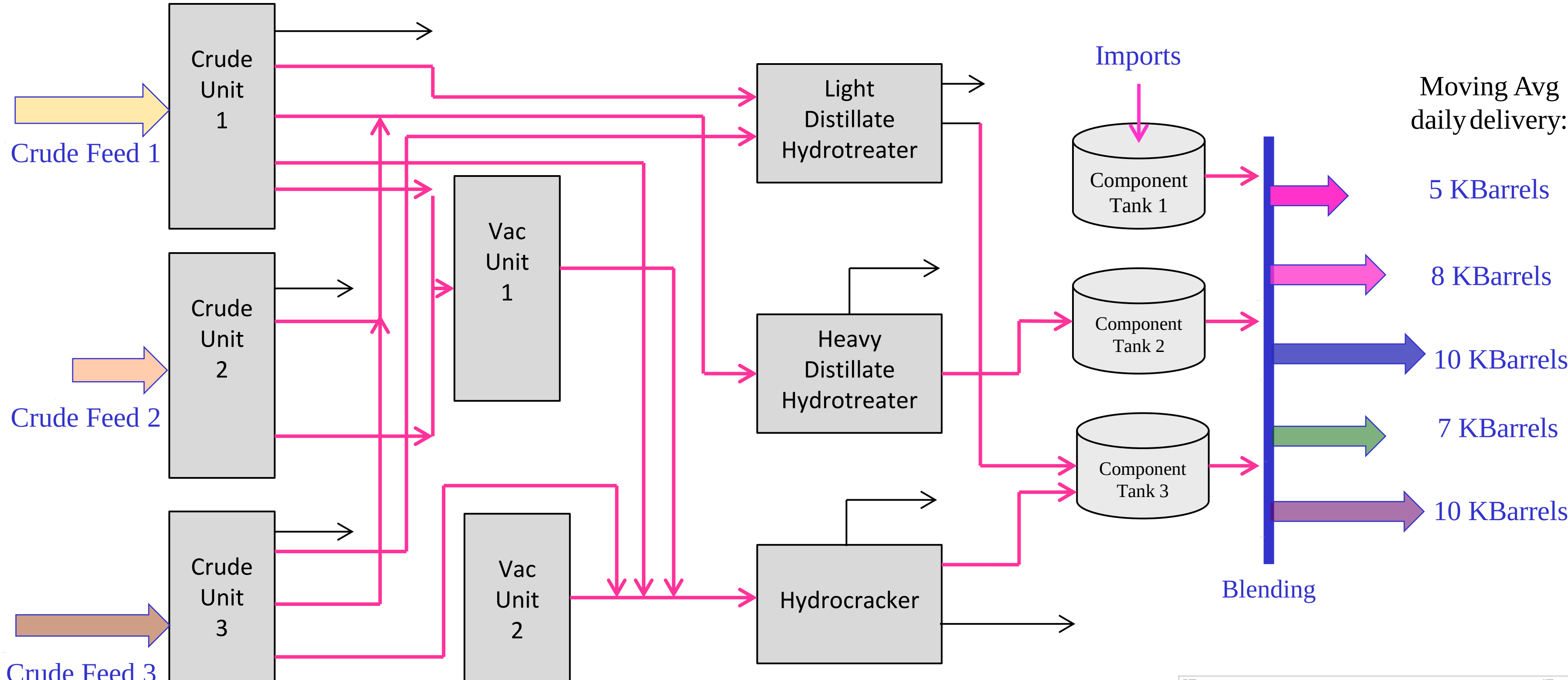
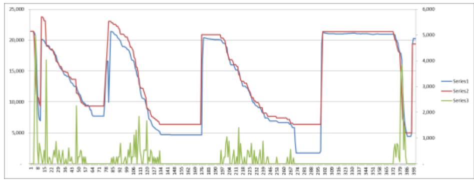
JIT manufacturing viewed as a control problem

Scope: the distillate production pool in an oil refinery

✓ It is simpler but still captures most of the important issues



Material Balance & Inventory Control



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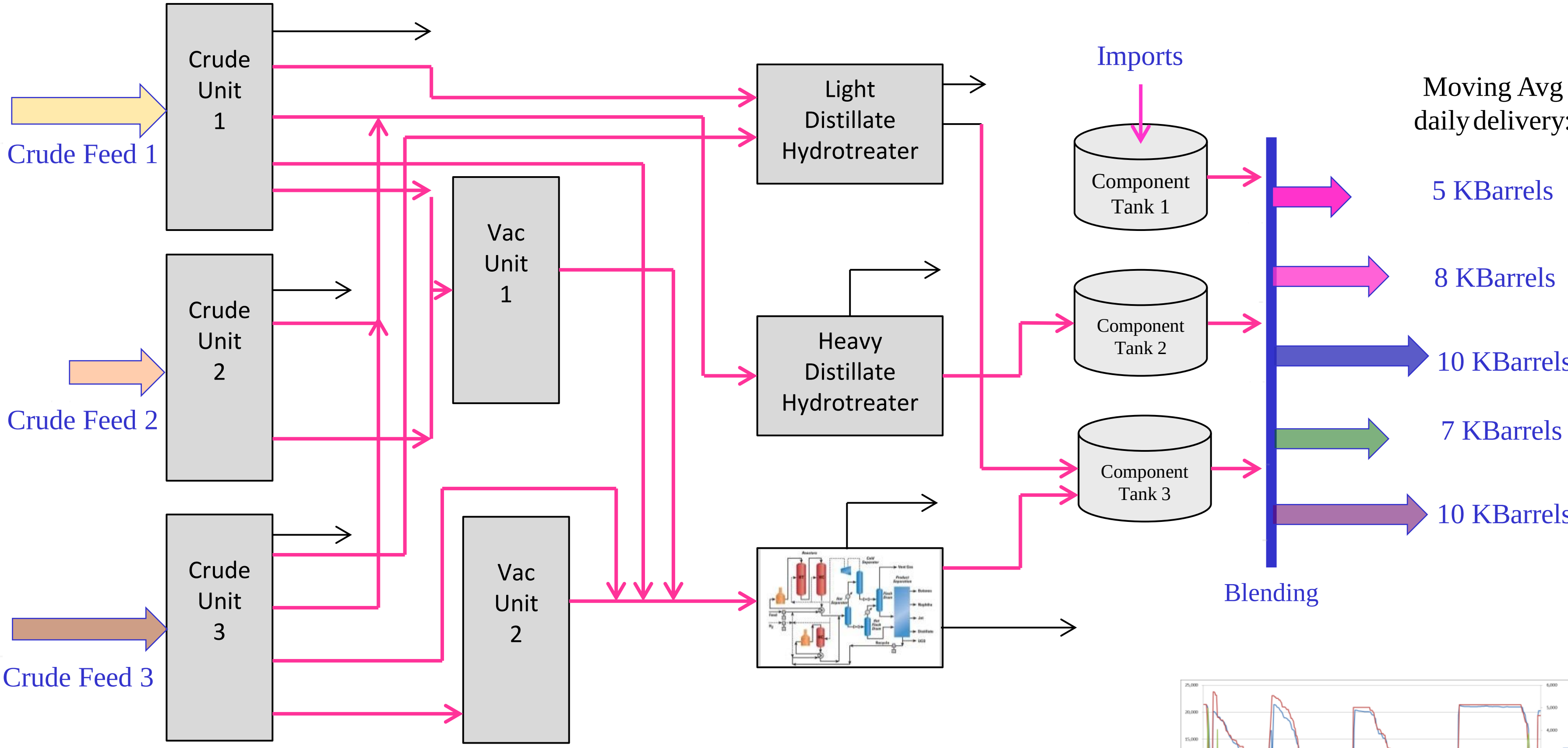

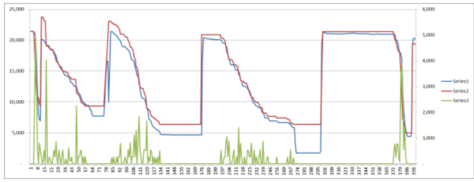

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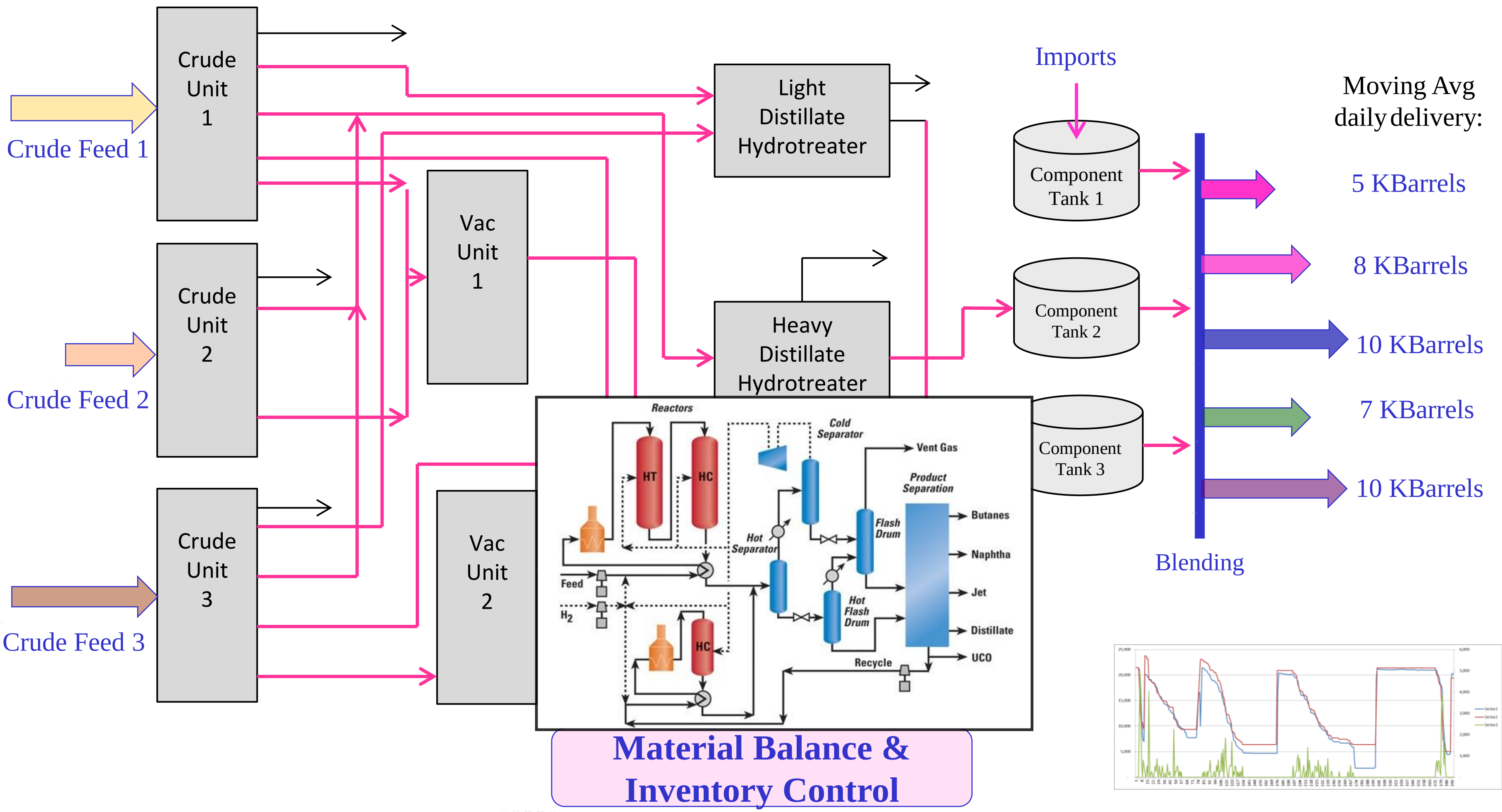

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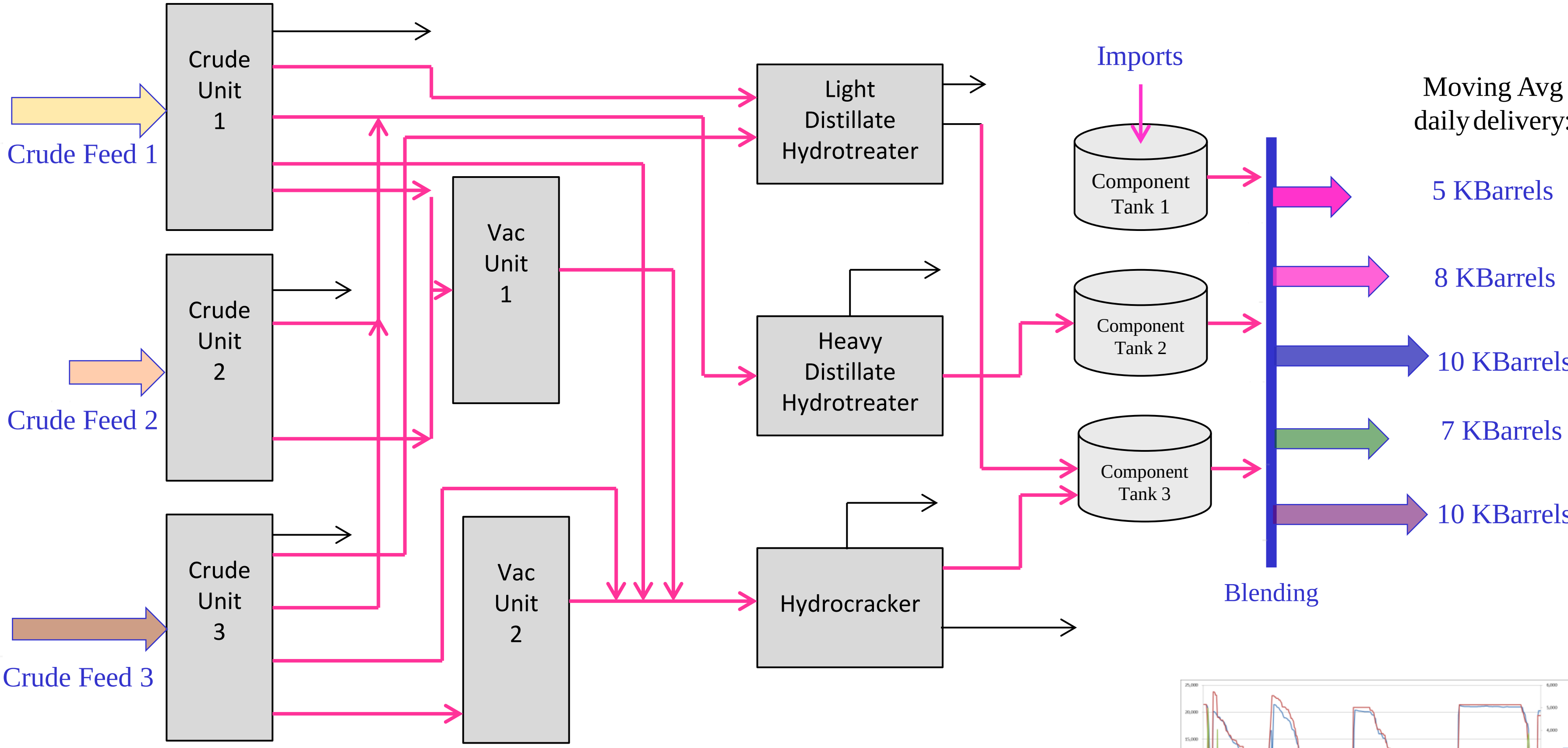

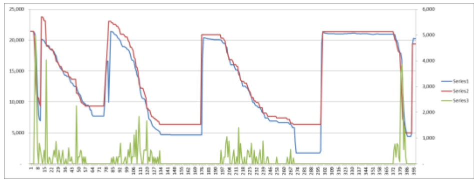

Material Balance & Inventory Control

Just-in-Time Manufacturing – Quality Control (1)

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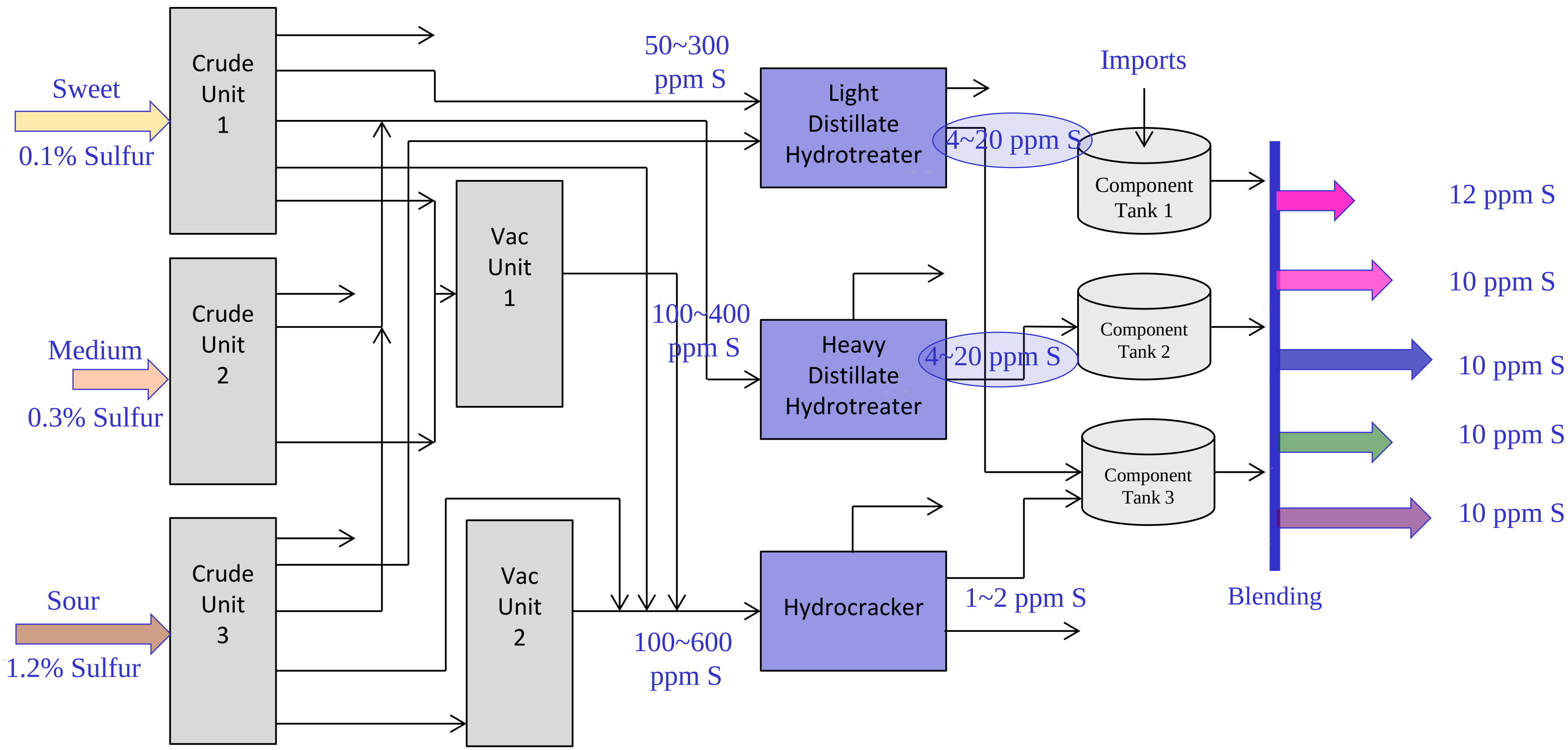
Quality Control - Sulfur

Legend: Control handles



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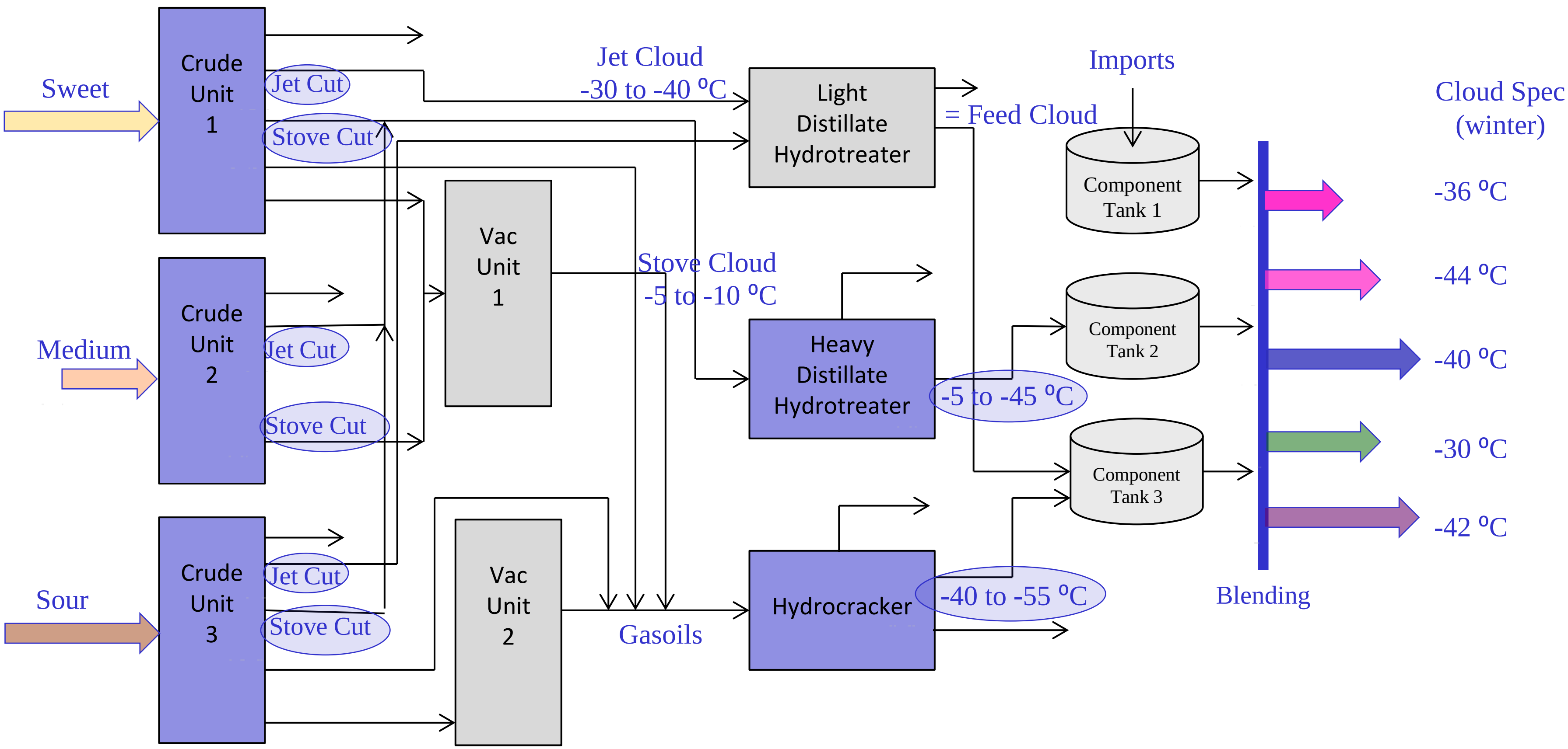
Quality Control - Cloud Point

Legend: Control handles



- Few if any (closed-loop) control solutions are available for this class of problems!

