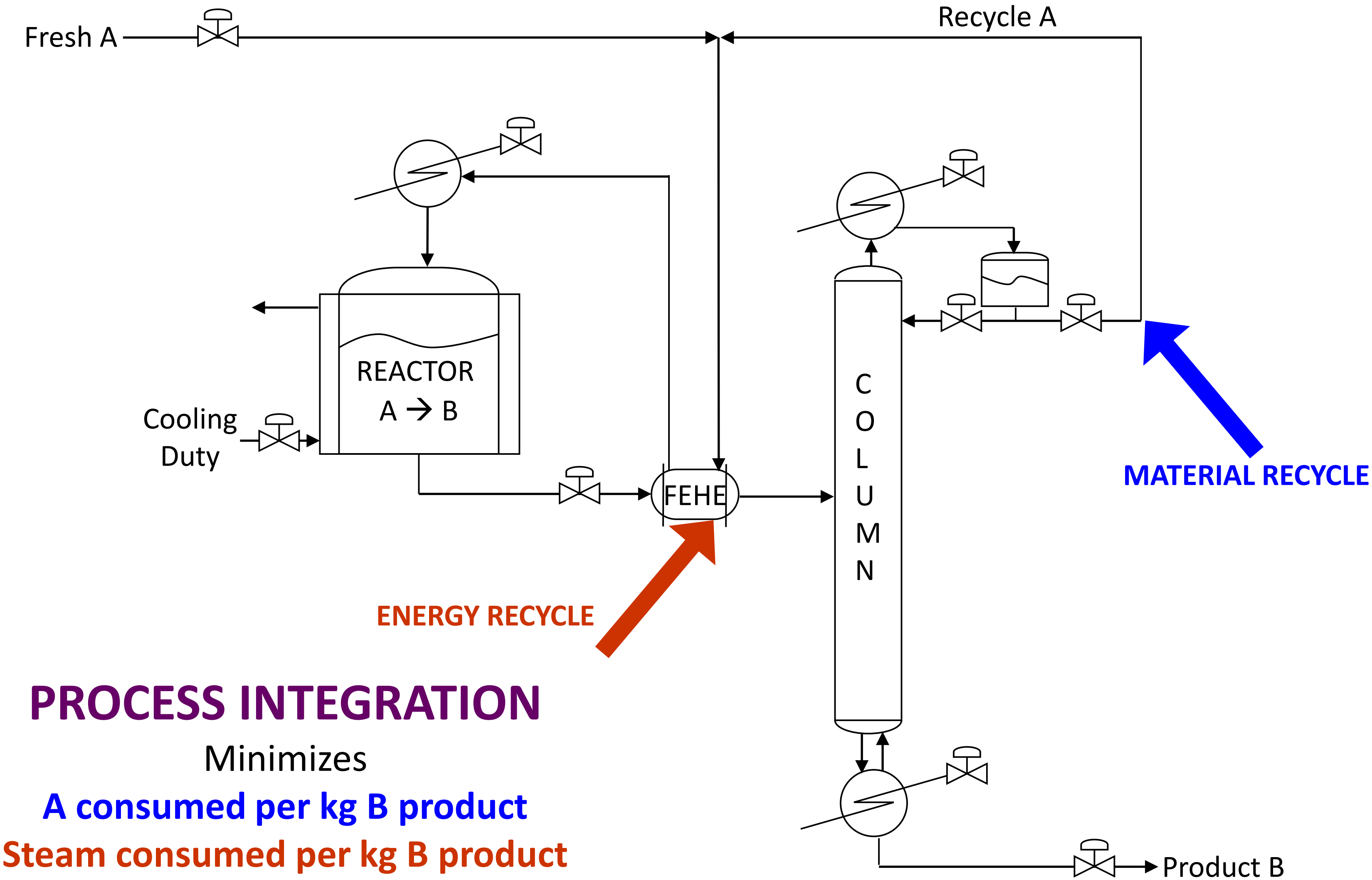
PWC Basics: A Simple Chemical Process



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

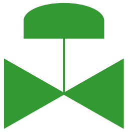
- Ambient Conditions
- Raw material Quality
- Sensor Noise
- Equipment Characteristics

PWC Basics

Safety

Stability ≡ **Operate Process at Steady State**

Accumulation Rate $\rightarrow$ 0 = Rate In − Rate Out + Generation Rate



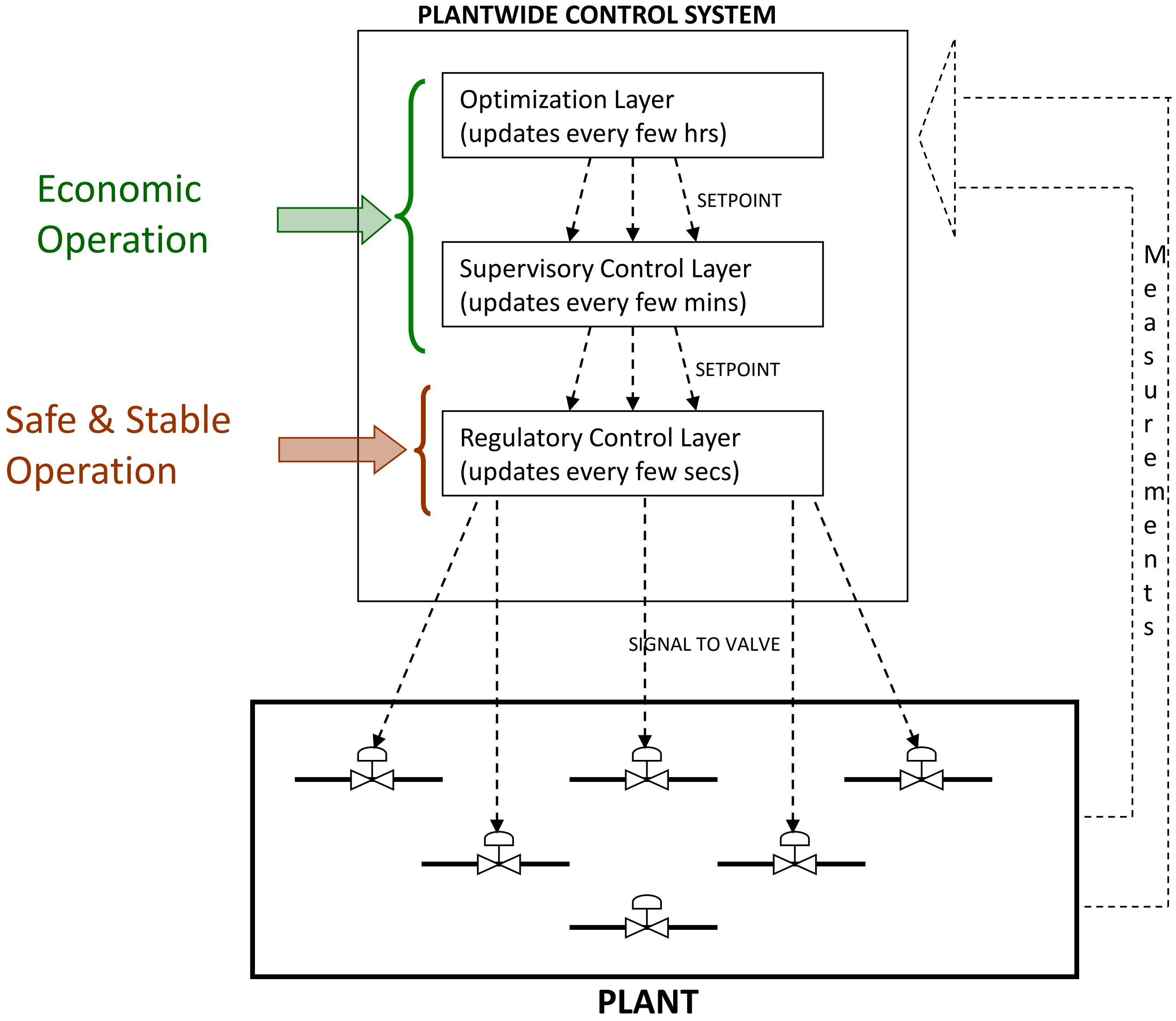
Need PWC to drive accumulation of all independent inventories to zero

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

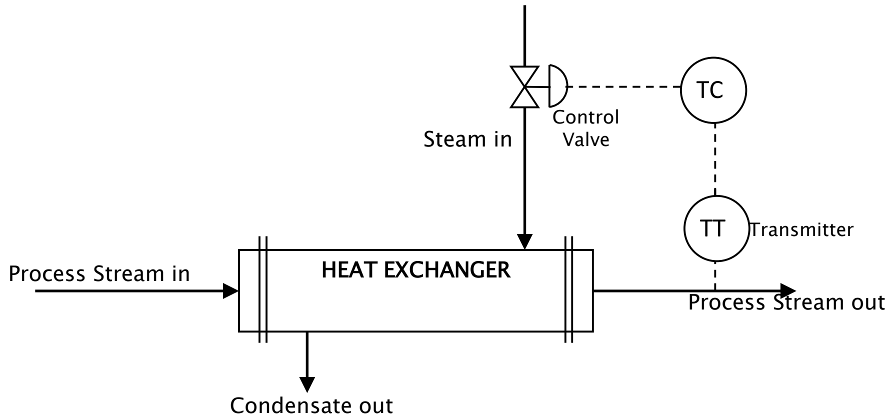


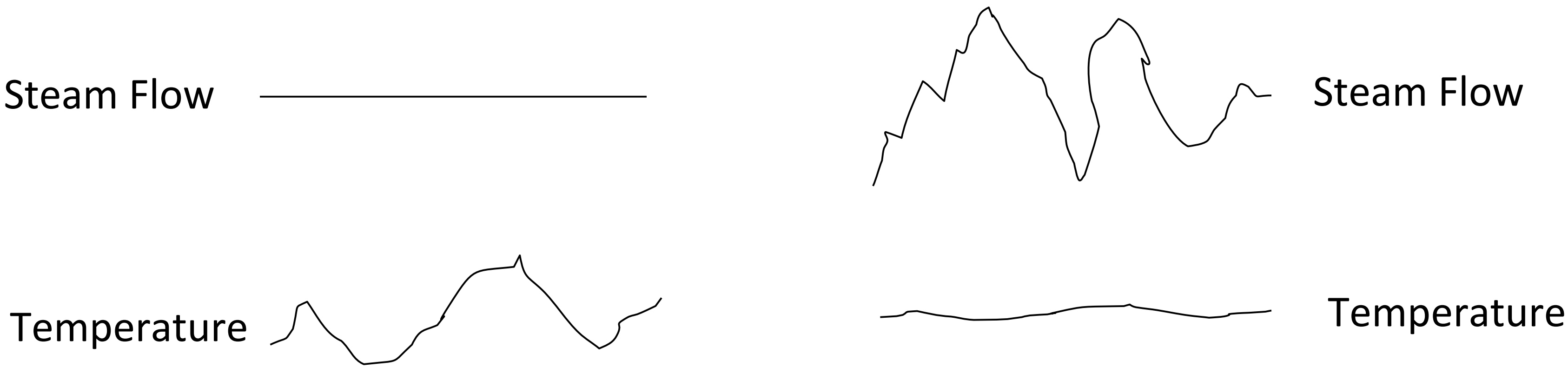
Regulatory PWCS Design

- 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
  - Pair close
    - Fast dynamics
    - Tight closed loop control
- Location of through-put manipulator a key decision for inventory management and economics

