The NIT Jalandhar Lecture

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Throughput Manipulation: The Key to Robust Plantwide Control

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Outline

- About ChE@IITK
- Plantwide Control Basics
  - Why do we need a control system
  - The control system as variability transformer
  - Variability propagation around recycle loops
  - Control structure guideline for recycle loops
  - Throughput Manipulation
  - PWCS Exercise
  - PWCS Design Steps
- Example Case Studies
- Summary

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Bay of Bengal
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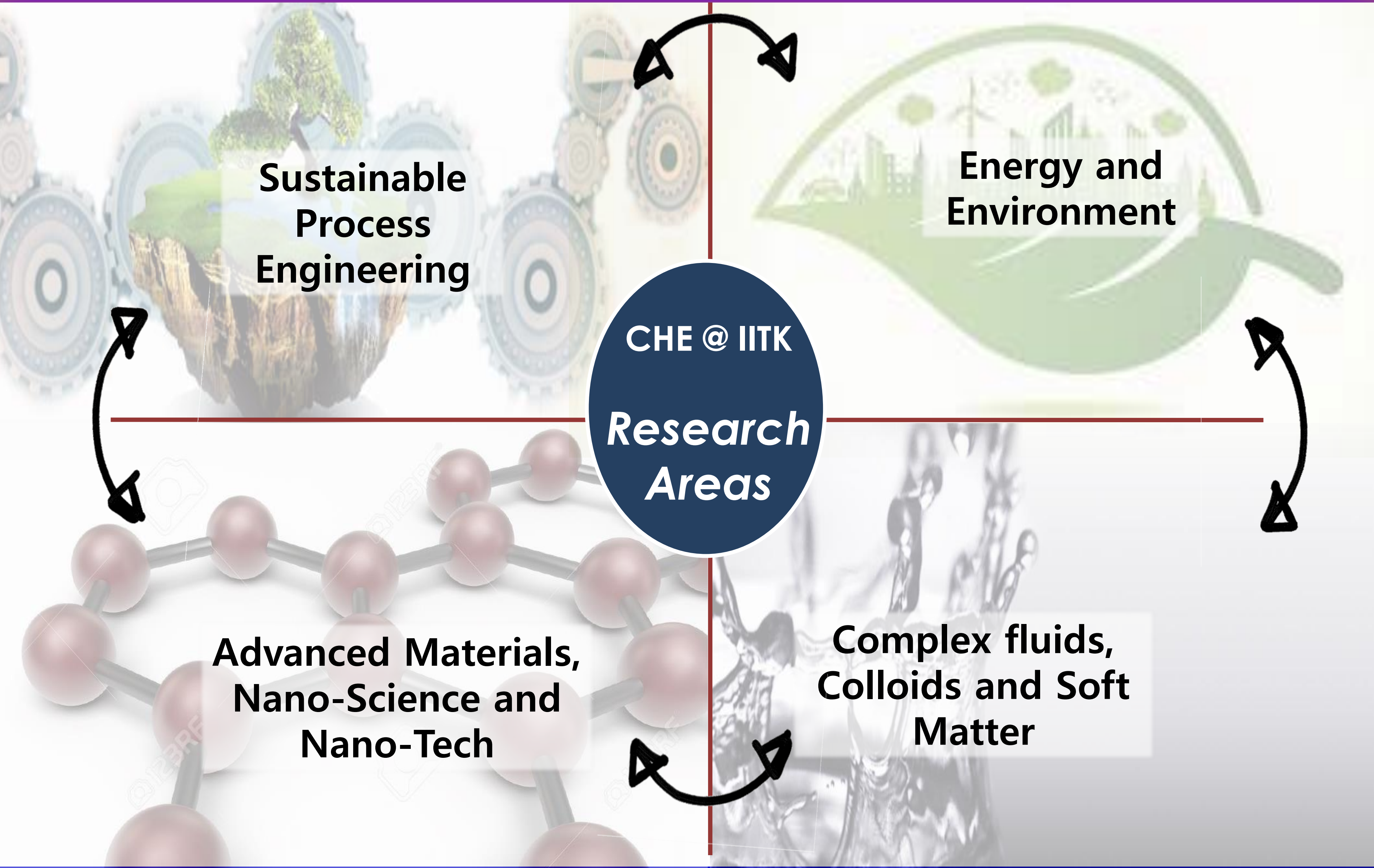
ChE@IITK

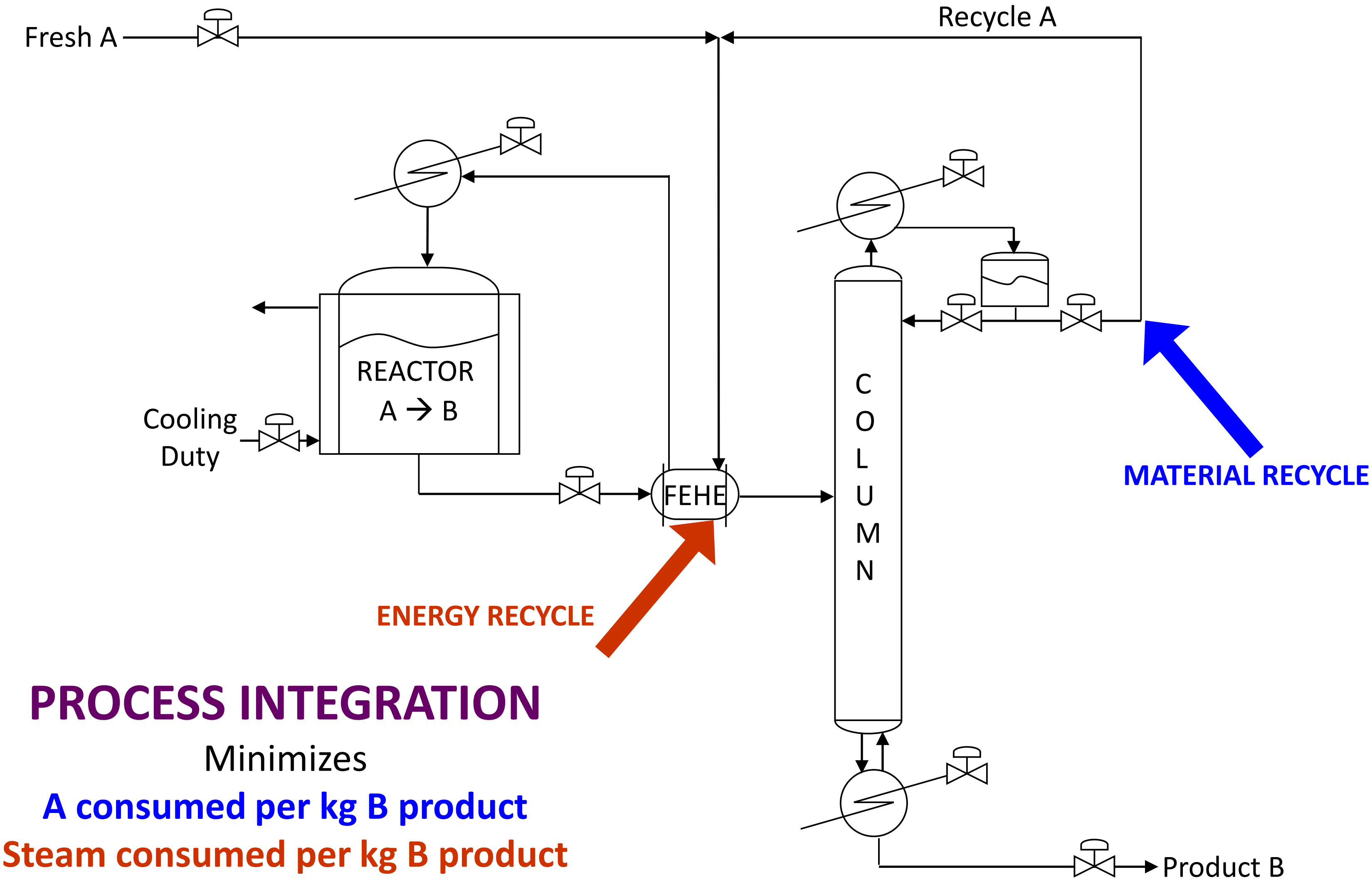
- 21 Faculty Members

- Programs
  - B Tech (4 yr) and Dual (5 yr)
    - ~80 freshmen each year
    - ~60 B Tech and ~20 Dual
  - M Tech (2 yr)
    - 20-25 join every year
  - PhD (4-6 yr)
    - ~15 join every year

ChE@IITK: Research



PWC Basics: A Simple Chemical Process



PROCESS INTEGRATION

Minimizes

A consumed per kg B product

Steam consumed per kg B product

ENHANCES PROCESS PROFITABILITY

PWC Basics: Chemical Process Operation

Key Production Objectives
- Safety
- Stability
- Economics
  - Production Rate
  - Product Quality
  - Effluent Specs

Operate plant to meet production objectives 24X7

Production Objective Itself Can Change

Process Disturbances
- Ambient Conditions
- Raw material Quality
- Sensor Noise
- Equipment Characteristics

PWC Basics

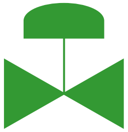
Safety

Stability

≡

Operate Process at Steady State

Accumulation Rate = 0 = Rate In − Rate Out + Generation Rate



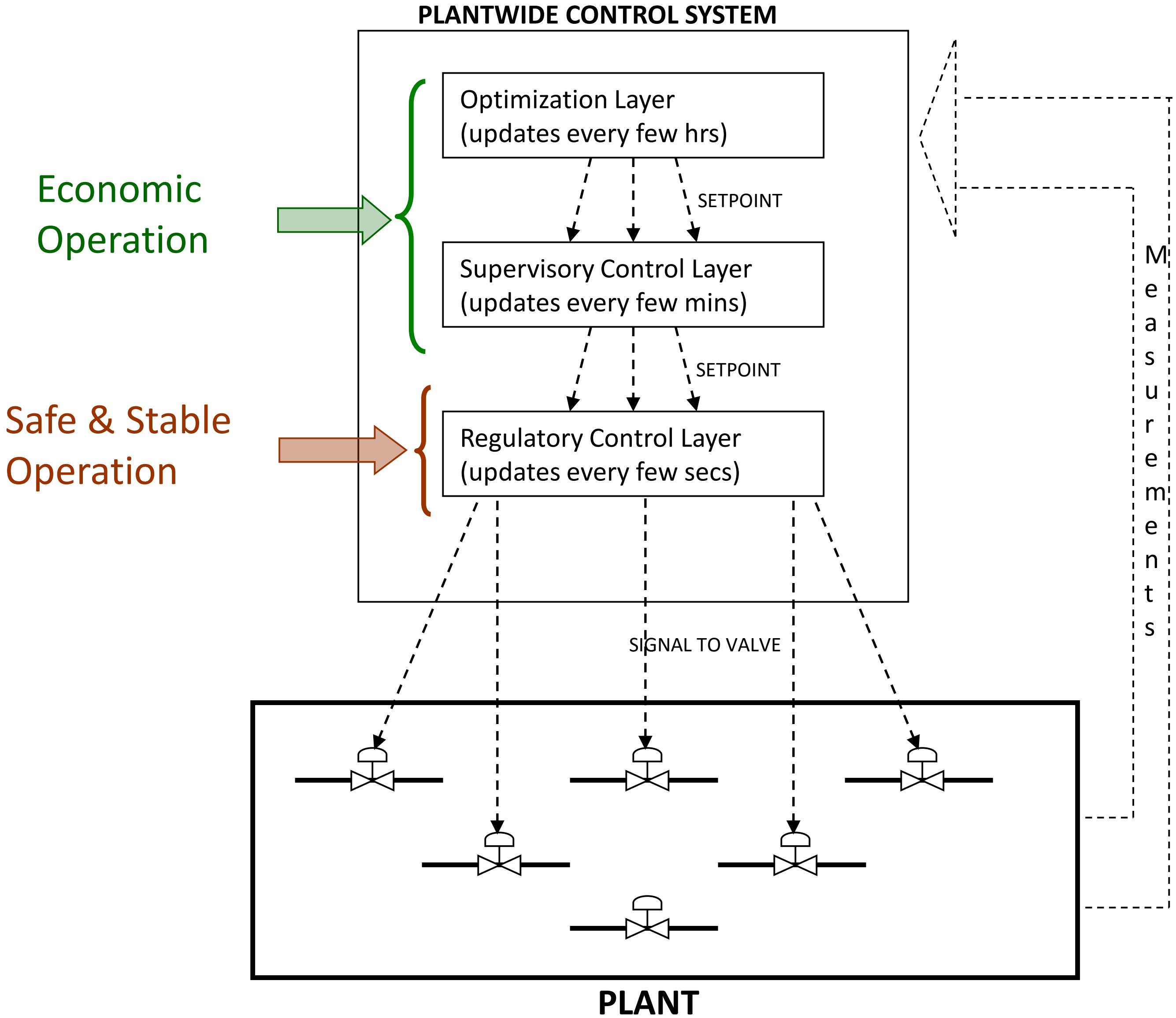
Need PWC to drive accumulation of all independent inventories to zero

PWC Basics

- Regulatory Control System
  - Drives all inventory accumulation terms to zero
  - Ensures plant operation around a steady state

- What steady state to operate at
  - Economic Optimum
    - Minimize expensive utility consumption
    - Maximize production

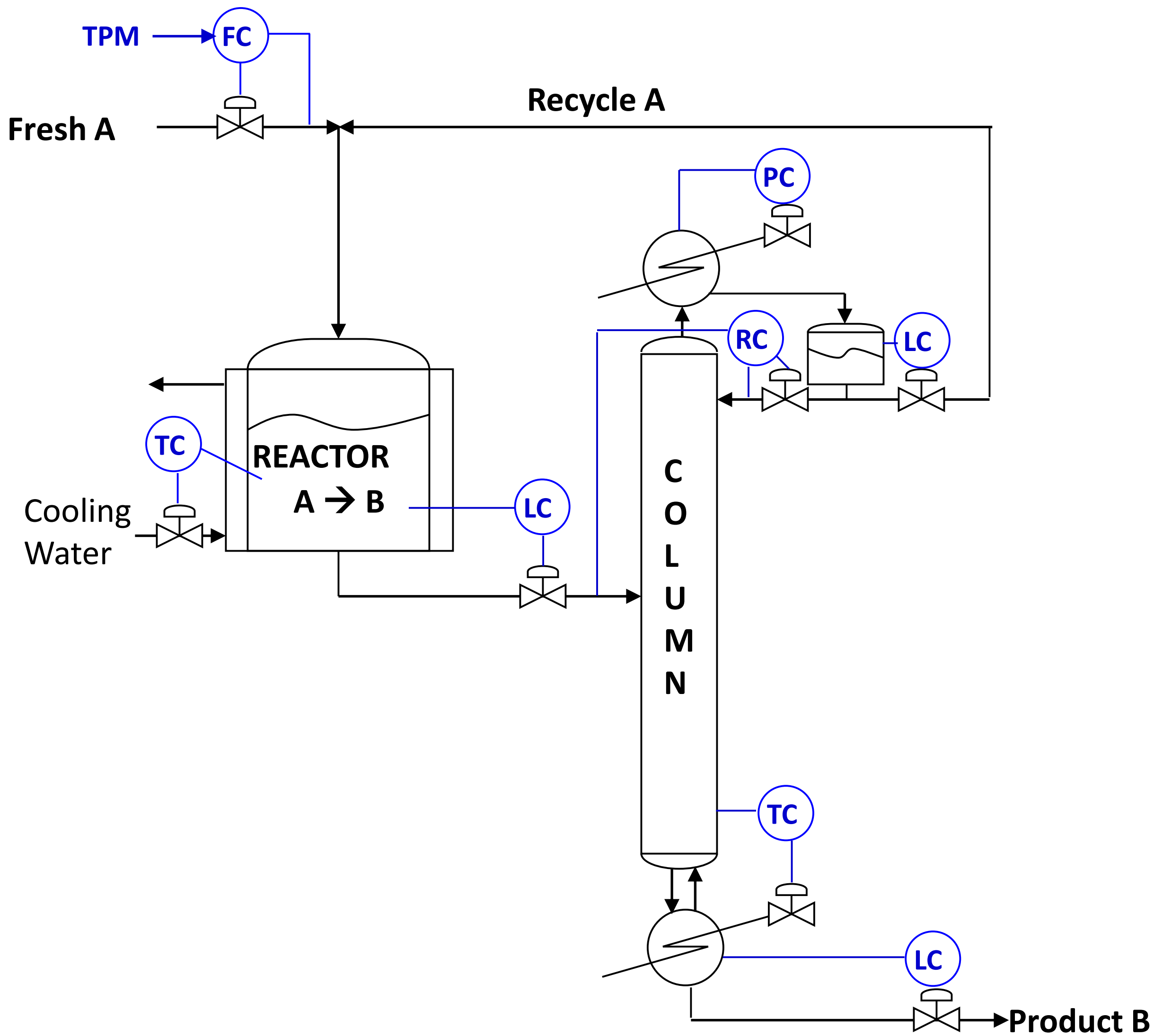
Plantwide Control Hierarchy



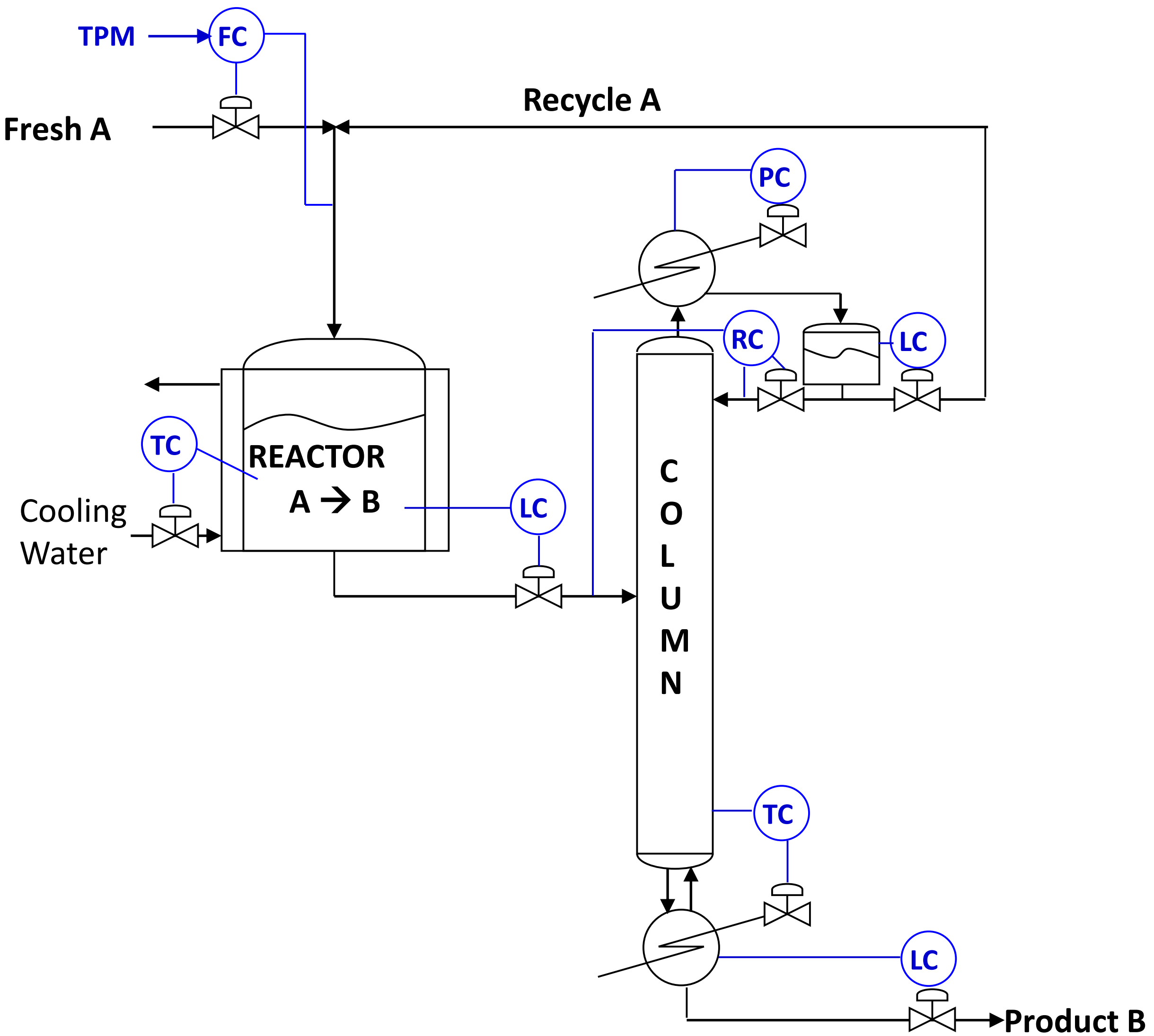
Regulatory PWCS Design

- What to Control
  - All independent inventories (DOF)
    - Material – Liquid level or gas pressure
    - Energy – Temperature or vapor pressure
    - Component – Composition, tray temperature (inferential)
  - Throughput or Production Rate
- Degree of tightness of control
  - Should energy inventories be tightly controlled?
  - Should surge level inventories be tightly controlled?
- What to manipulate
  - The largest term on the RHS of the inventory balance
    - Richardson's Rule
  - Pair close
    - Fast dynamics
    - Tight closed loop control