Control Model Matrix for the Master MPC

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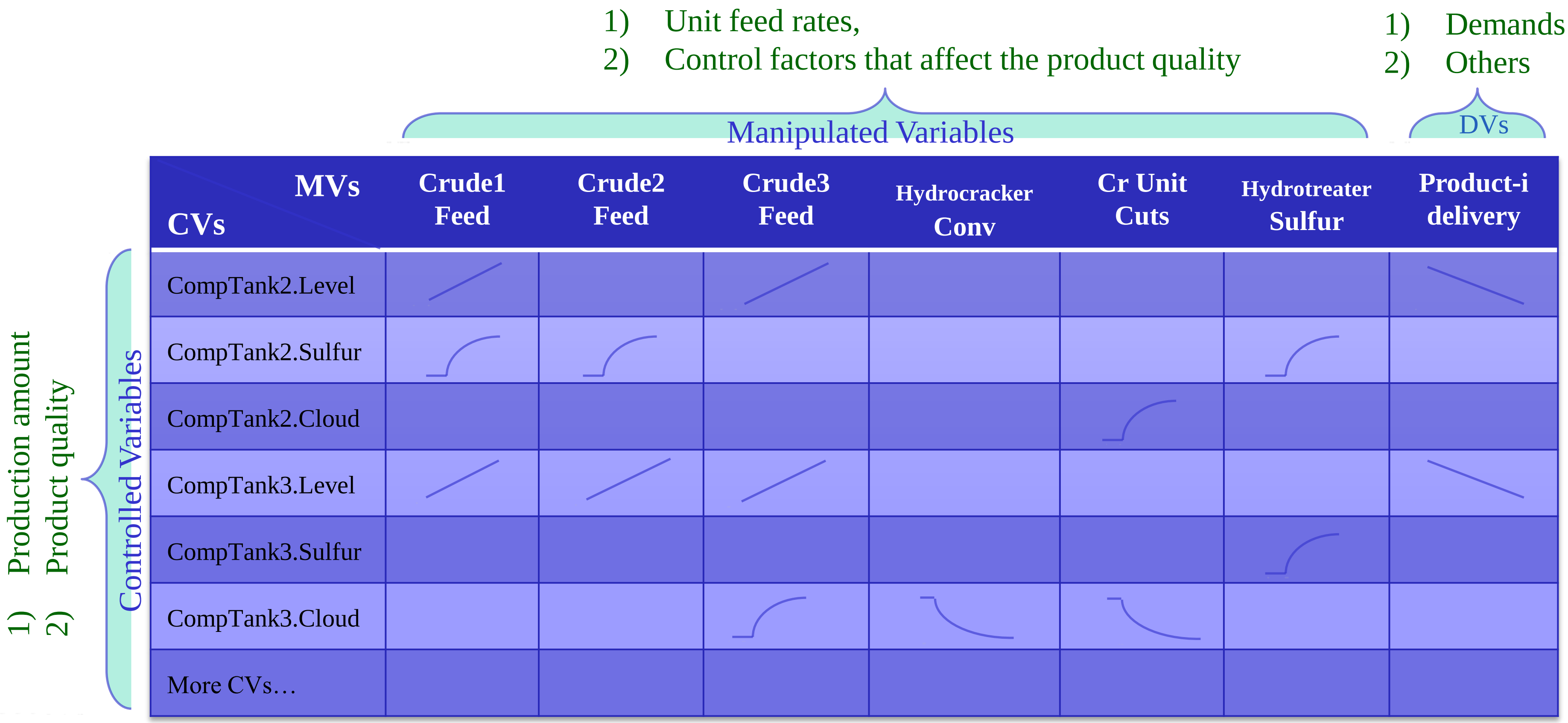


- ✓ Each (i, j) entry contains a dynamic model $g_{i,j}(s)$:
- ✓ Often simple dynamics such as $\dfrac{k}{as^2+bs+1}e^{-\theta s}$ or $\dfrac{k}{s(\tau s+1)}e^{-\theta s}$ would suffice
- ✓ Notice that there is no setpoint in this control problem – just constraint control

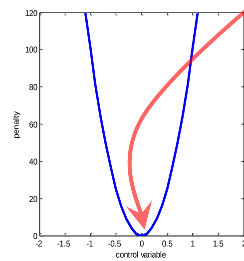
Model Predictive Range Control

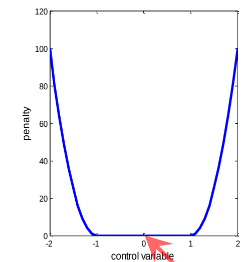
Versatile control needs in MIMO applications

- ✓ Regulatory control
- ✓ Constraint control
- ✓ Transition control

Regulatory Control

$$\Delta u^* = \arg\min_{\Delta u} \left\| A\Delta u + \tilde{y} - r \right\|_Q^2 + \left\| \Delta u \right\|_R^2$$





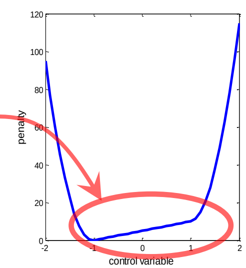
Model Predictive Range Control

- ✓ Output prediction: $y = A\Delta u + \tilde{y}$
- ✓ The set-point is changed into a “set-range”
- ✓ A slack variable s is introduced in the formulation
- ✓ Additional degrees of freedom are used for
  - ➢ Optimization: e.g.,

$$\Delta u^* = \arg\min_{\Delta u, s} \left\| A\Delta u + \tilde{y} - s \right\|_Q^2 + \left\| \Delta u \right\|_R^2$$

$$y_{LO} \le s \le y_{HI}$$

$$\min y; \quad y_{LO} \le y \le y_{HI}$$



Range Control

Range MPC Design and Solution

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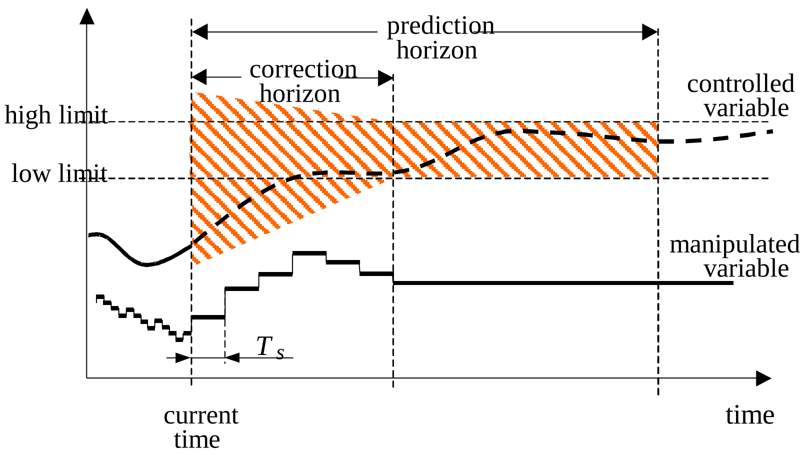
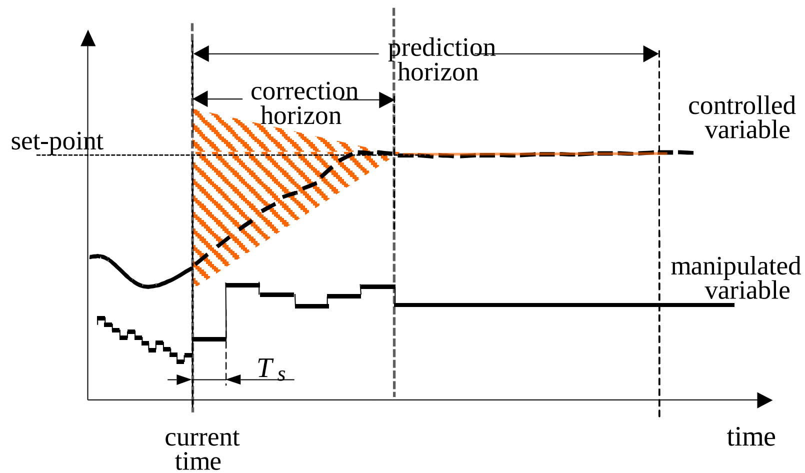
- Performance Specification:





Range control algorithm

✓ Two-stage analytic approach

a) solve the range control problem

$$\Delta u^* = \arg\min_{\Delta u, s} \left\| A\Delta u + \tilde{y} - s \right\|_Q^2 + \left\| \Delta u \right\|_R^2;$$

b) If soln to (a) is not unique, solve for the minimum effort control

$$\Delta u^* = \arg\min_{\Delta u} \left\| \Delta u \right\|_R^2; \qquad y_{LO} \le A\Delta u + \tilde{y} \le y_{HI}$$

✓ Online algorithm similar to the active-set QP:

(here assume R = 0)

$$\Delta u^* = \arg\min_{\Delta u, w} \left\| \begin{bmatrix} A_{act} \\ A_{free} \end{bmatrix} \Delta u - \begin{bmatrix} w_{act} \\ w_{free} \end{bmatrix} \right\|_Q^2$$

$$\text{Let} \quad Q^{1/2} A_{act}^{(k)} = U_k R_k V_k^T$$

$$\Delta u^* = \arg\min_{\Delta u} \left\| \left[U_k R_k V_k^T \right] \Delta u - w_{act} \right\|_2^2$$

Master MPC for JIT Manufacturing in closed loop?

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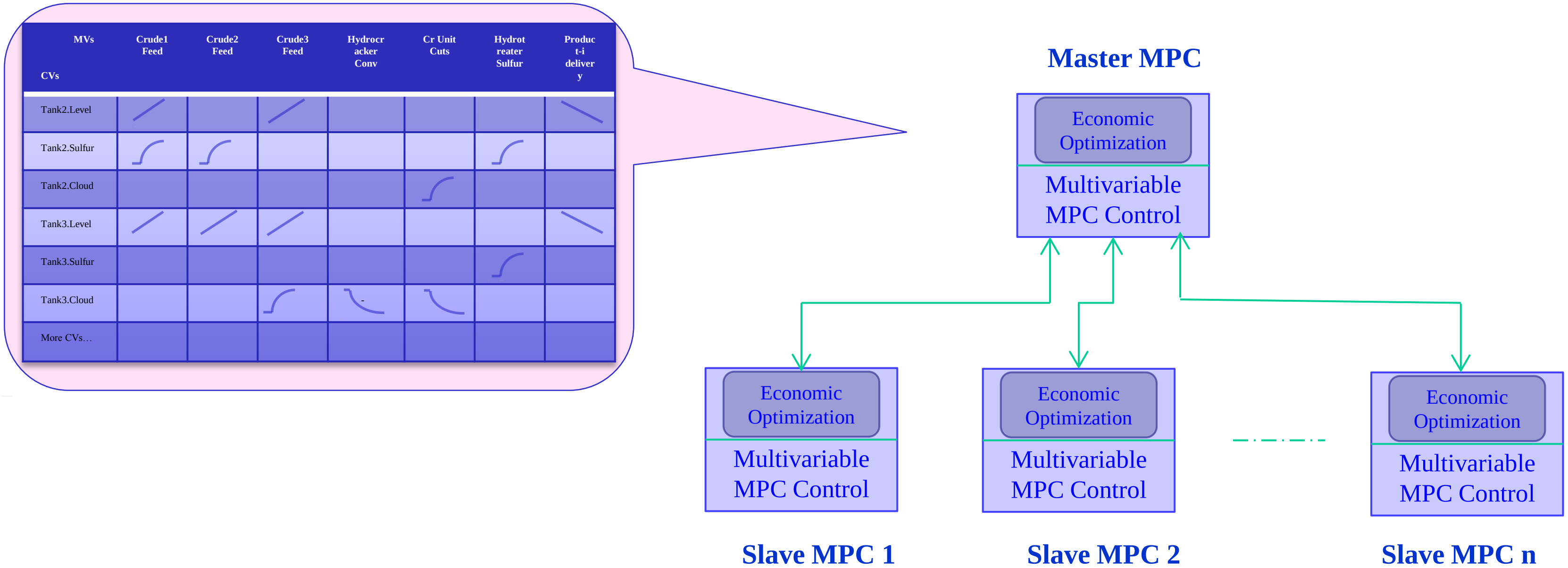
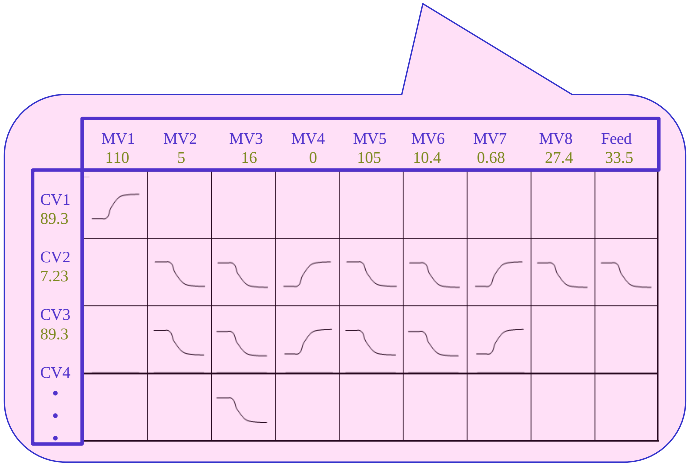


- ✓ Yes, if the solution for JIT manufacturing from the Master MPC is *implementable* by the Slave MPCs.
- ✓ No, if the solution from the Master MPC can cause one or more Slave MPCs to wind up (i.e. sustained CV constraint violations).
- ✓ The Real Challenge:
  - ➢ What's implementable now (or today) may not be implementable in the future (or tomorrow)
  - ➢ The slave constraints change over time



Master-Slave Models: a side-by-side view

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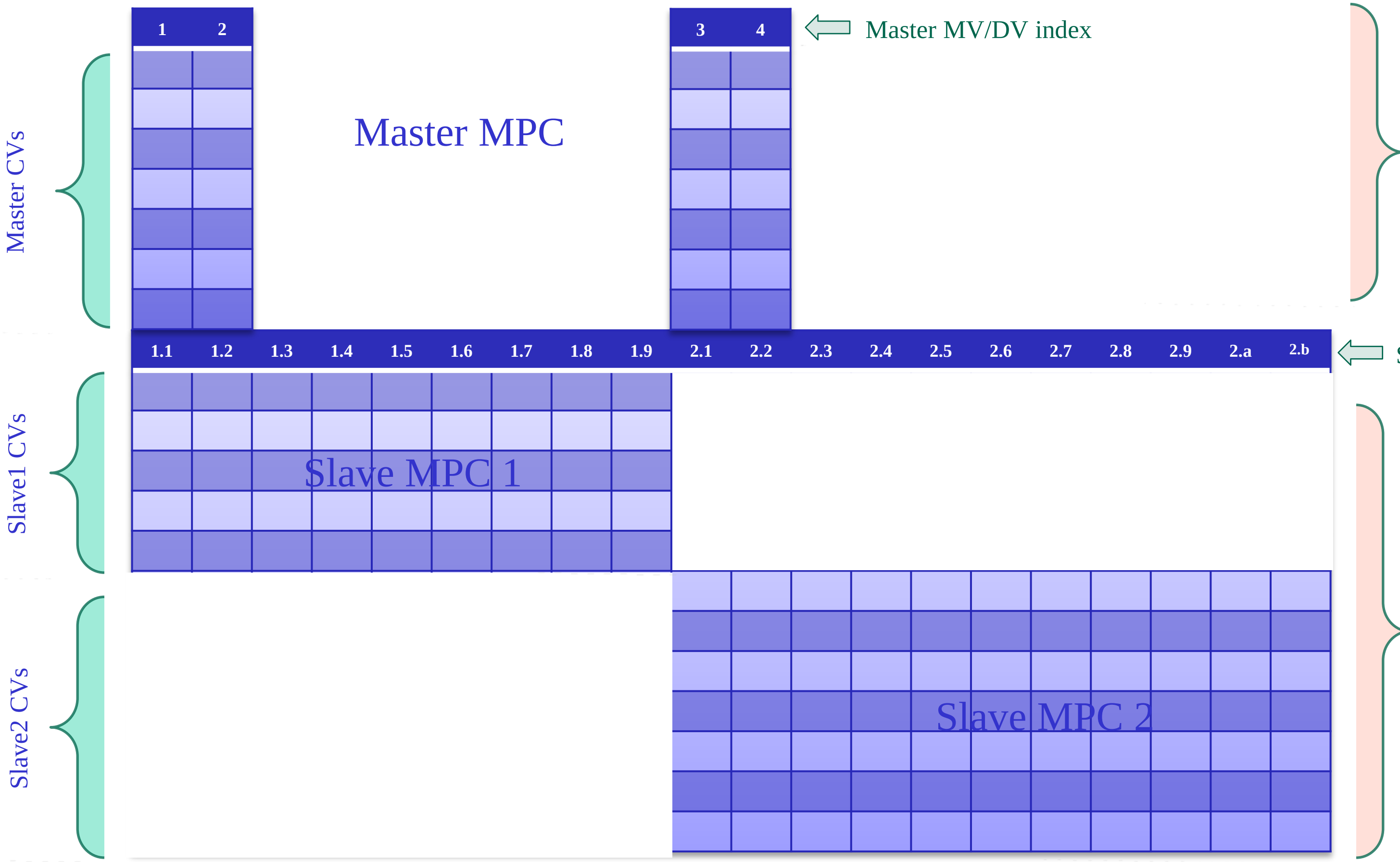
- ✓ Below is an illustration of the model structure for 2 combined units:



Different Tasks

Plantwide Optimization
- Inventory control
- Quality control
- Cost and profit

Unit Process Control
- Safe/smooth operation
- Unit efficiency
- Intermediate Quality
- Local Optimization

- ✓ The relationship is a bit convoluted, so let's first look at the simplest case: 1 conjoint variable per Slave MPC