The Transformation of Variability Perspective

HEAT EXCHANGER EXAMPLE





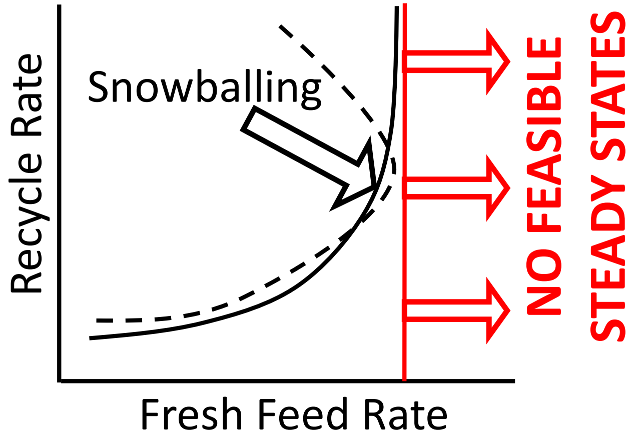
CONTROL SYSTEM

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 to avoid large drifts
  - All equipment inside recycle loop see acceptable variability

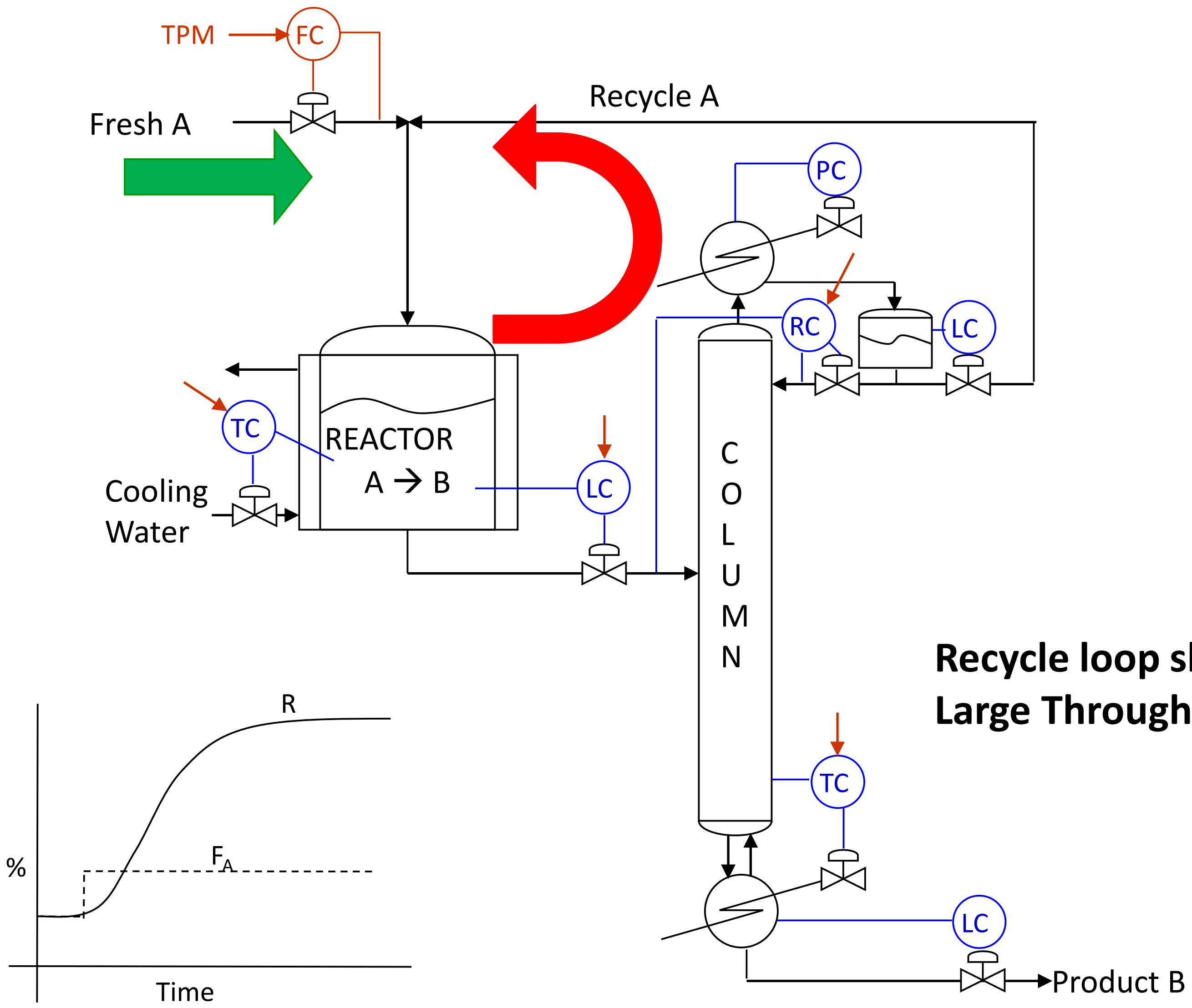
Nonlinearity in Material Recycle Loops



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

Possibility of overfeeding induced instability

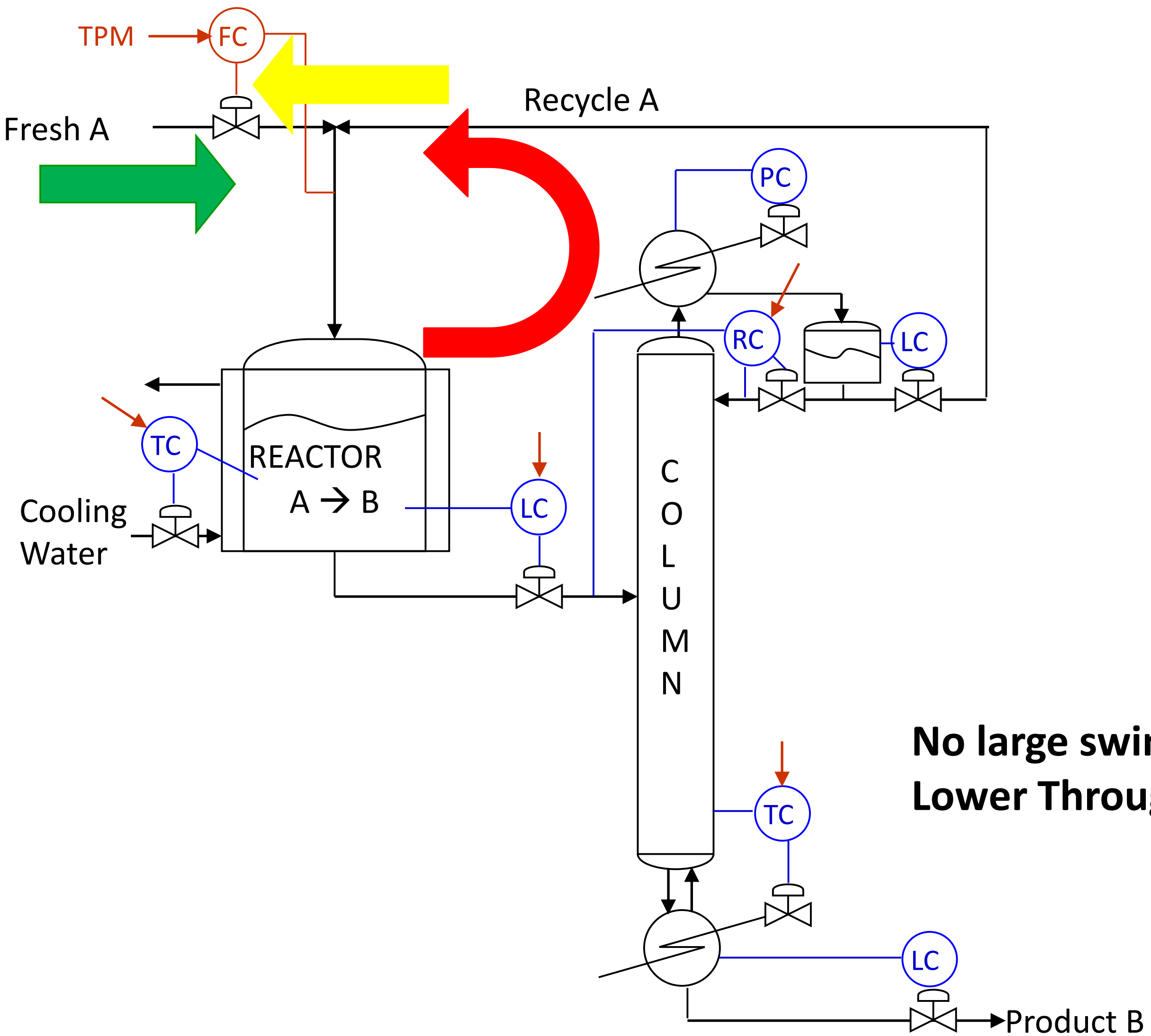
Material Recycle Snowball Effect



Recycle loop shows large swings

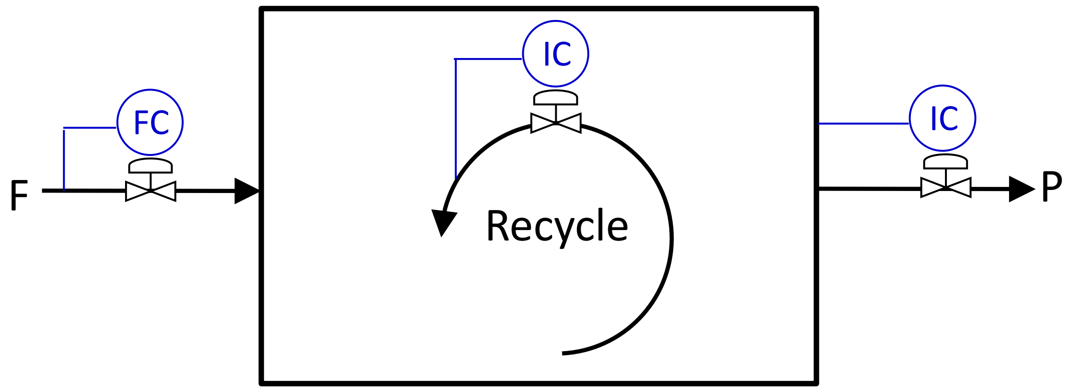
Large Throughput De-rating

Material Recycle Snowball Effect

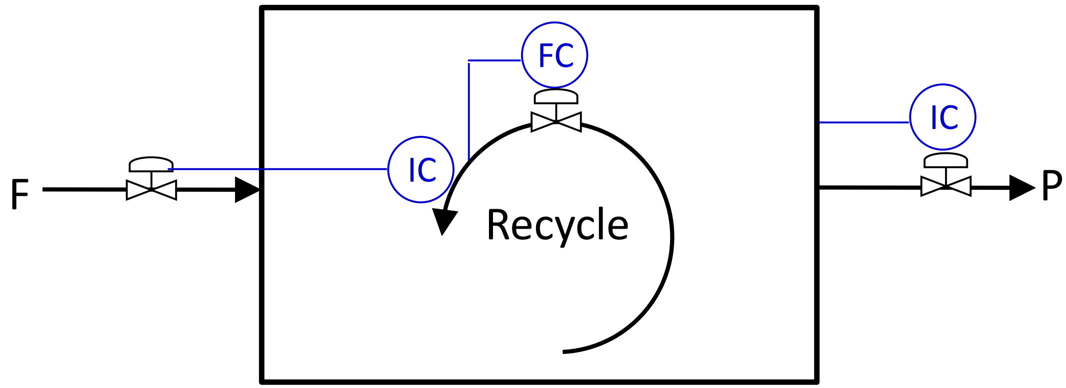


No large swings in recycle rate
Lower Throughput De-rating