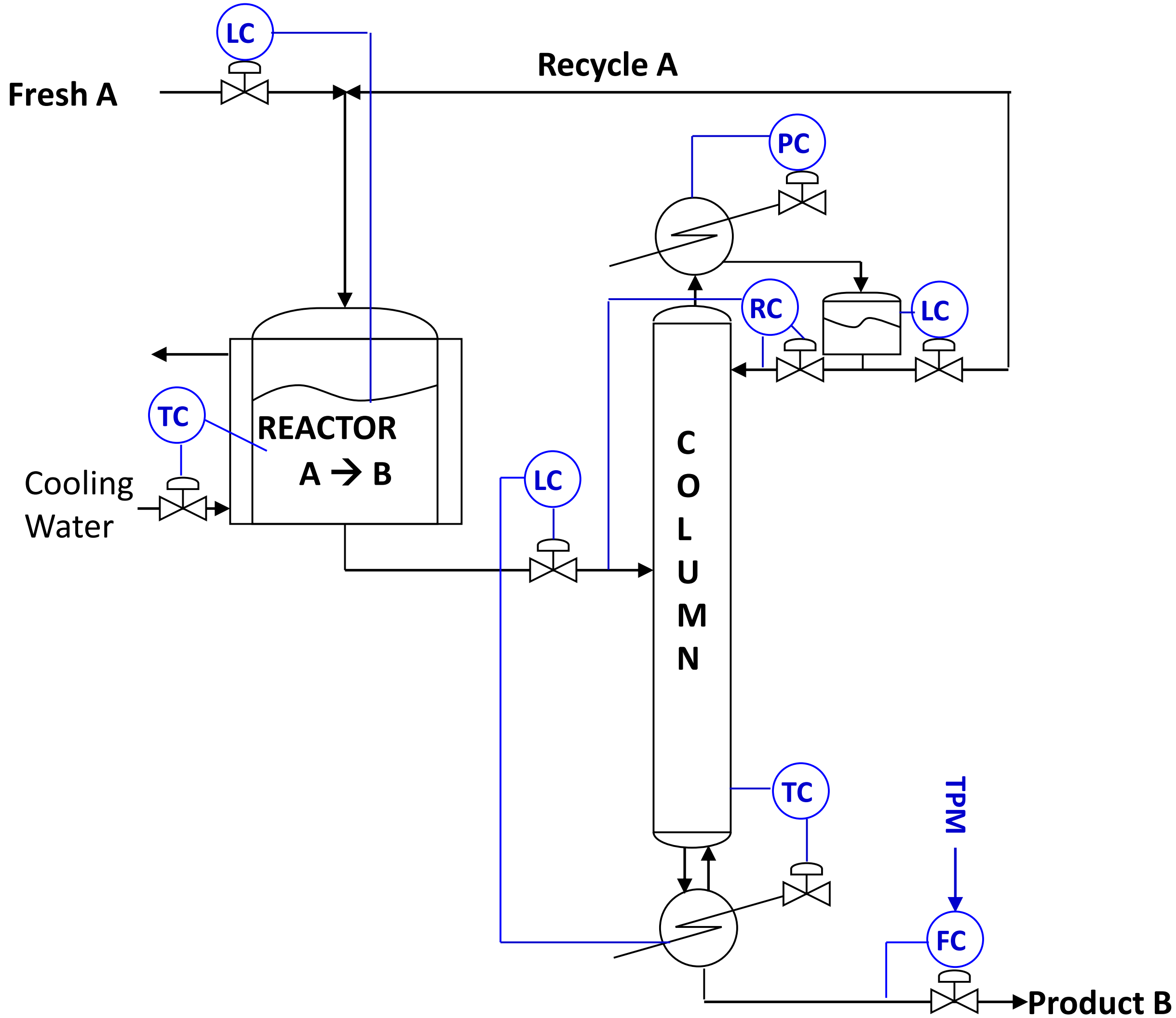
Control Structure Alternatives



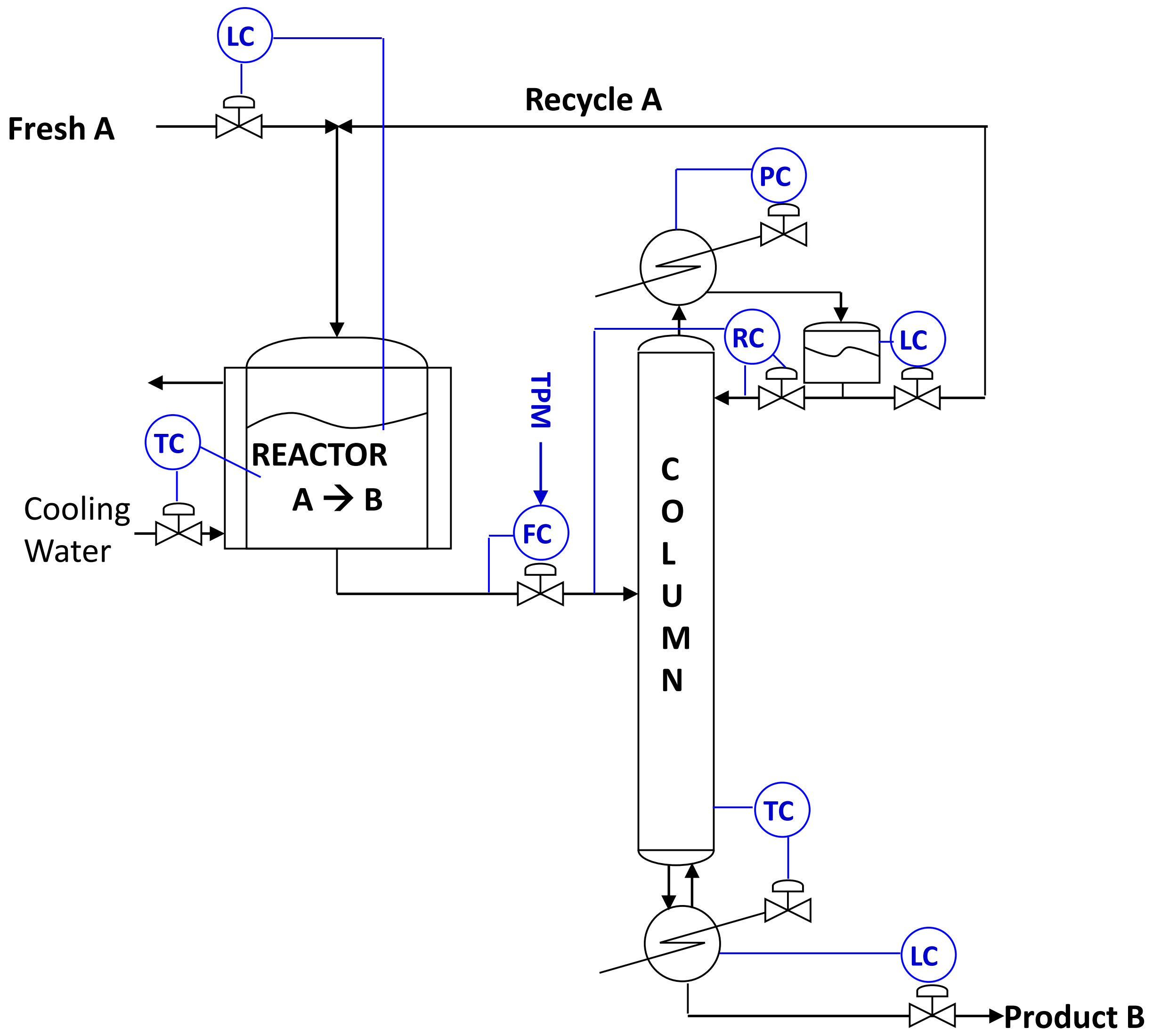
Alternative Control Structures



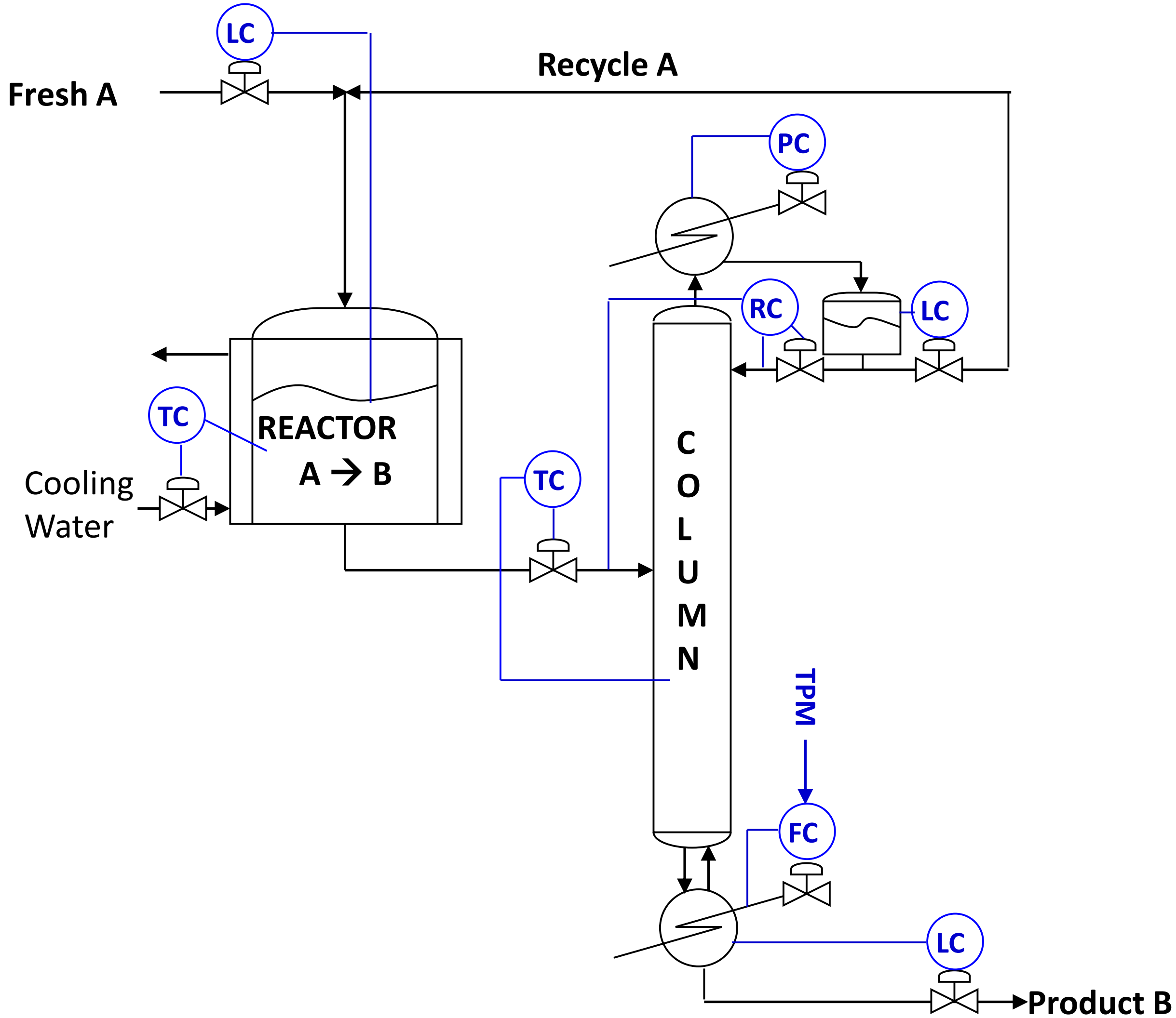
Alternative Control Structures



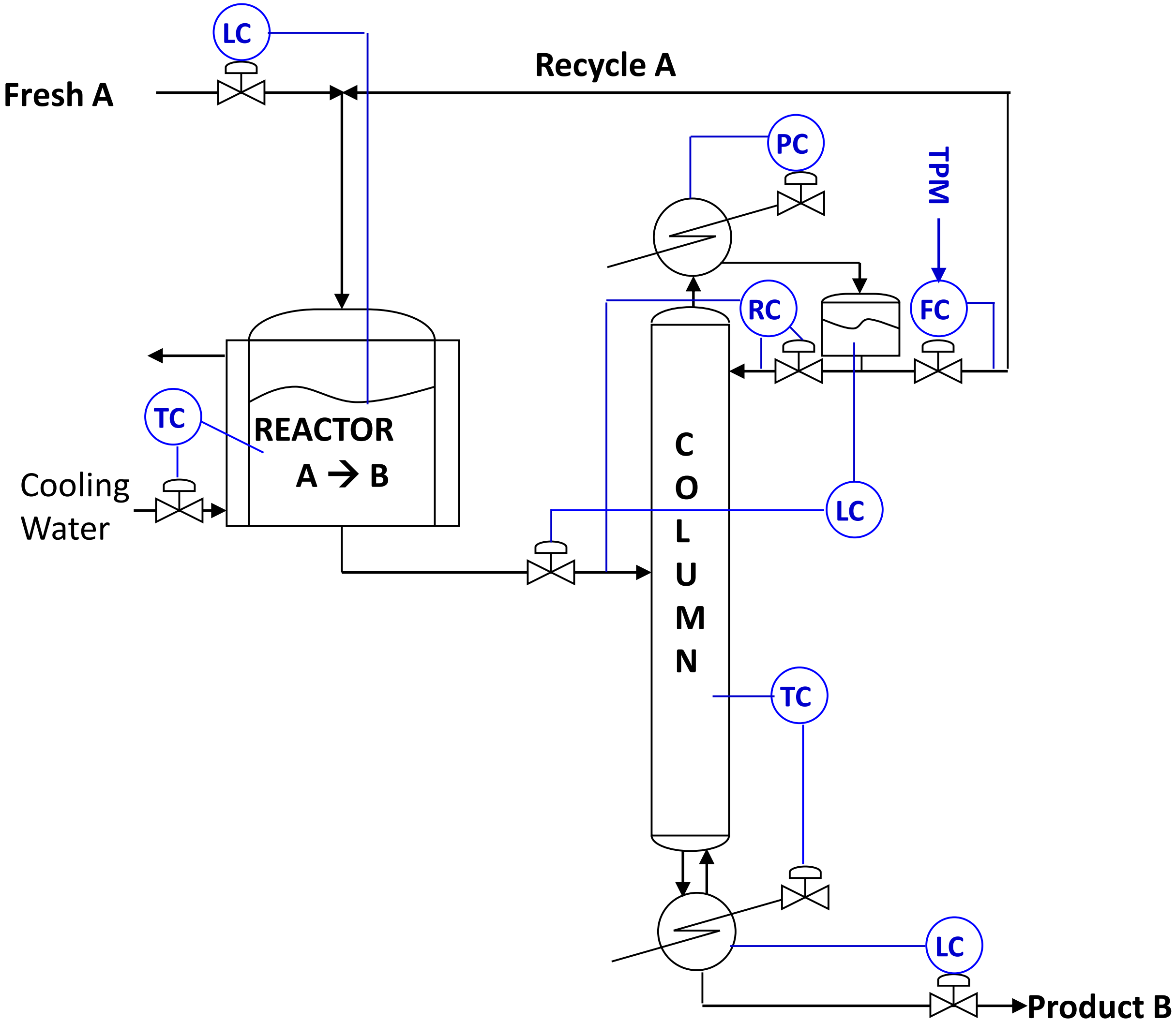
Alternative Control Structures



Alternative Control Structures



Alternative Control Structures

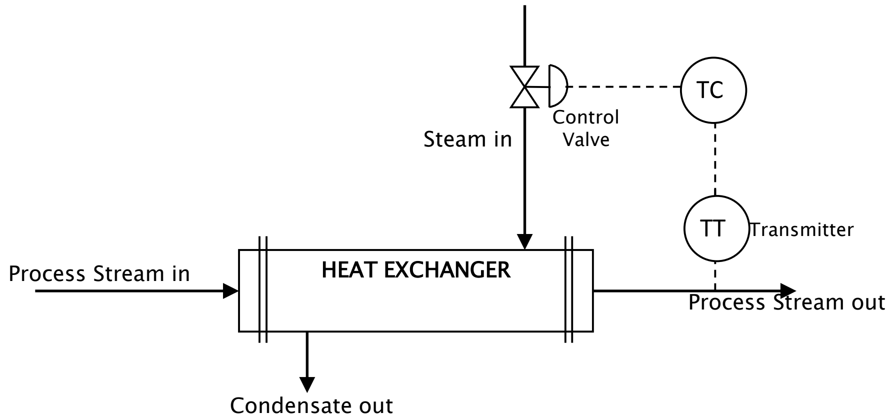


PWCS Design: Key Points

- Location of through-put manipulator a key decision for inventory management
- Several alternative 'reasonable' plant-wide control structures
- Which one is the 'best'
- How do you bring method to the madness

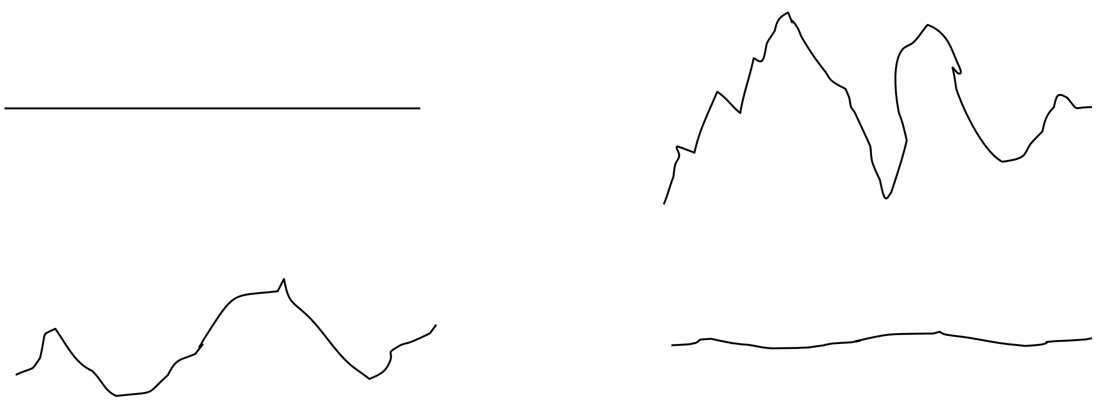
The Transformation of Variability Perspective

HEAT EXCHANGER EXAMPLE



Steam Flow

Steam Flow



Temperature

Temperature

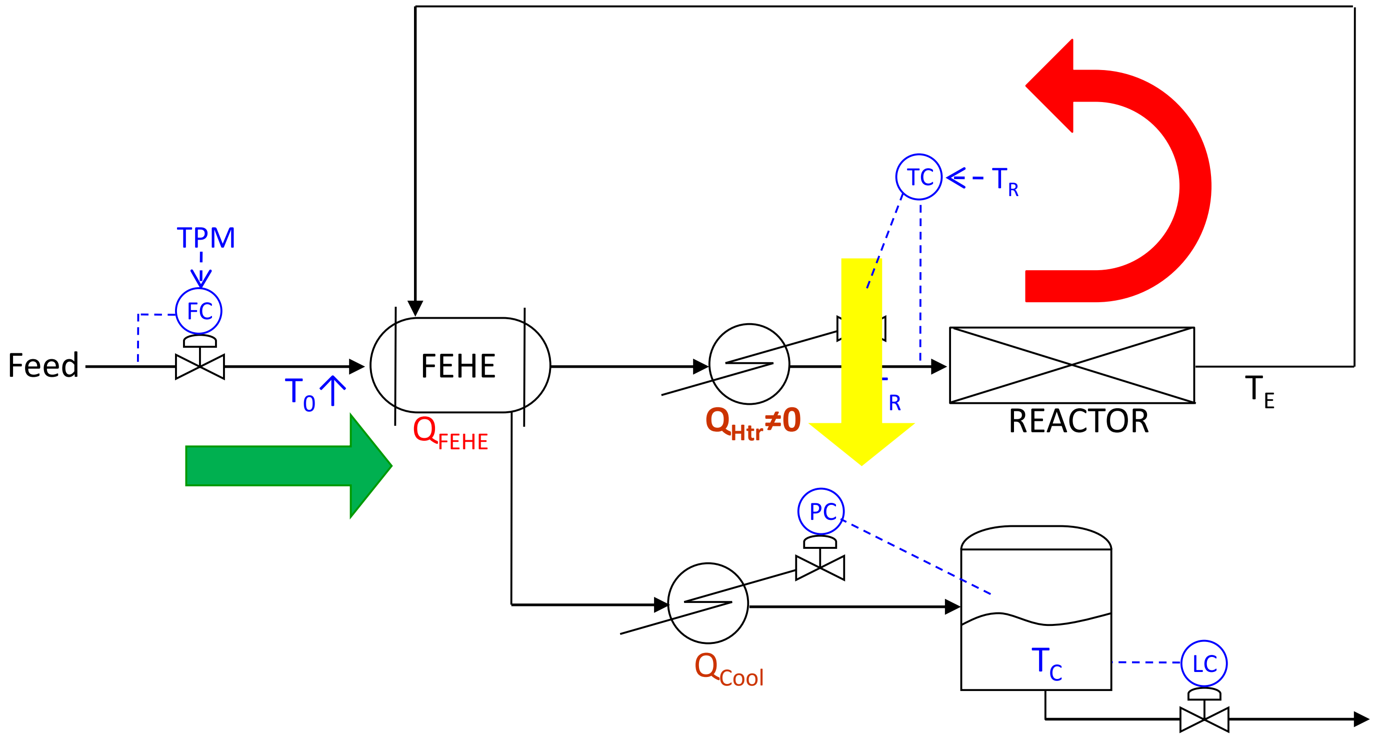
CONTROL SYSTEM

Agent for transformation / management of process variability

Where to Transform Variability

- Surge level
  - Does not affect steady state
  - Regulate loosely for filtering out flow transients
- Energy Inventories
  - Regulate tightly to guarantee safety (rxn runaway?)
- Product quality
  - Regulate tightly
  - Minimize “free” product give-away
- Production rate
  - Often “loose” is OK (eg meet the monthly target)
- Recycle loop circulation rates
  - Regulate tightly
  - All equipment inside recycle loop see low variability
  - May need to let it float for overall balance closure