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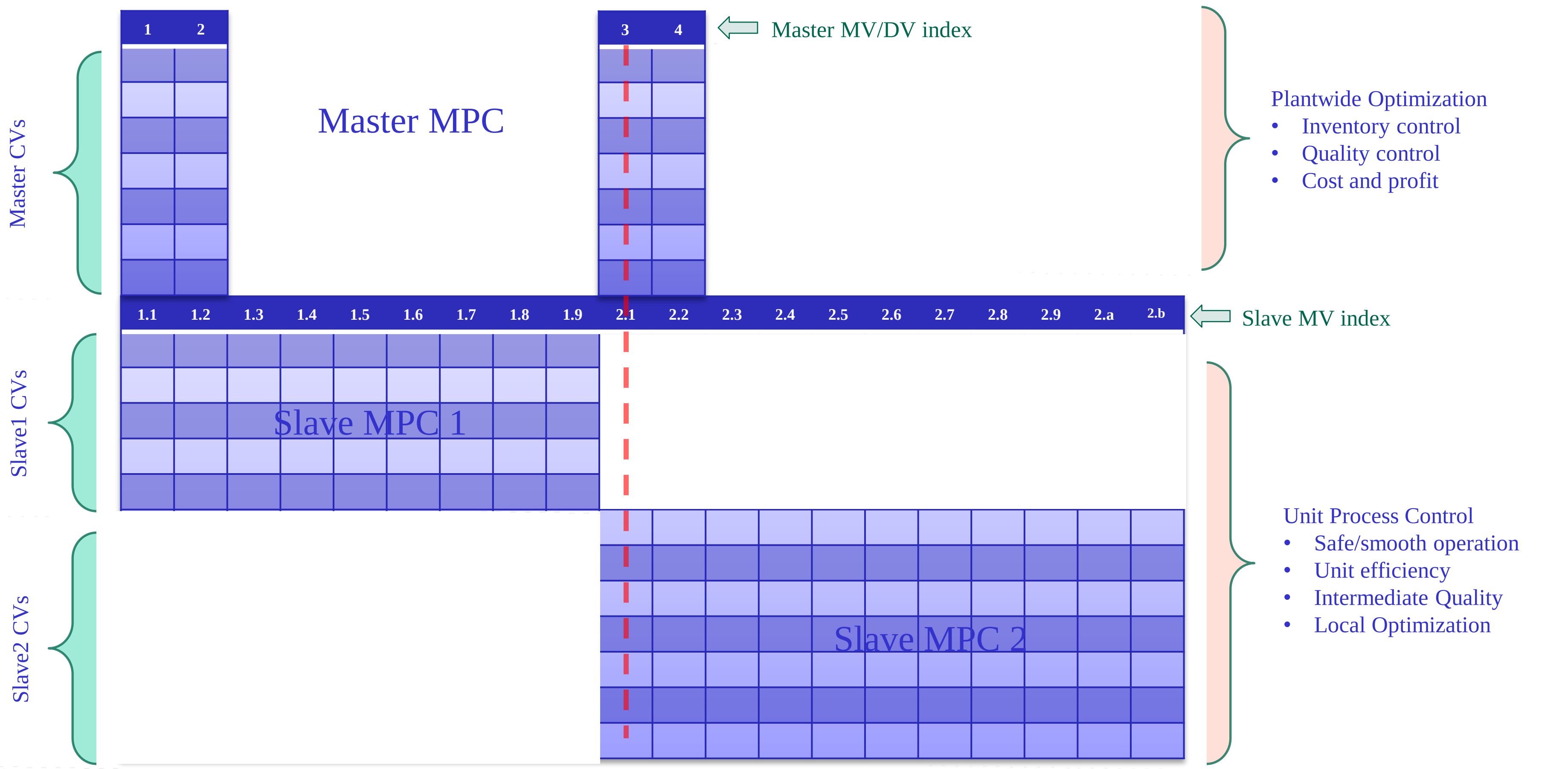

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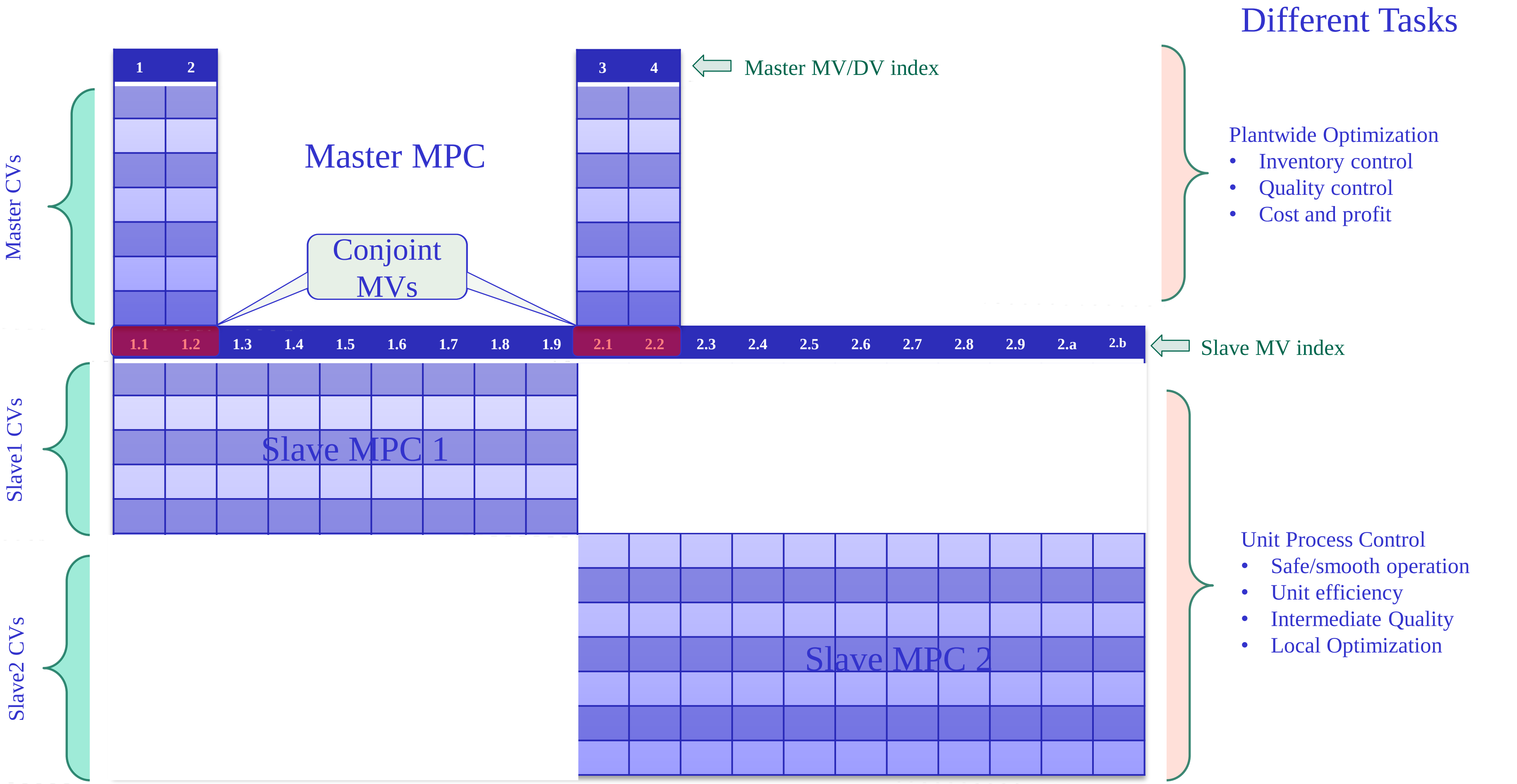

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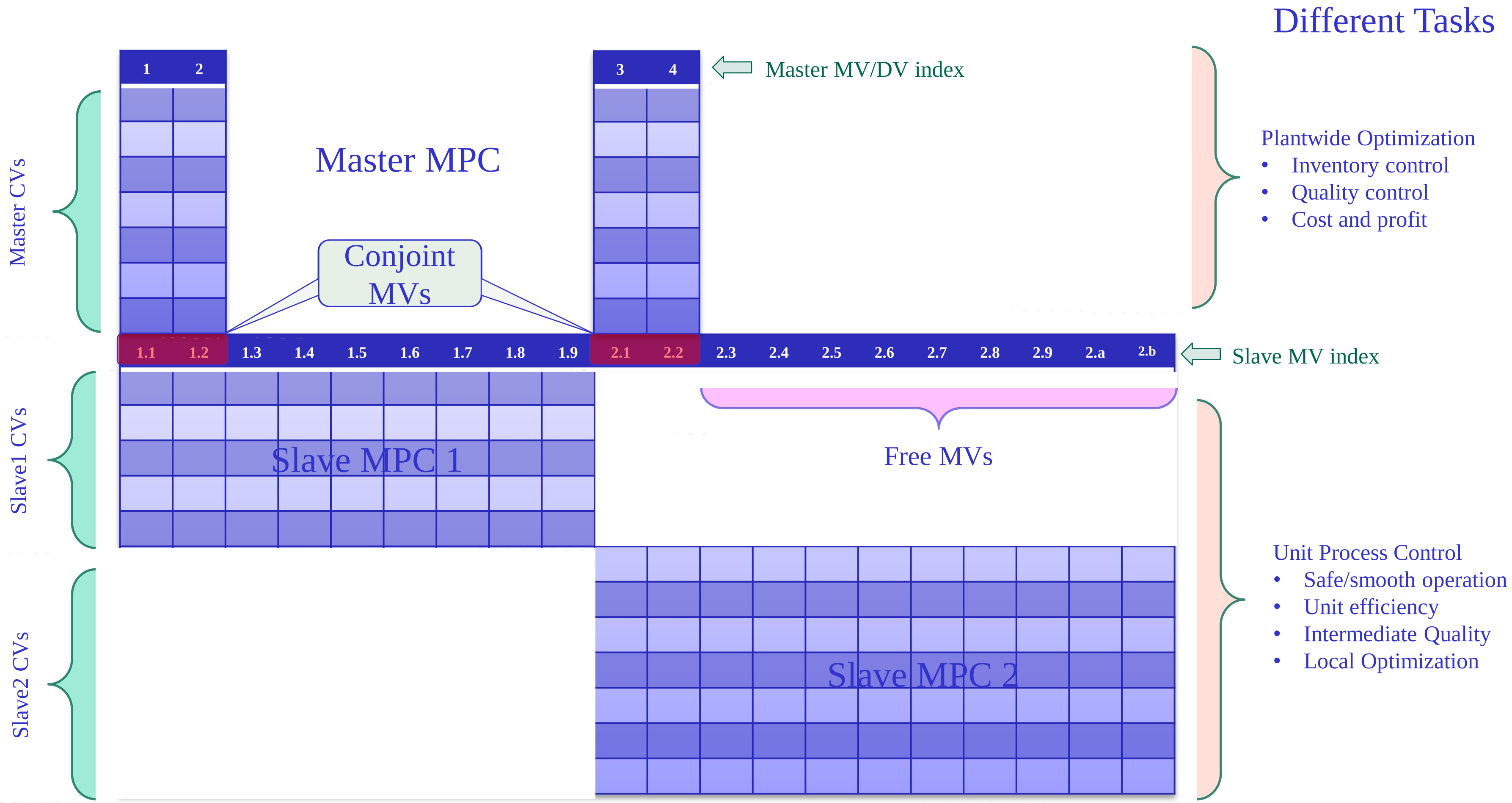

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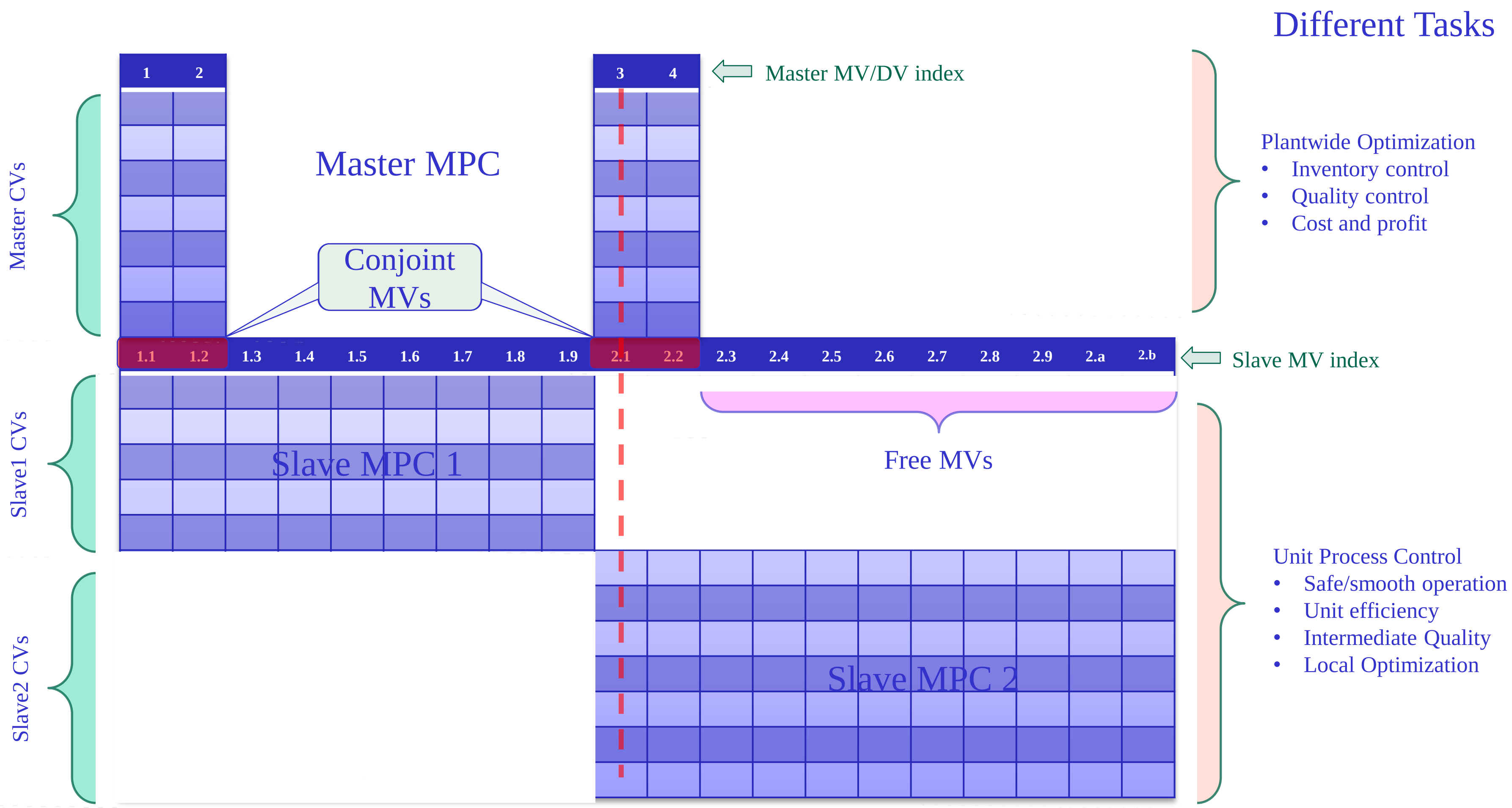

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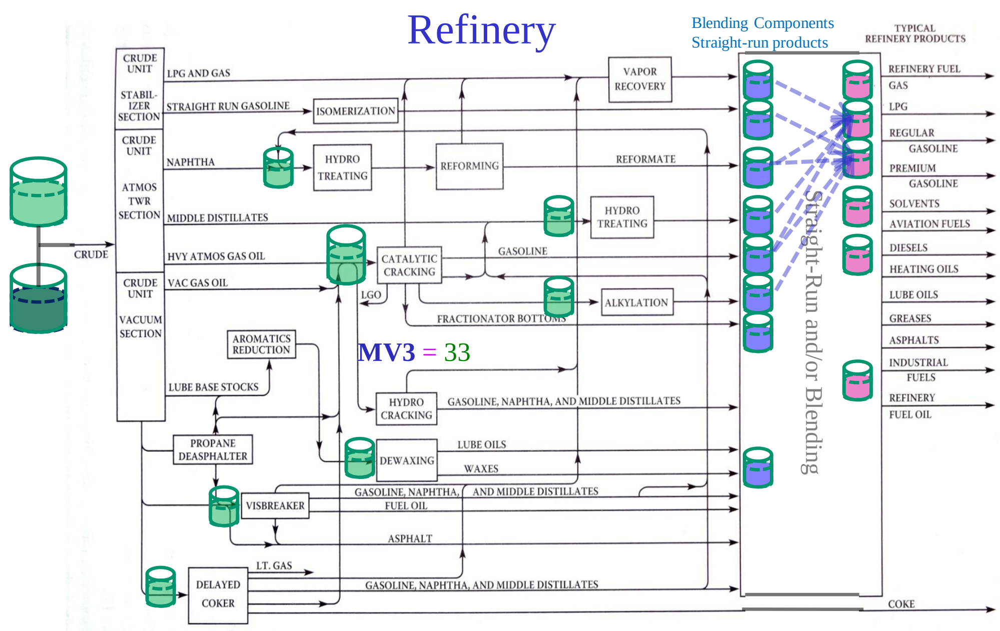
<u>Steps in the hydrocraker example</u>:

1) The HC feed is MV3 in the Master.
2) Its current value is 33
3) The Master makes an inquiry call to the Slave to maximize the feed, subject to the Slave constraints
4) The call returns the following:
   a) the maximum feed = 38, and
   b) other active CV/MV constraints
5) The master uses the maximum feed limit of 38 as a **proxy limit** for all Slave constraints.



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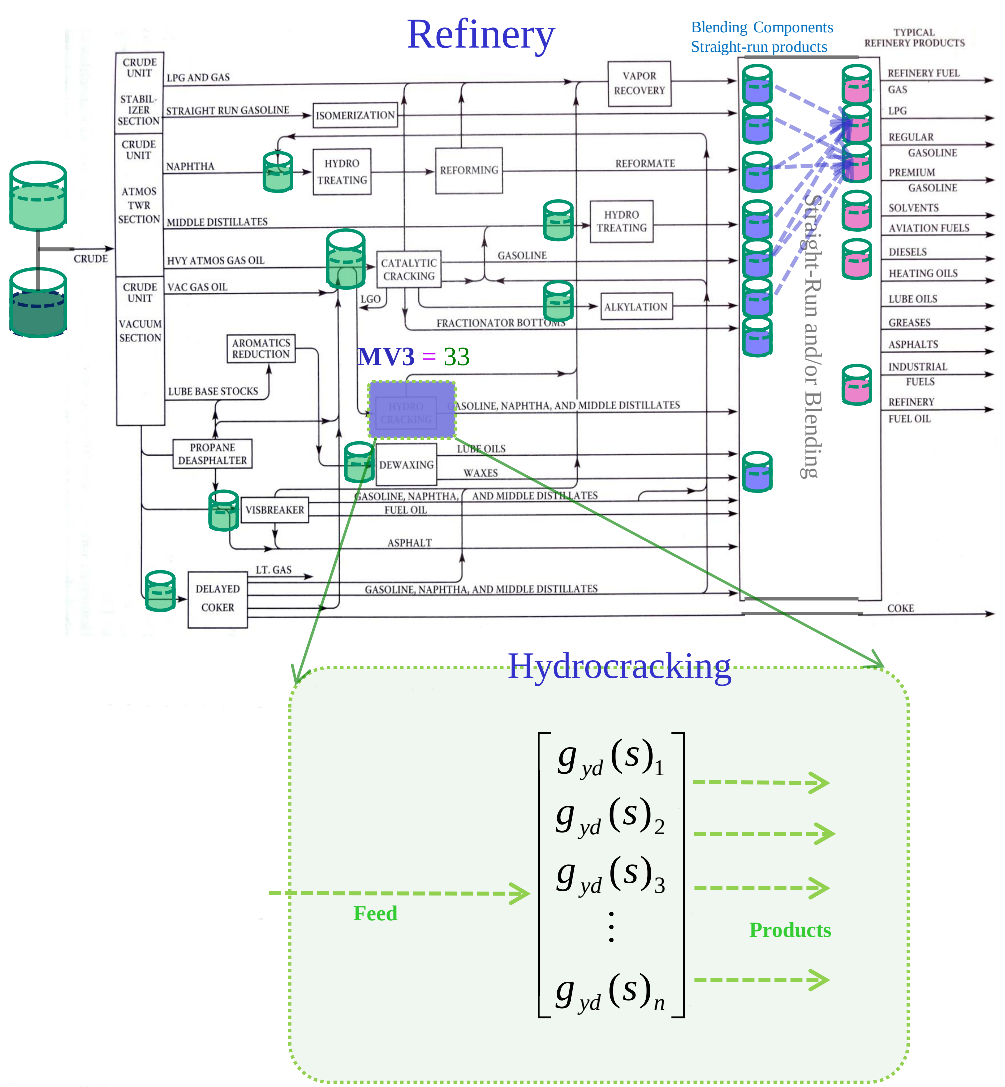

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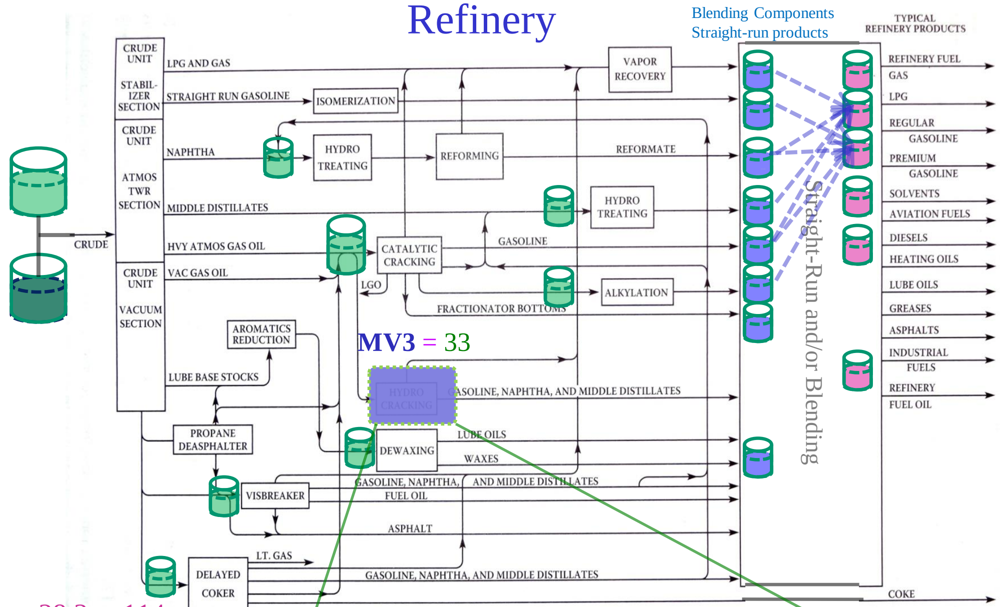
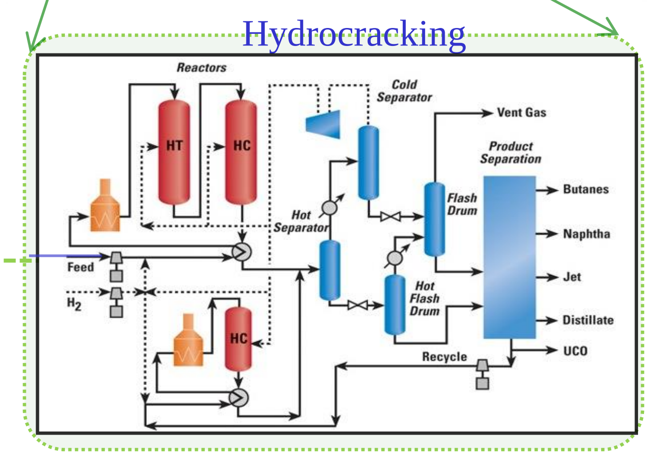