Alternative Material Balance Control Schemes



Fixed Feed
Recycle Floats



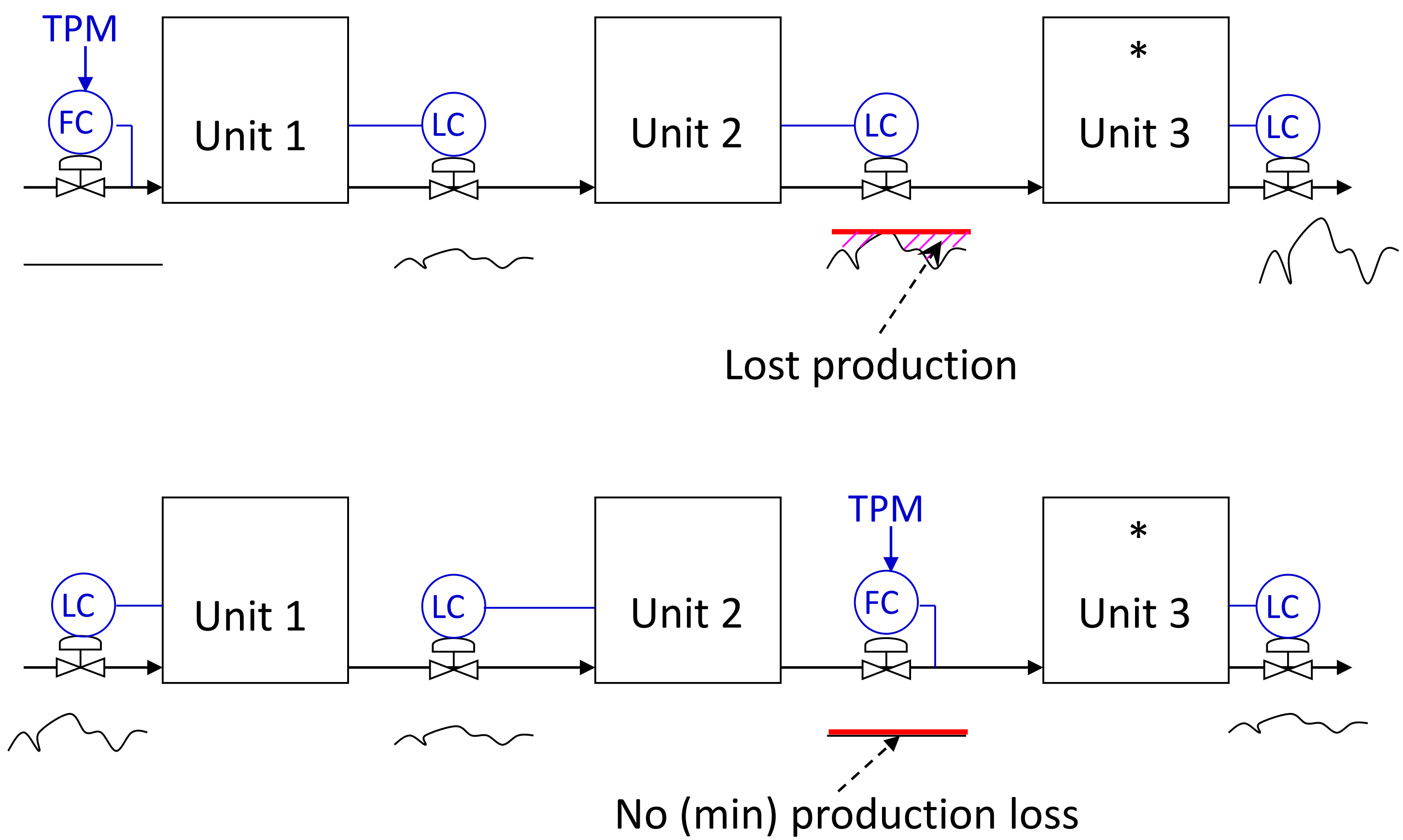
Fixed Recycle
Feed Floats

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

PWC Basics: Throughput Manipulation

THROUGHOUT MANIPULATOR (TPM)

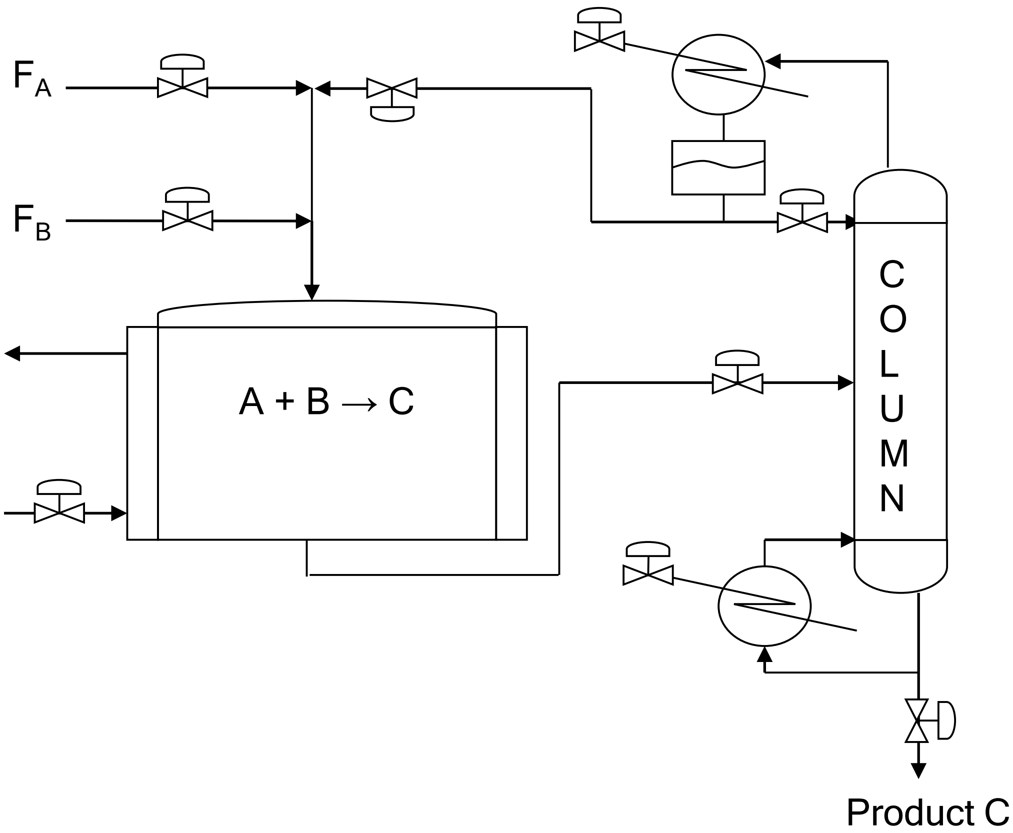
The setpoint adjusted to effect a change in production/processing rate



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

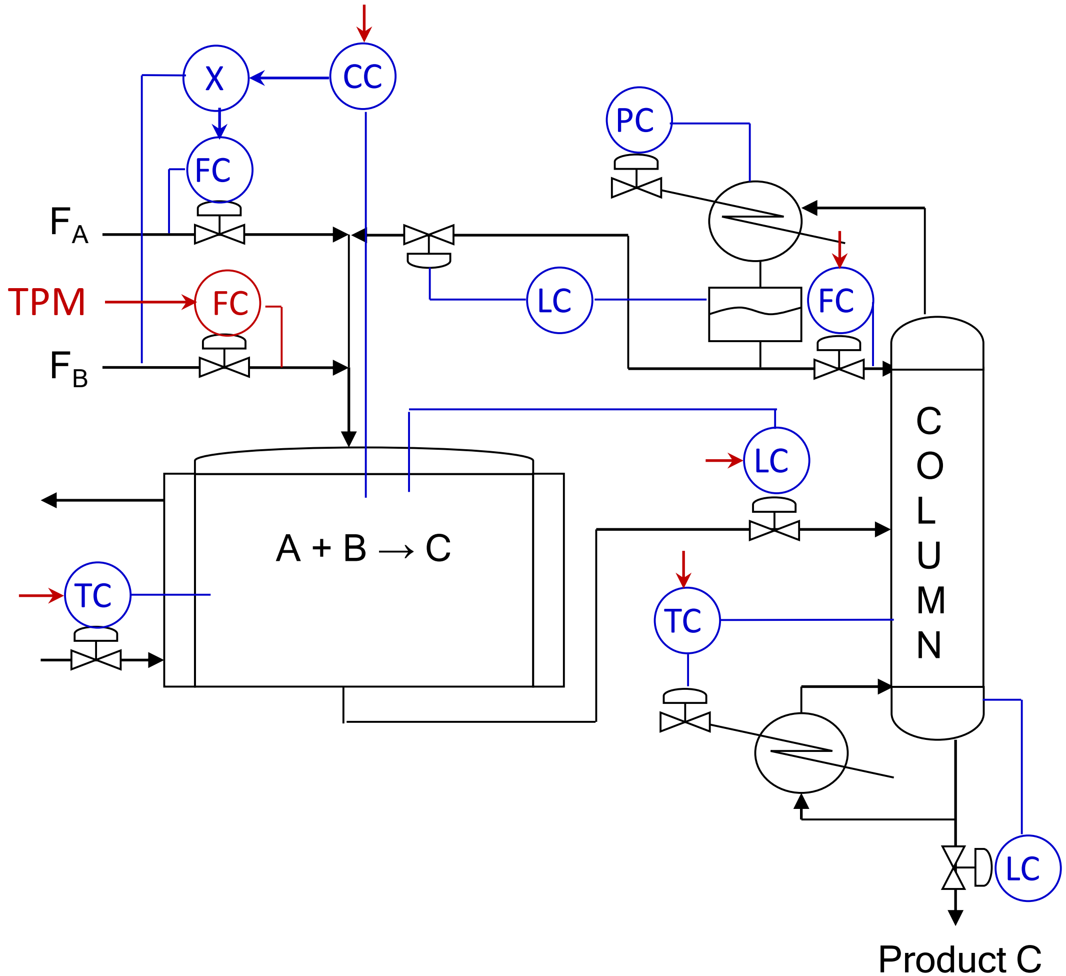
Reactor Separator Recycle Process



Control DOFs	9
Surge Levels	-2
Given Column Pr	-1

Steady State DOF	**6**

PWCS Design: TPM at Fresh Feed



PWCS Design: Recycle Drifts

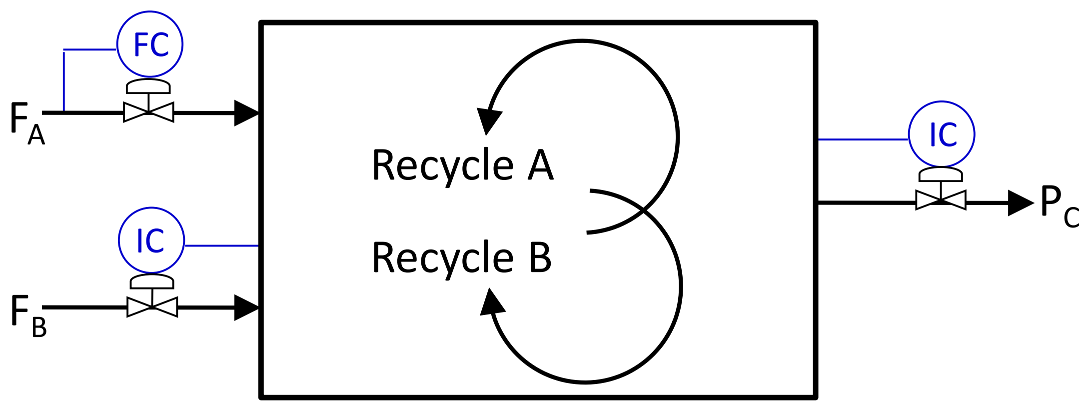
Beware of subtle plantwide recycle loop inventory drifts