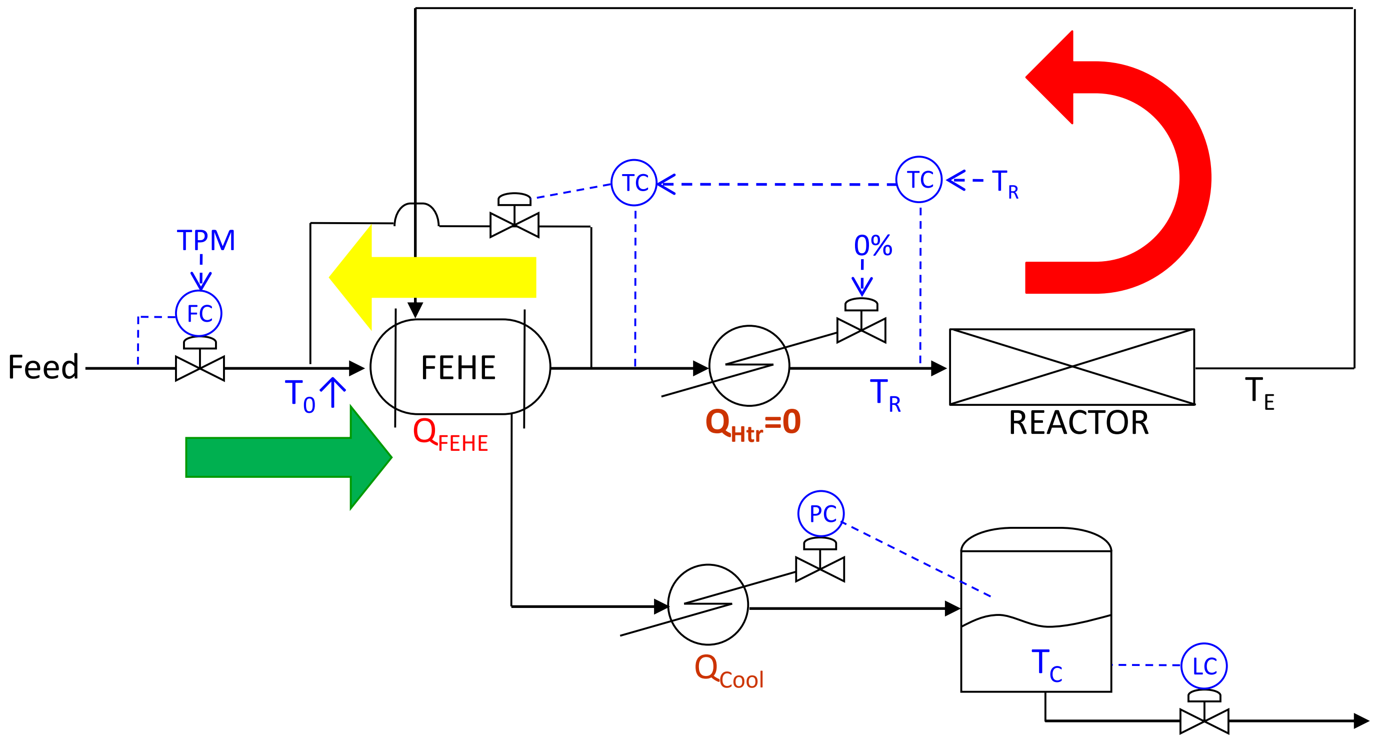
A Common Energy Recycle Loop



Temperature controller transforms energy balance variability out of recycle loop

Regulates energy recycled in FEHE

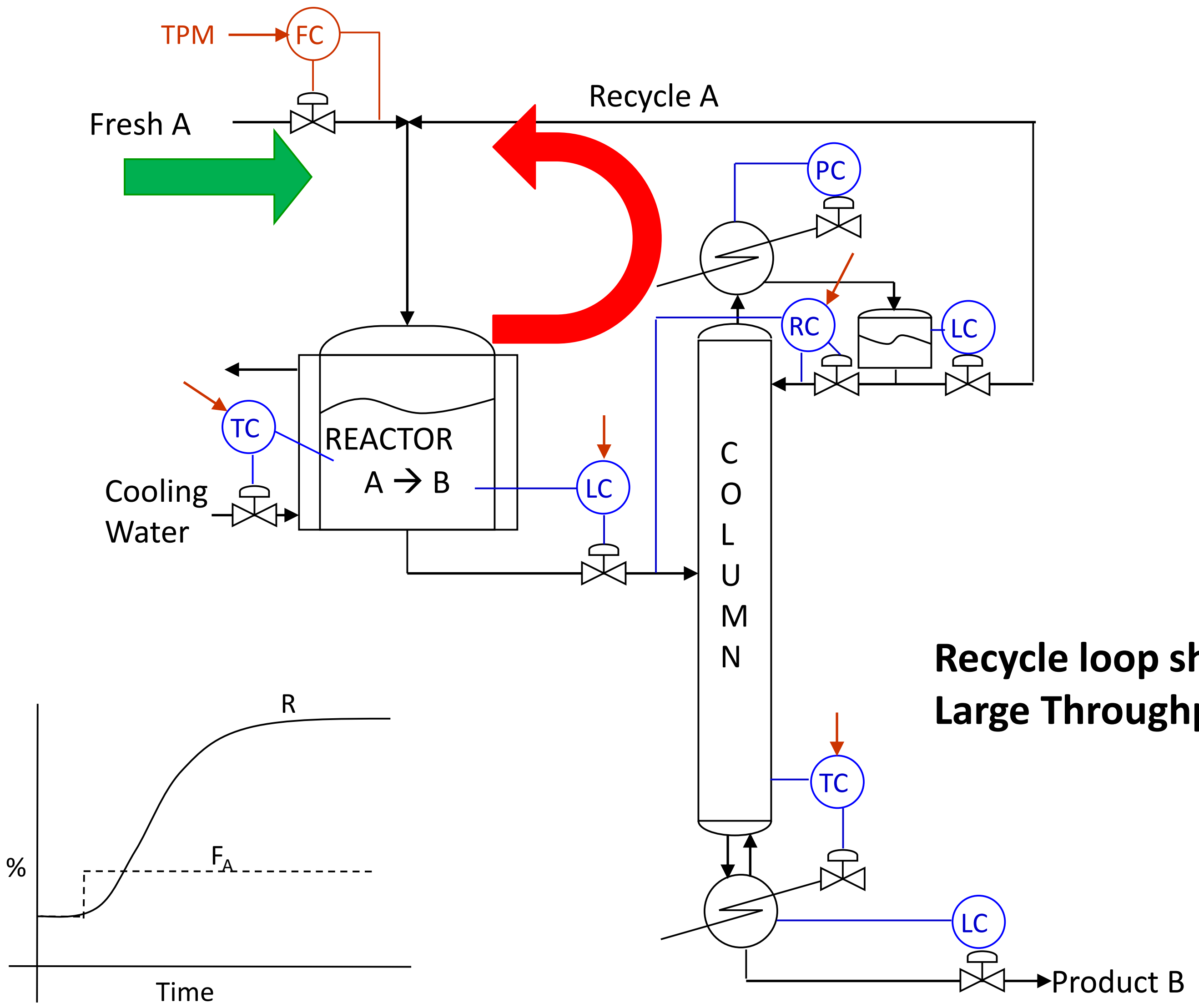
A Common Energy Recycle Loop



Temperature controller transforms energy balance variability out of recycle loop

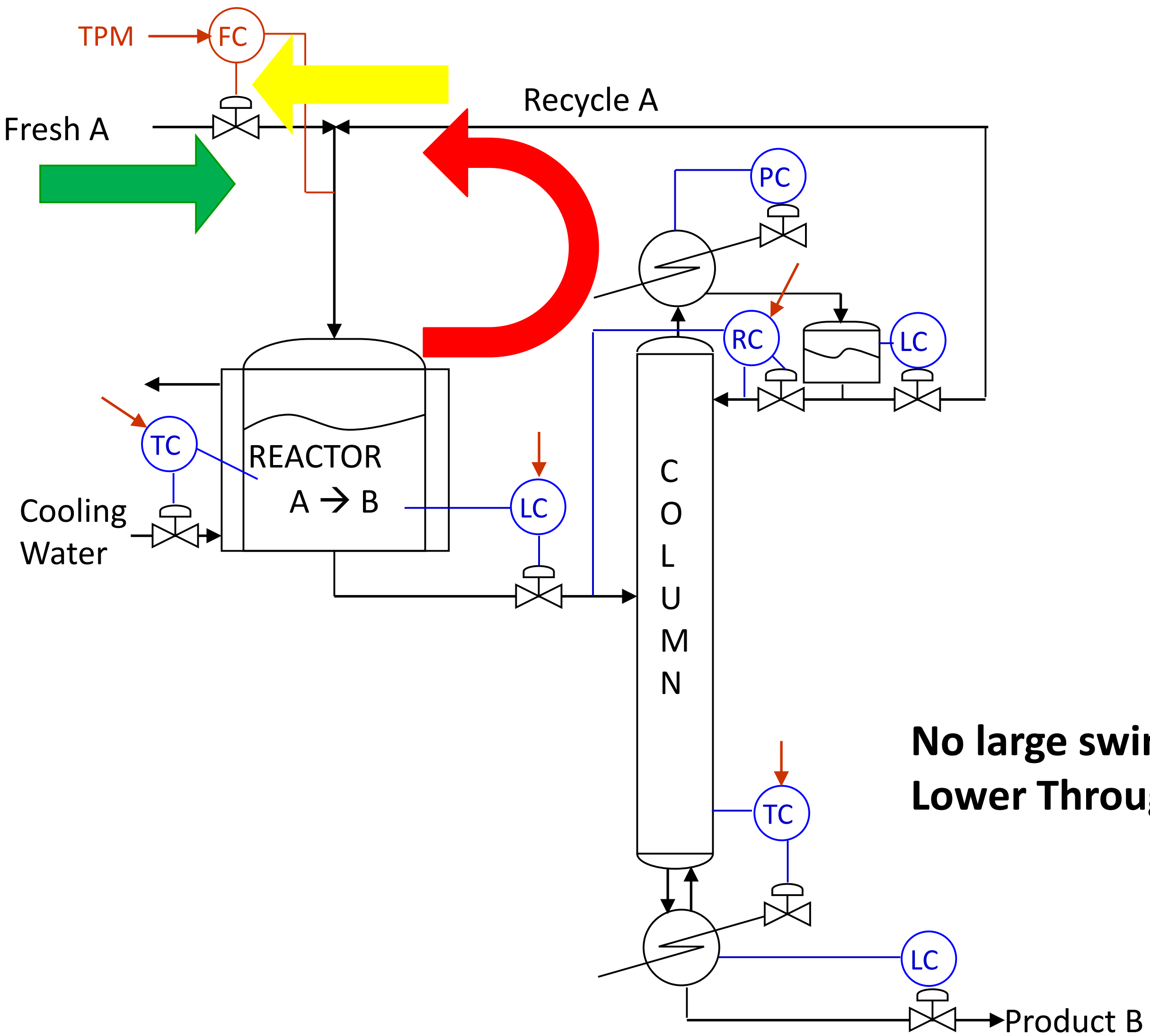
Regulates energy recycled in FEHE

Material Recycle Snowball Effect



Recycle loop shows large swings
Large Throughput De-rating

Material Recycle Snowball Effect

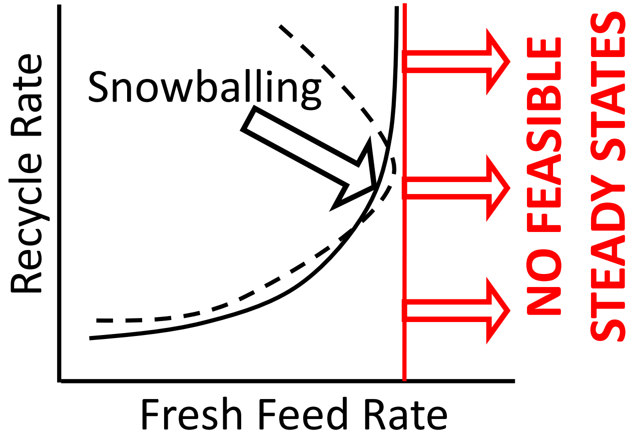


No large swings in recycle rate
Lower Throughput De-rating

Key Guideline for Recycle Loops

- **Structure the control system to transform variability out of the recycle loop**
  - Hold what's going around the recycle loop
- Energy Recycle Loop
  - Hold a temperature inside the recycle loop
- Material Recycle Loop
  - Hold component rate(s) going around recycle loop
  - Material balance control structure brings in fresh component(s) that are recycled as make-up streams

More on Recycle Loops: Nonlinearity



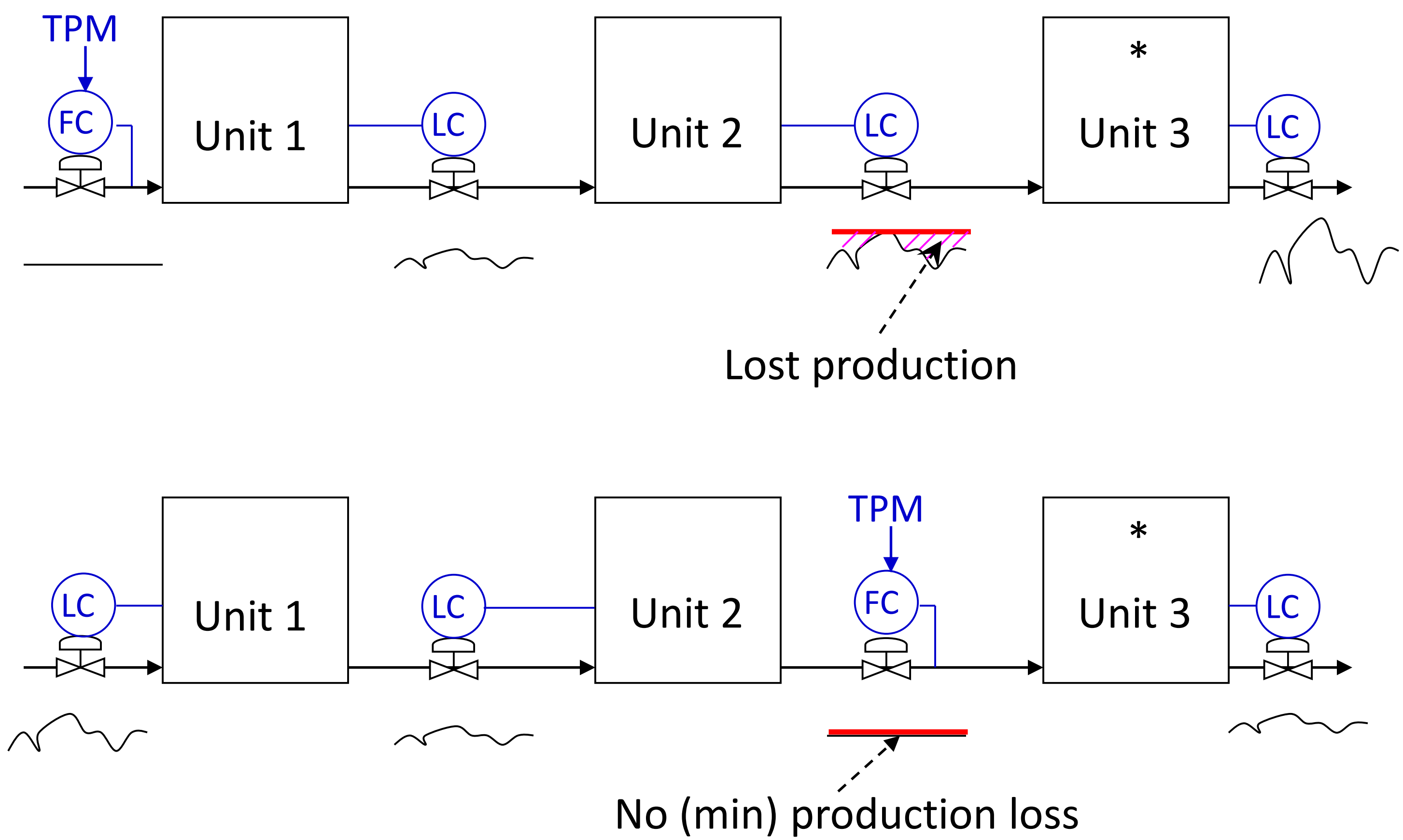
Fixing the fresh feed rate of a recycled component is NOT a good idea

Possibility of overfeeding induced instability

PWC Basics: Throughput Manipulation

THROUGHOUT MANIPULATOR (TPM)

The setpoint adjusted to effect a change in production/processing rate



PWC Basics: TPM Selection

- When is TPM choice flexible
  - Large storage tanks supply the fresh feed(s)
  - Variability in storage tank level is acceptable
    - Allows structures that bring in fresh feed(s) as make-up
- Usually plant designs have large recycle rates
  - Design in the snowballing region
  - Capacity bottleneck then is likely inside the loop
- Where to locate the TPM
  - Inside the recycle loop
  - If multiple recycle loops, on a common branch
  - If bottleneck is known, AT the bottleneck

Key PWC Guidelines

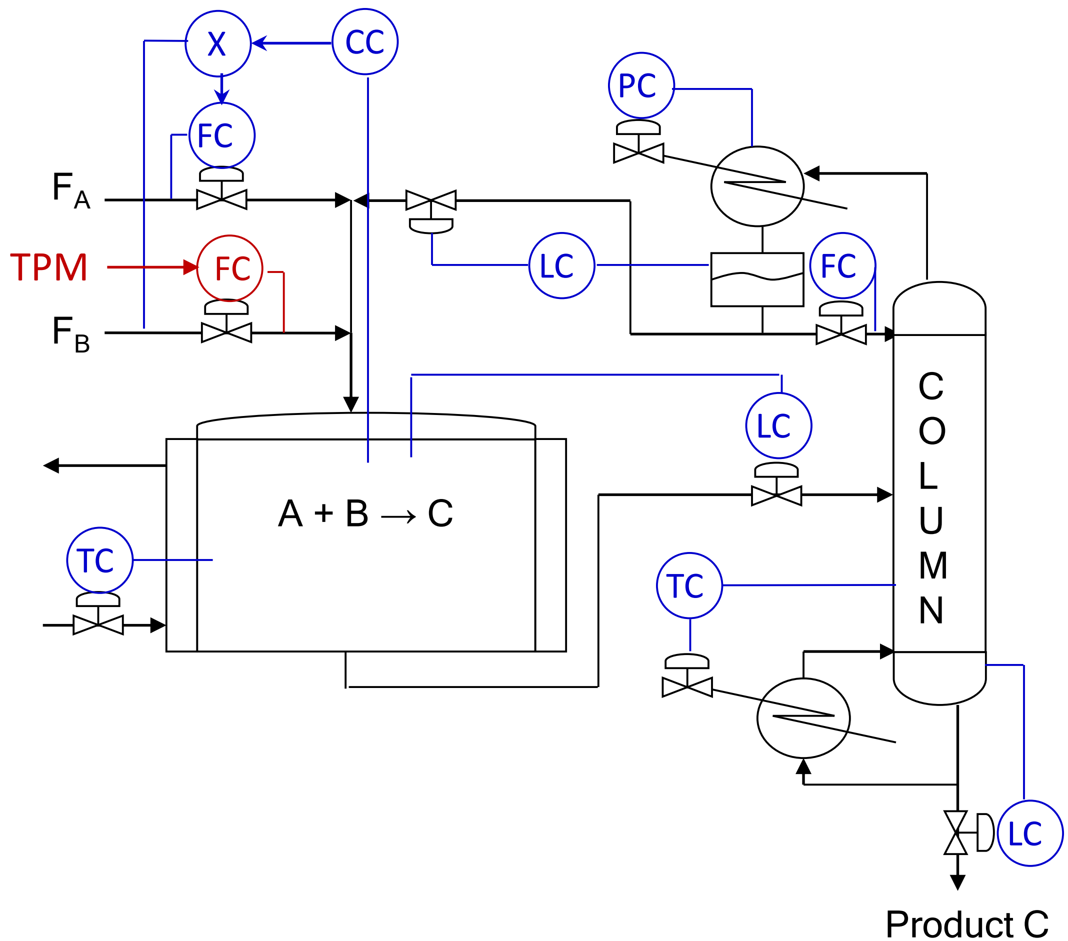
- Configure control structure to transform recycle rate variability out of the recycle loop