		Feed 33	MV2 5	MV3 16	MV4 0	MV5 105	MV6 10.4	MV7 0.68	MV8 27.4	MV9 110
Opt Value		38	4.5	2.3	<u>10</u>	<u>40</u>	10.7	1.25	28.3	114
<u>100</u>	CV1 89.3									
6.20	CV2 7.23									
<u>75.0</u>	CV3 89.3									
	CV4 •									



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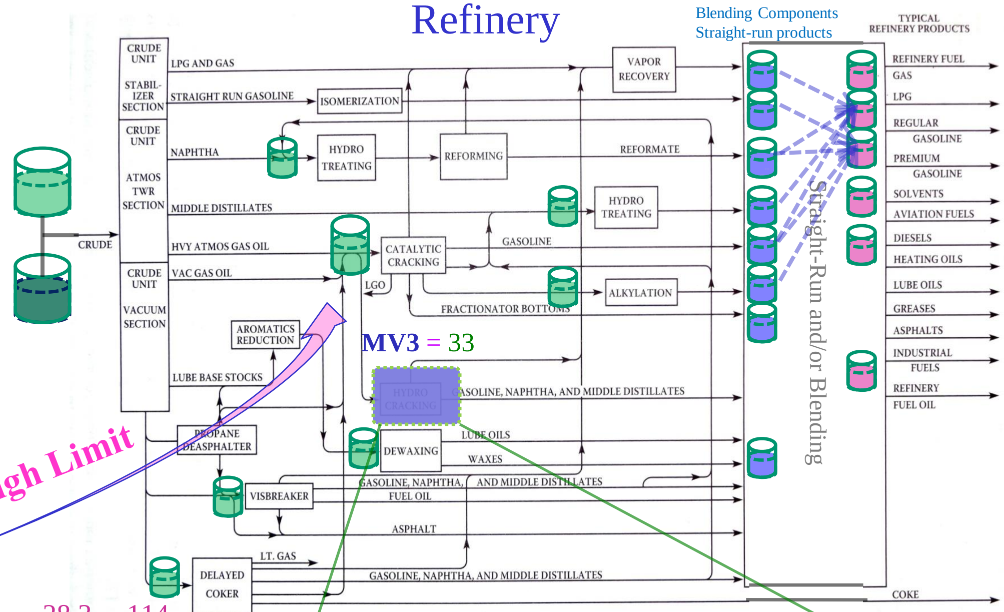

Opt Value		Feed	MV2	MV3	MV4	MV5	MV6	MV7	MV8	MV9
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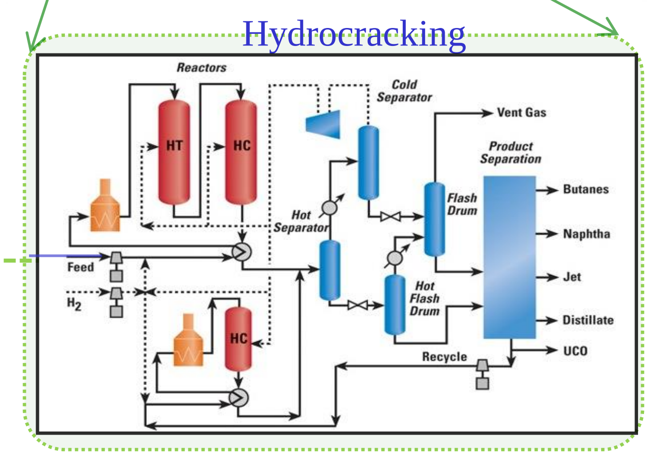

Approximate the feasible region defined by the Slave constraints for 2 (or more) conjoint variables

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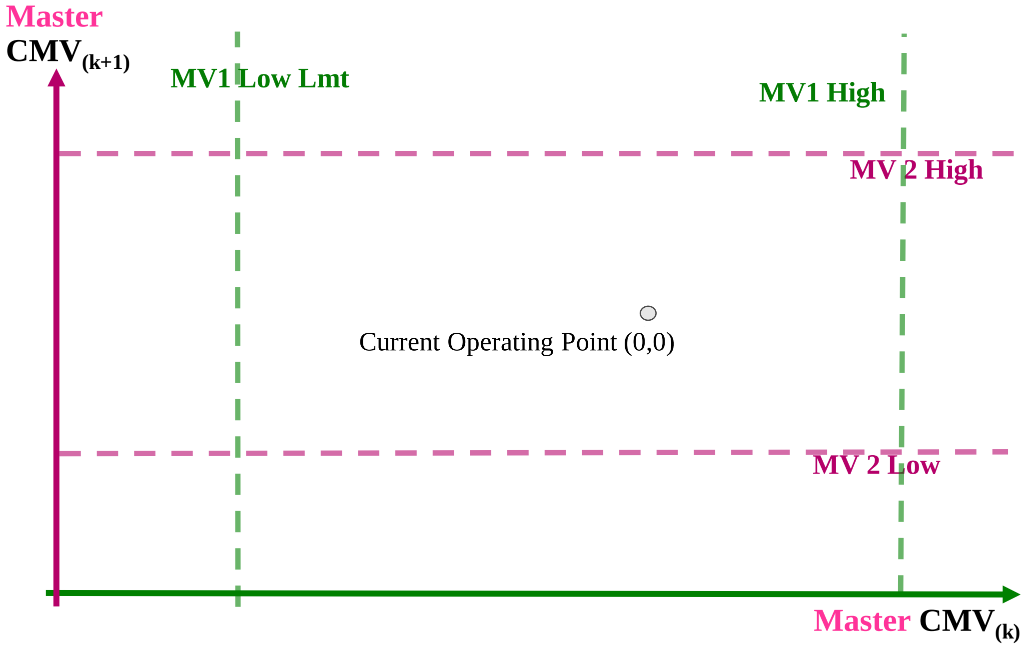
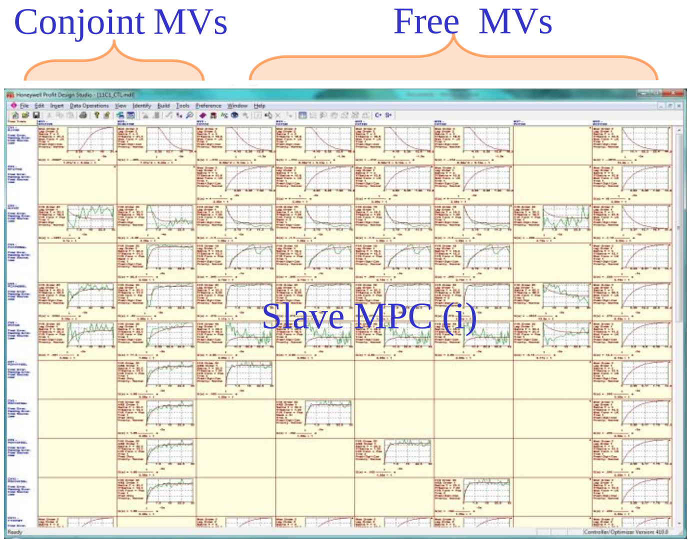


Master MVs

k	k+1



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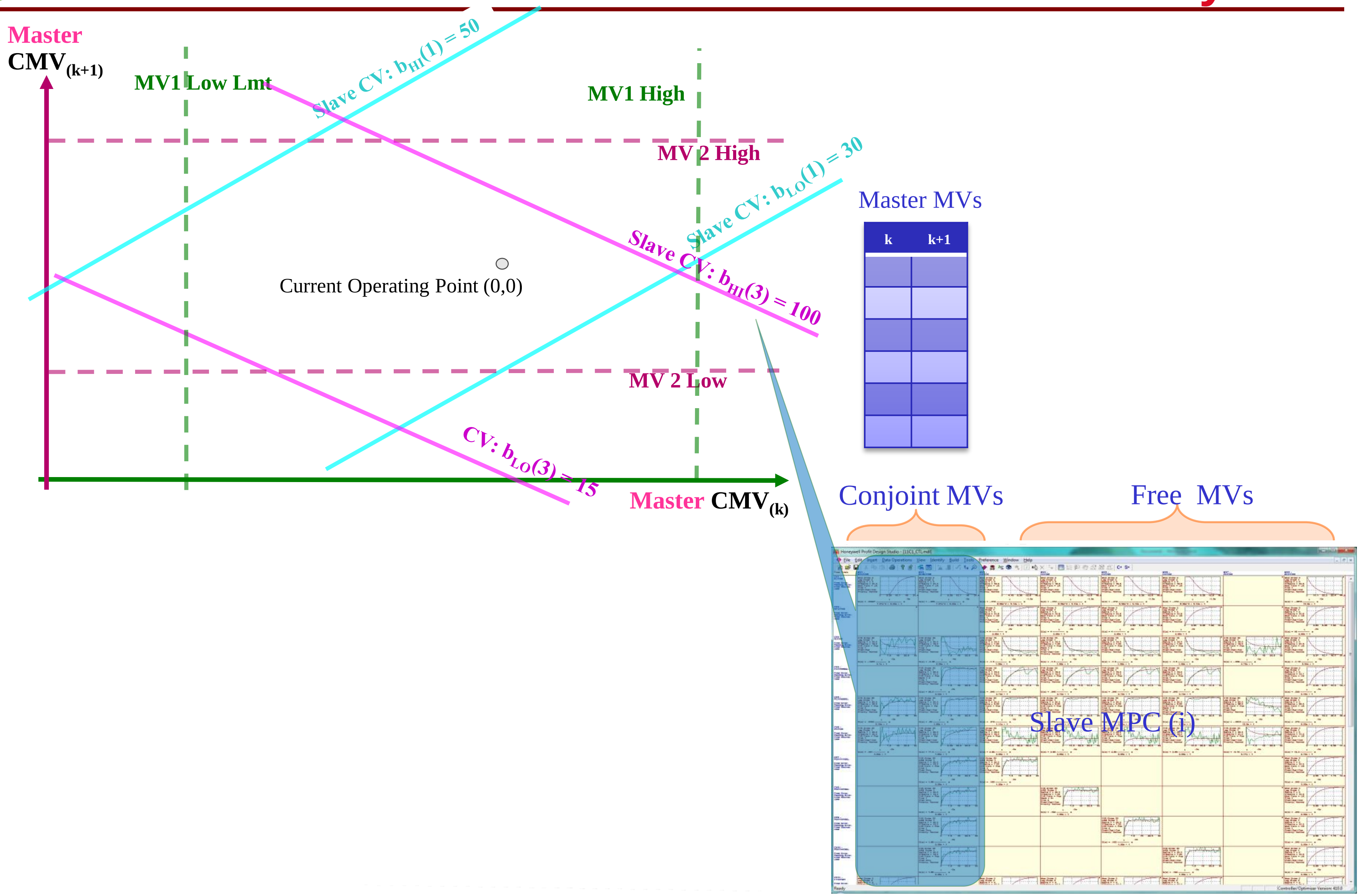

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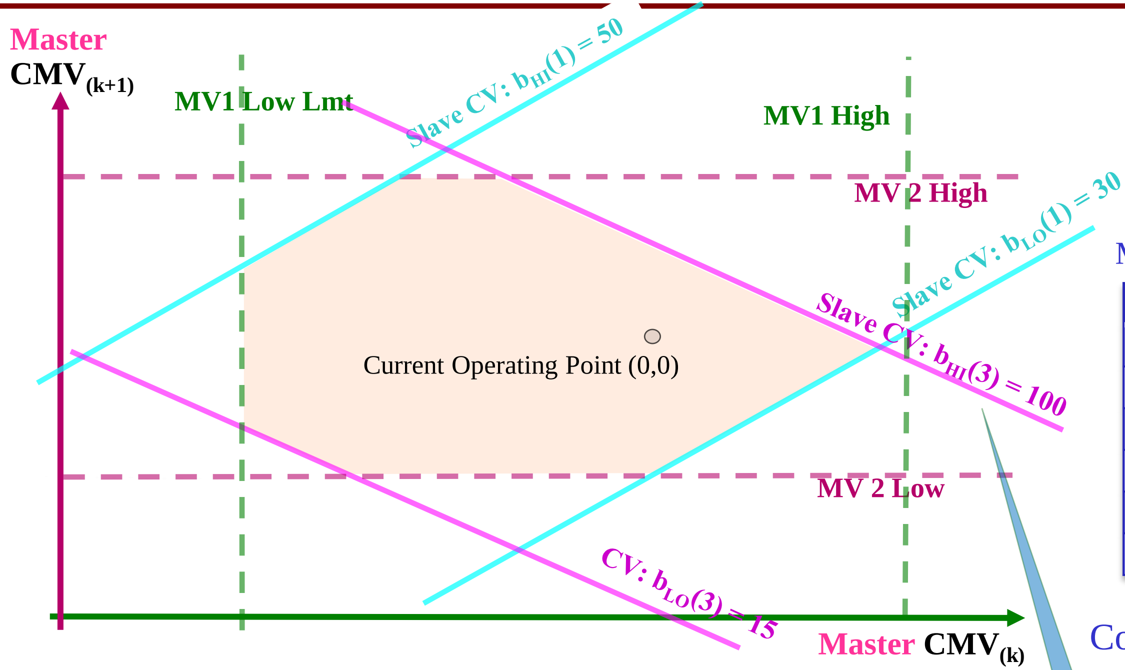

Master MVs

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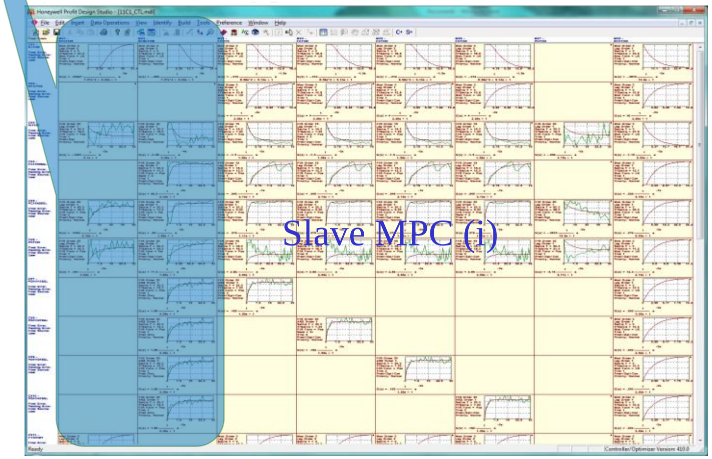
Conjoint MVs

Free MVs



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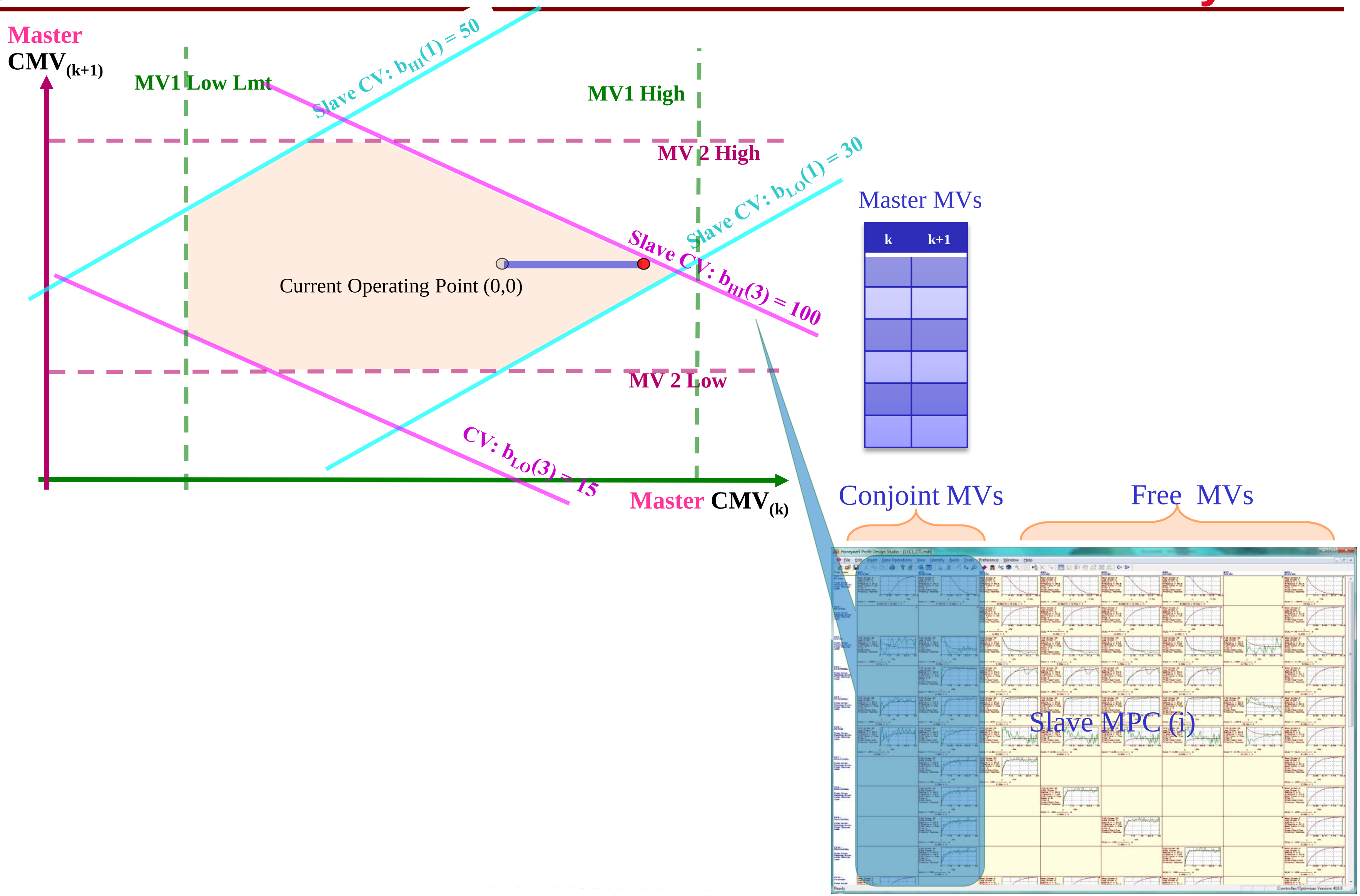

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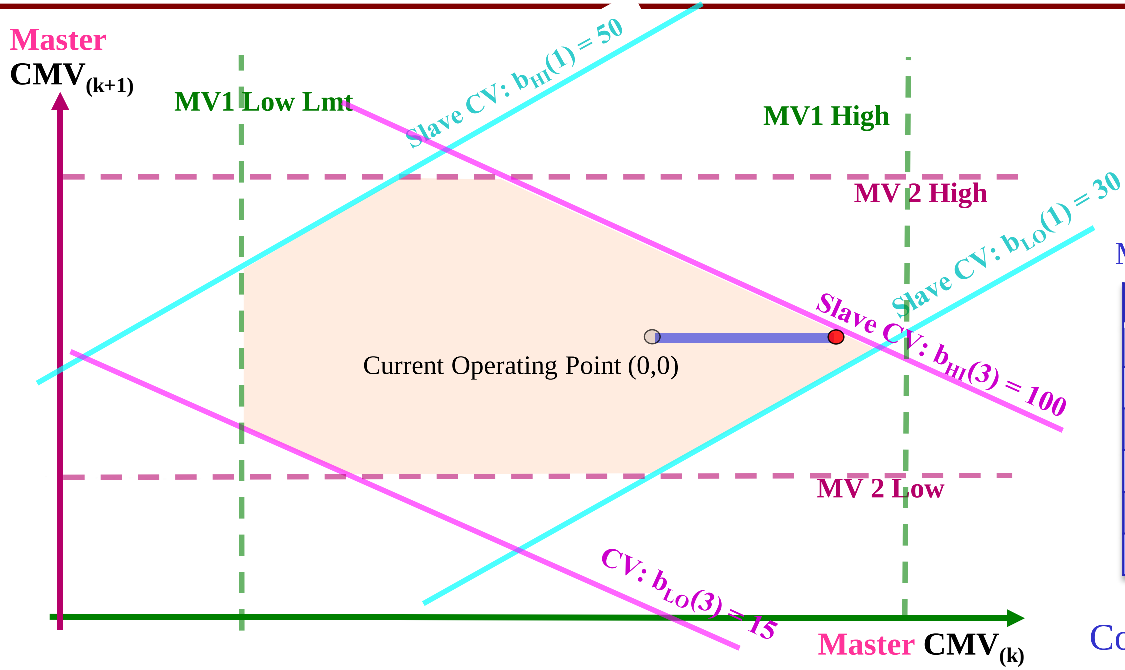
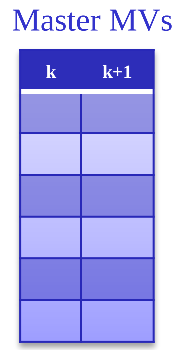
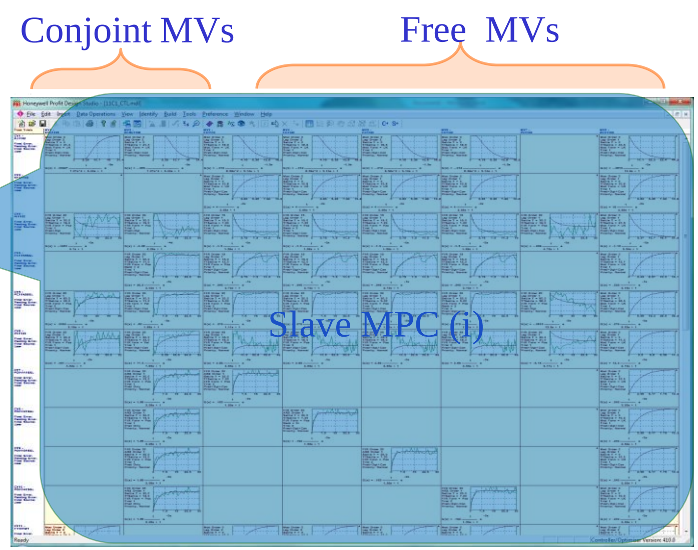