Stoichiometric feed balancing

Plantwide balances close slowly due to recycle

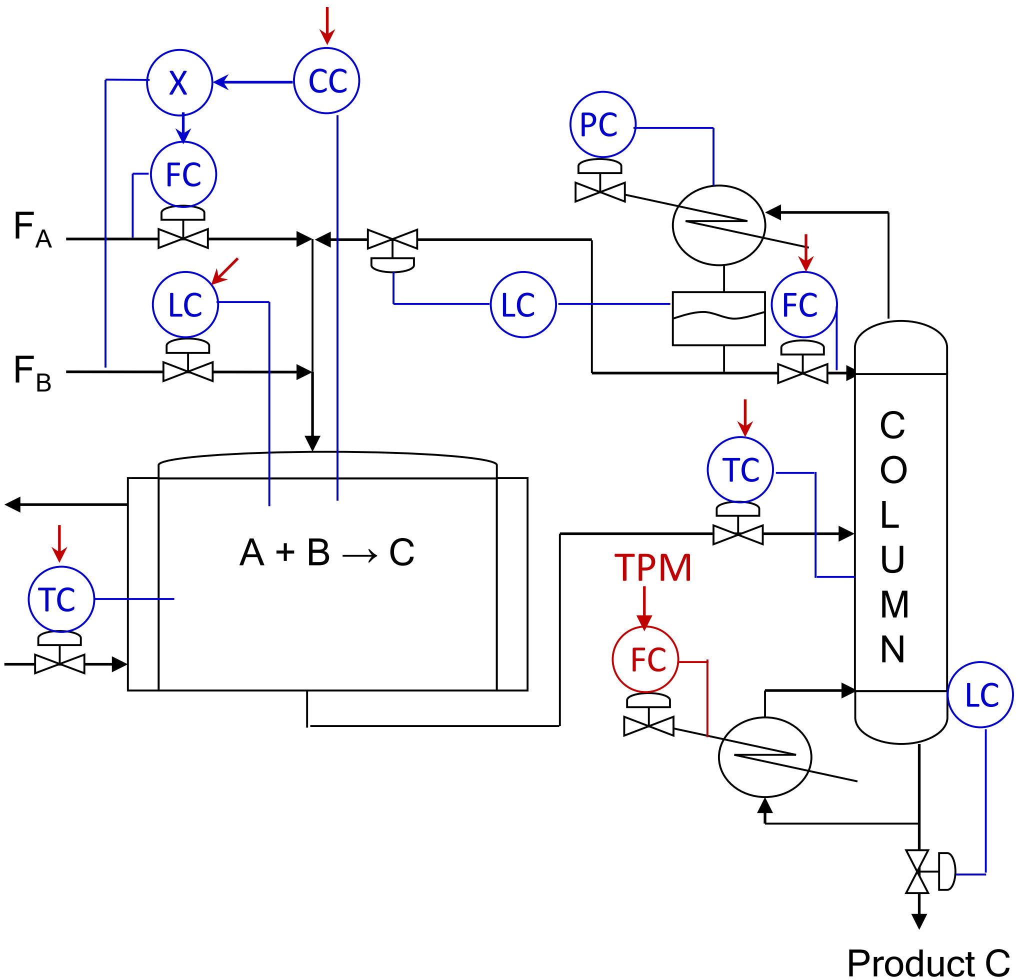
Always examine process input-output structure

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



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

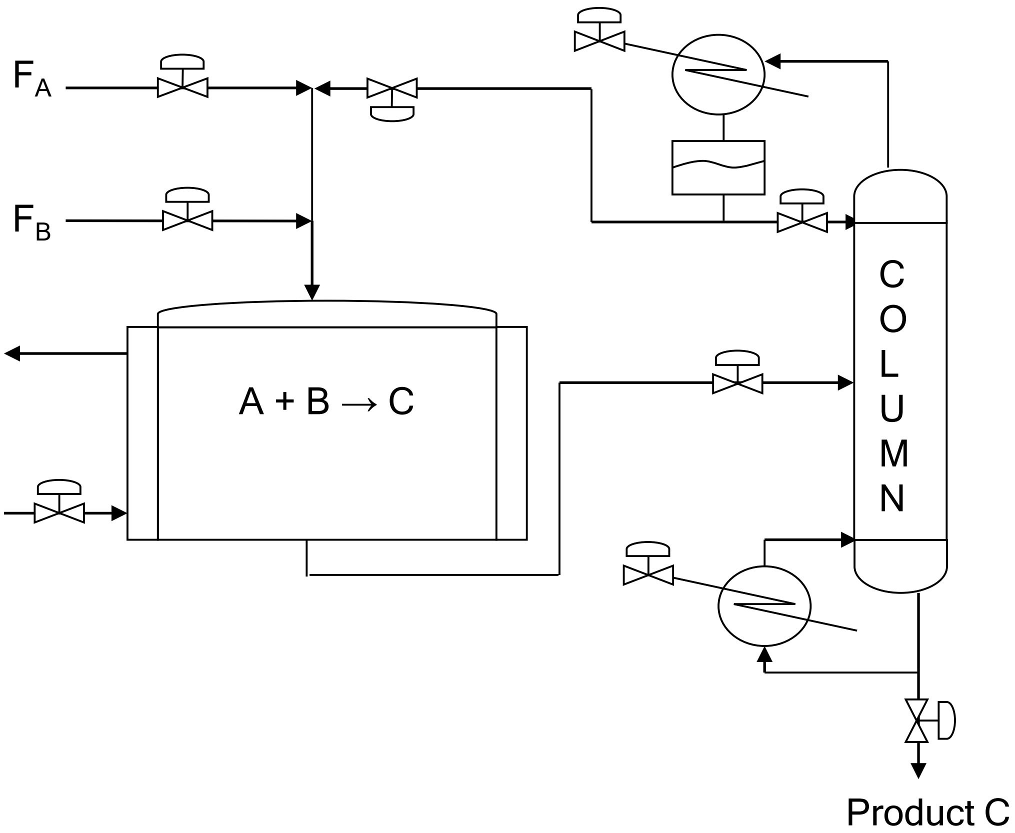
PWCS Design: TPM at Column Boilup



PWCS Design Steps

- DOF analysis and control objectives
  - Production rate, Product quality
  - Safety limits (eg UFL < gas loop composition < LFL)
  - Inventories
  - 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**)
- Design economic control loops
  - Active constraint control & SOCV control

Mode I Optimum Operation



OBJECTIVE

MIN J = Boilup

at given throughput

subject to process constraints

ACTIVE CONSTRAINTS

$\mathbf{T_{rxr}^{MAX}}$	Max reactor temperature
$\mathbf{LVL_{rxr}^{MAX}}$	MAX reactor level
$\mathbf{x_C^{prdMIN}}$	MIN product purity

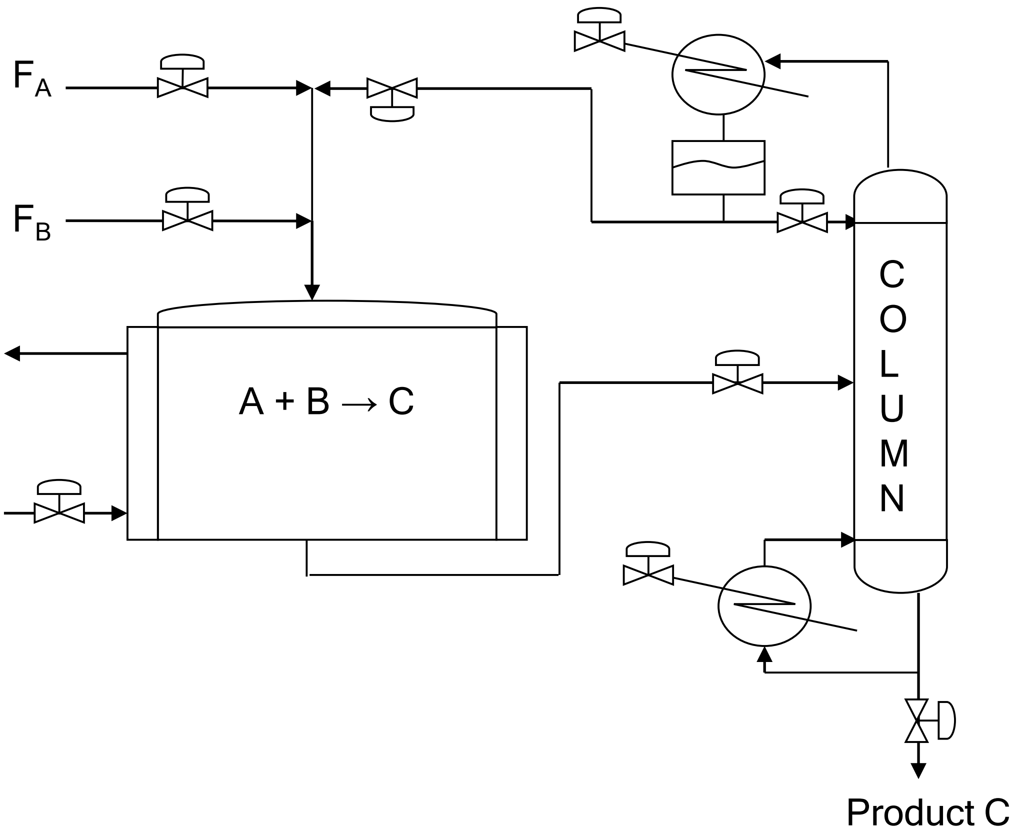
EQUALITY CONSTRAINT

P	Given throughput

UNCONSTRAINED DOFs

SOCV1	**L/F**	Reflux to feed ratio
SOCV2	$\mathbf{[A/B]_{rxr}}$	Reactor A/B ratio

Mode II Optimum Operation



OBJECTIVE

MAX J = Throughput (P)
subject to process constraints

ACTIVE CONSTRAINTS

$\mathbf{T_{rxr}^{MAX}}$	Max reactor temperature
$\mathbf{LVL_{rxr}^{MAX}}$	MAX reactor level
$\mathbf{x_C^{prdMIN}}$	MIN product purity
$\mathbf{\Delta P^{MAX}}$	Capacity bottleneck

UNCONSTRAINED DOFs

SOCV1	**L/F**	Reflux to feed ratio
SOCV2	$\mathbf{[A/B]_{rxr}}$	Reactor A/B ratio