- Provide control DOFs for fast “local” control
- “Pair” locally for fast control

- Choose TPM at bottleneck constraint to transform variability away from bottleneck
  - Almost always, bottleneck is inside the recycle loop

PWCS Design Exercise I

TPM at Fresh B Feed



PWCS Exercise I Continued

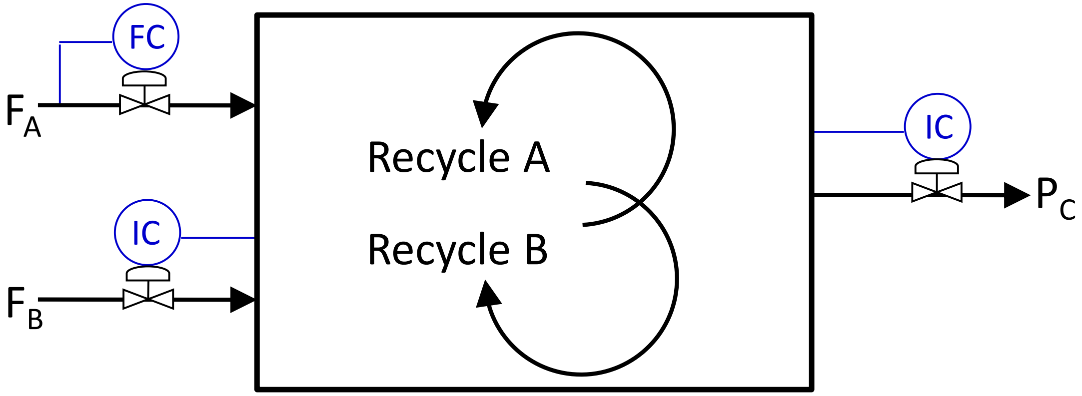
Beware of subtle plantwide recycle loop inventory drifts

Stoichiometric feed balancing

Plantwide balances close slowly due to recycle

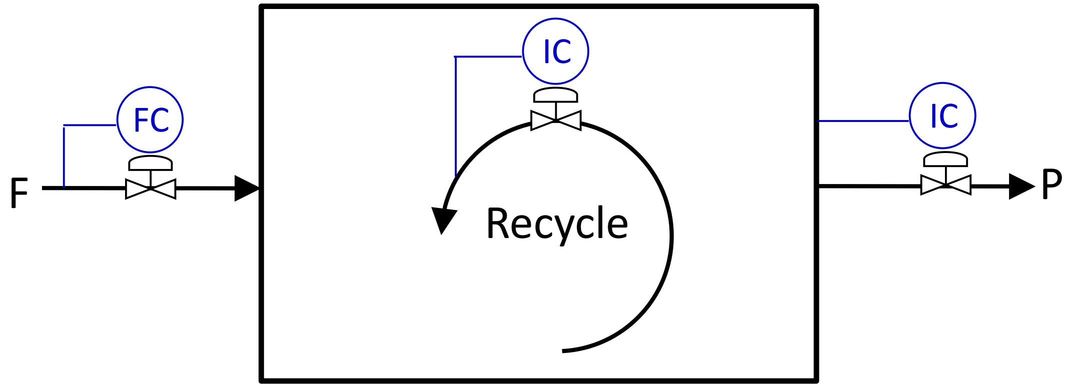
Always examine process input-output structure

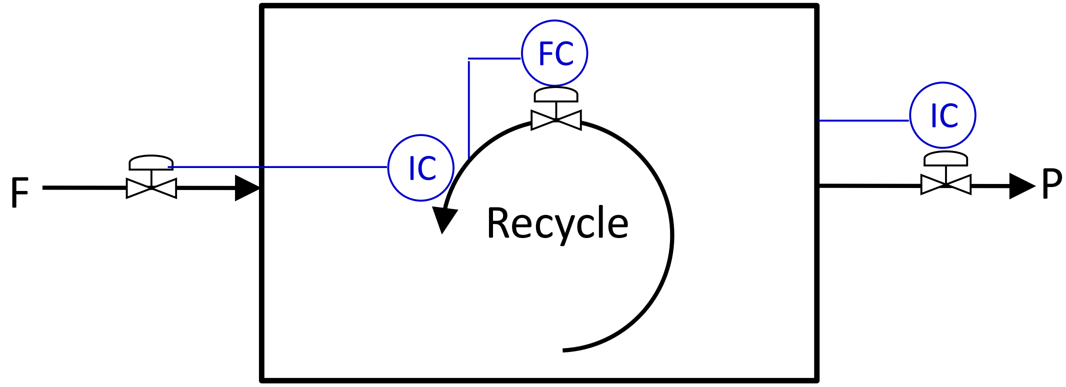
Every component must find a way out or get consumed **(DOWNS' DRILL)**



For (near) pure C product, $F_A = F_B$

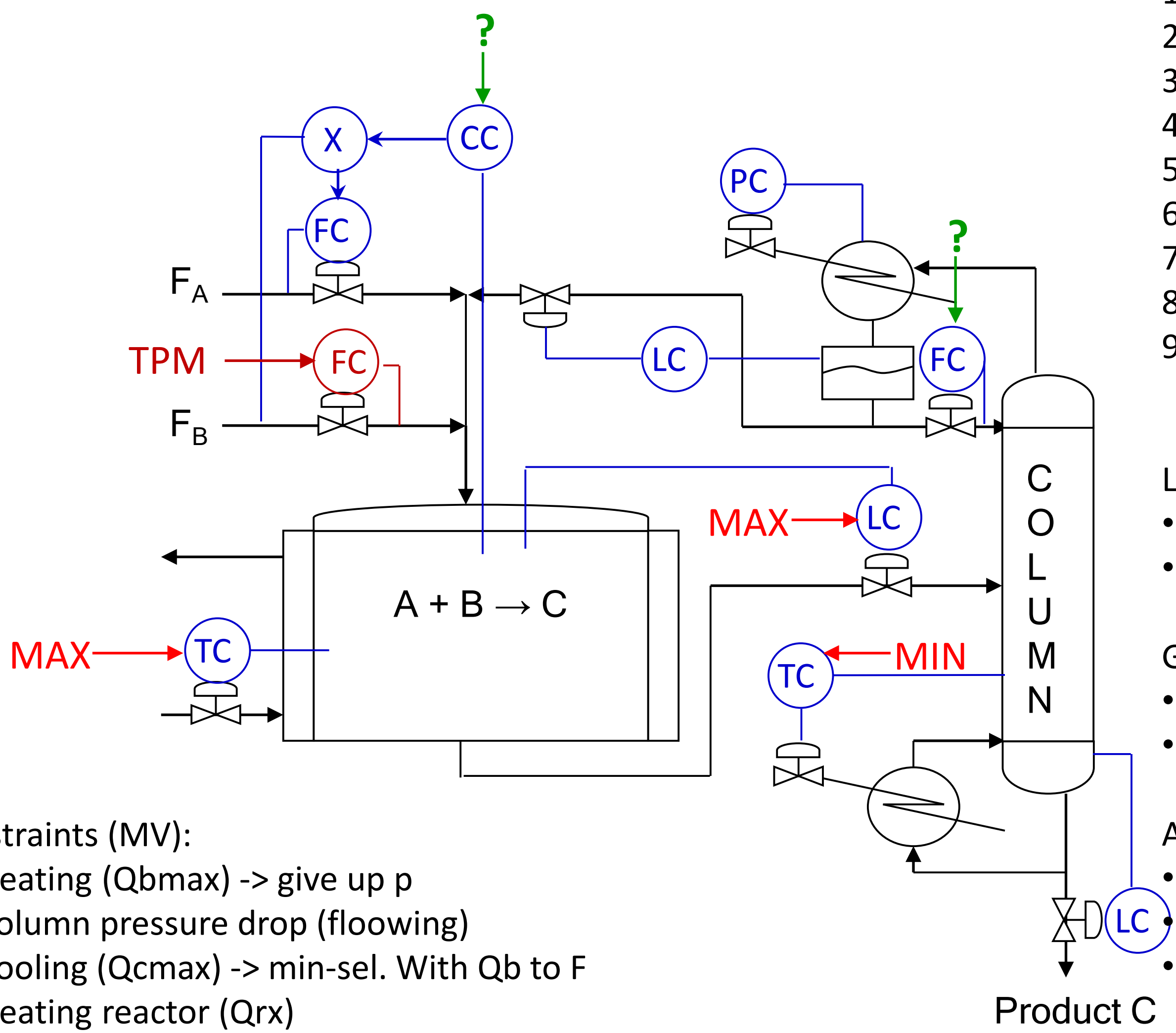
PWCS Design Exercise I Continued





PWCS Design Exercise I Continued

TPM at Fresh B Feed



DOF:

1. Feed A
2. Feed B
3. Heat Qrx
4. Column feed F
5. Reflux L
6. Boilup V (Qb)
7. Bottoms B
8. Distillate (recycle) D
9. Cooling column (Qc)

Levels (2) that neeed to be contro

- Md
- Mb

Given (setpoint) (1): (can be given

- Feedrate
- Column pressure

Active constraints (3) :

- Max reactor volume
- Max reactor temperature
- Min. product purity xC (no giv

Self-optimizing (2)

- A/B in feed
- L/F

Other constraints (MV):

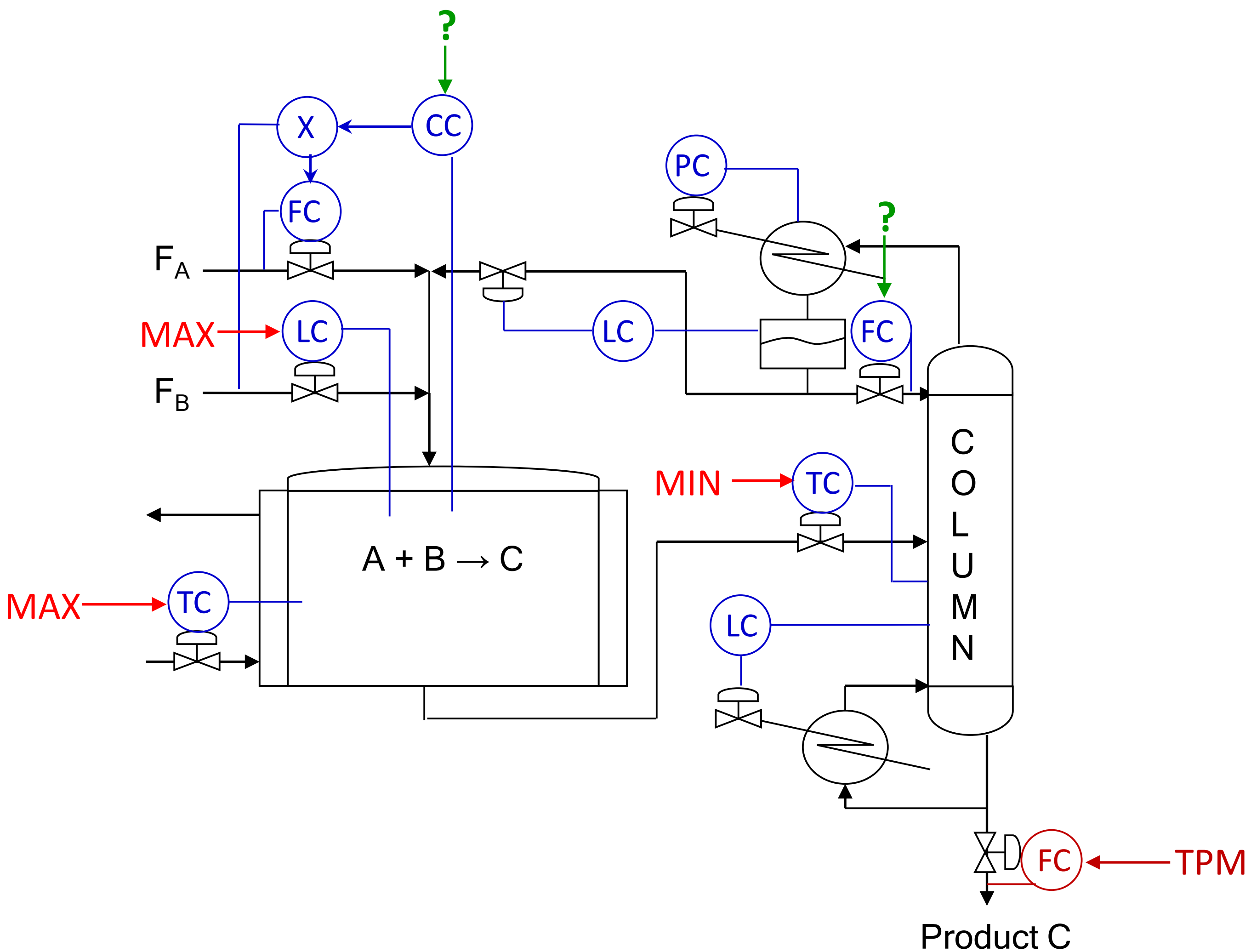
- Max. heating (Qbmax) -> give up p
- Max. column pressure drop (floowing)
- Max. cooling (Qcmax) -> min-sel. With Qb to F
- Max. heating reactor (Qrx)

Other constraints (CV)