8 inquiry calls:

Call #	c^t		d^t	
1	-1	0	0	1
2	1	0	0	1
3	0	-1	1	0
4	0	1	1	0
5	-1	1	1	1
6	1	-1	1	1
7	1	1	1	-1
8	-1	-1	1	-1

$$\min_x c^t x_{conj}$$

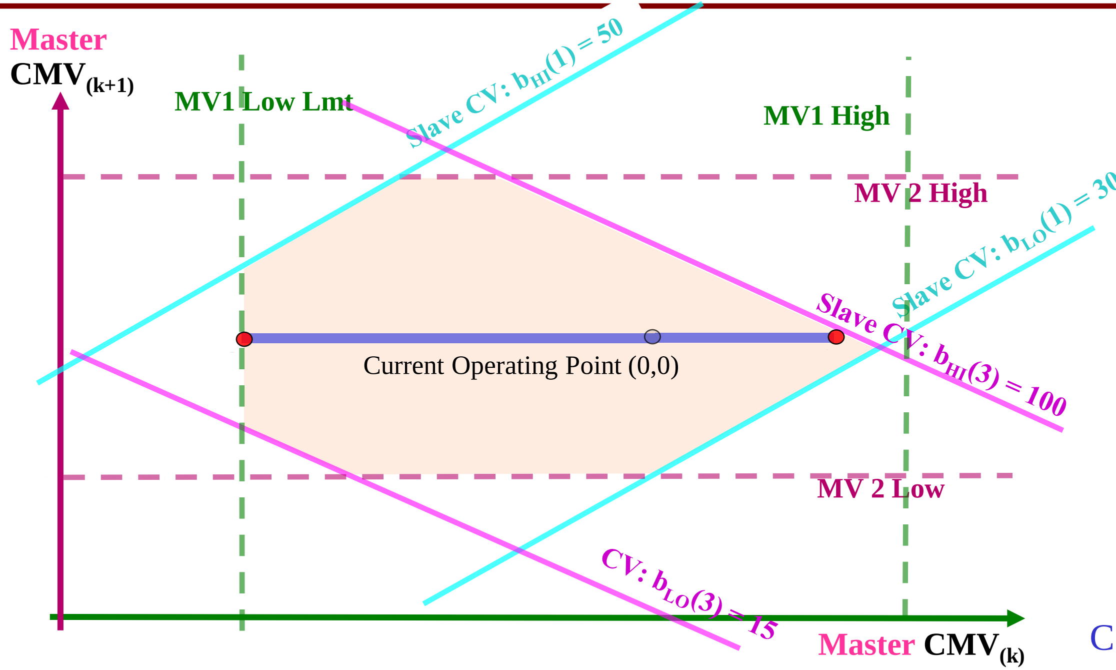
$$b_{LO} \le A_c x_{conj} + A_f x_{free} \le b_{HI}$$

$$d^t x_{conj} = 0$$

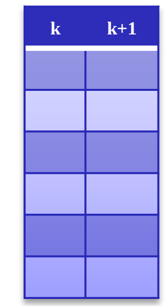
Where, $A = \begin{bmatrix} G \\ I \end{bmatrix}$

Approximate the feasible region defined by the Slave constraints for 2 (or more) conjoint variables

Honeywell

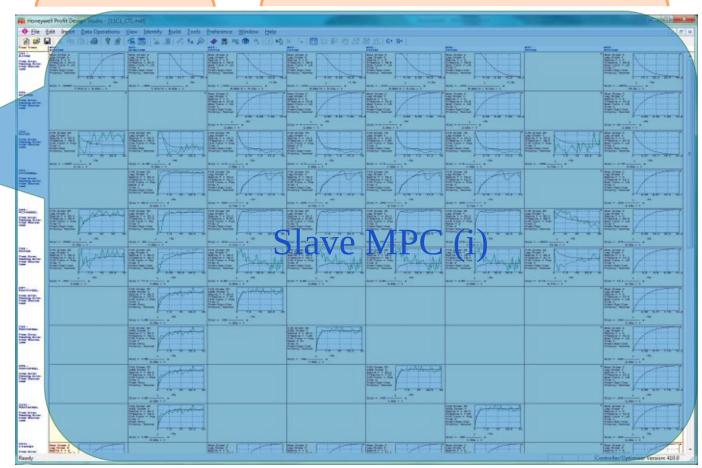


Master MVs



Conjoint MVs

Free MVs



8 inquiry calls:

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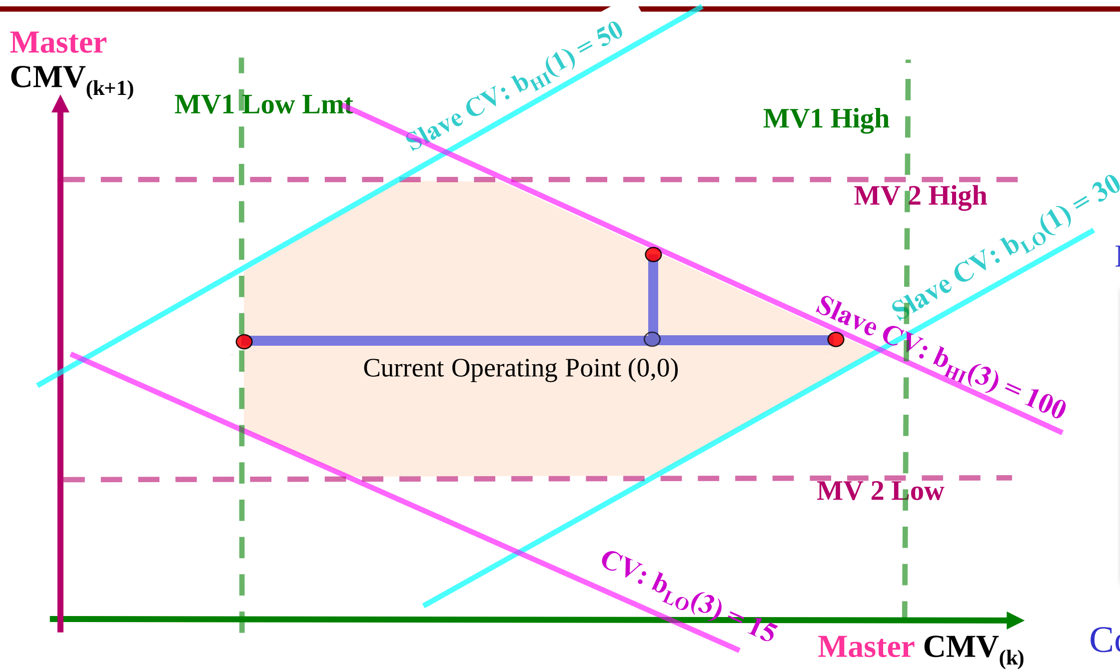

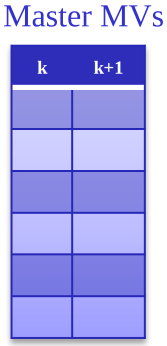

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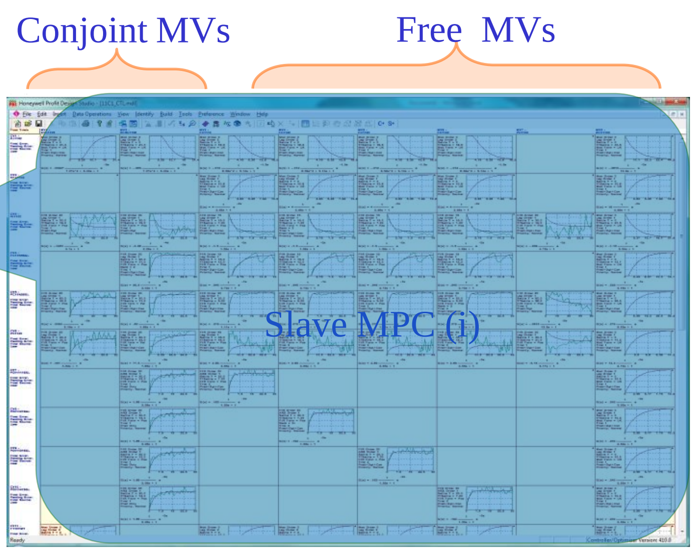
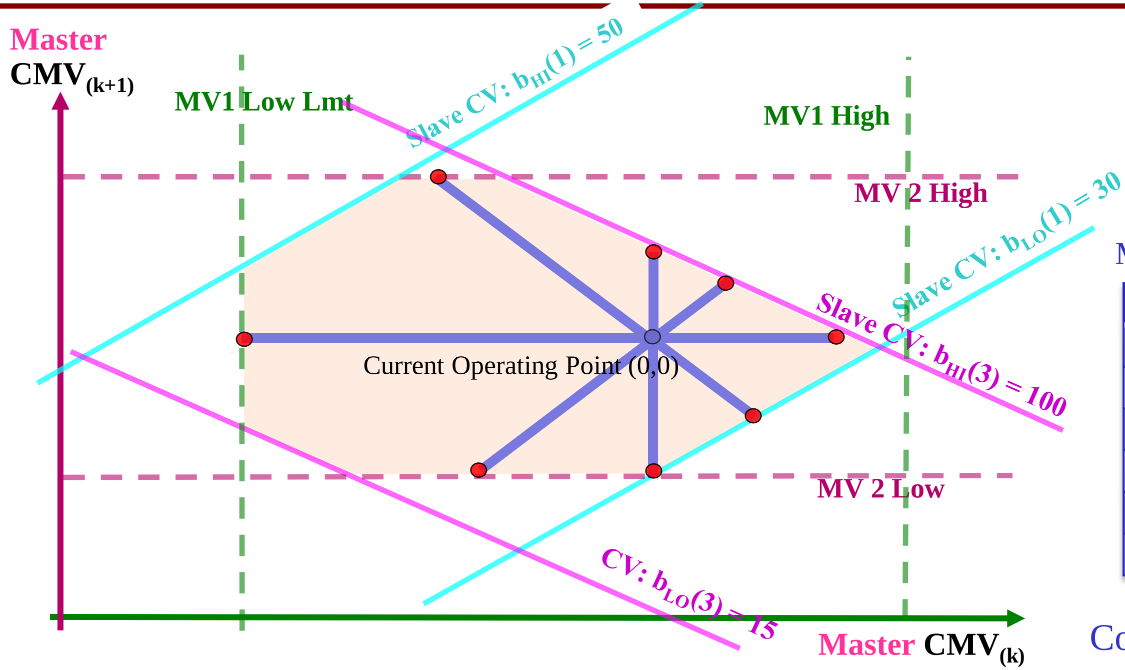
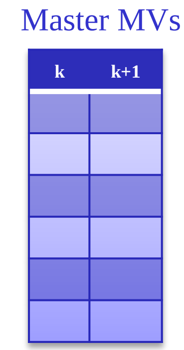
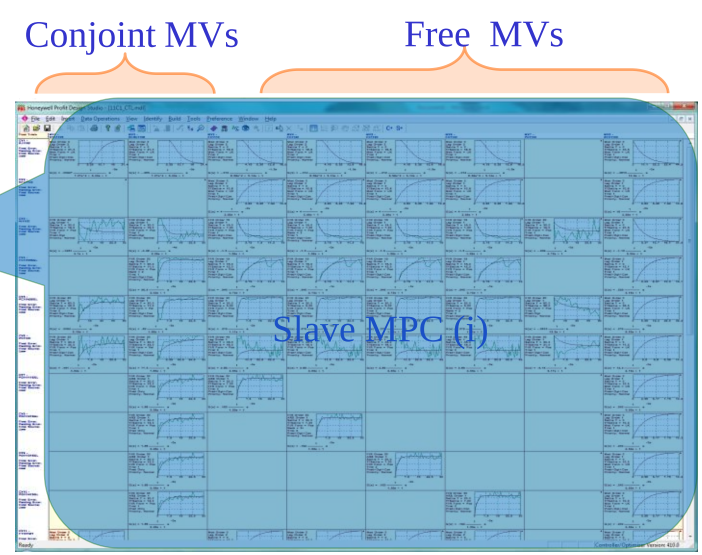


Approximate the feasible region defined by the Slave constraints for 2 (or more) conjoint variables

Honeywell







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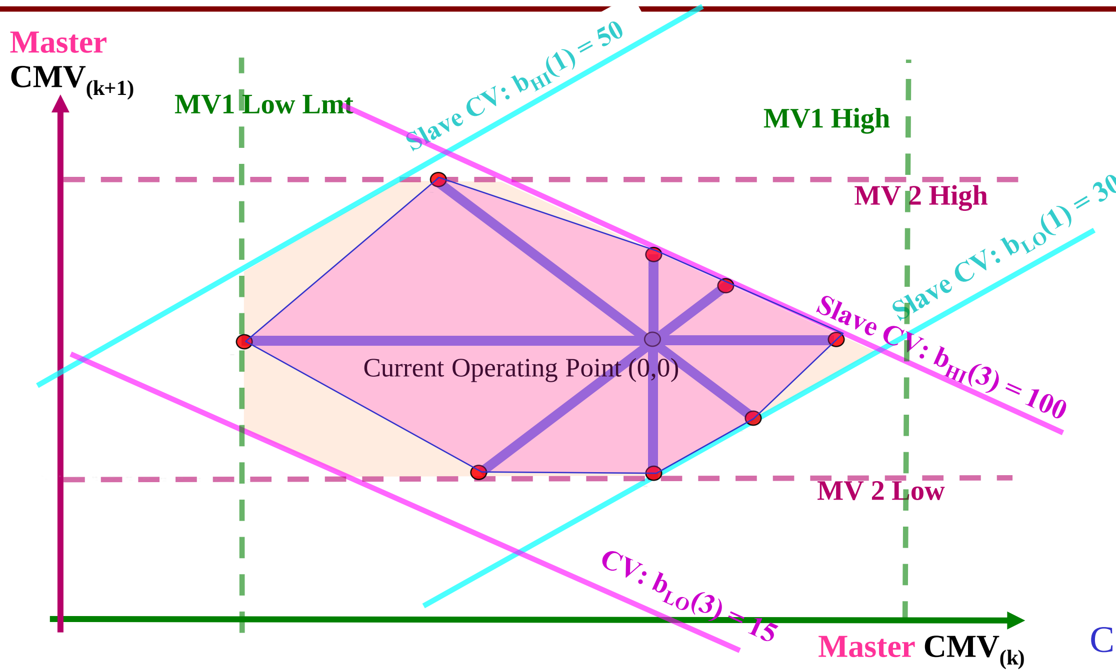
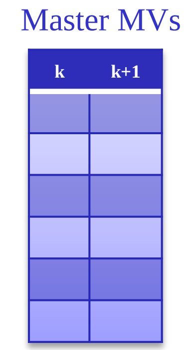
Approximate the feasible region defined by the Slave constraints for 2 (or more) conjoint variables

Honeywell



Master MVs



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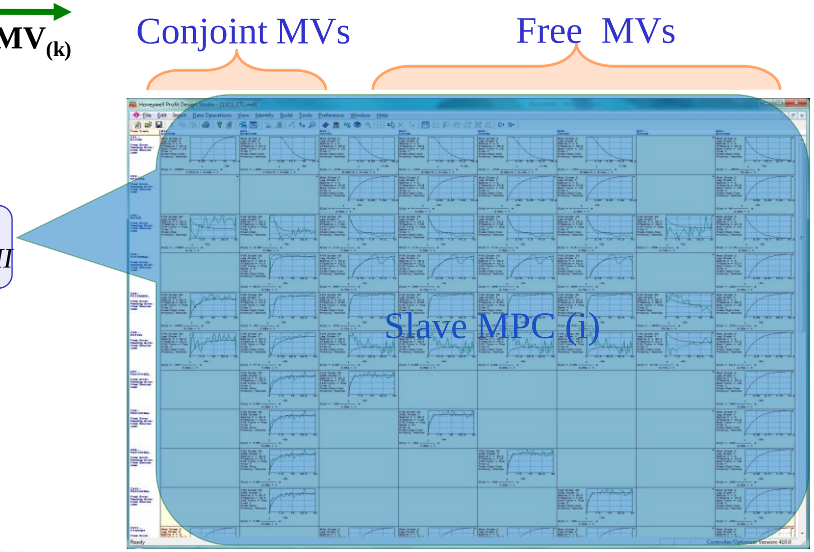

Append the Proxy CV Limits to the Master's Model

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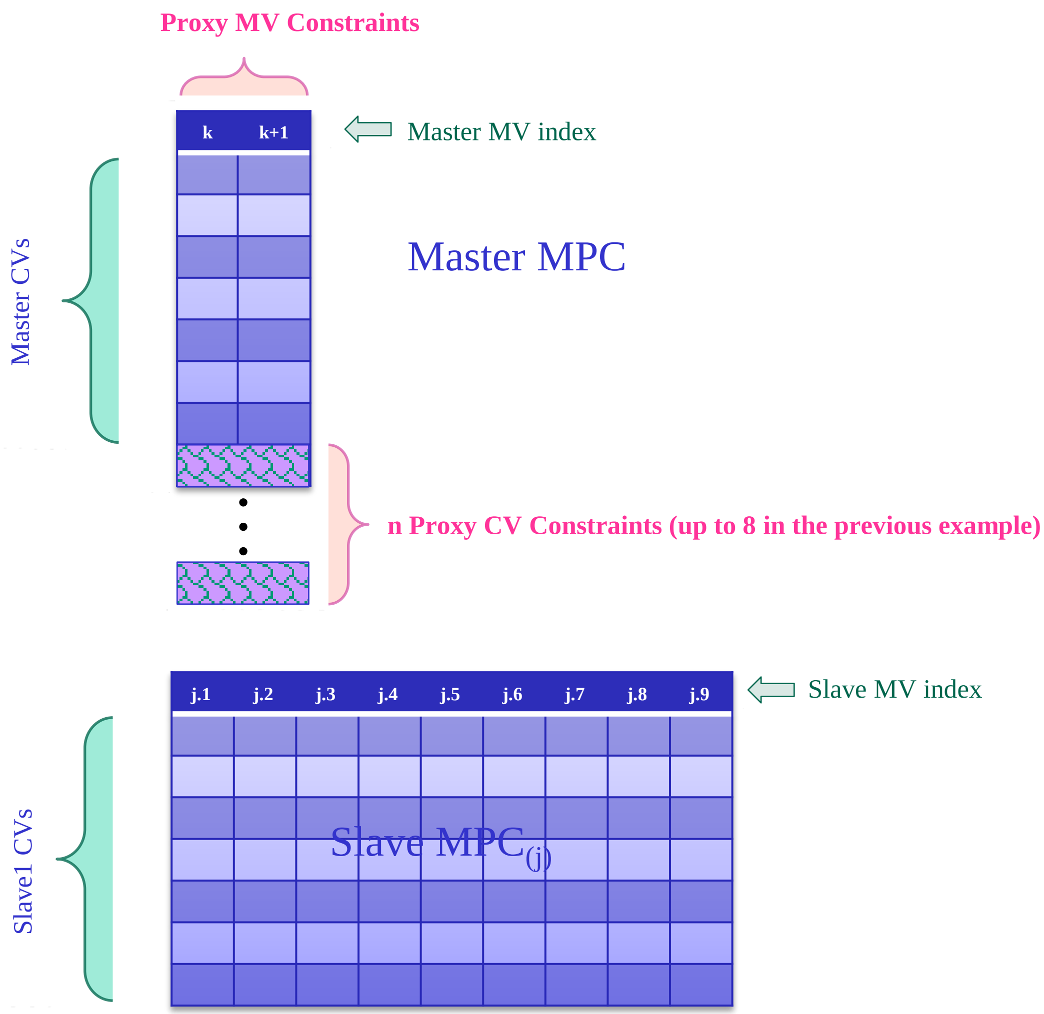

- The feasible region defined by a slave MPC can be approximated by Proxy CV constraints.

✓ With both Proxy MV and CV limits, the Master's solution will always be implementable by the Slave MPCs.