PWCS Design: TPM at Fresh Feed

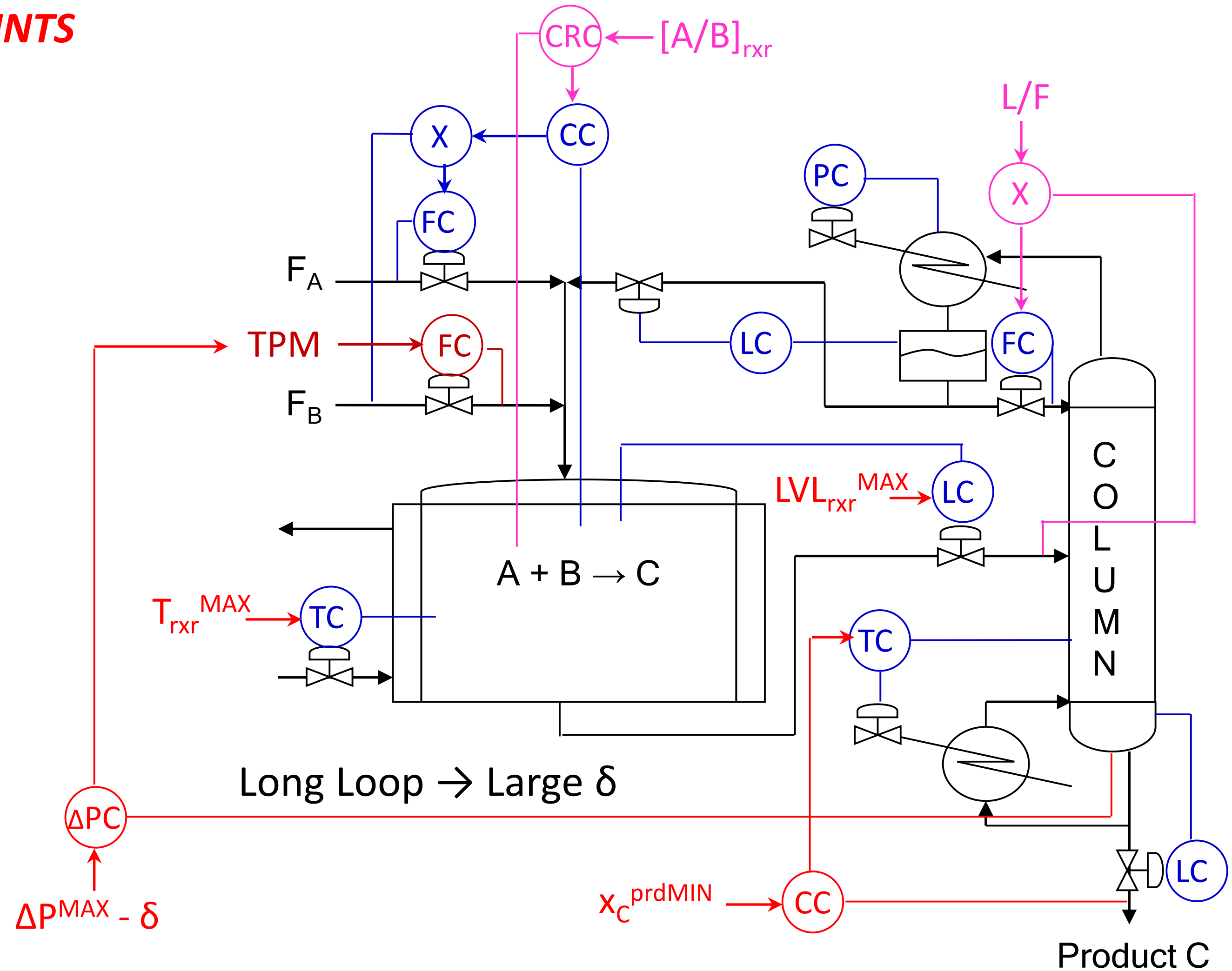
MODE II CONSTRAINTS

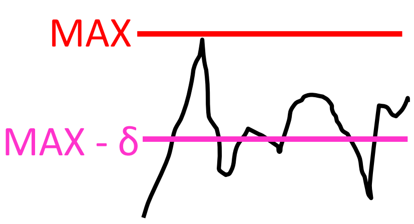
T_{rxr}^{MAX}, LVL_{rxr}^{MAX}

x_C^{prdMIN}, ΔP^{MAX}

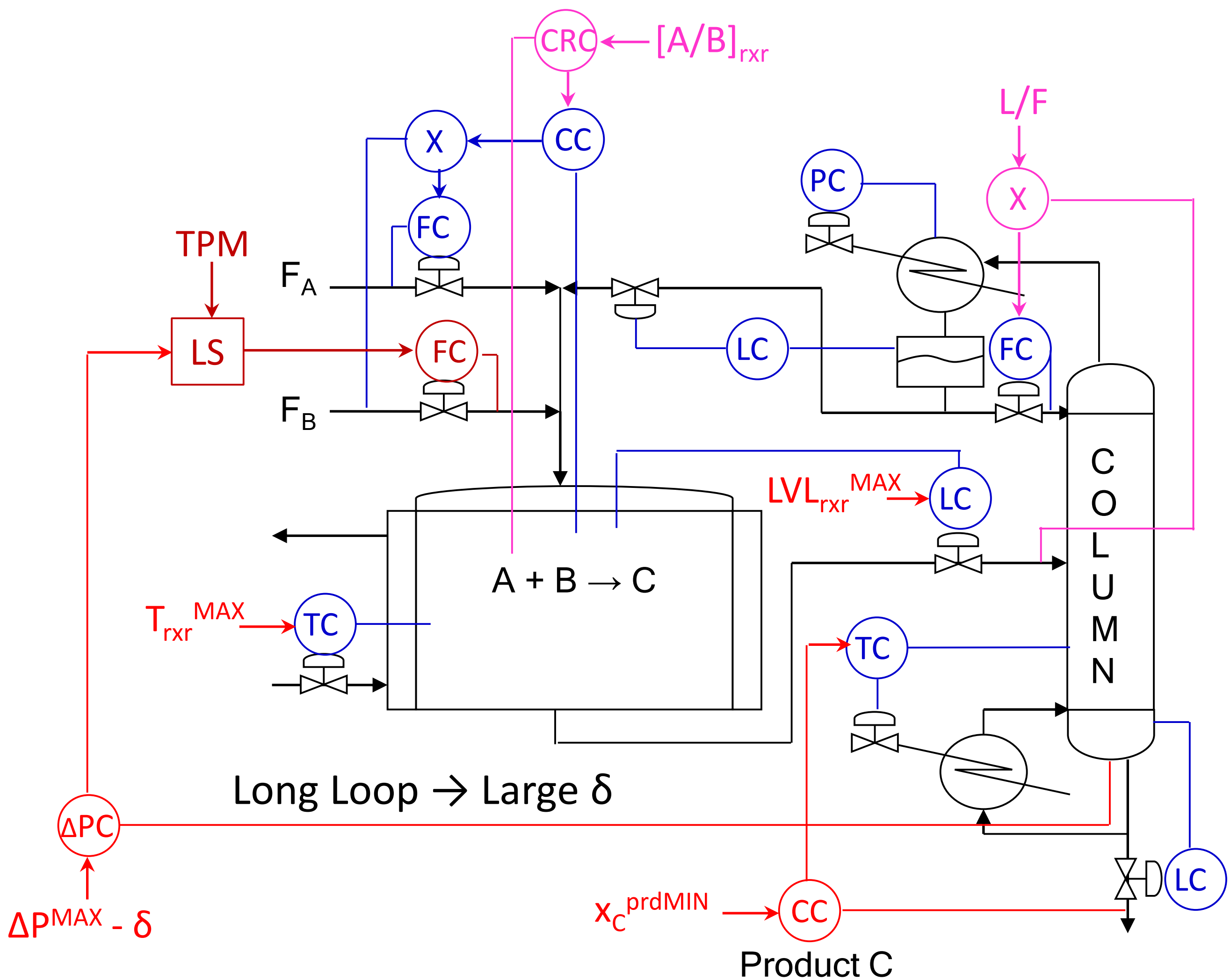
SOCVs

L/F, $[A/B]_{rxr}$

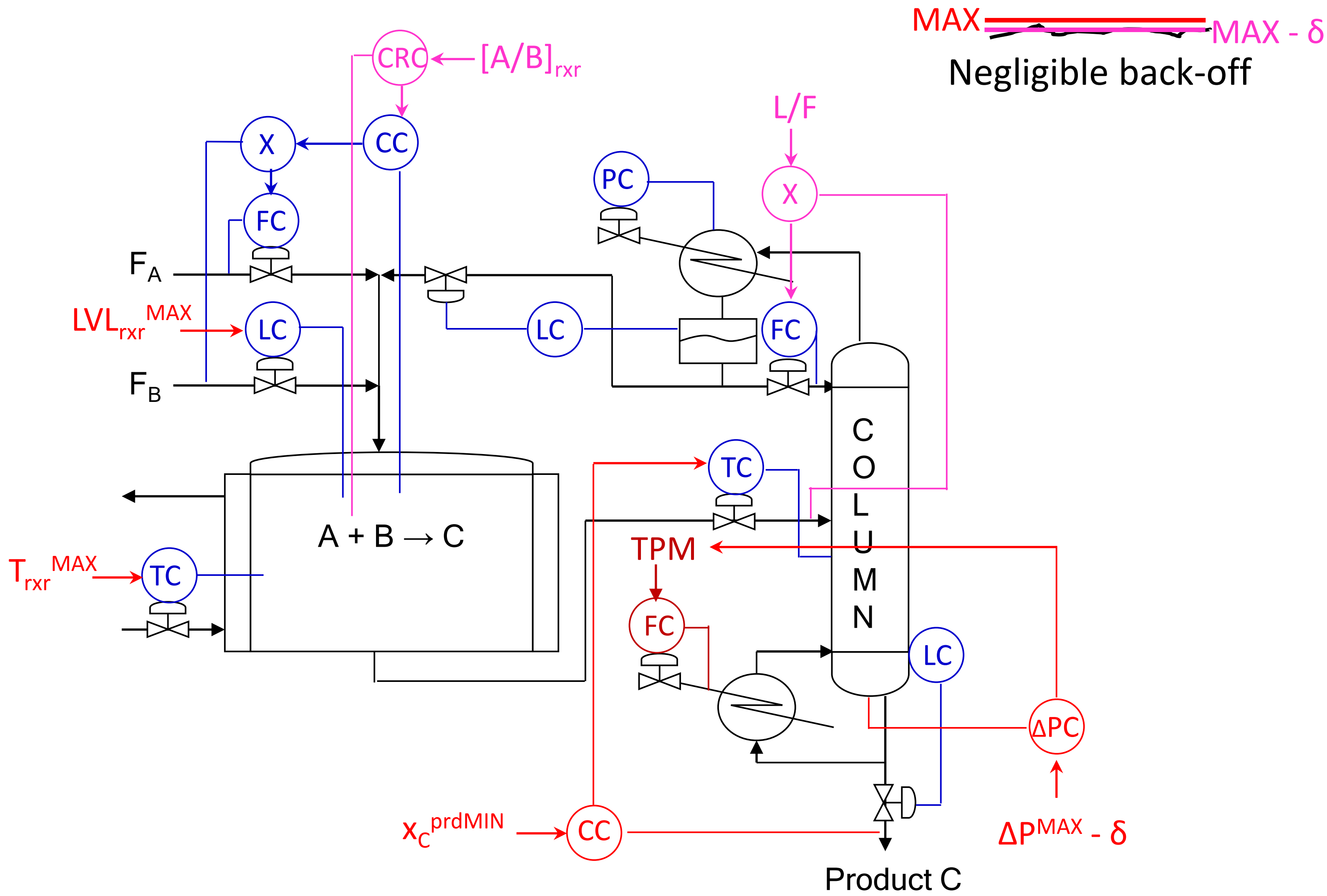