- Max. pressure (p) -> selector to Qb

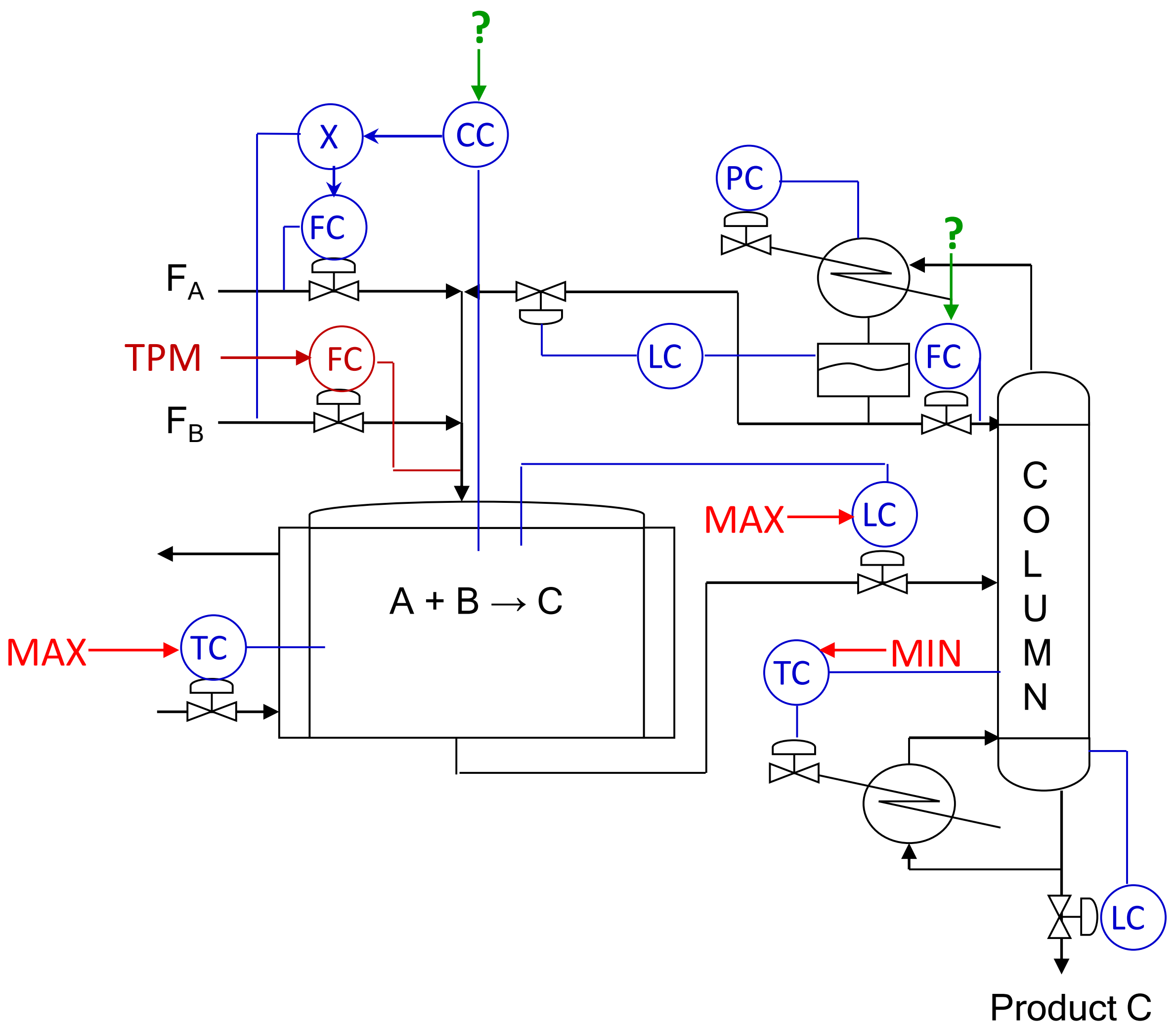
PWCS Design Exercise II

TPM at Product Stream: On Demand Operation



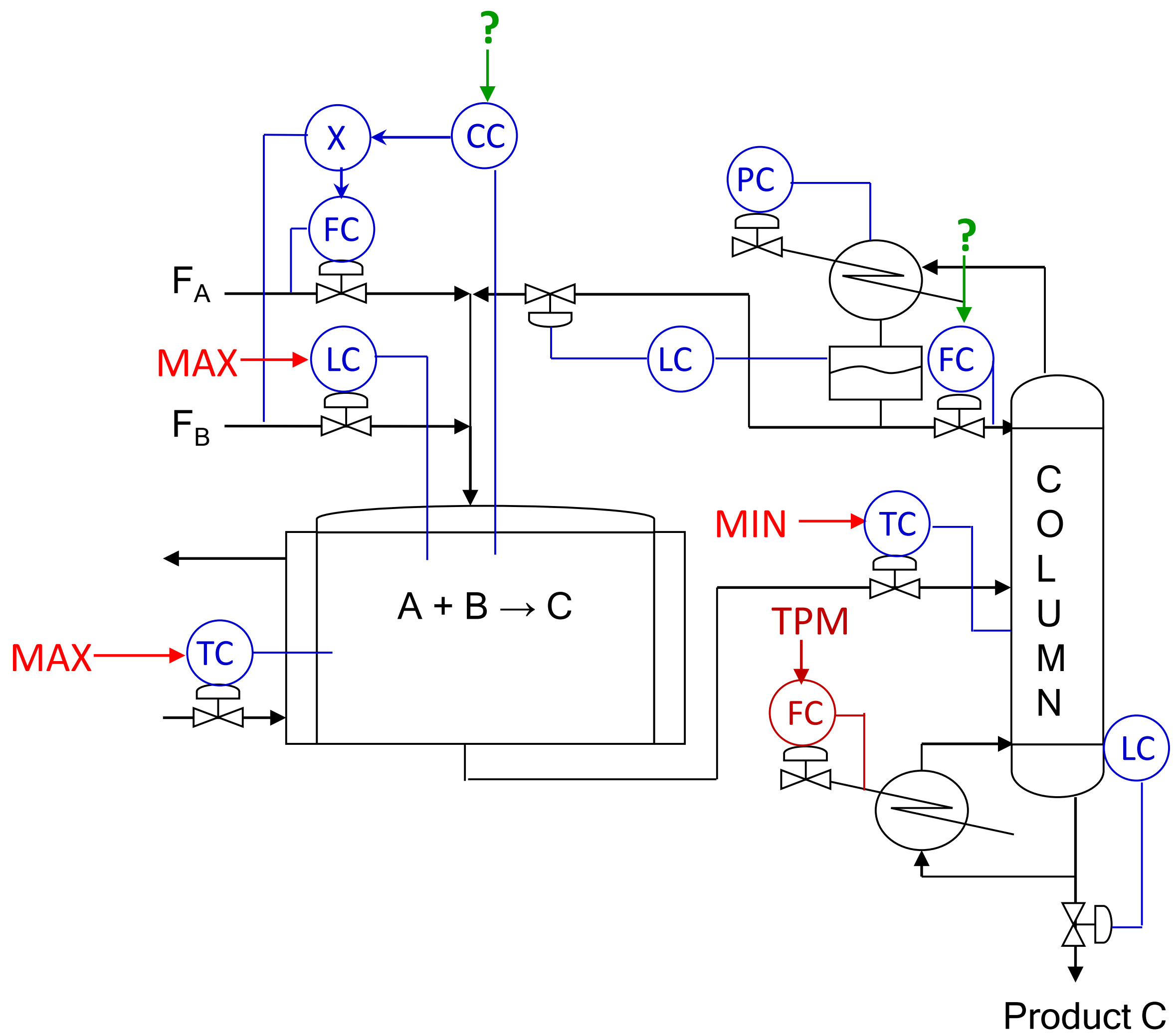
PWCS Design Exercise III

TPM Location Flexible: At Reactor Feed

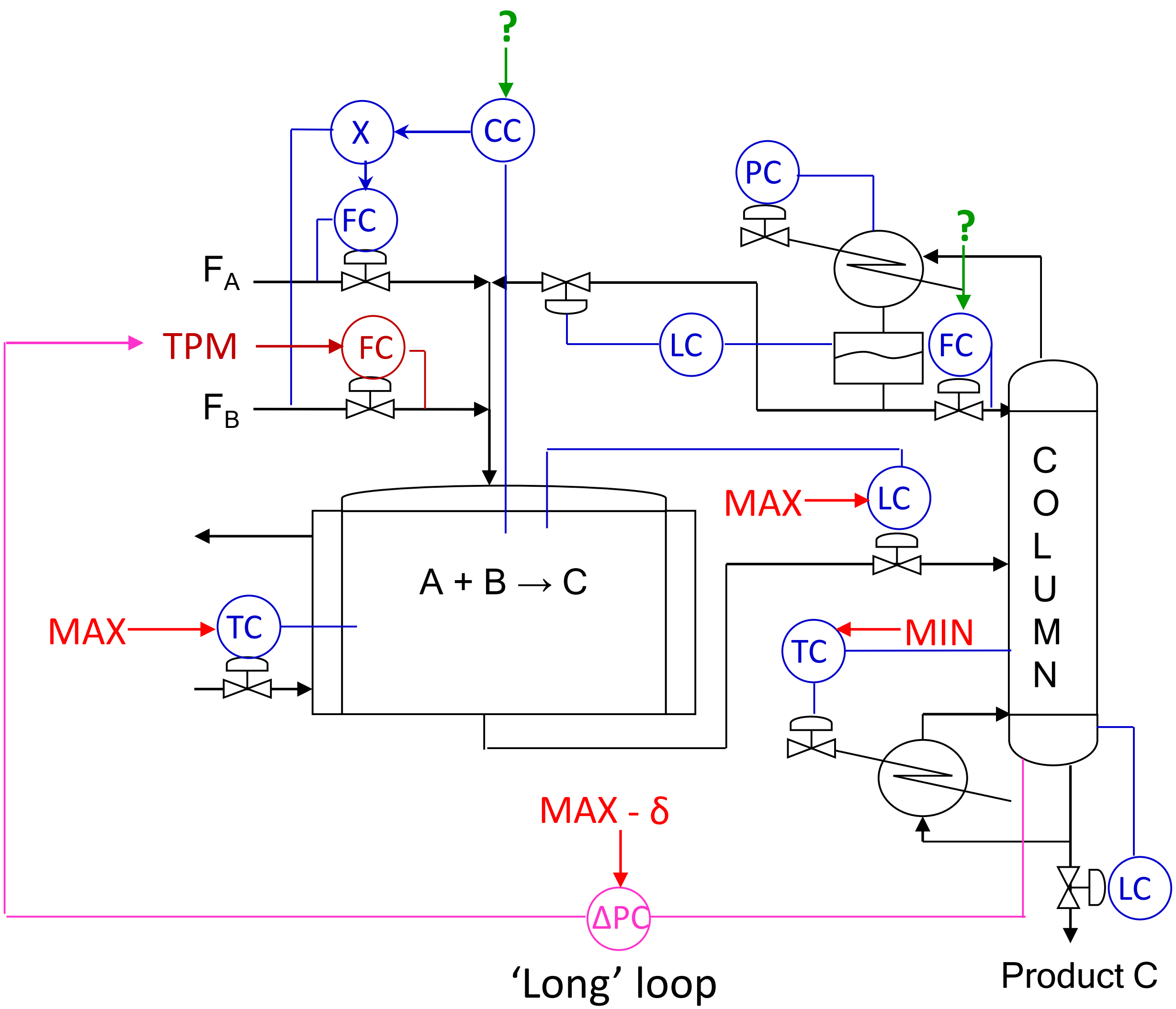


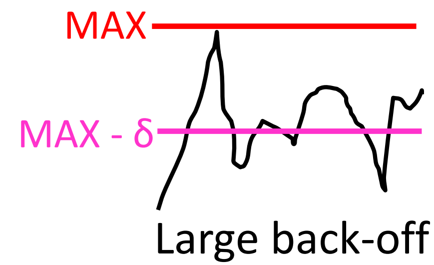
PWCS Design Exercise IV

TPM Location Flexible: At Column Boil-up



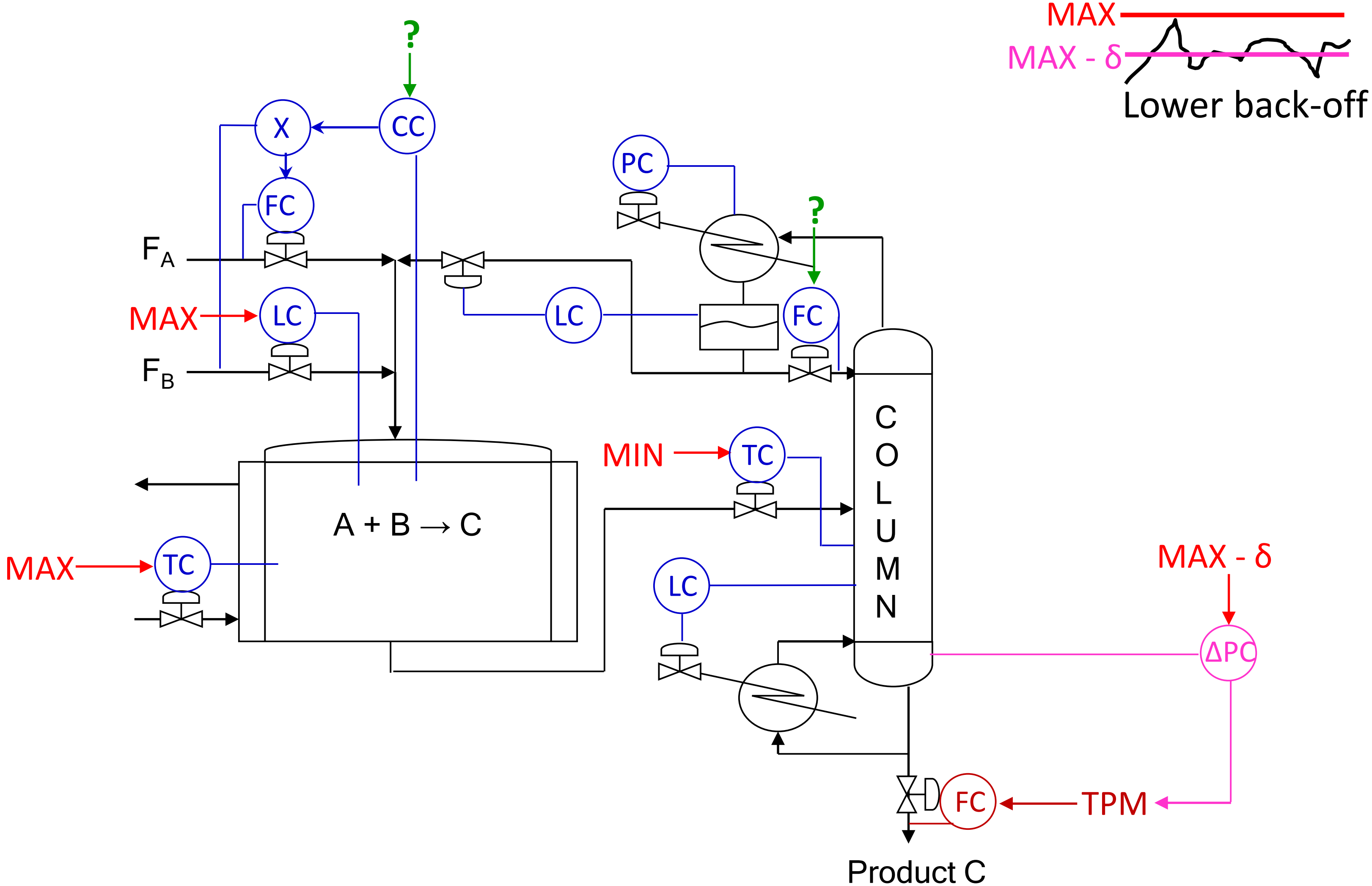
Throughput Maximization Exercise I



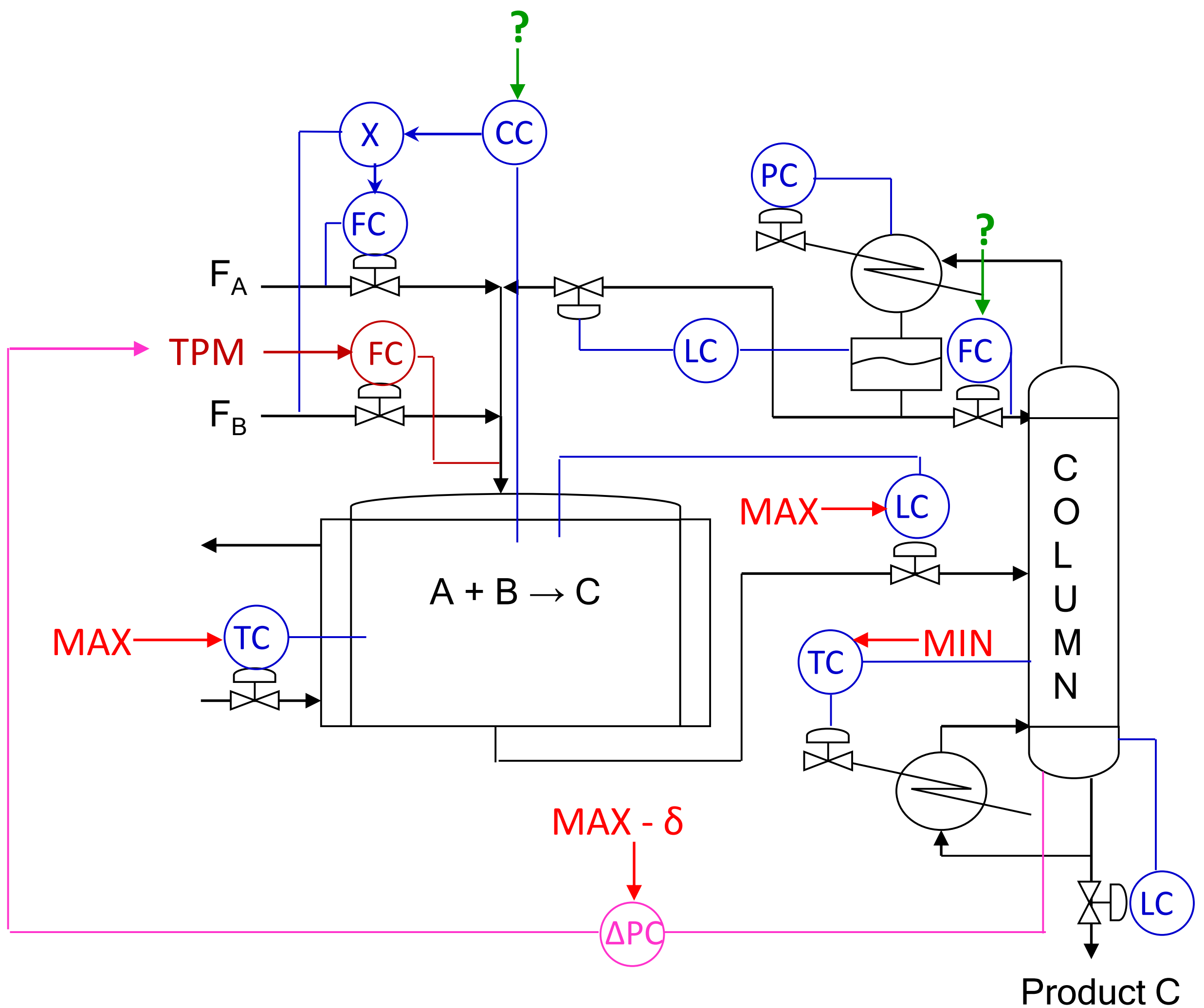


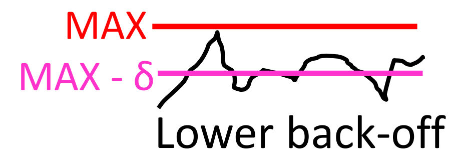
Throughput Maximization Exercise II

NOT A LIKELY SCENARIO FOR ON-DEMAND STRUCTURES

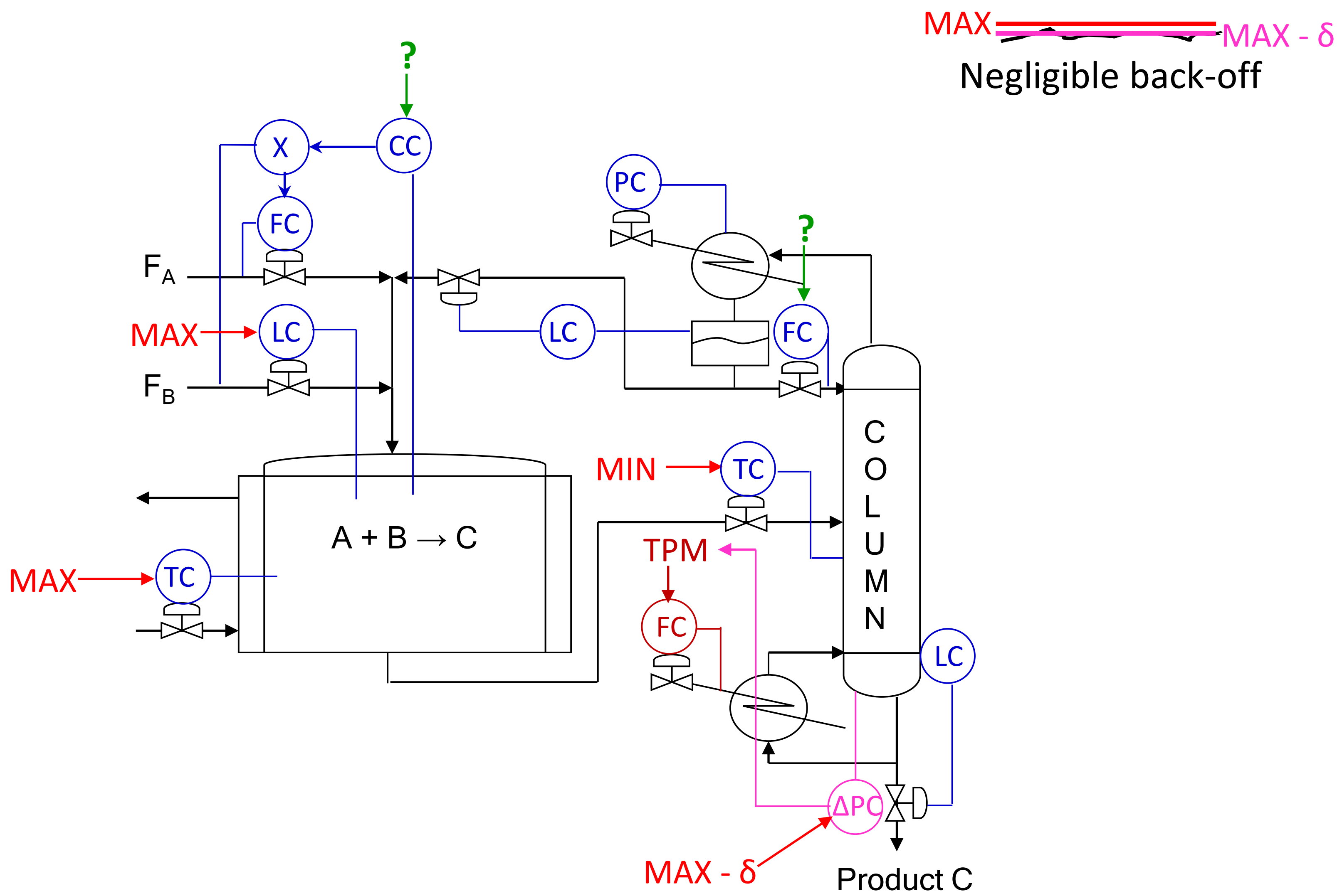


Throughput Maximization Exercise III





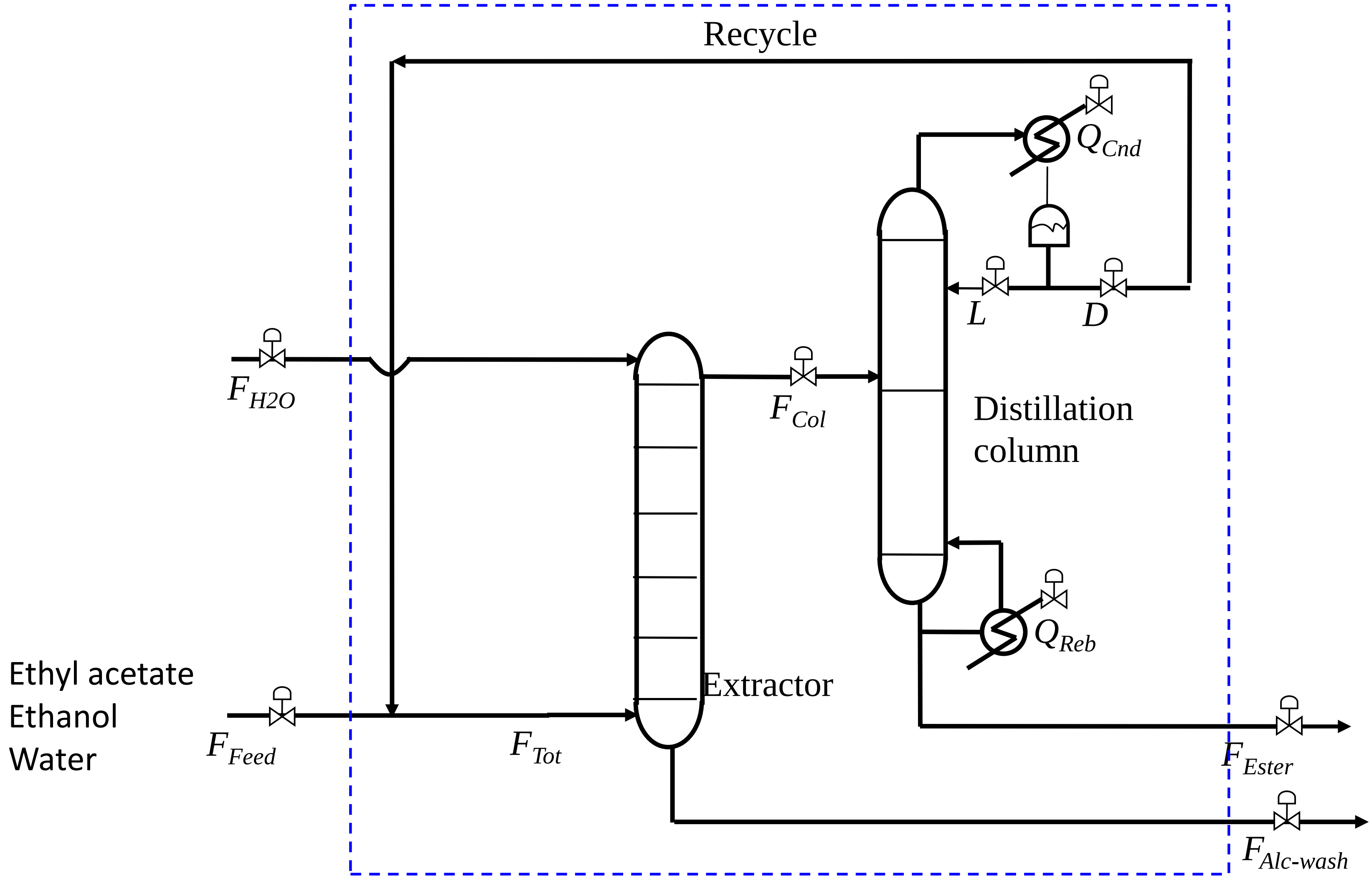
Throughput Maximization Exercise IV



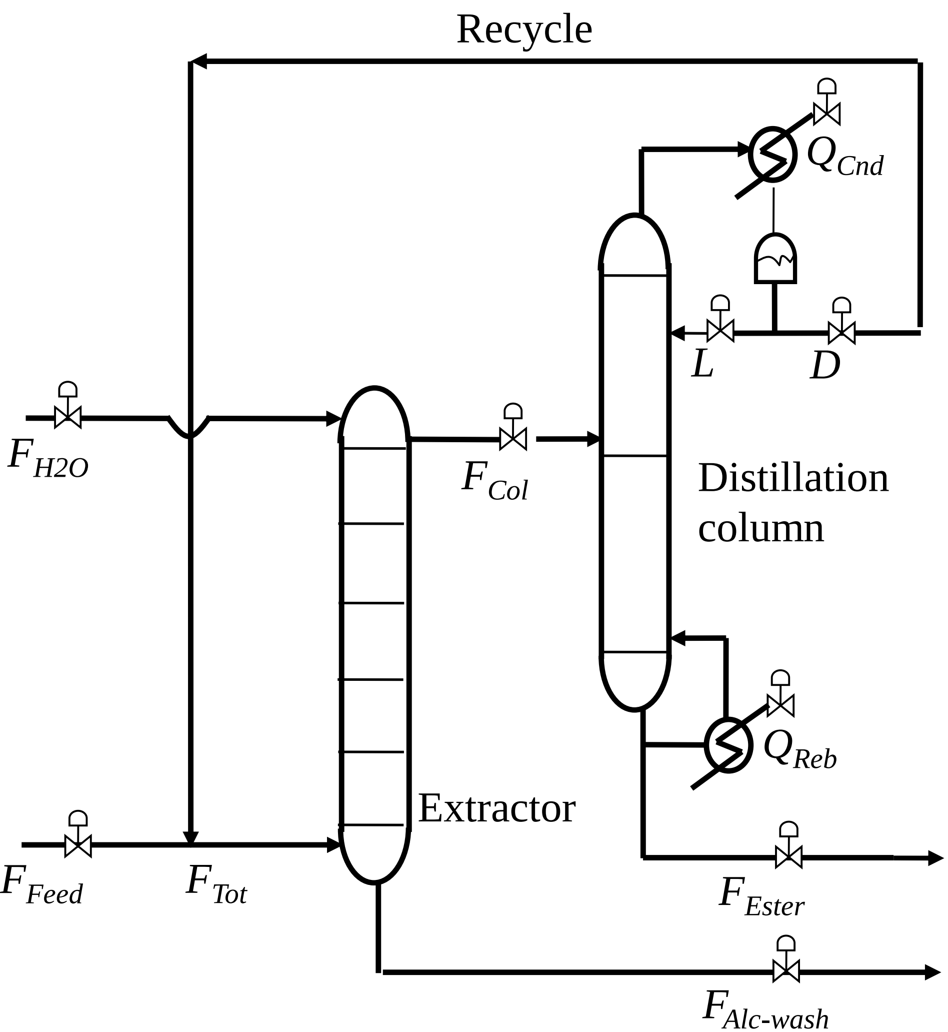
PWCS Design Steps

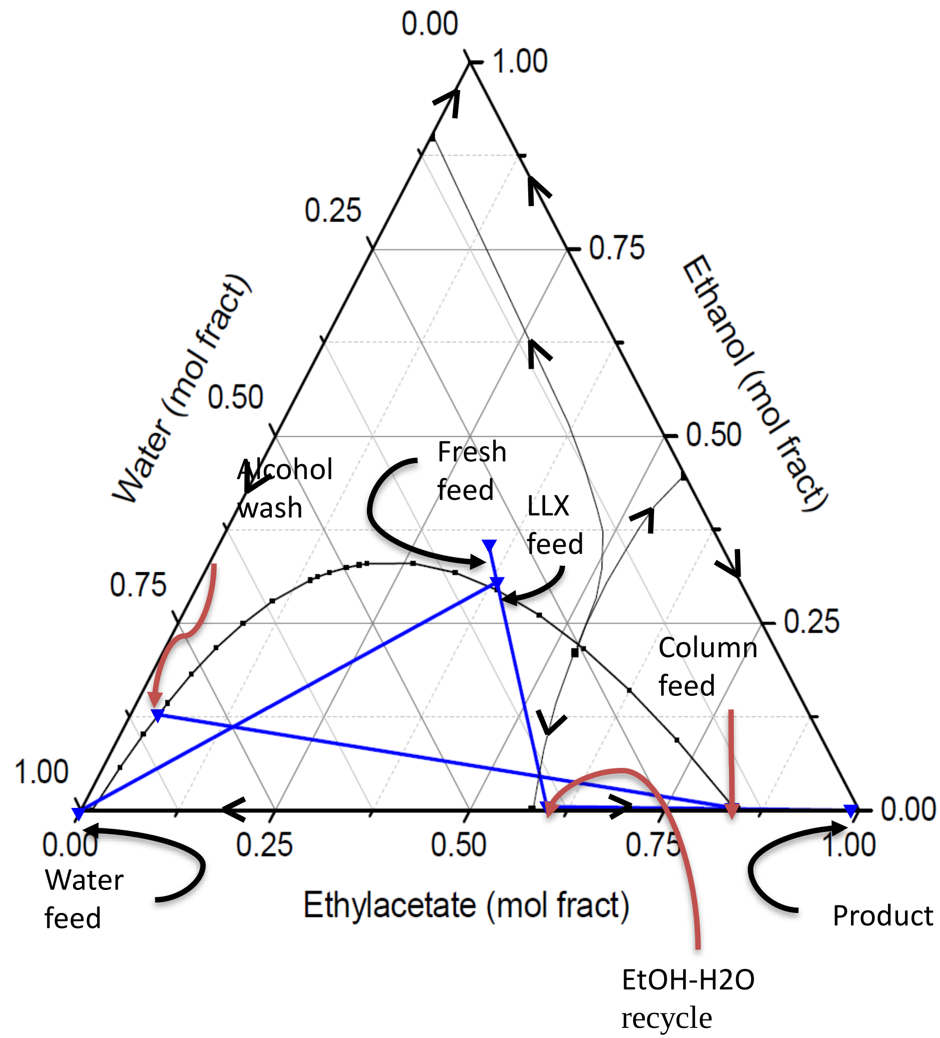
- DOF analysis and control objectives
  - Production rate