Simulation Study and Benefit Analysis

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- ✓ A customer requested a simulation study for benefit analysis
  - ➢ Planning model, plant economics and operating data were provided
- ✓ The distillate production pool was chosen as the study scope
  - ➢ The same scope as in the previous illustration
  - ➢ There were 3 instances of unit shutdowns (ranging from 5 to 35 days each)

Study Scope Includes:

- ✓ 3 Crude Units
- ✓ 2 Vacuum Towers
- ✓ 2 Hydrotreating Units
- ✓ 1 Hydrocracking Unit
- ✓ 1 Fluidized Catalyst Cracking (FCC) Unit
- ✓ 2 blending component tanks

Study Scope: distillate production of an oil refinery

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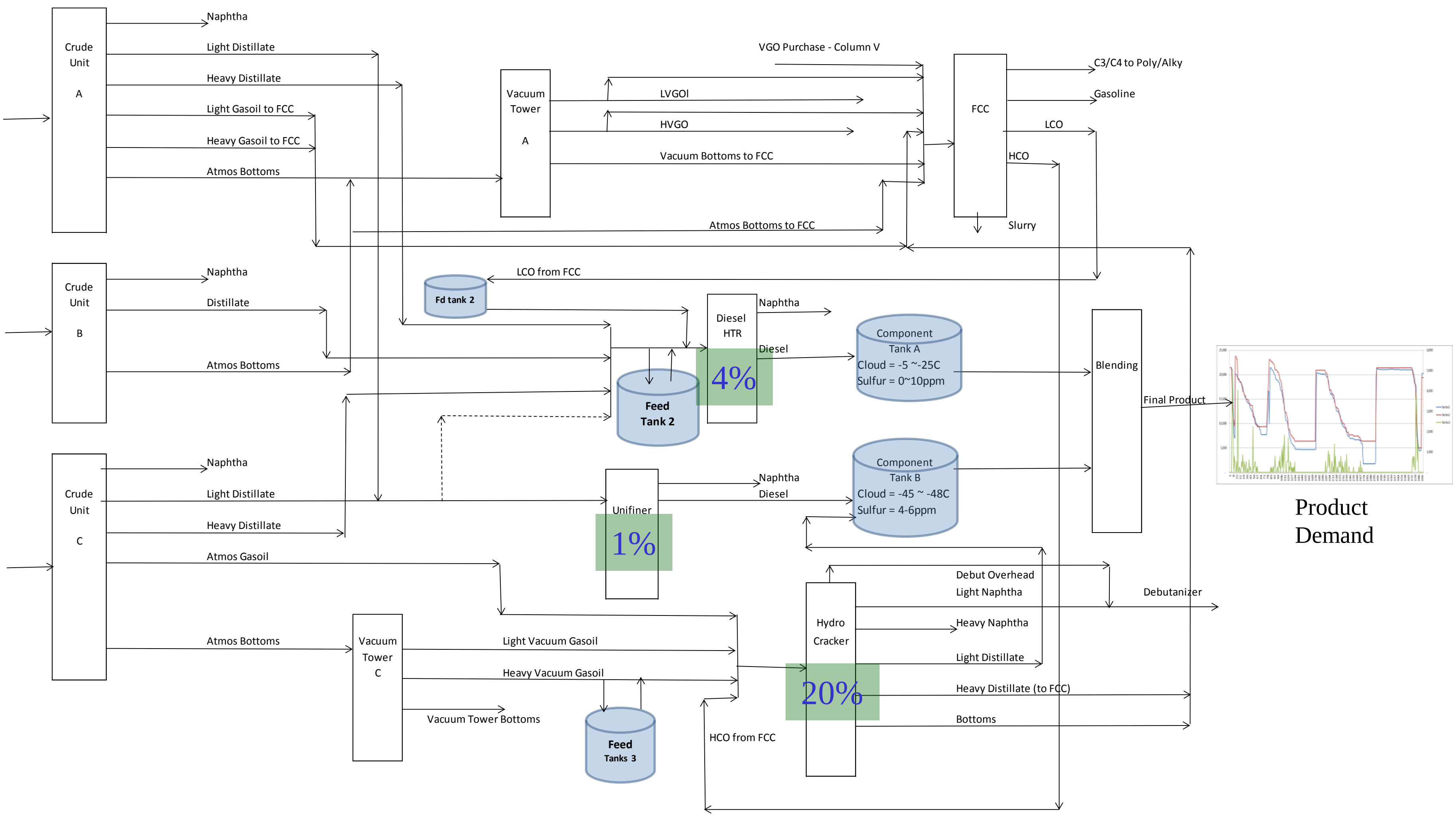
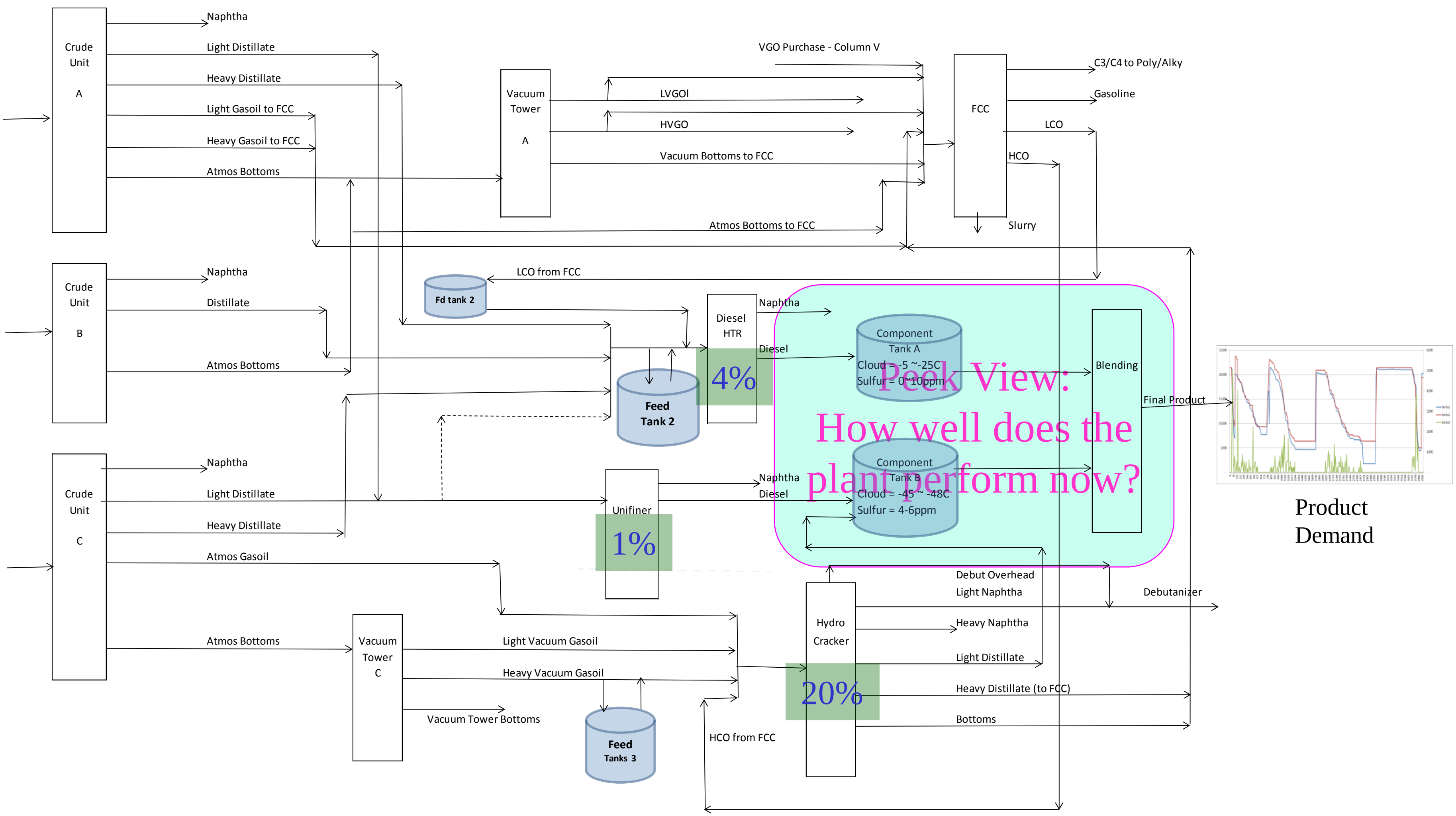
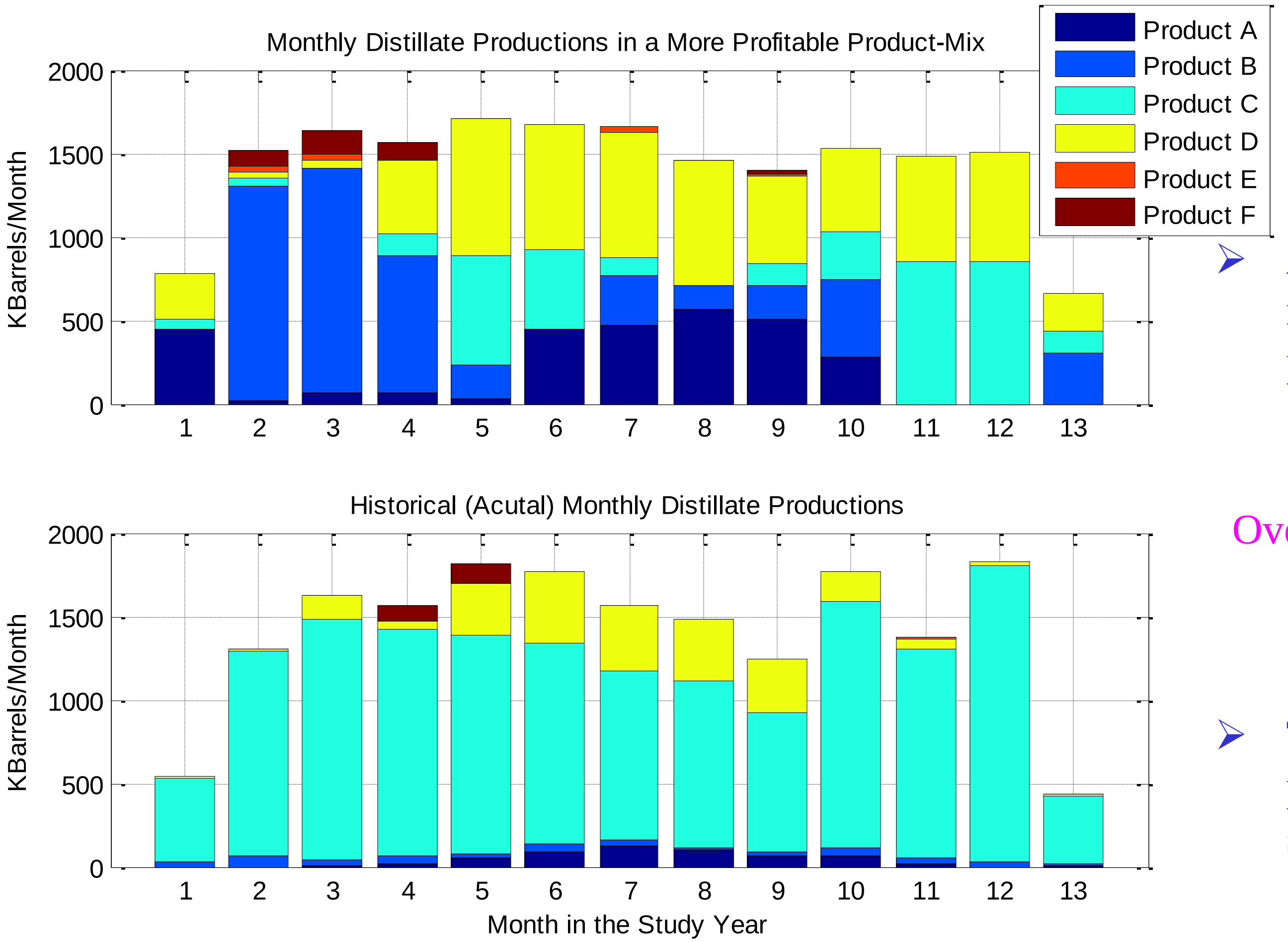


Study Scope: distillate production of an oil refinery

Honeywell



Current Performance: Significant Quality Giveaways
The components exceeded the necessary qualities



- A more profitable product mix could have been produced in the study year

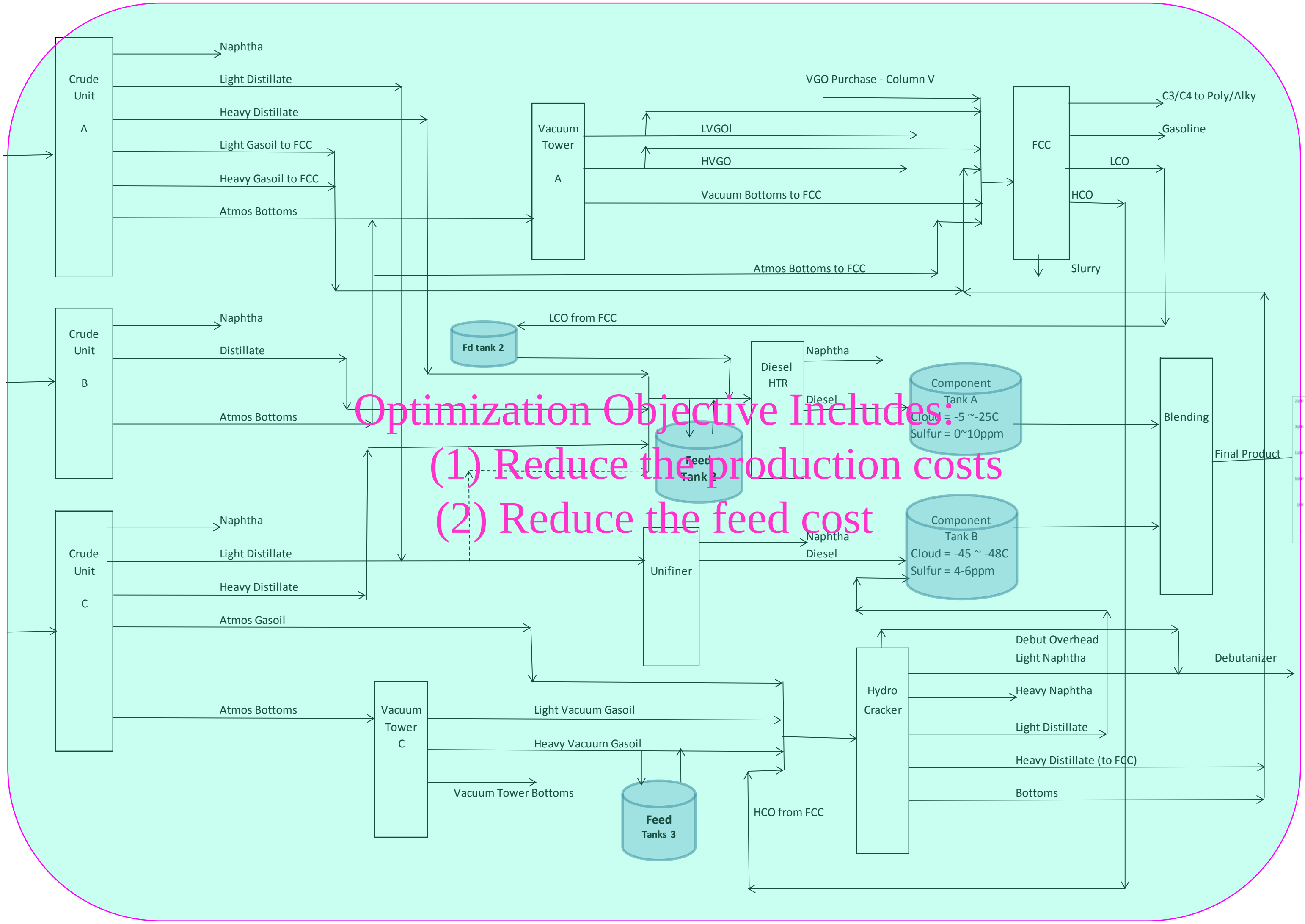
Over-Qualification: $65M/year
~$3/Barrel of Product

- The actual product mix was produced and sold in the study year

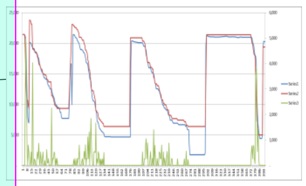
The purpose for estimating the quality giveaway ($65/M year in this specific case):

- **is** to show how less optimally the components were produced at a potentially higher cost.
- **is** to show the potential room for reducing the component quality and still meeting the same demand.

How can we improve?
JIT manufacturing with an MPC cascade control



Optimization Objective Includes:
(1) Reduce the production costs
(2) Reduce the feed cost



Same product deliveries

First Step: Build the Master MPC Controller

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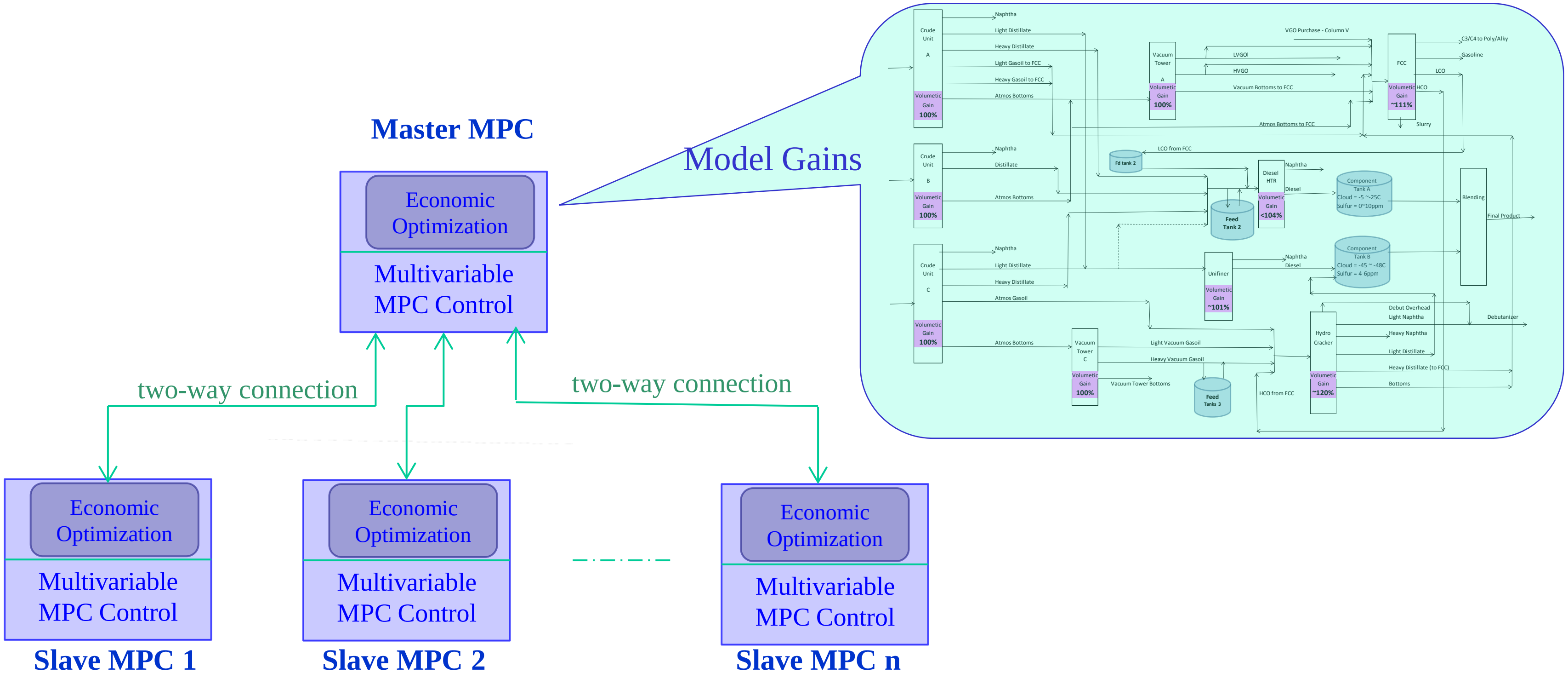

- ➢ The Master MPC model gains are extracted from the existing planning model (coarser scale model)
  - ◆ Dynamics of the model are obtained from the operational data
- ➢ The Slave MPCs are the existing APC controllers.