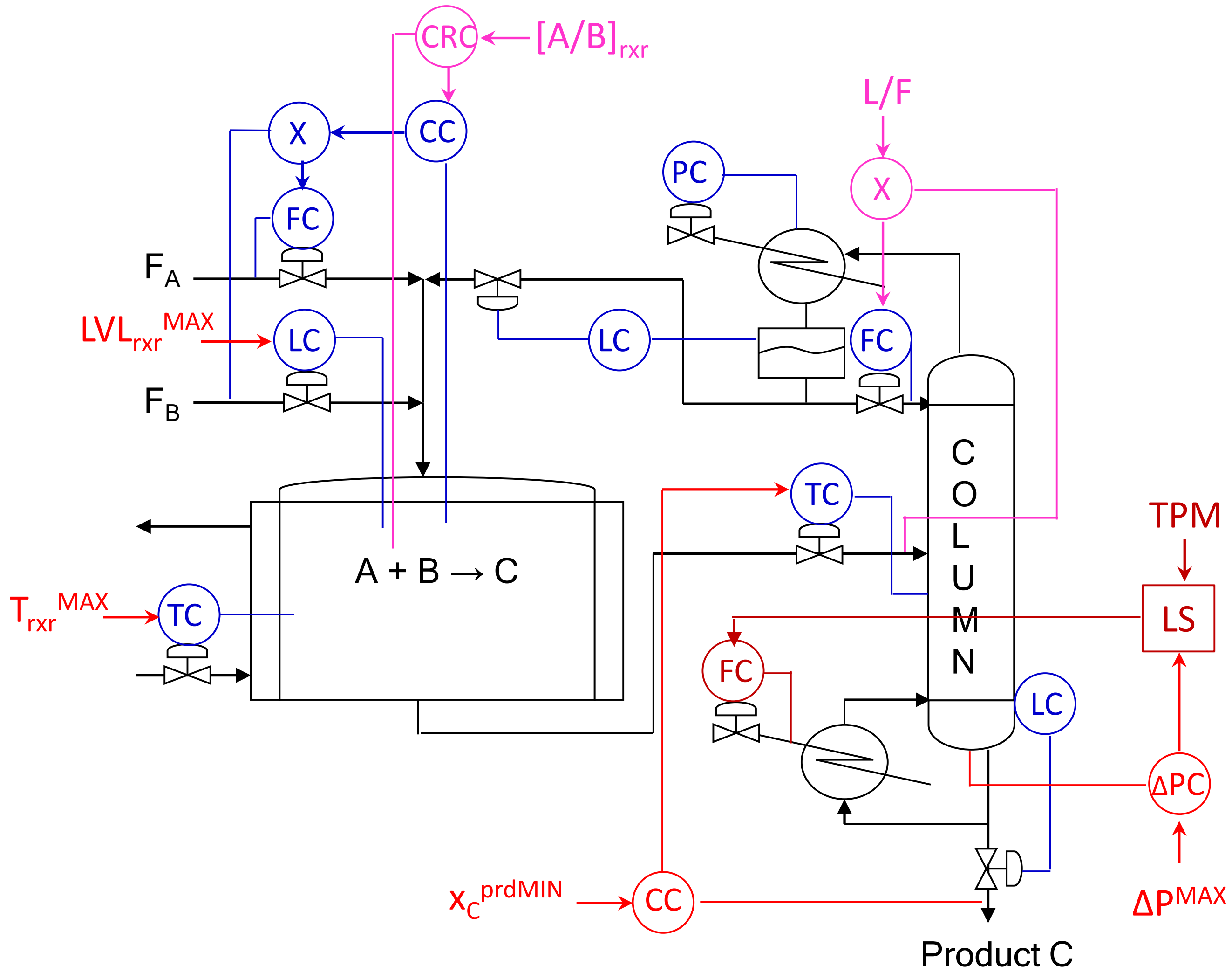
PWCS Design: TPM at Fresh Feed



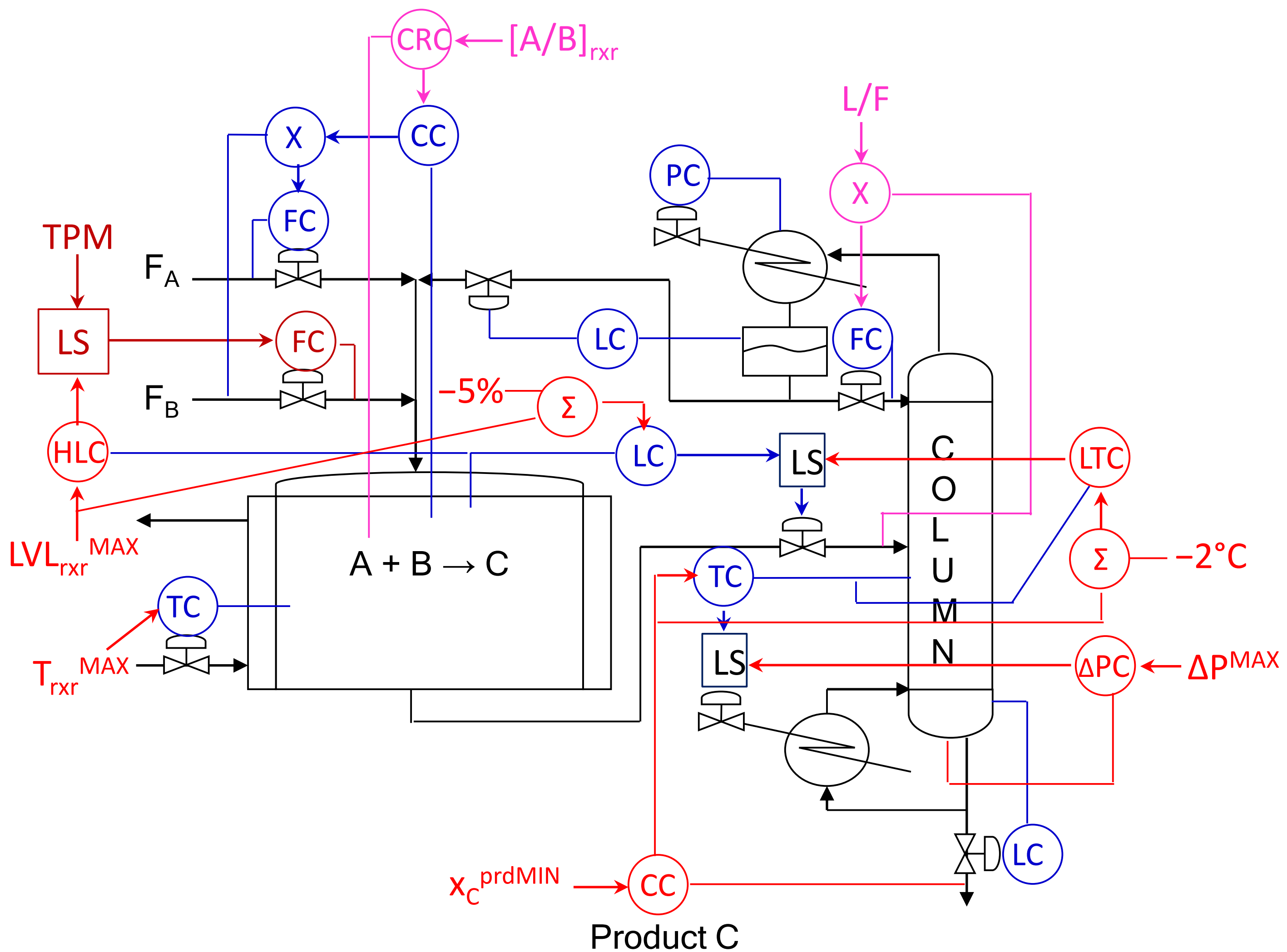
PWCS Design: TPM at Bottleneck



PWCS Design: TPM at Bottleneck



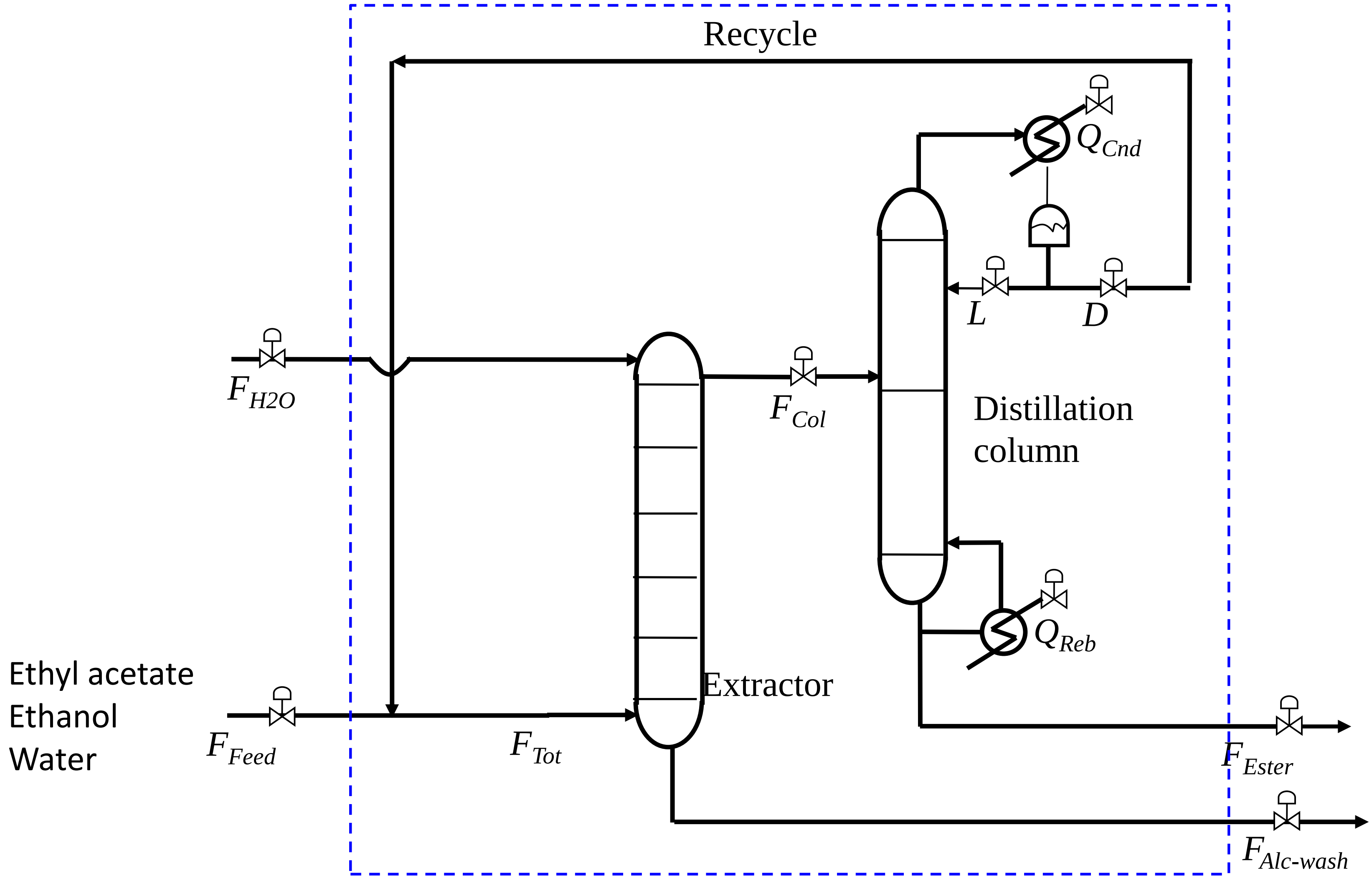
Switching Regulatory Control Structure



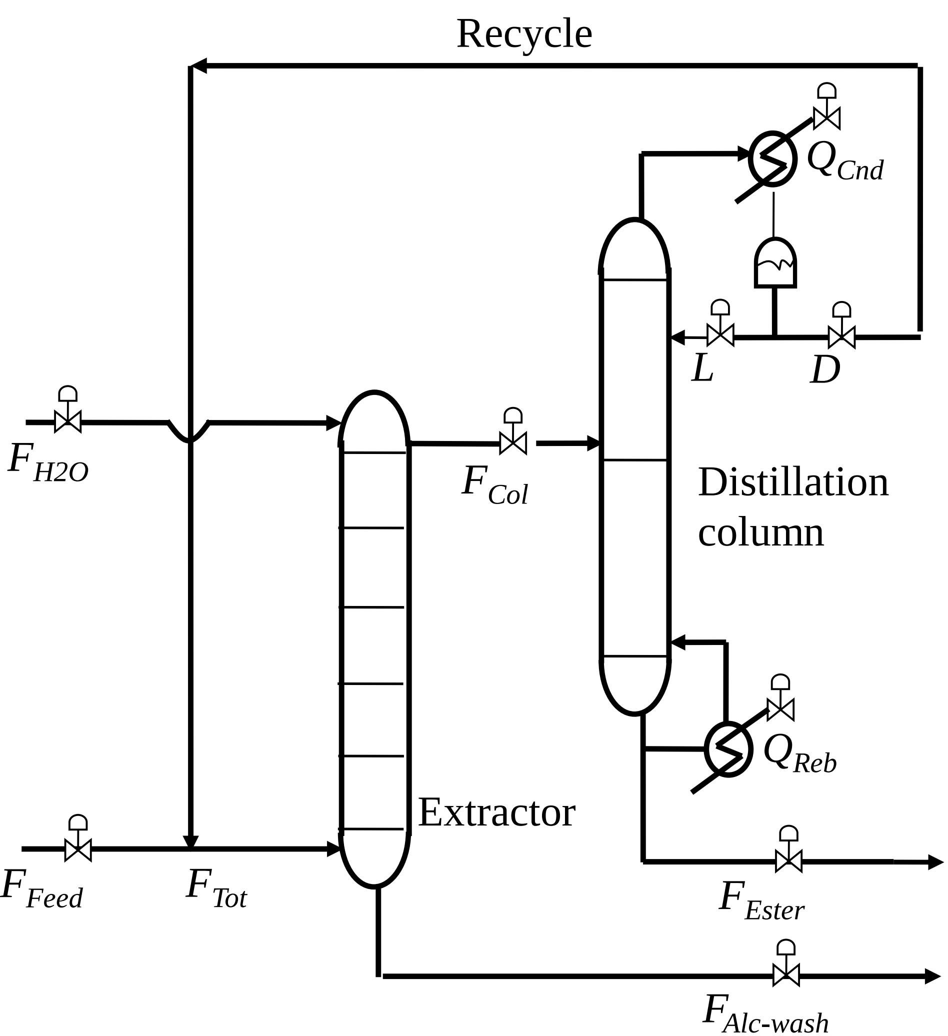