  - Product quality
  - Safety limits (eg UFL < gas loop composition < LFL)
  - Economic
- Choose TPM
  - Feed set by an upstream process
  - On demand operation (utility plants)
  - Flexible
    - Inside the recycle loop at the feed of the most non-linear/fragile unit
    - If bottleneck is known, at the bottleneck inside the recycle loop
- Design "local" loops for closing all independent material and energy balances around the TPM
  - Radiate outwards from the TPM
  - Check consistency of material / energy balance closure (**Downs' Drill**)
- Choose loop setpoints "wisely"
  - Usually governed by economic considerations

Case Study I: Ester Purification Process



Flowsheet Material Balances



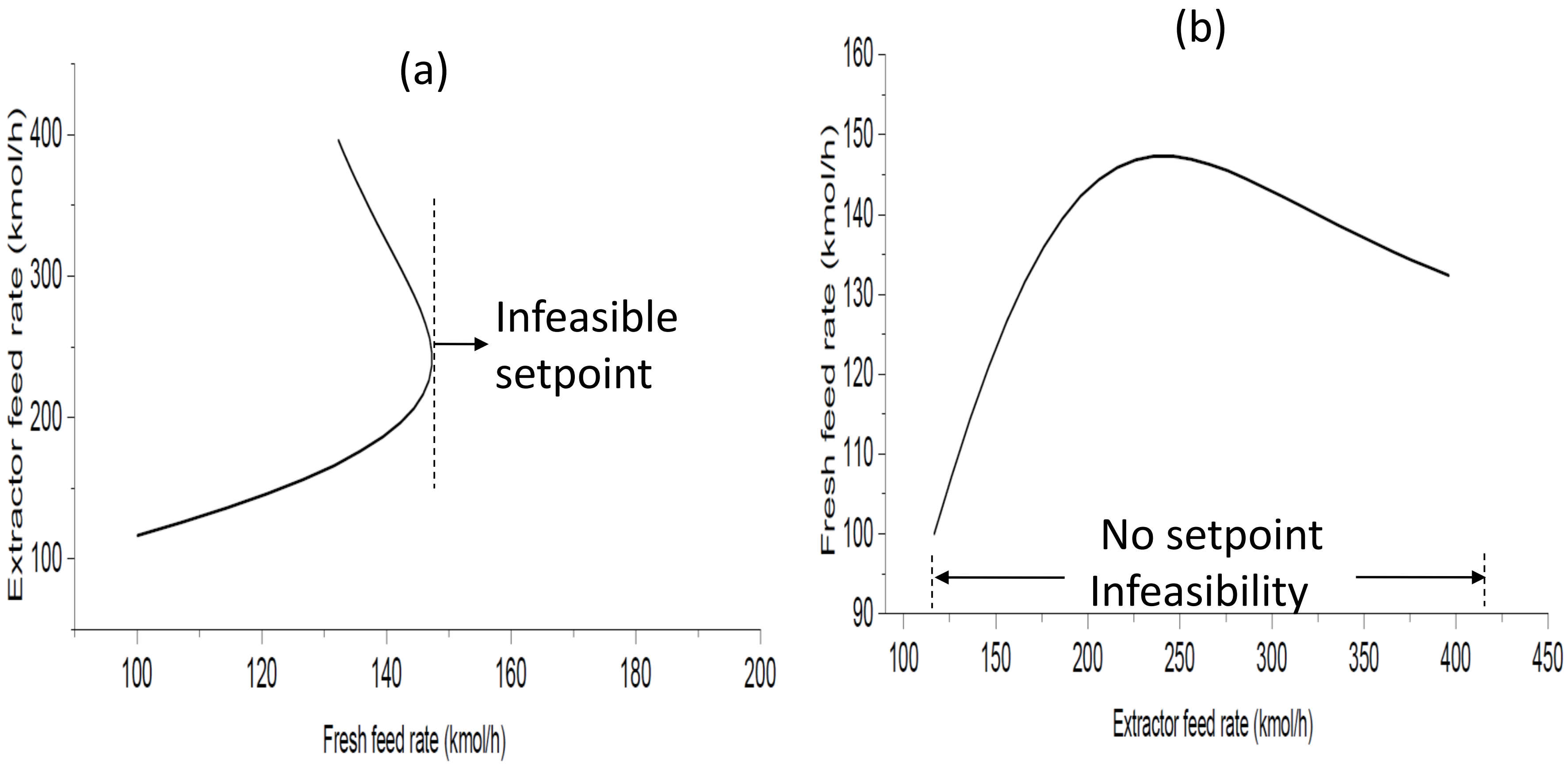


Control Objective

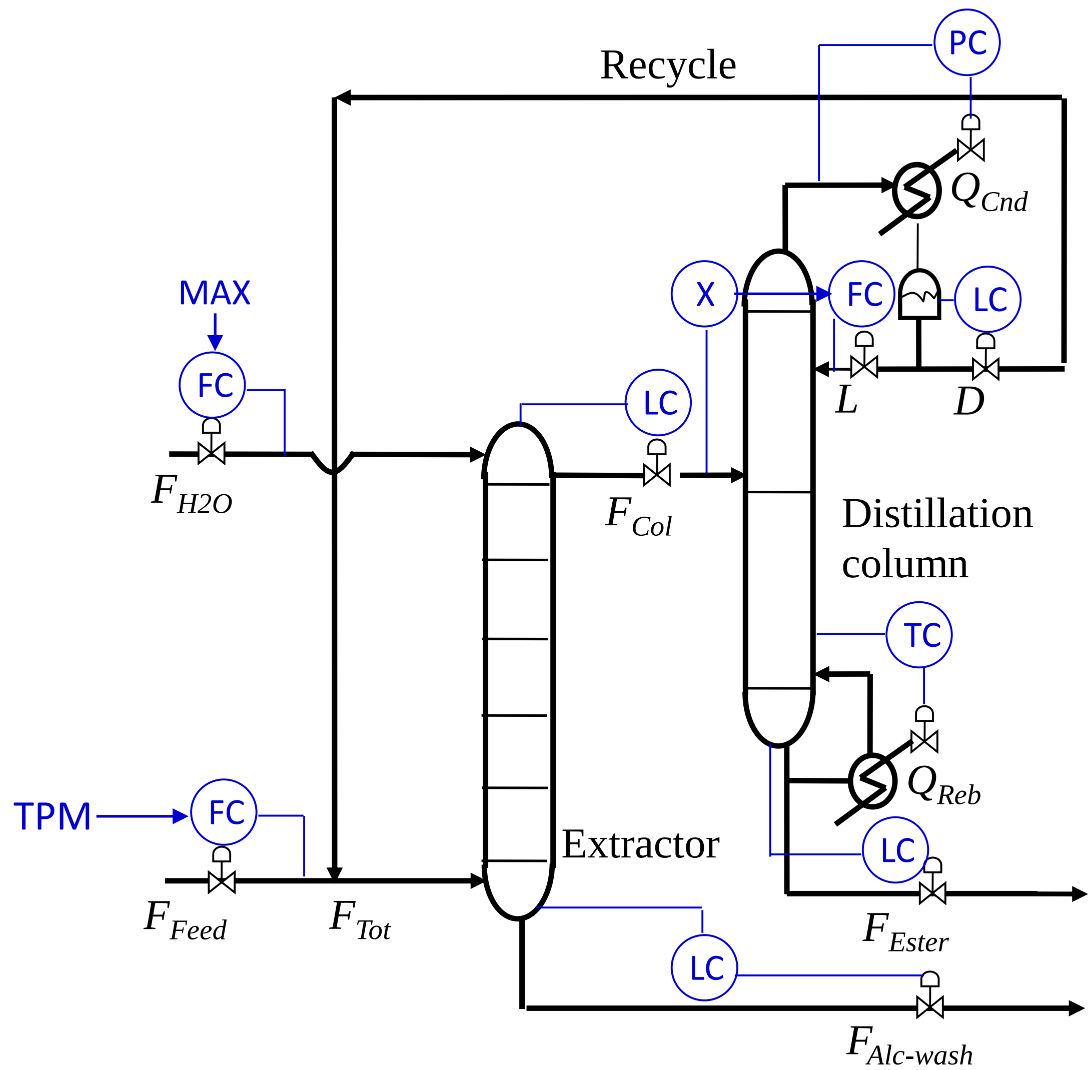
- Operate plant to maximize ester production
- BOTTLENECK
  - Maximum water solvent rate to the extractor
    - Hydraulic constraint
  - Limits alcohol extraction capacity