Next Step: Estimate the Proxy Limits

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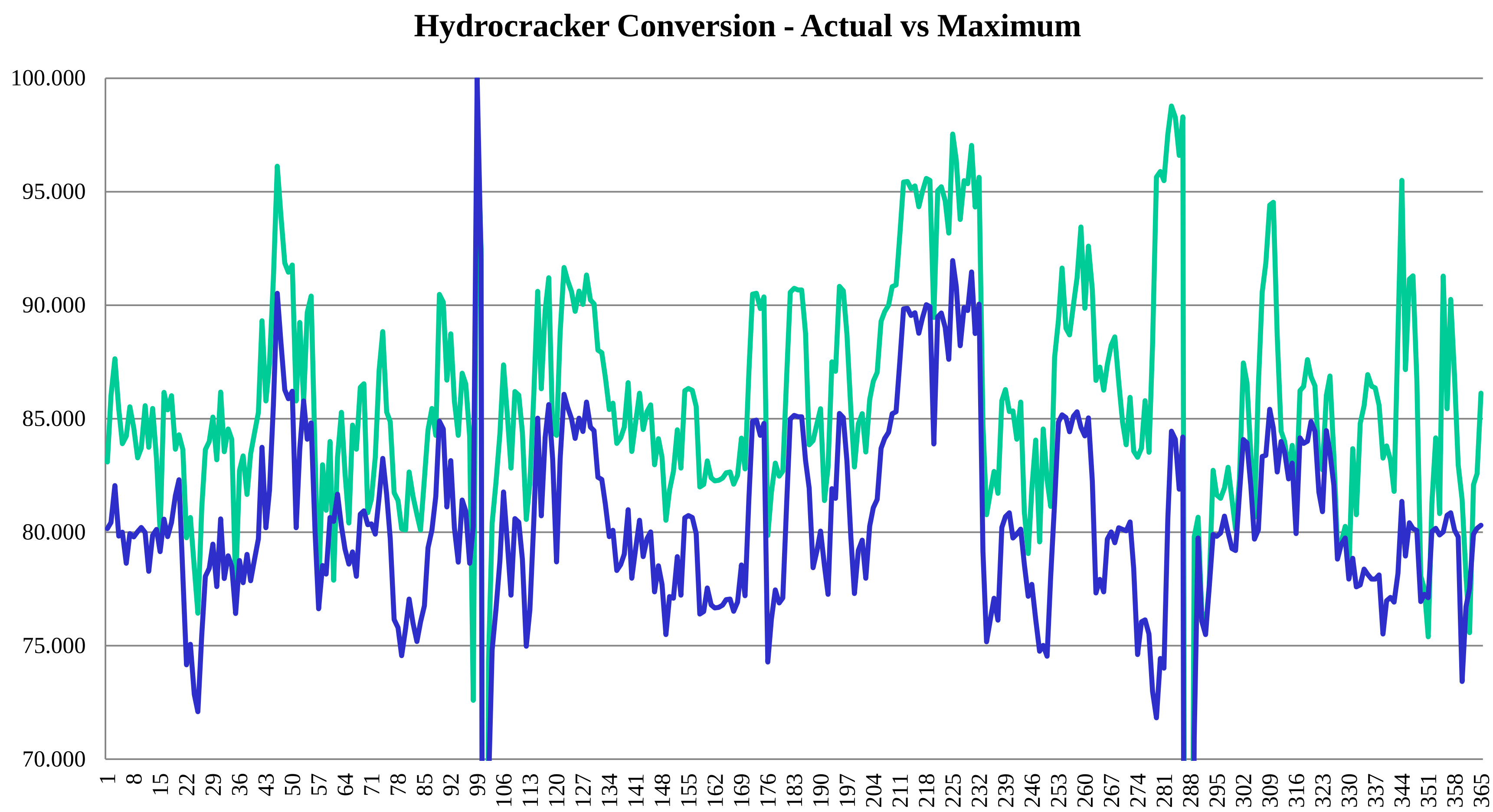
To what extent is the Master MPC allowed to change the Slave unit's operations?



Next Step: Estimate the Proxy Limits (2)

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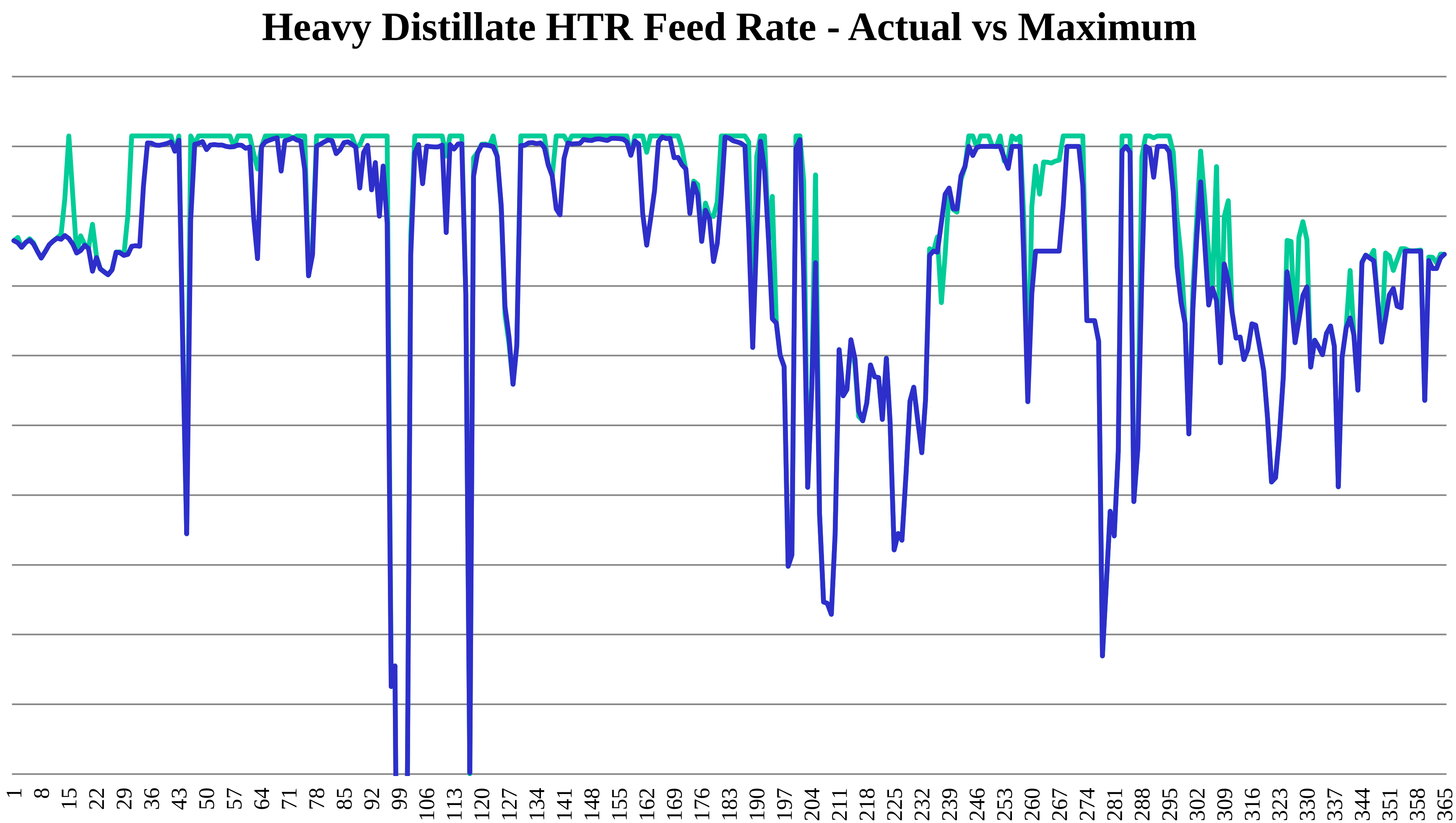

Master's Control and Optimization Results: Component Quality Changes in Tank #3

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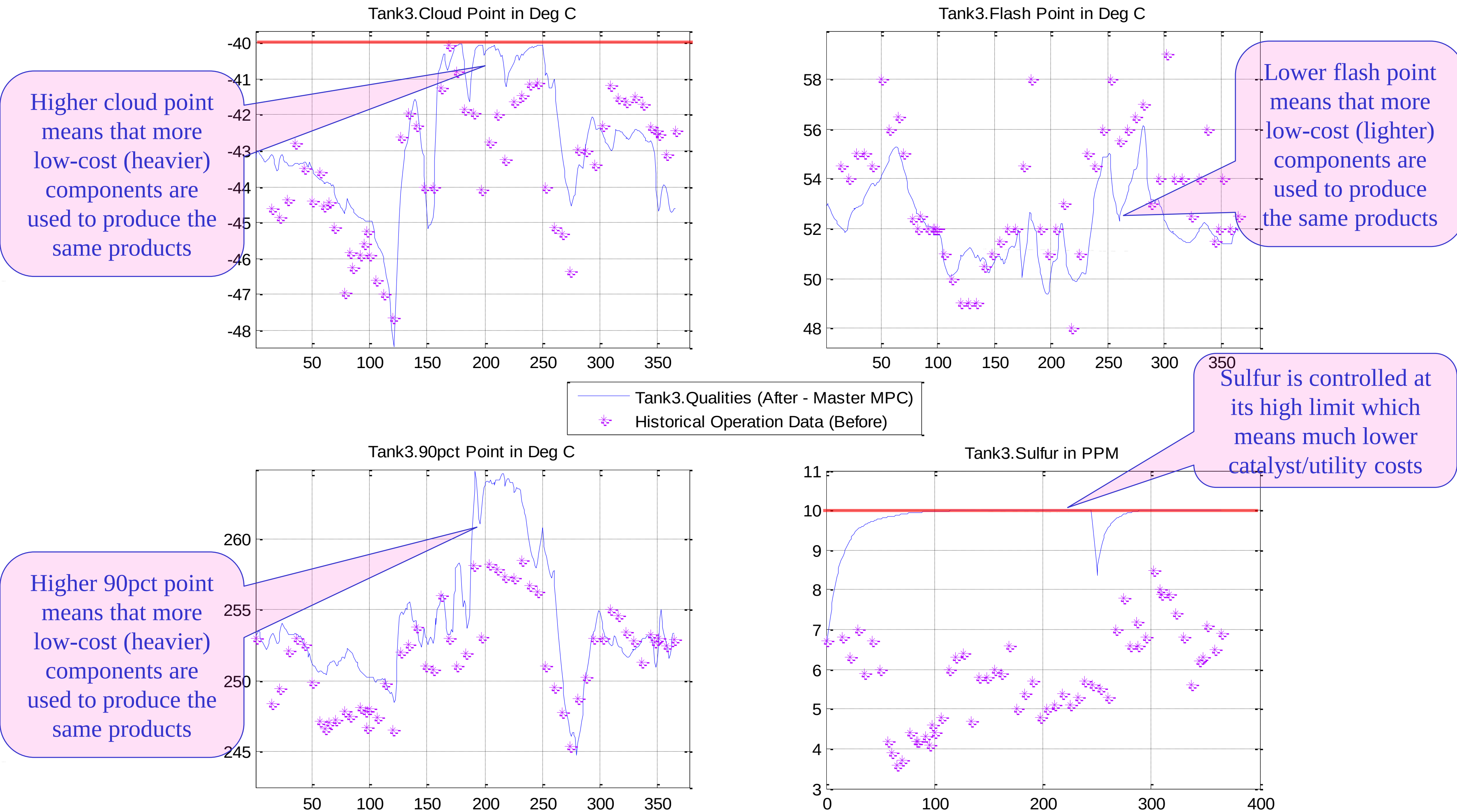

Component production costs are significantly reduced!

Feed Saving by Leveraging Volumetric Gains

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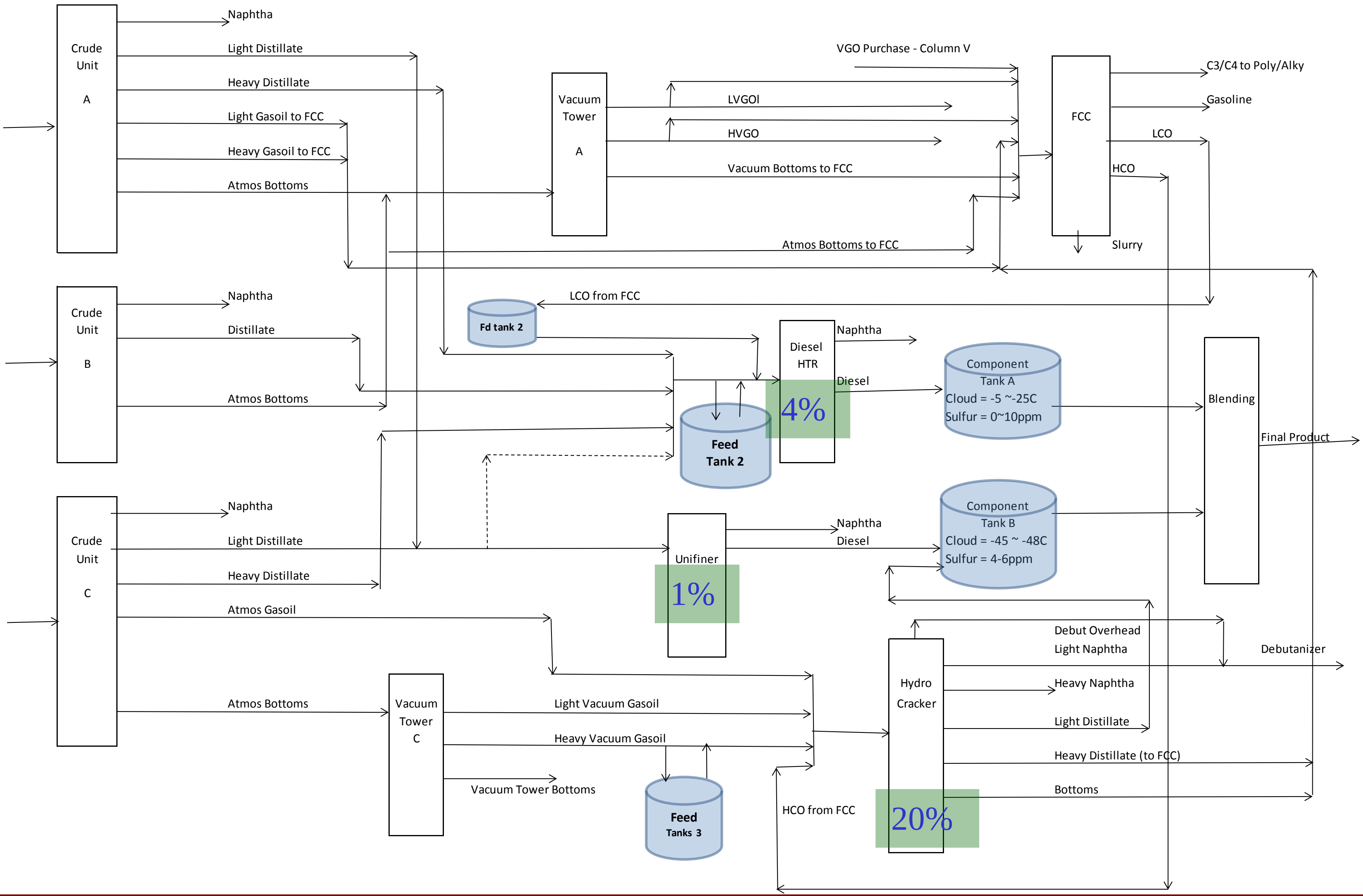

Feed Saving by Leveraging Volumetric Gains

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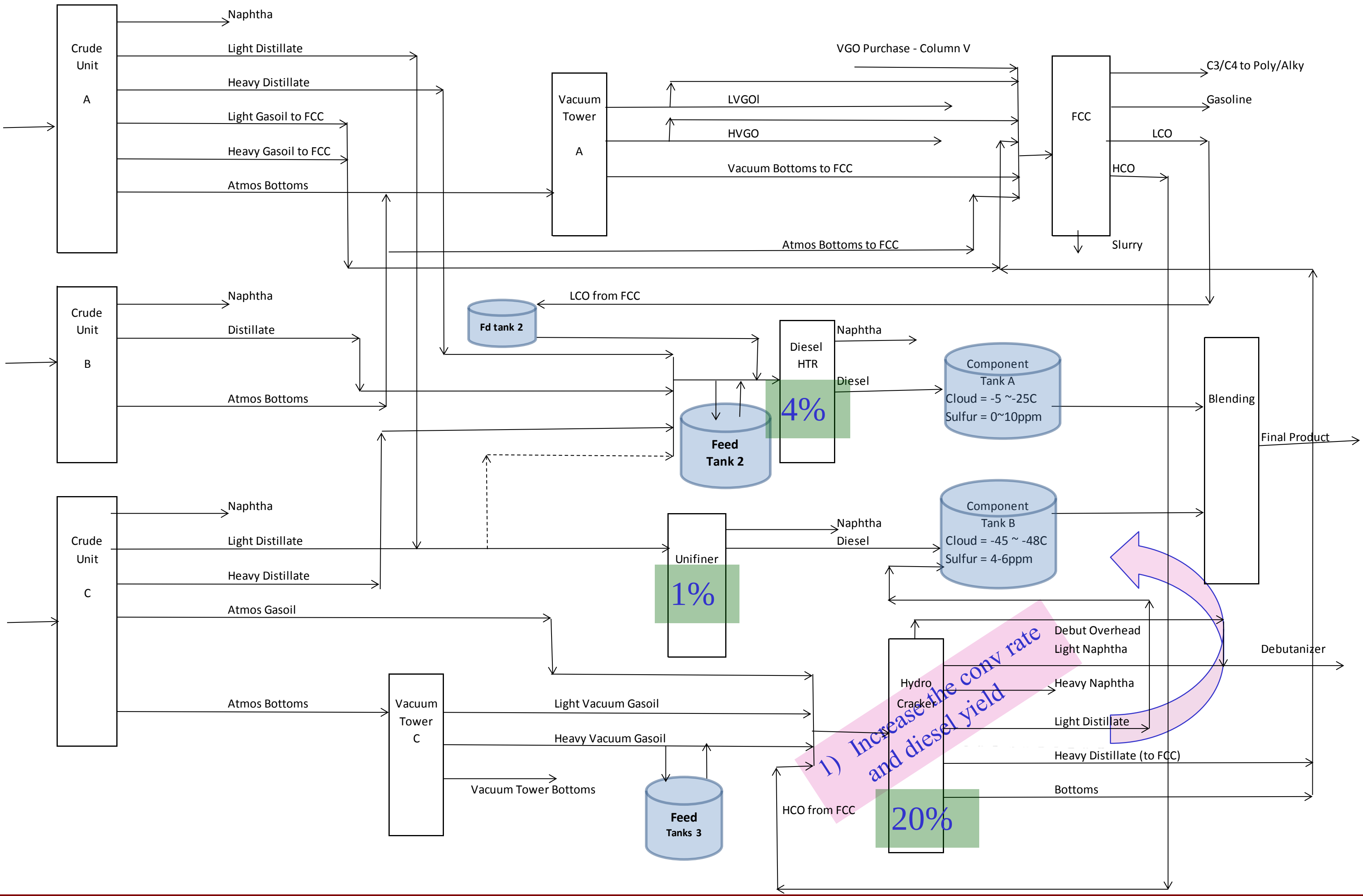

Feed Saving by Leveraging Volumetric Gains

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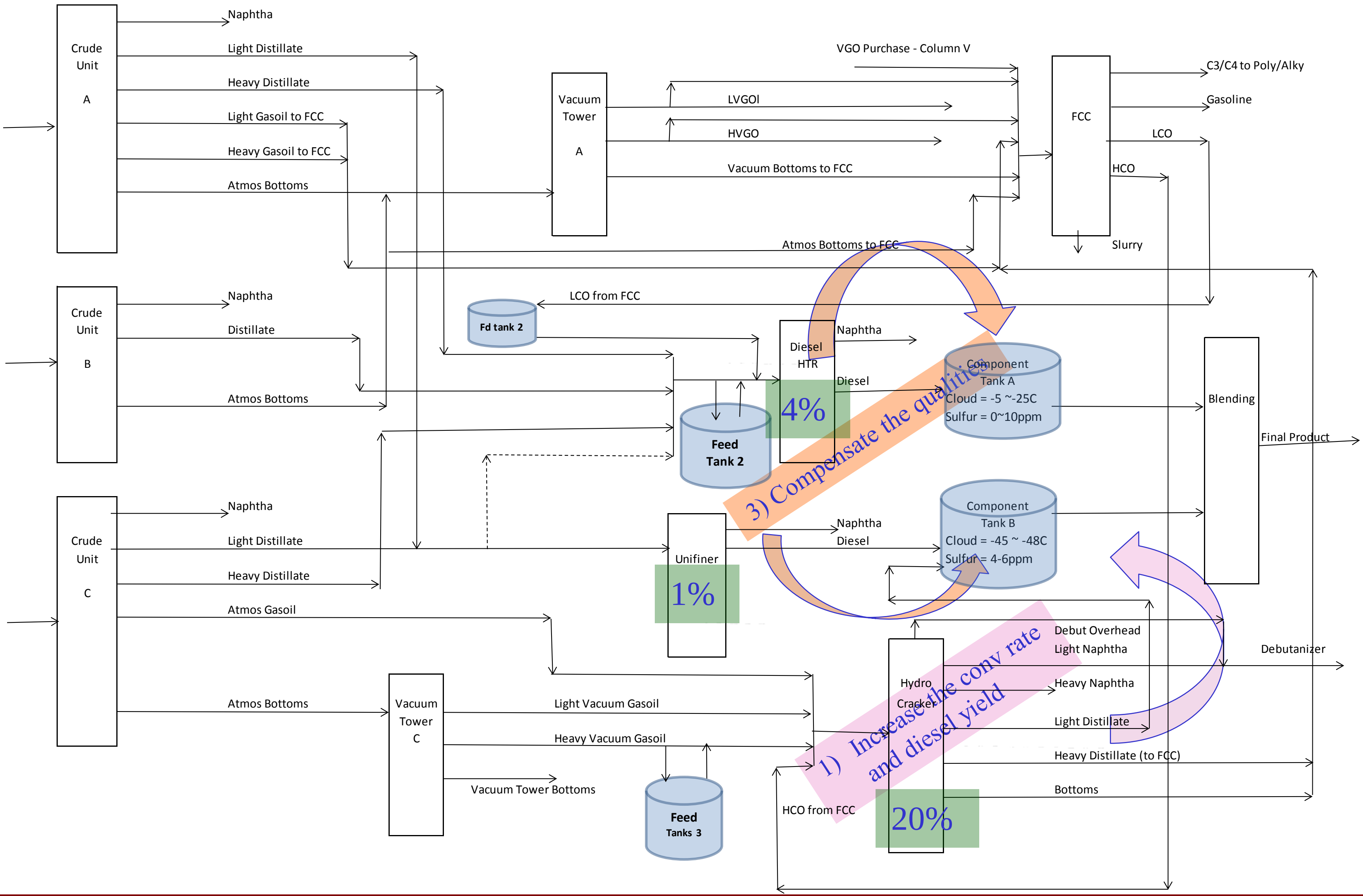