Summary

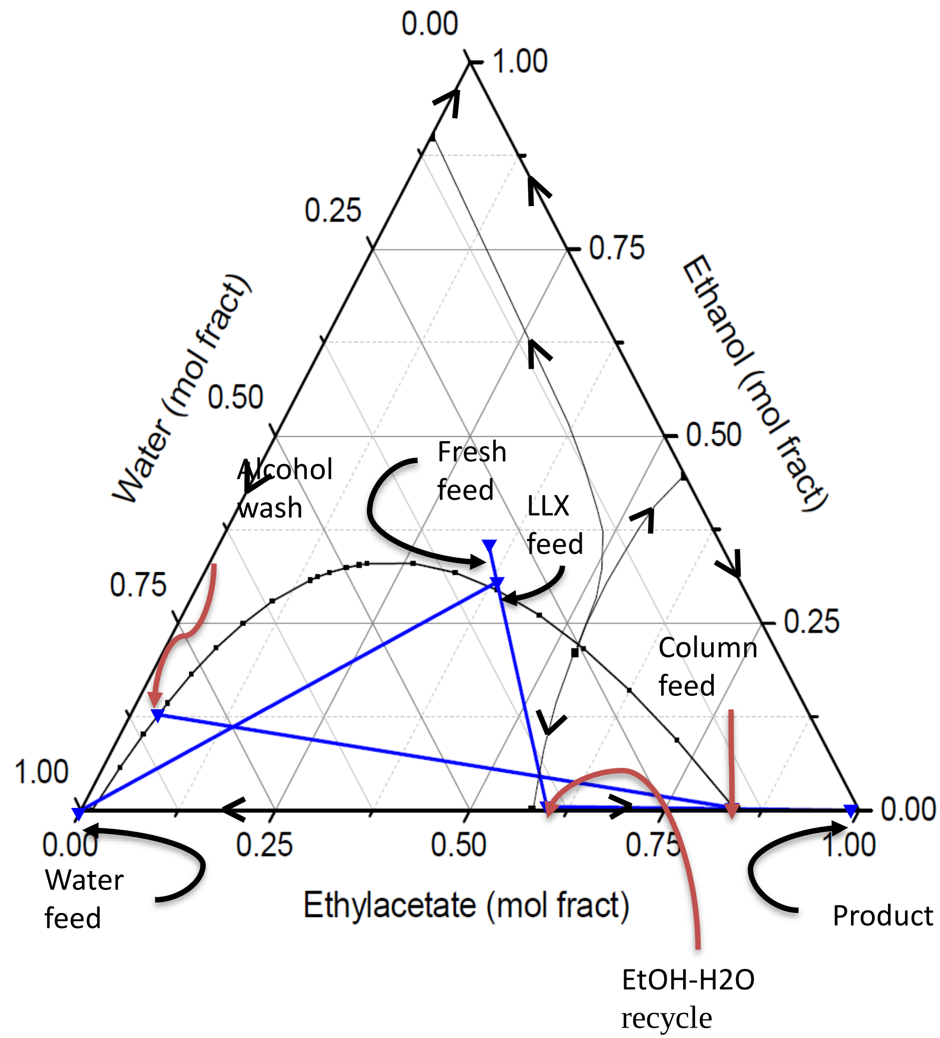
- Locate TPM at bottleneck inside recycle loop
- Economic considerations play a major role in regulatory control layer design
- COMMON SENSE MUST PREVAIL
  - Everything must be carefully thought through
  - It pays to be systematic