Steady State Bifurcation Analysis

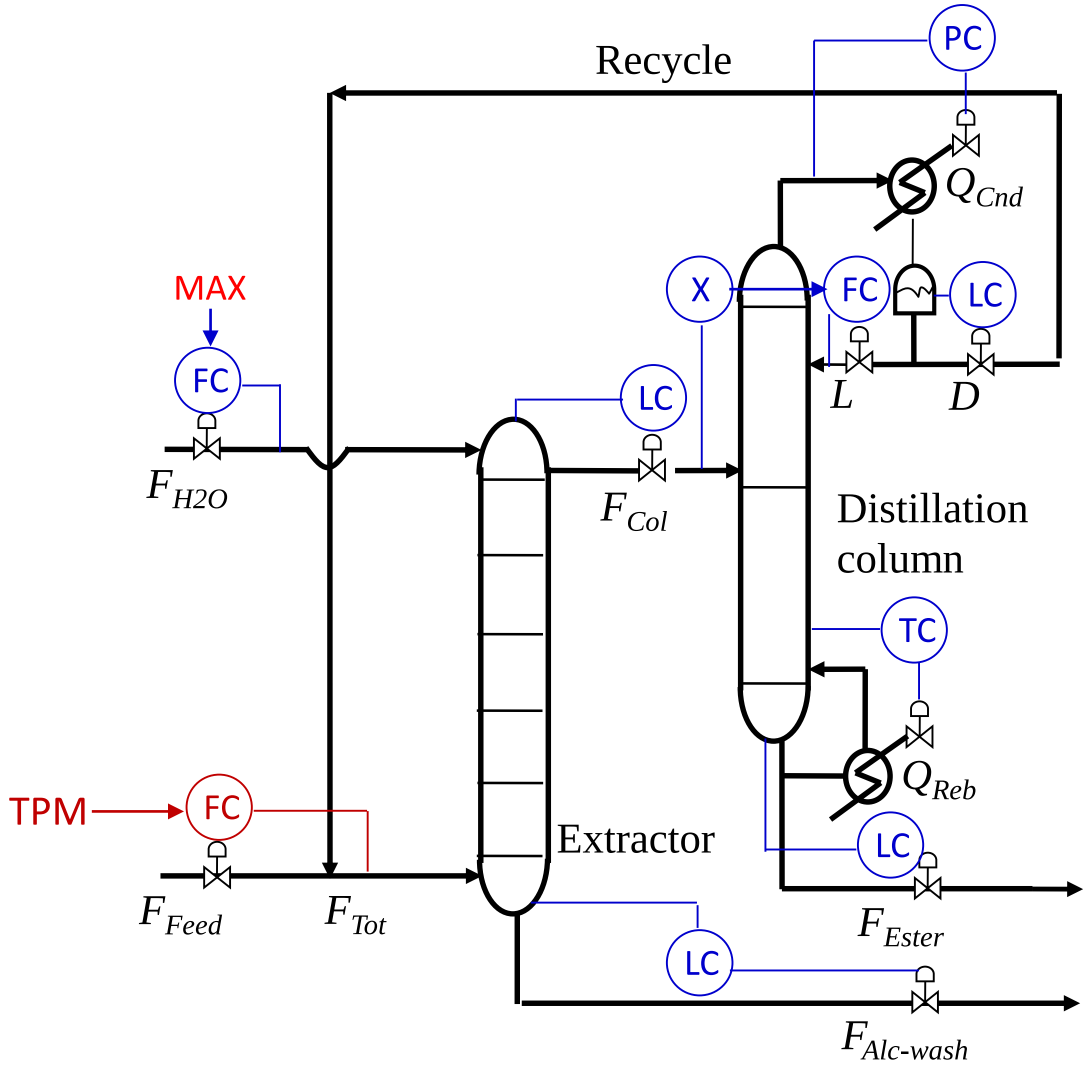
Fresh Water Rate = MAX



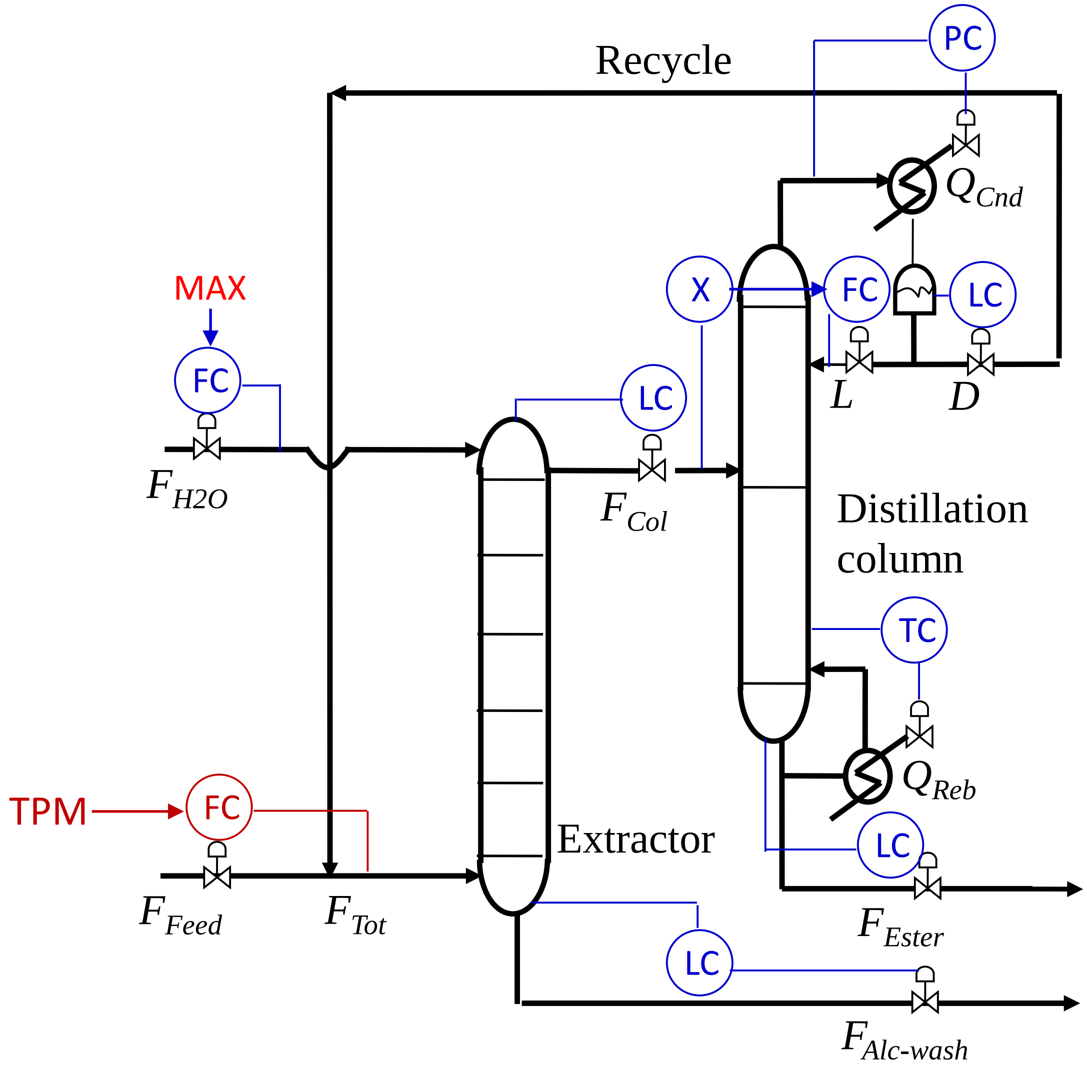
Control Structure 2



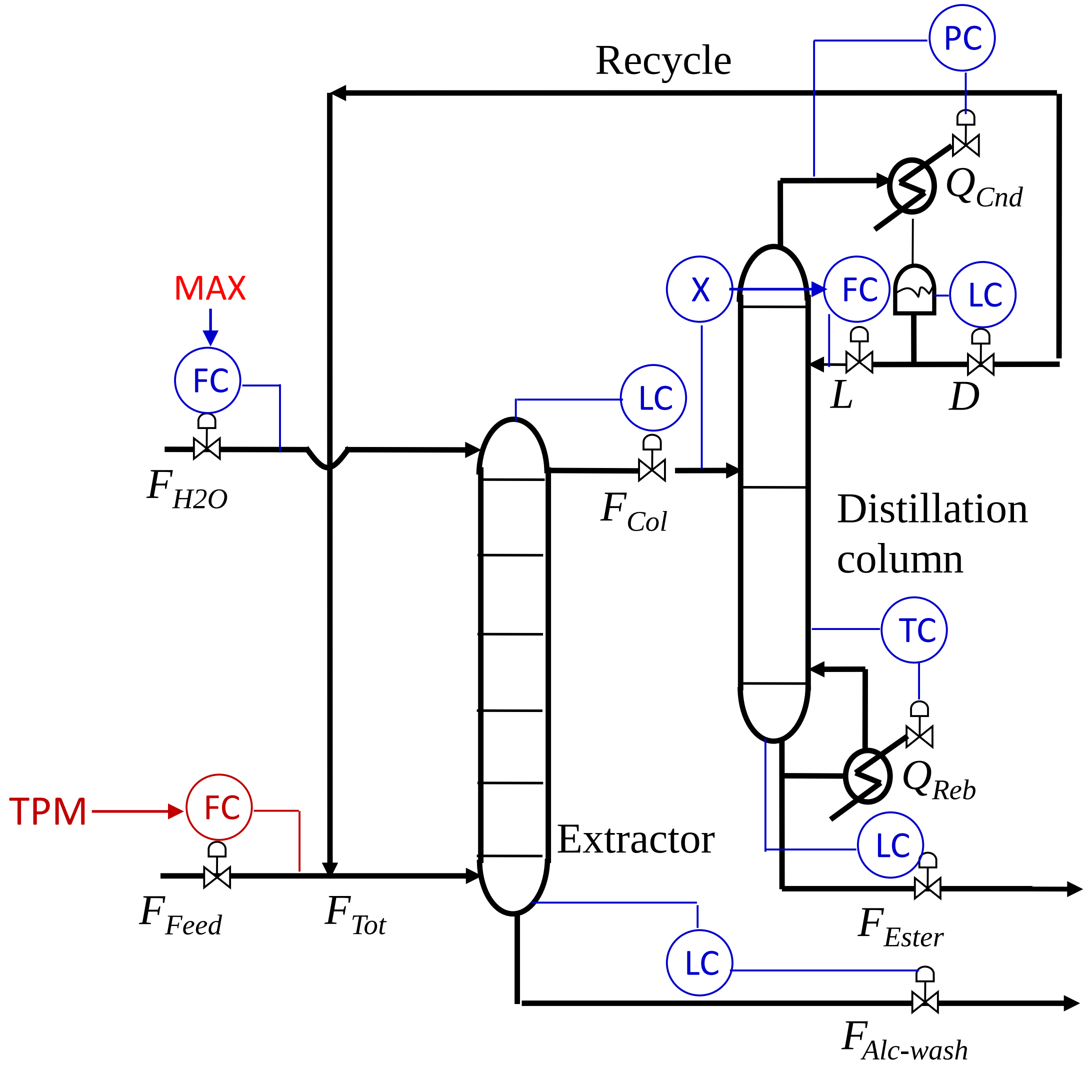
CS1: TPM at Bottleneck Feed



CS1: TPM at Bottleneck Feed

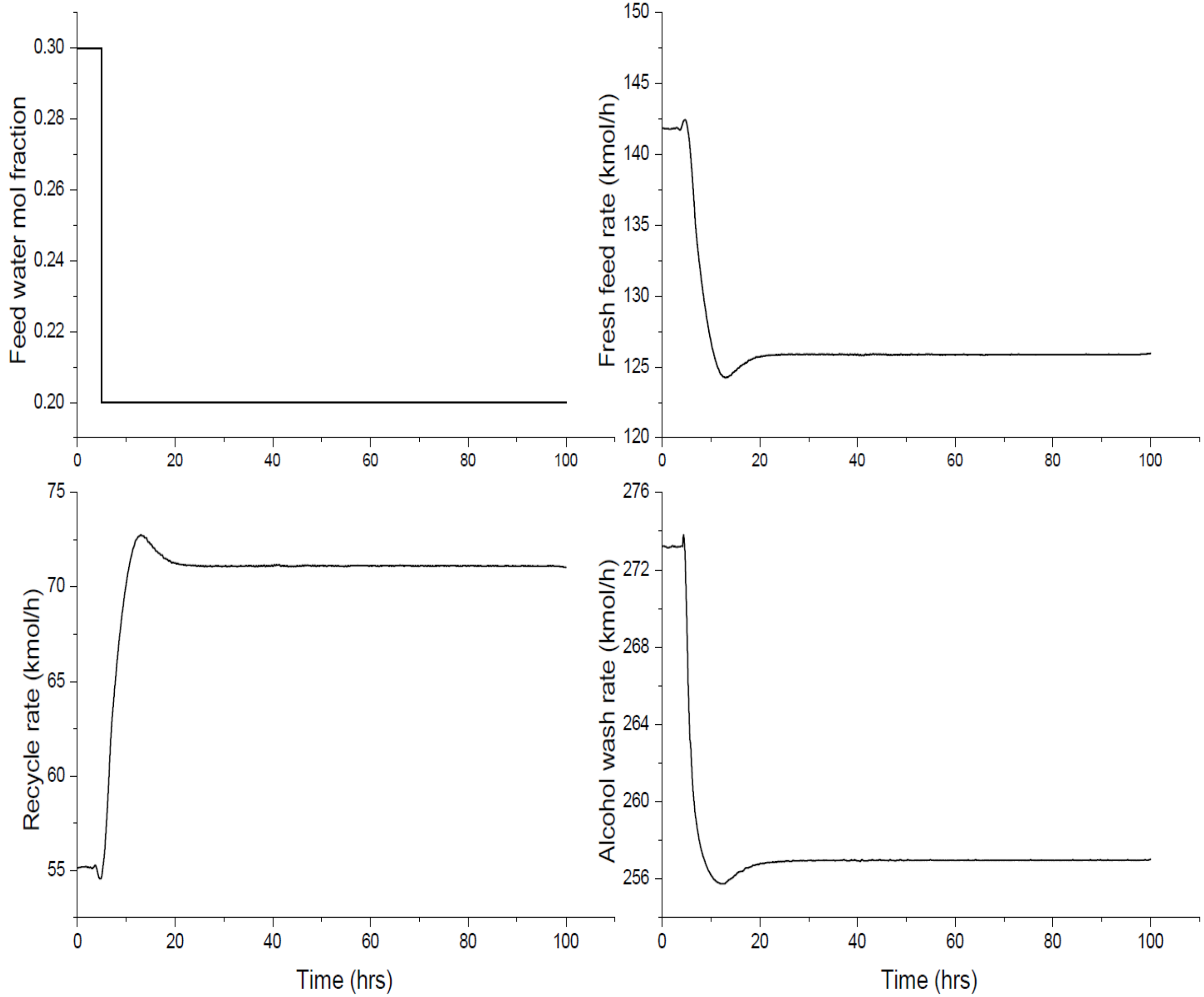


CS2: TPM at Fresh Feed



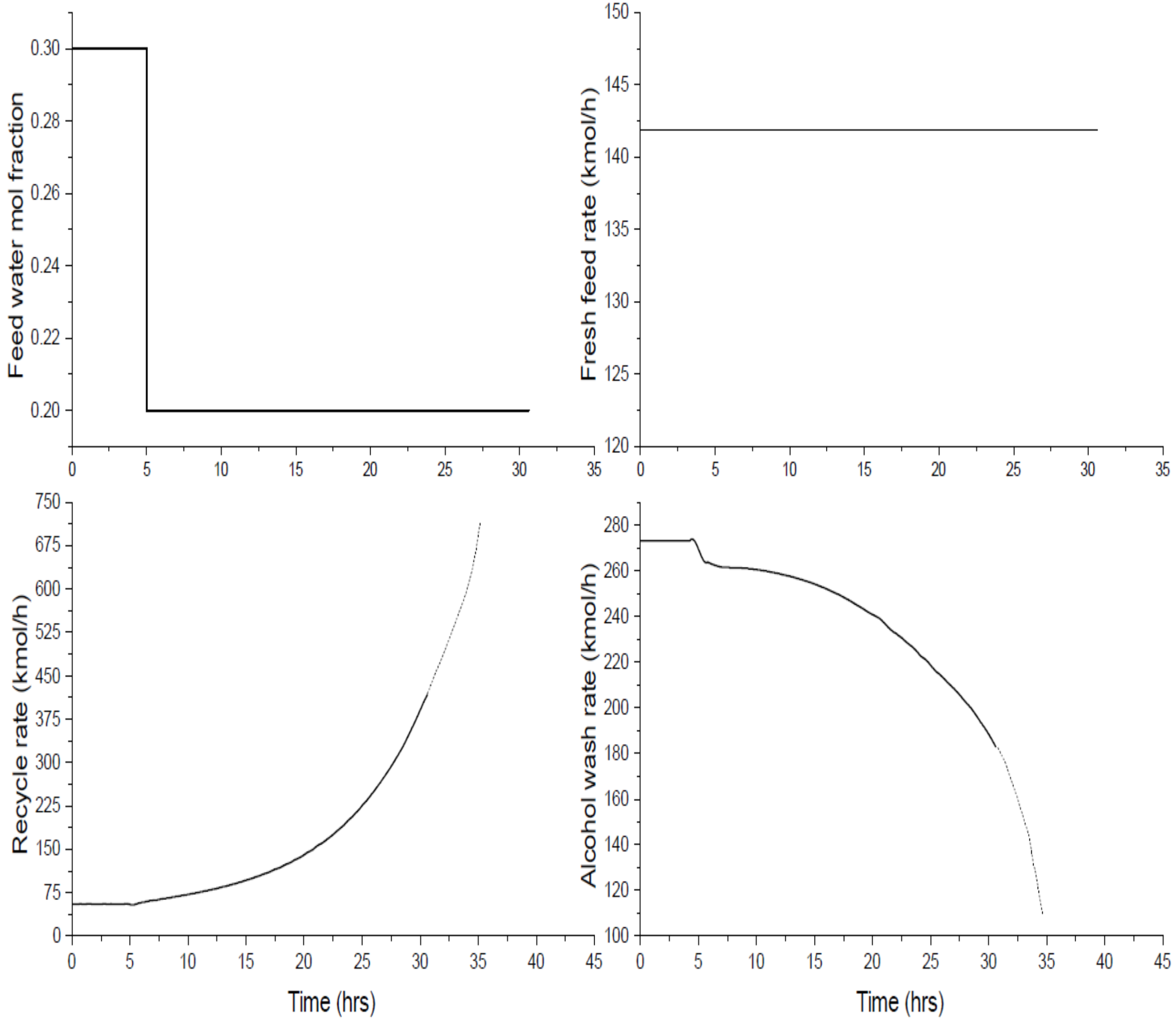
CS1 Closed Loop Transients

Large Feed Composition Change

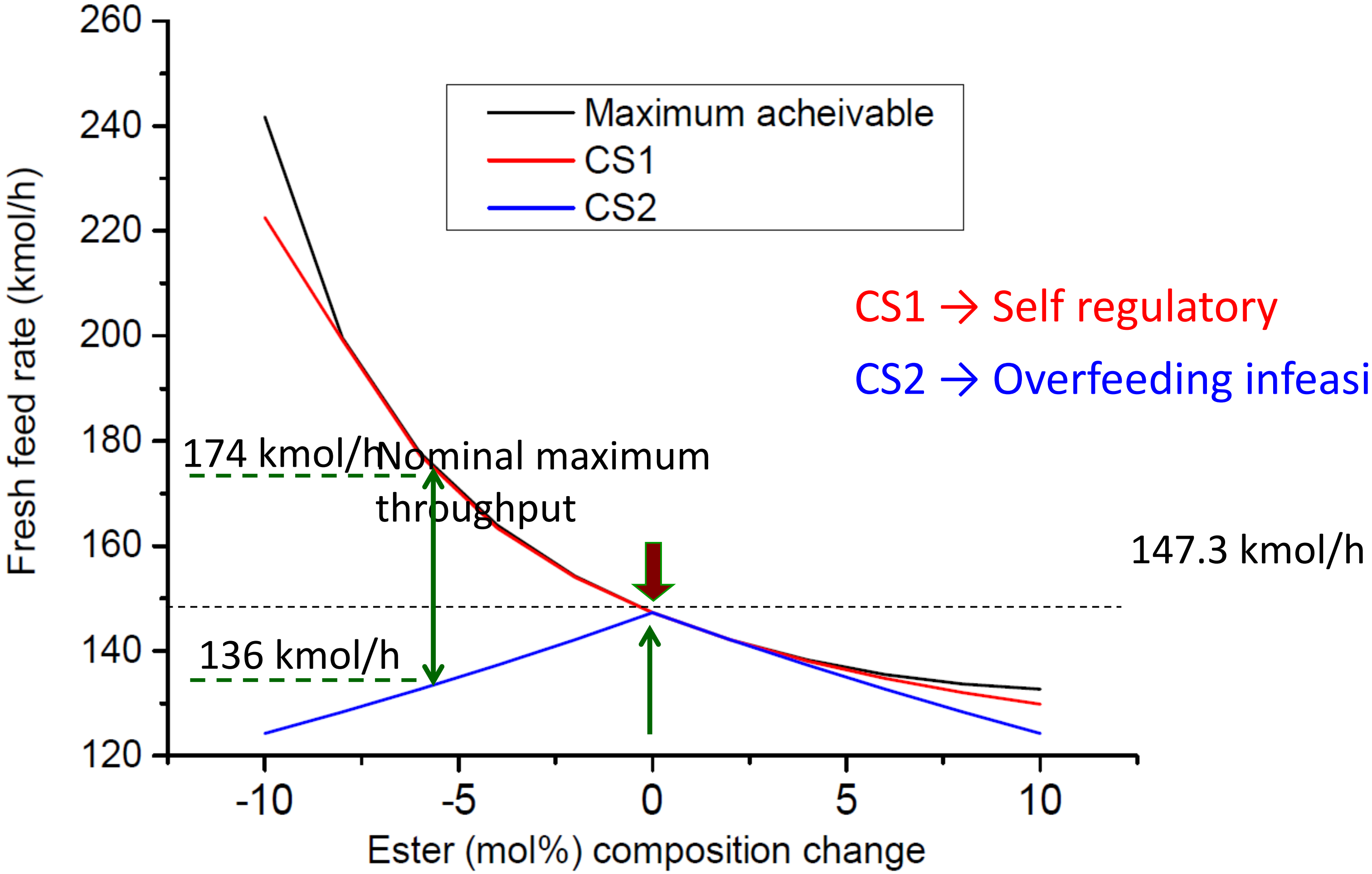


CS2 Closed Loop Transients

Large Feed Composition Change



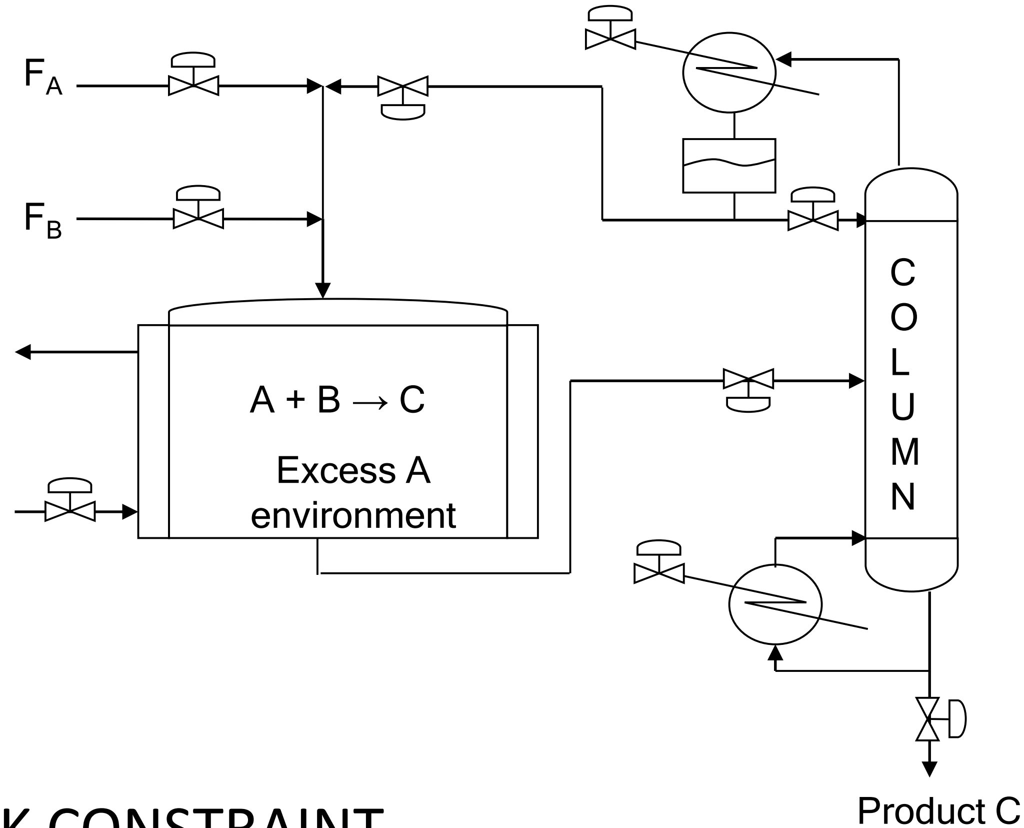
Throughout Maximization Results



CS1 → Self regulatory

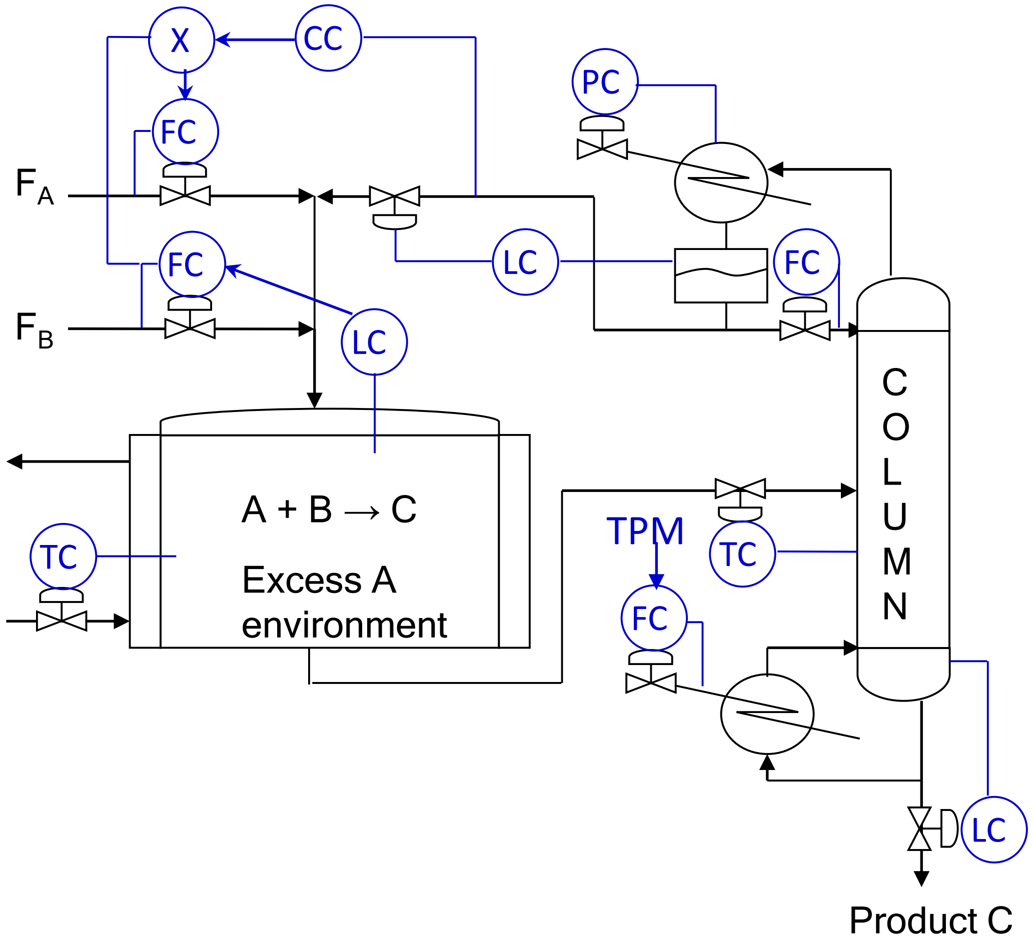
CS2 → Overfeeding infeasibility

CASE STUDY 2: Simple Recycle Process

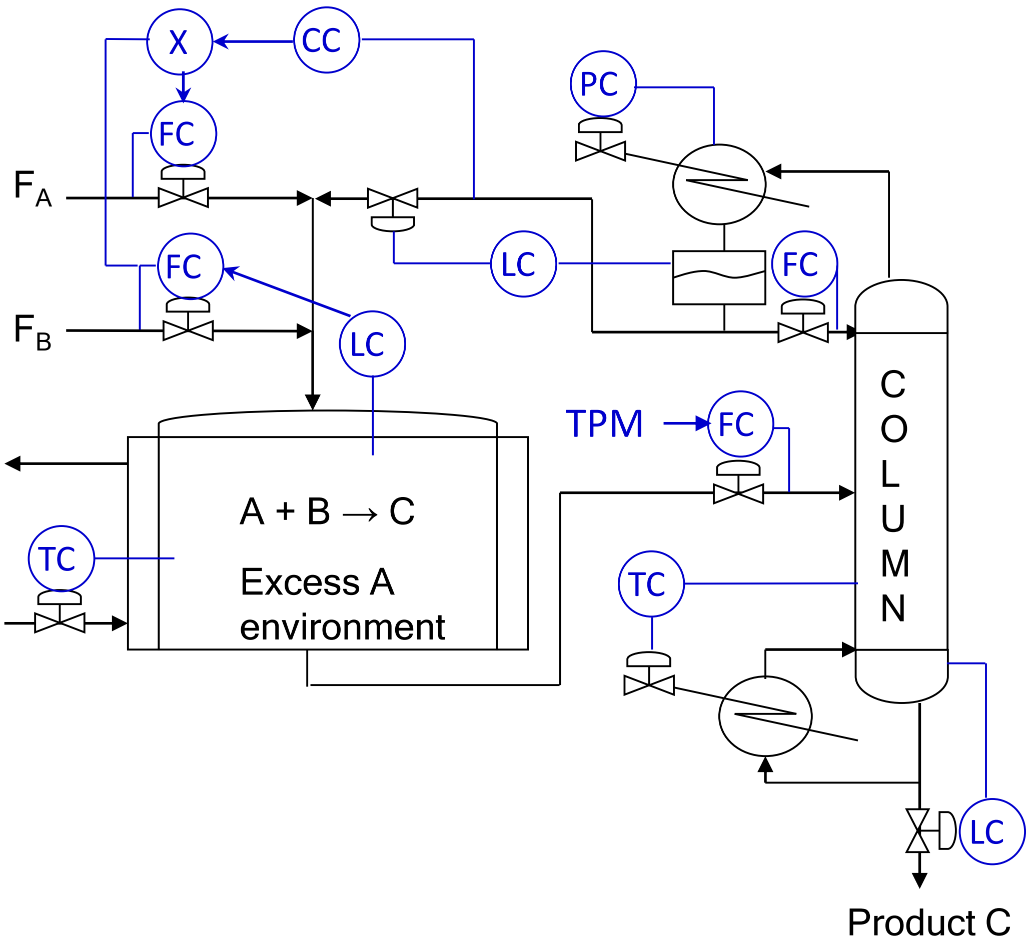


BOTTLENECK CONSTRAINT
Maximum Column Boilup

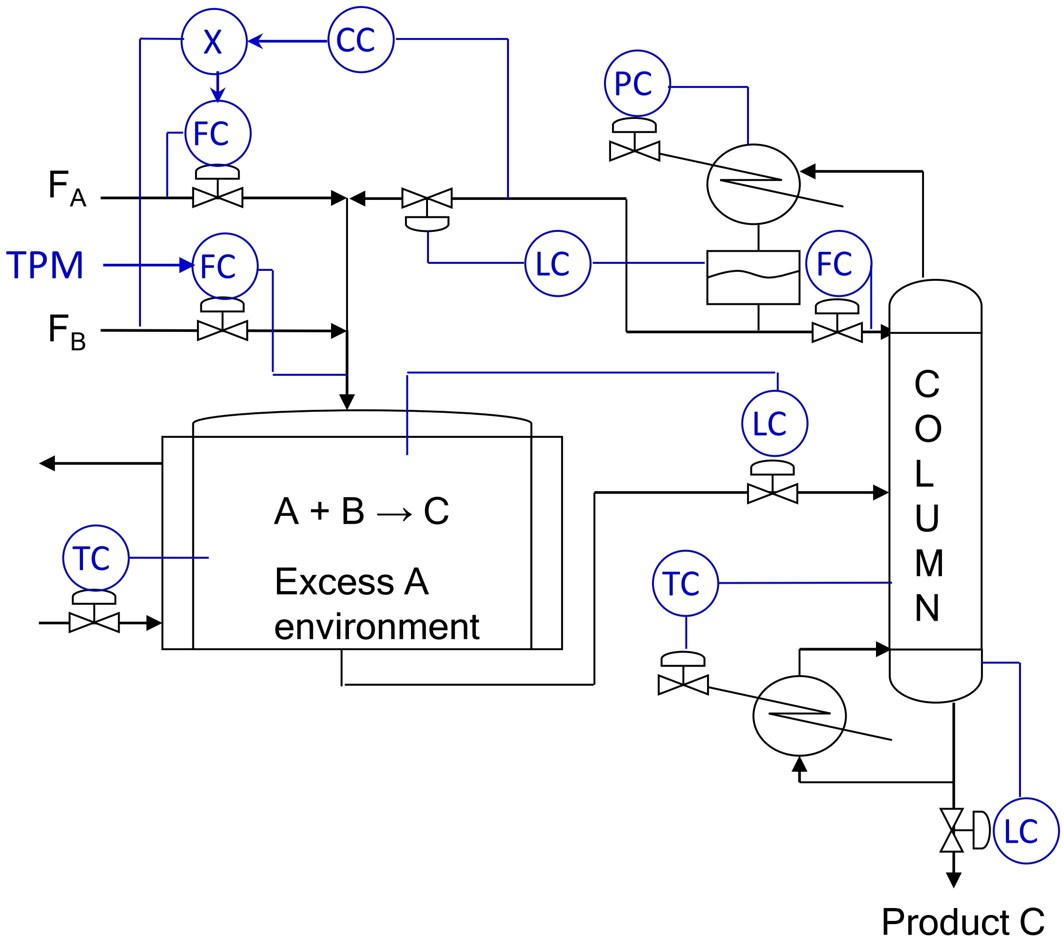