Feed Saving by Leveraging Volumetric Gains

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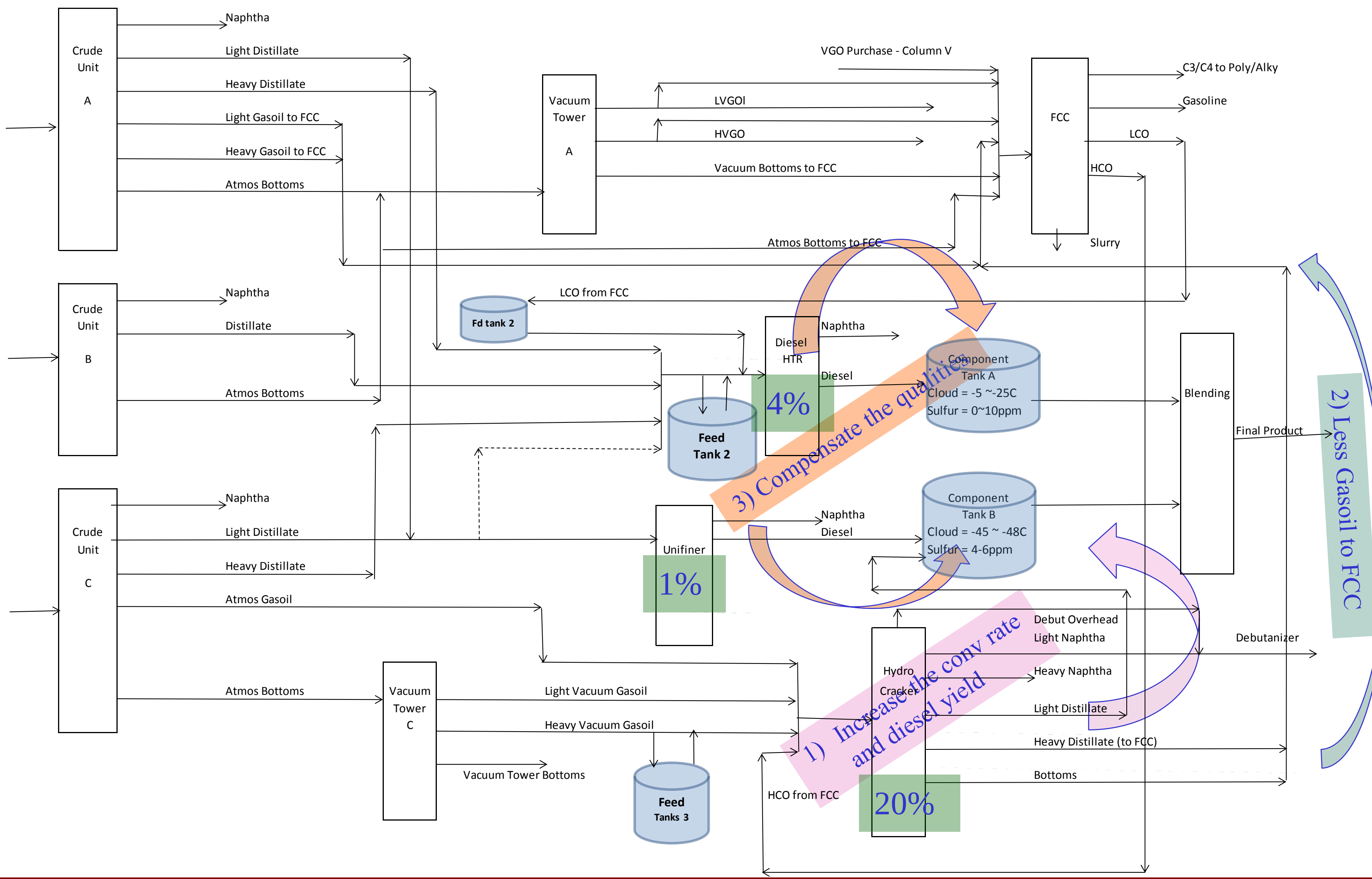

Feed Saving by Leveraging Volumetric Gains

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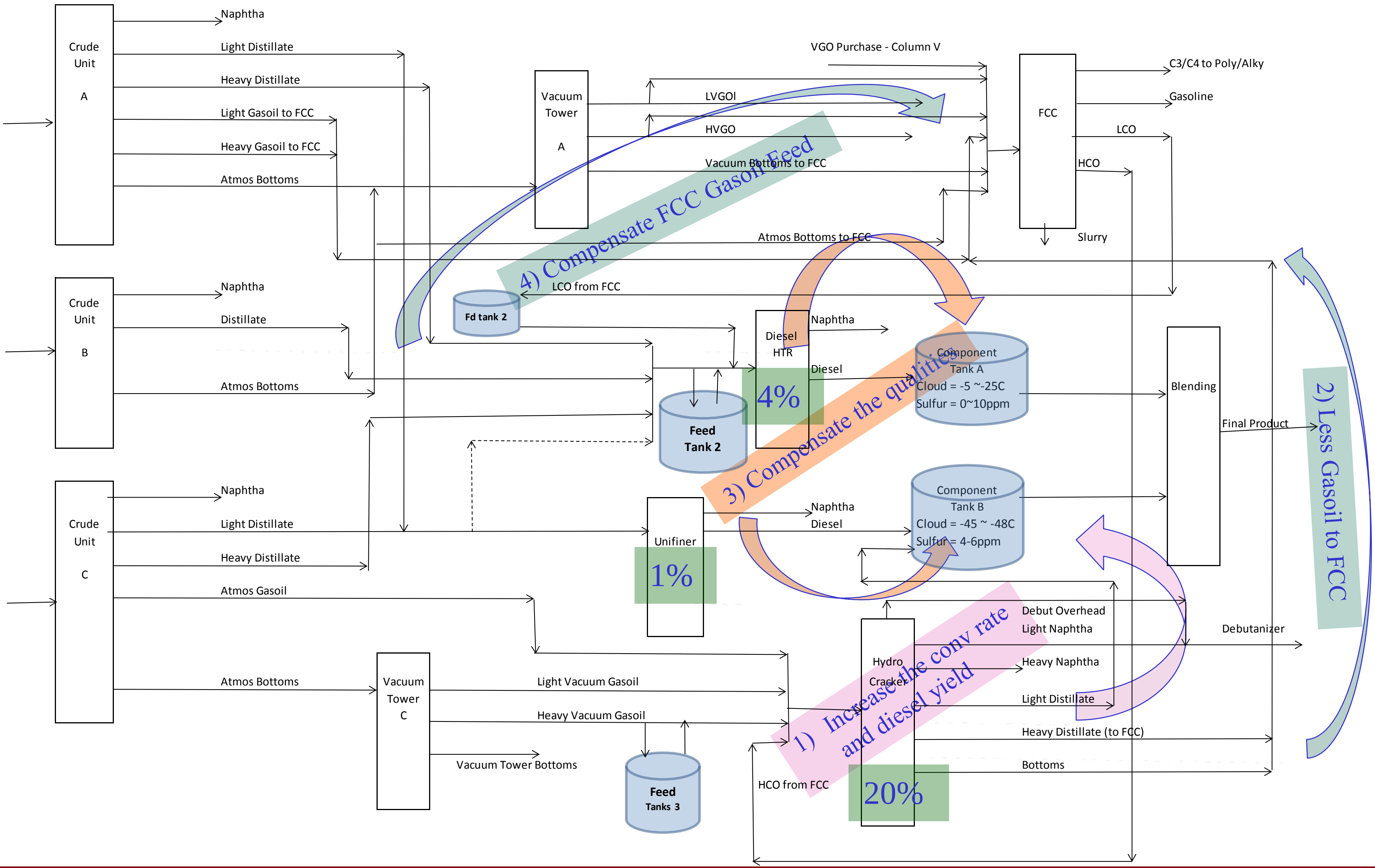
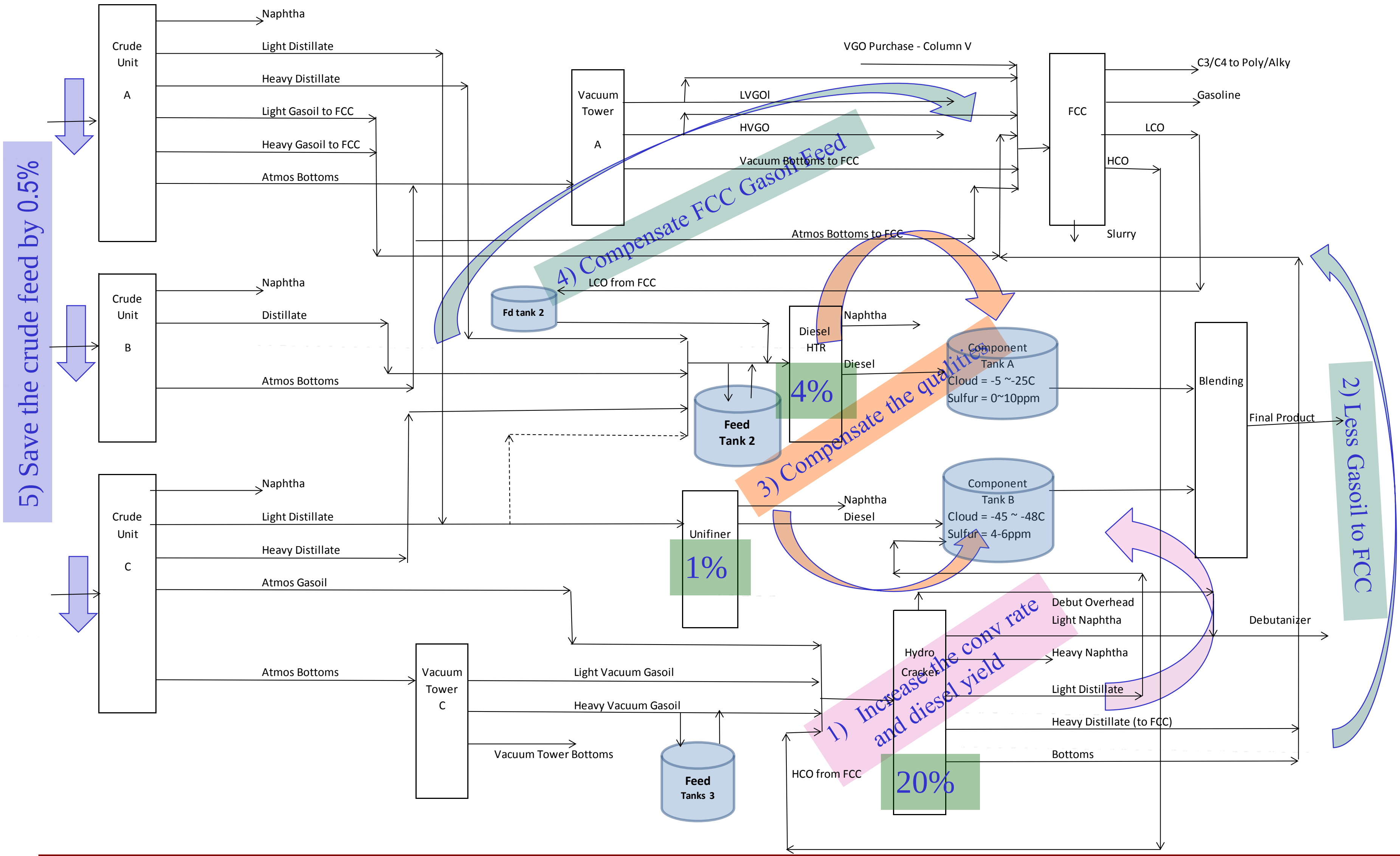


Feed Saving by Leveraging Volumetric Gains

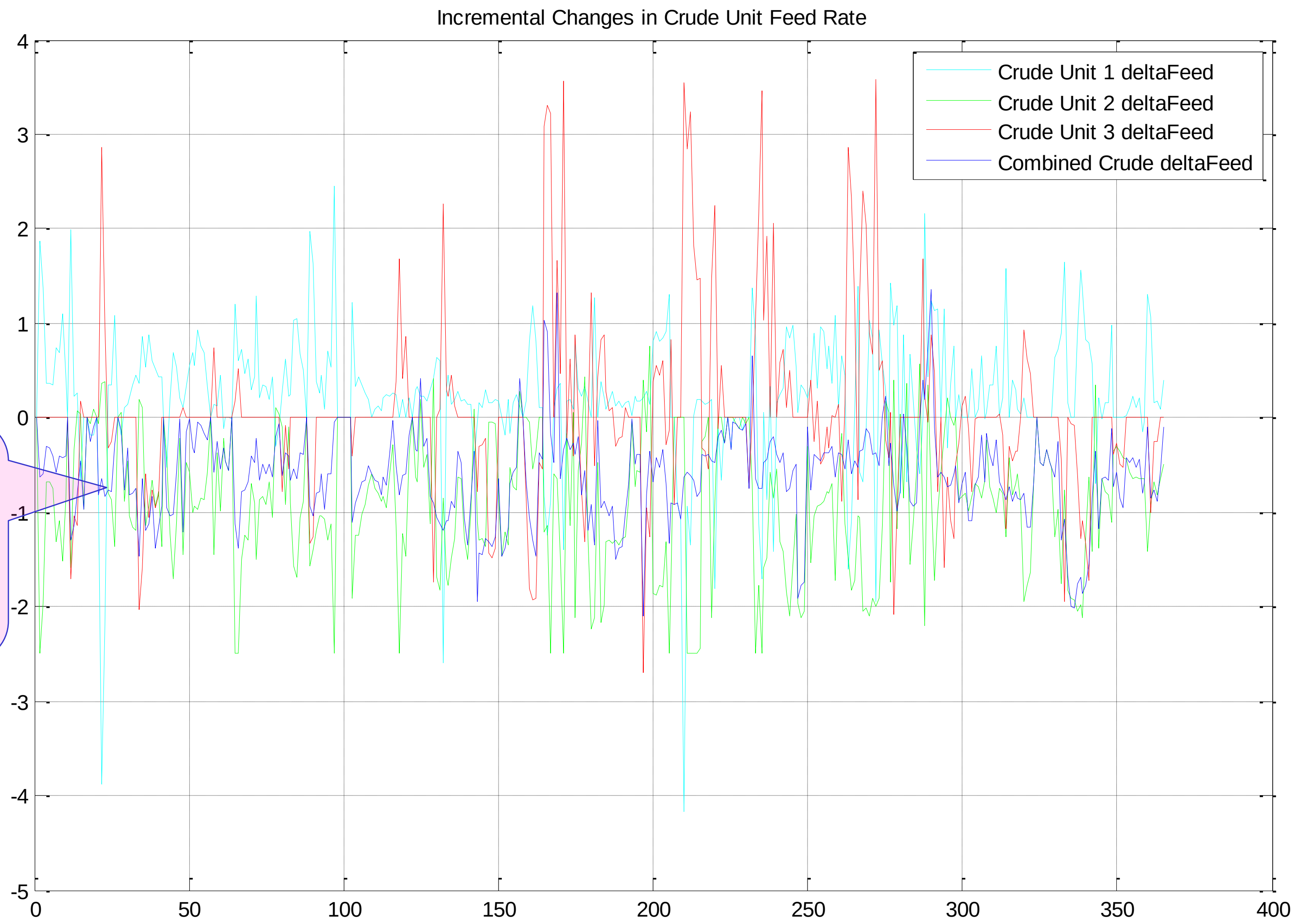
Honeywell



Feed Saving from Optimizing the Volumetric Gains

Honeywell

Net Result: Crude Reduction



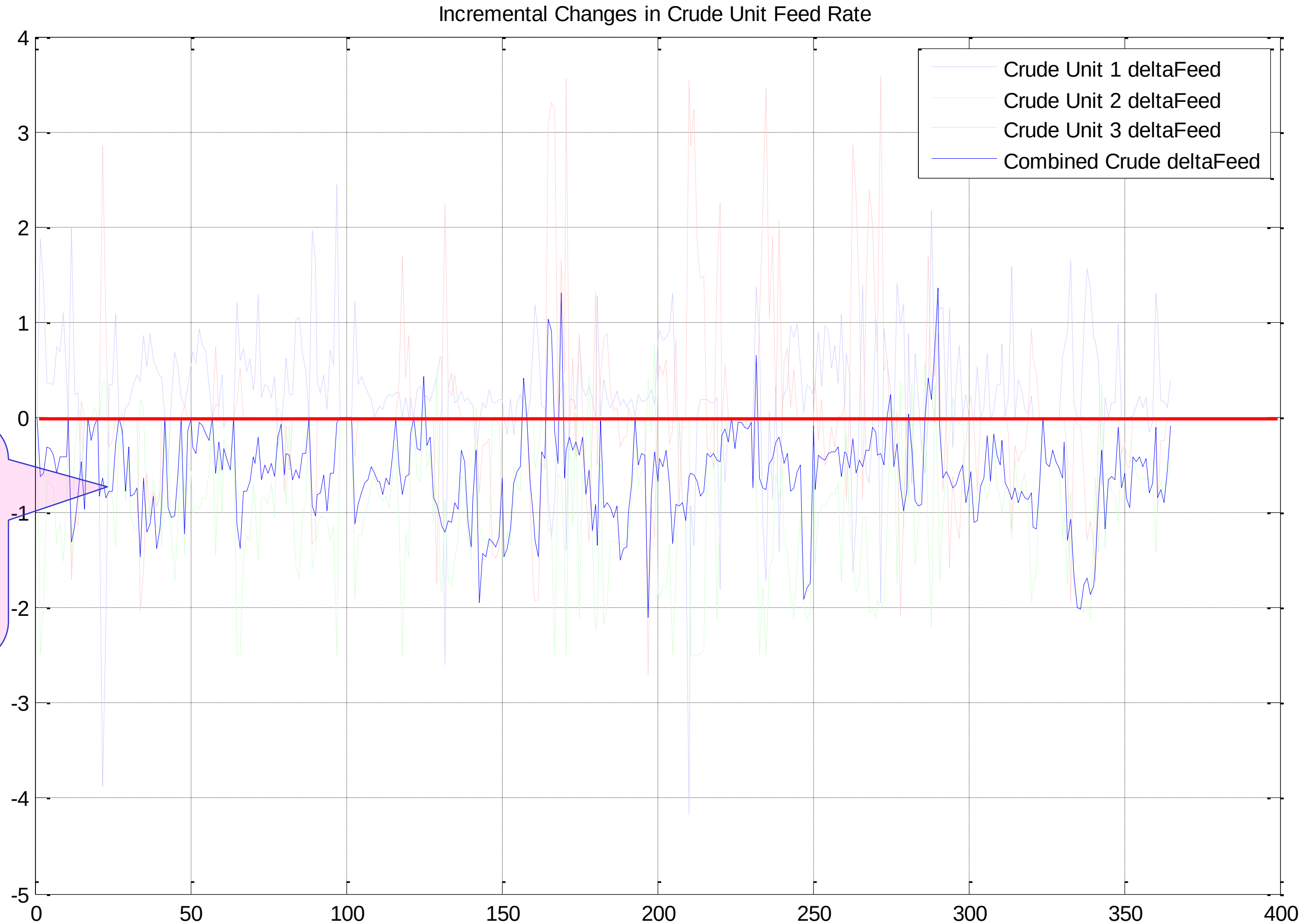
Average crude saving is ~ 0.5% for meeting the same product demand.

Huge cost saving!

Feed Saving from Optimizing the Volumetric Gains

Honeywell

Net Result: Crude Reduction



Average crude saving is ~ 0.5% for meeting the same product demand.

Huge cost saving!

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Concluding Remarks

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- ✓ A (multiscale) MPC cascade control is proposed
  - Current state-of-the-art: Planning is used as a form of open-loop control
  - Improvement: The planning model is fleshed out with dynamics and used in closed-loop control (inside an MPC cascade)
- ✓ This new MPC cascade solution provides better:
  - Scalability – Suitable for different plant size, small or large
  - Operability – Decentralized control is retained while providing centralized, plantwide optimization
  - Real-time responsiveness – The master runs like a regular MPC controller
- ✓ A large class of JIT manufacturing problems can be better controlled
- ✓ The potential benefits of better closed-loop plantwide control are significant
  - An oil refinery simulation study suggests that
    - Refineries can give away a significant amount of product quality due to inadequate closed-loop control – ~$65M/year (~$3/barrel) for a specific refinery distillate pool
    - The MPC cascade solution can capture ~$22M/year (~$1/barrel) without changing the product orders.

Future Work

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- ✓ More efficient methods for estimating the feasible region defined by the constraints in a Slave MPC
  - ➢ Particularly for # of Conjoint MVs > 4
- ✓ 3-level MPC Cascade for a larger part of the supply chain?
  - ➢ For example: a combination of multiple refineries and fuel/crude depots?