Control Structure 0



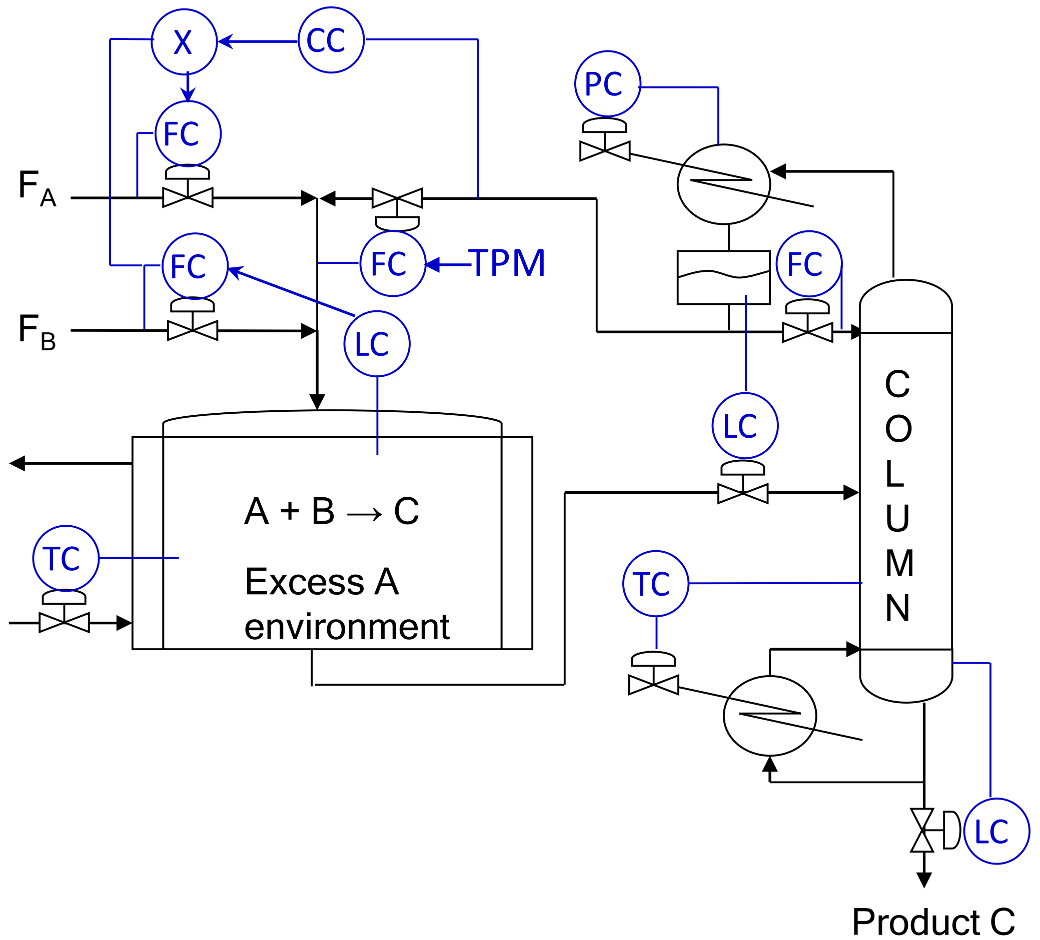
Control Structure 1



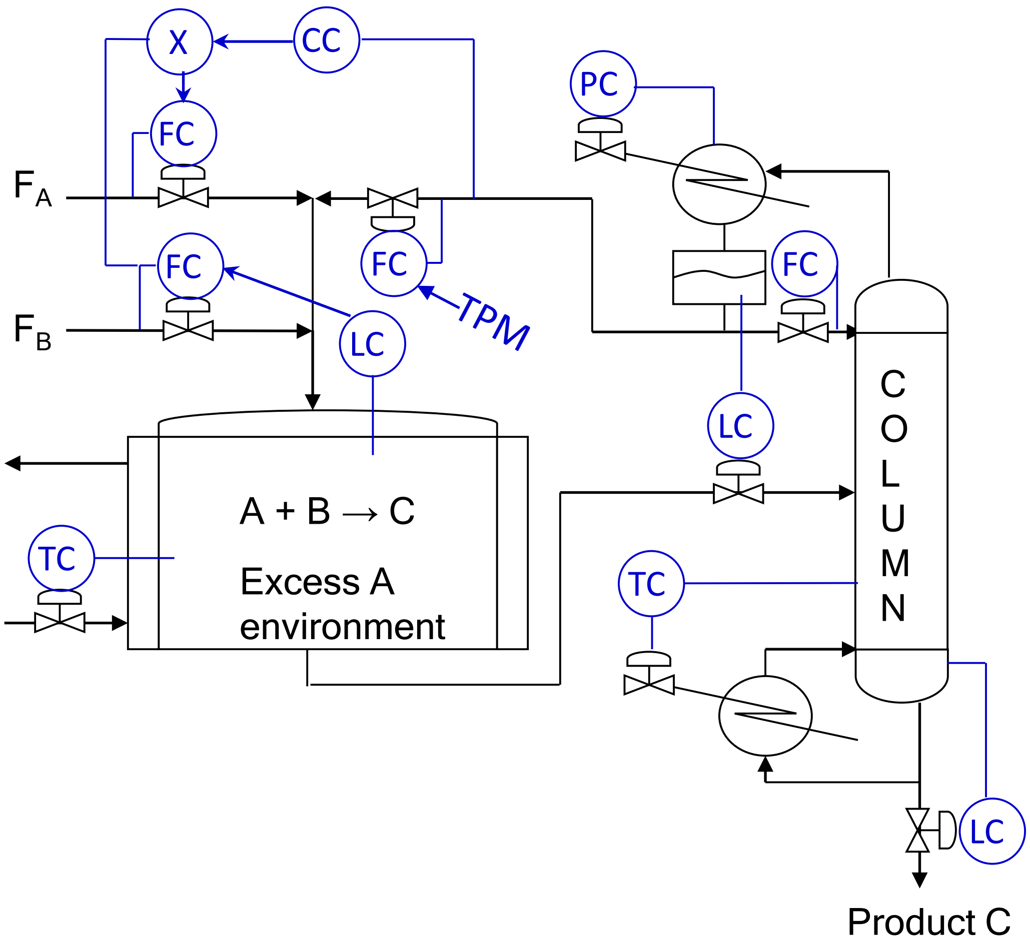
Control Structure 2



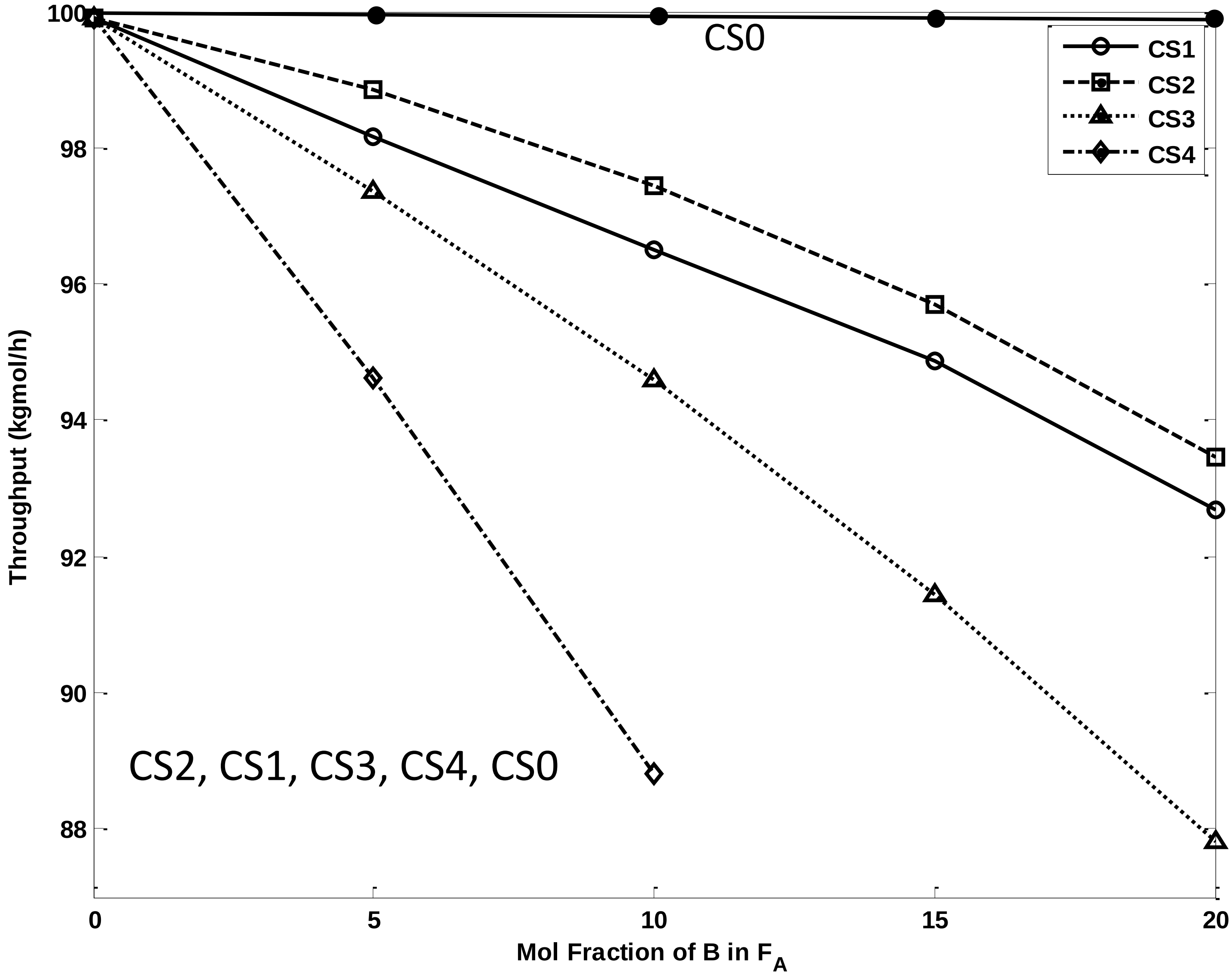
Control Structure 3



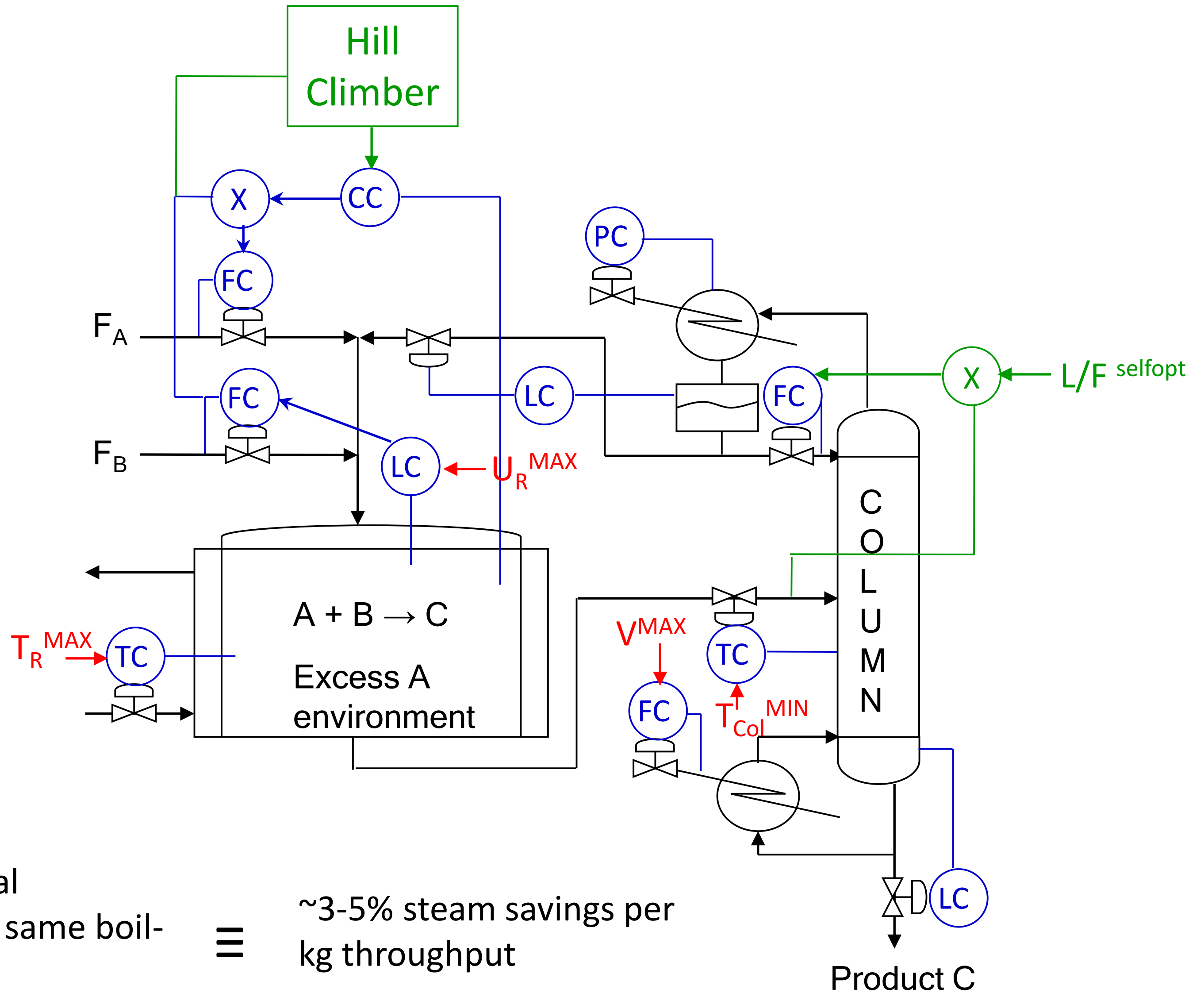
Control Structure 4



Maximum Throughput Results



Managing Unconstrained DOFs



~3-5% additional throughput for same boil-up ≡ ~3-5% steam savings per kg throughput

Summary

- Key guideline for recycle system PWC
  - Structure control system to hold recycle rate by manipulating in / out streams in loop
- Holding a fresh feed rate constant is NOT a good idea
- Locate TPM at bottleneck inside recycle loop
- Economic considerations play a major role in regulatory control layer design
- Quantitative case study results
  - Significantly higher maximum achievable throughput with fresh feed as make-up stream
- COMMON SENSE MUST PREVAIL