Case Study I: Ester Purification Process



Flowsheet Material Balances



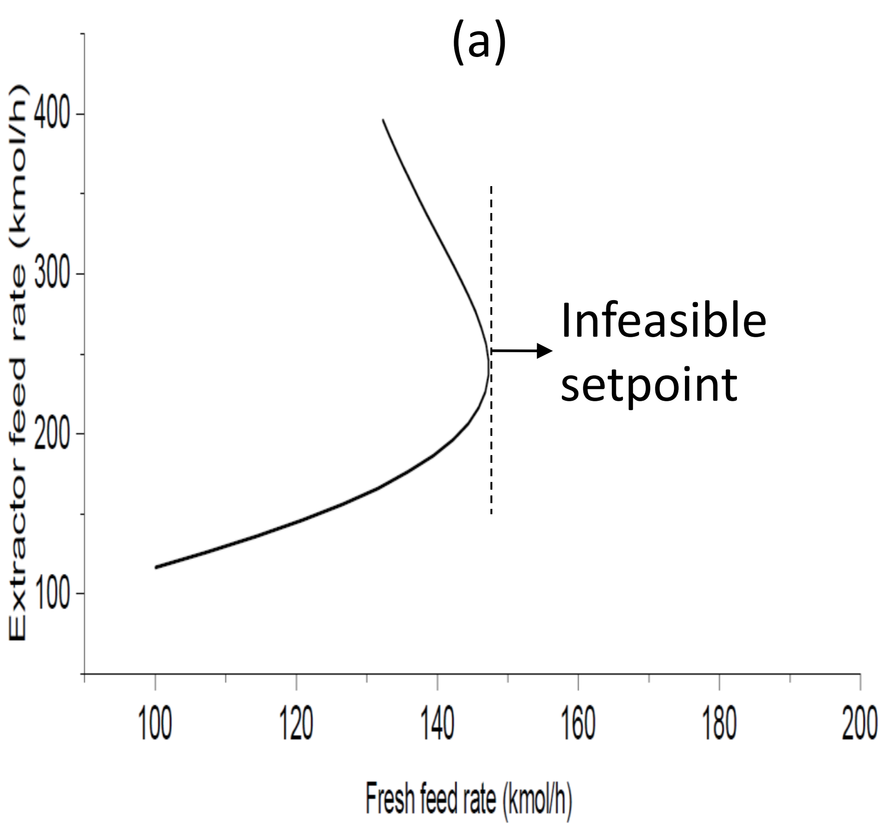


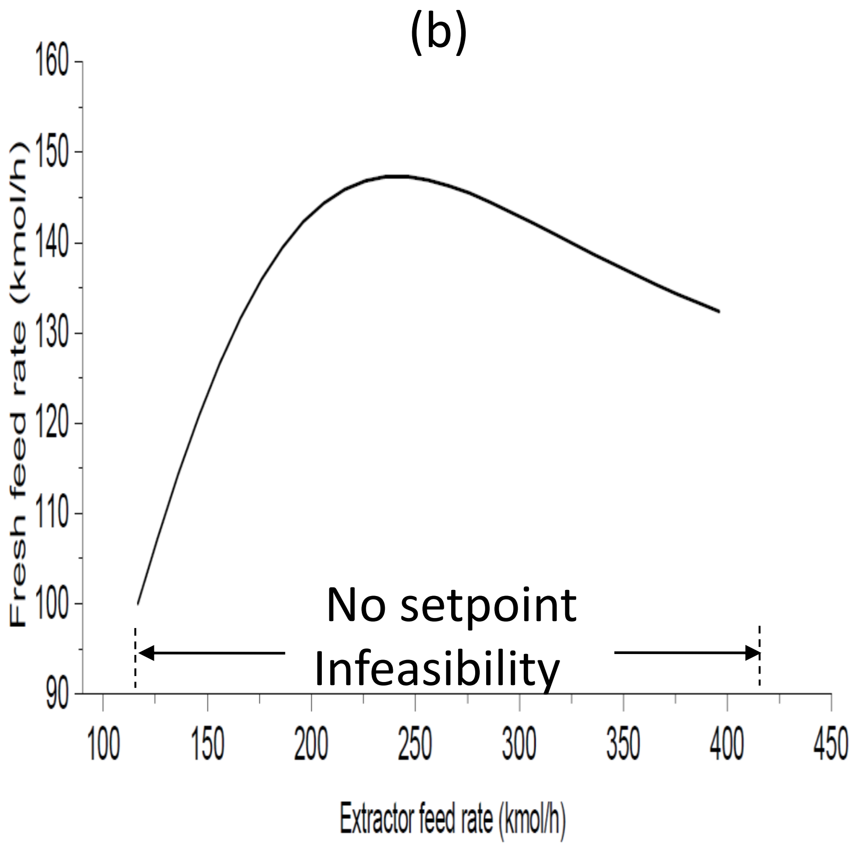
Control Objective

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

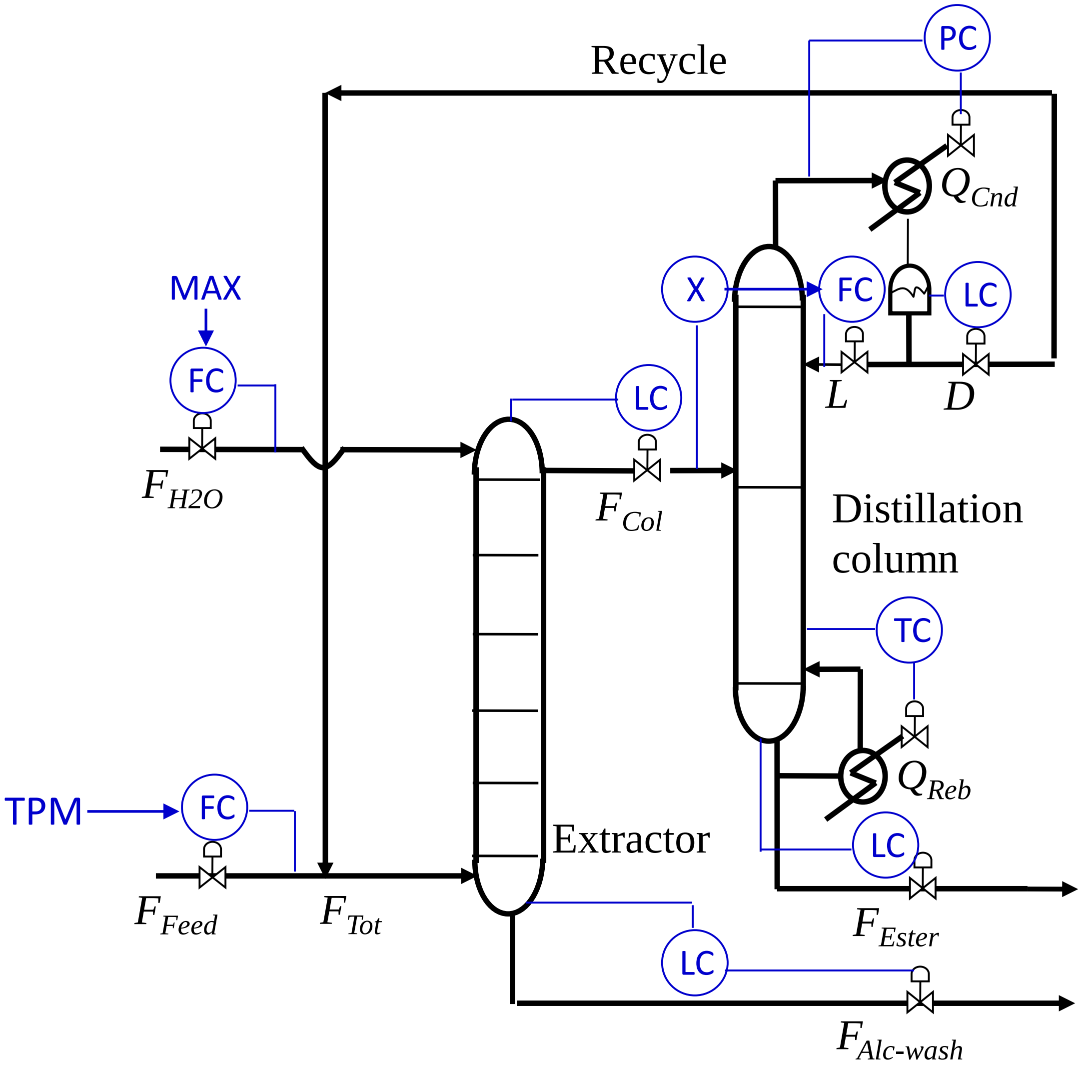
Steady State Bifurcation Analysis

Fresh Water Rate = MAX

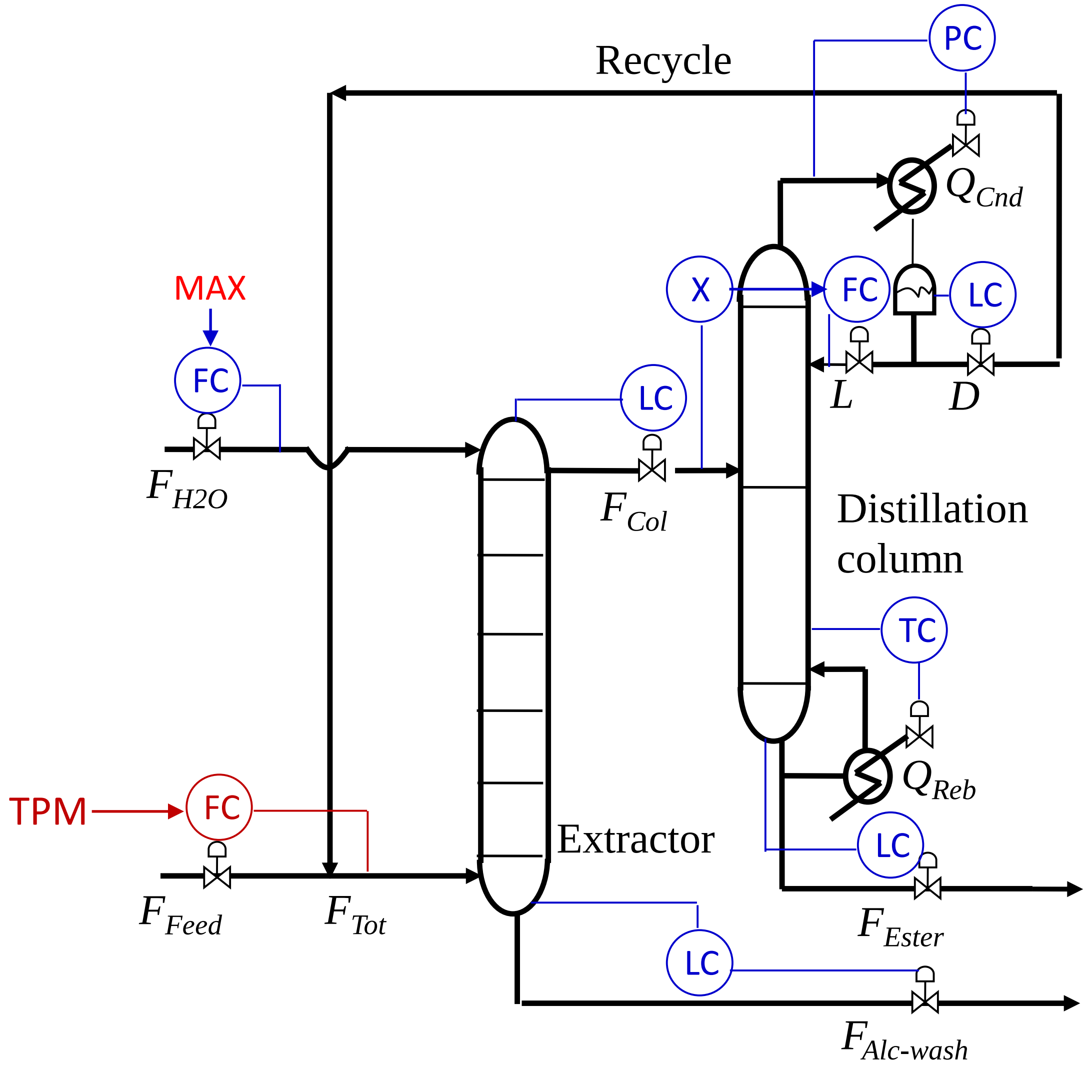




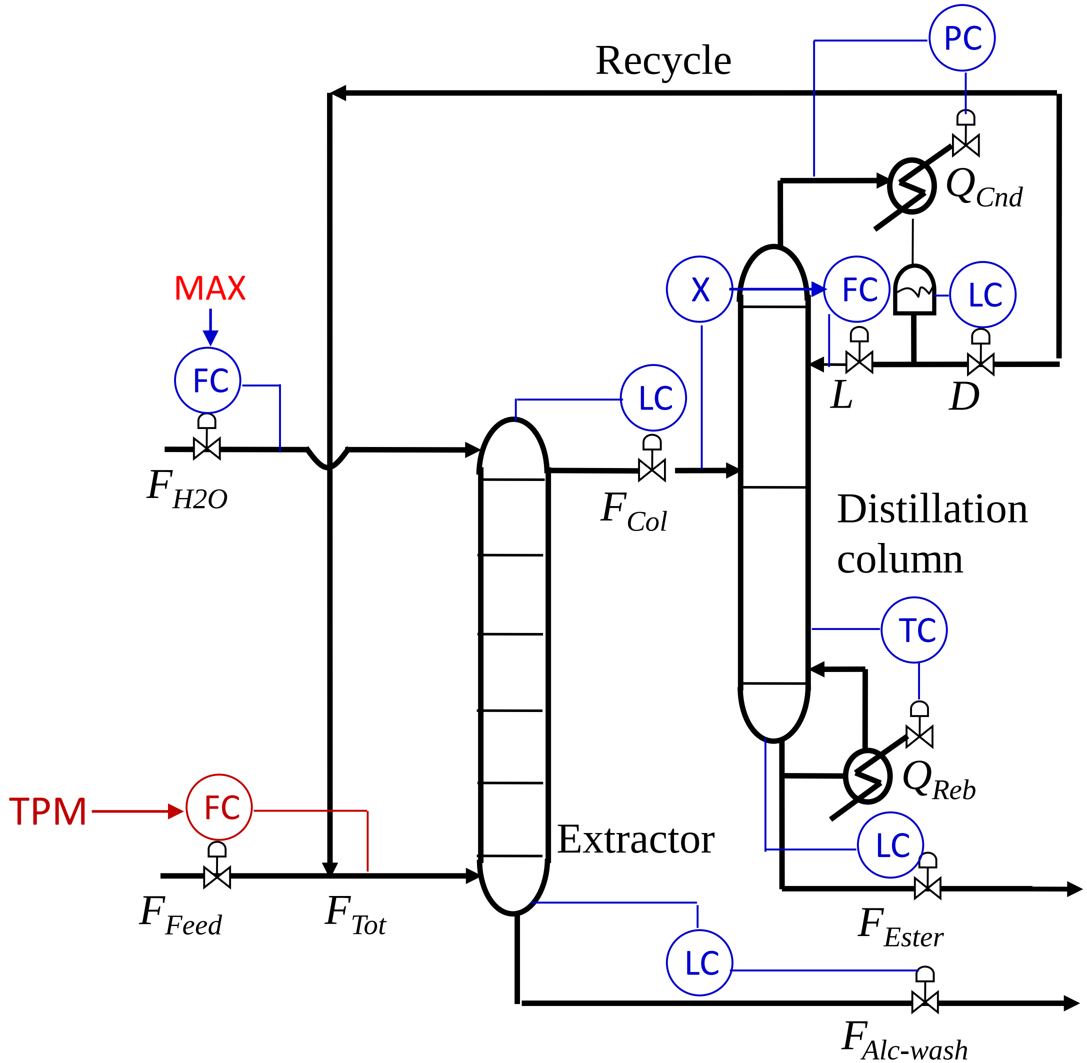
Control Structure 2



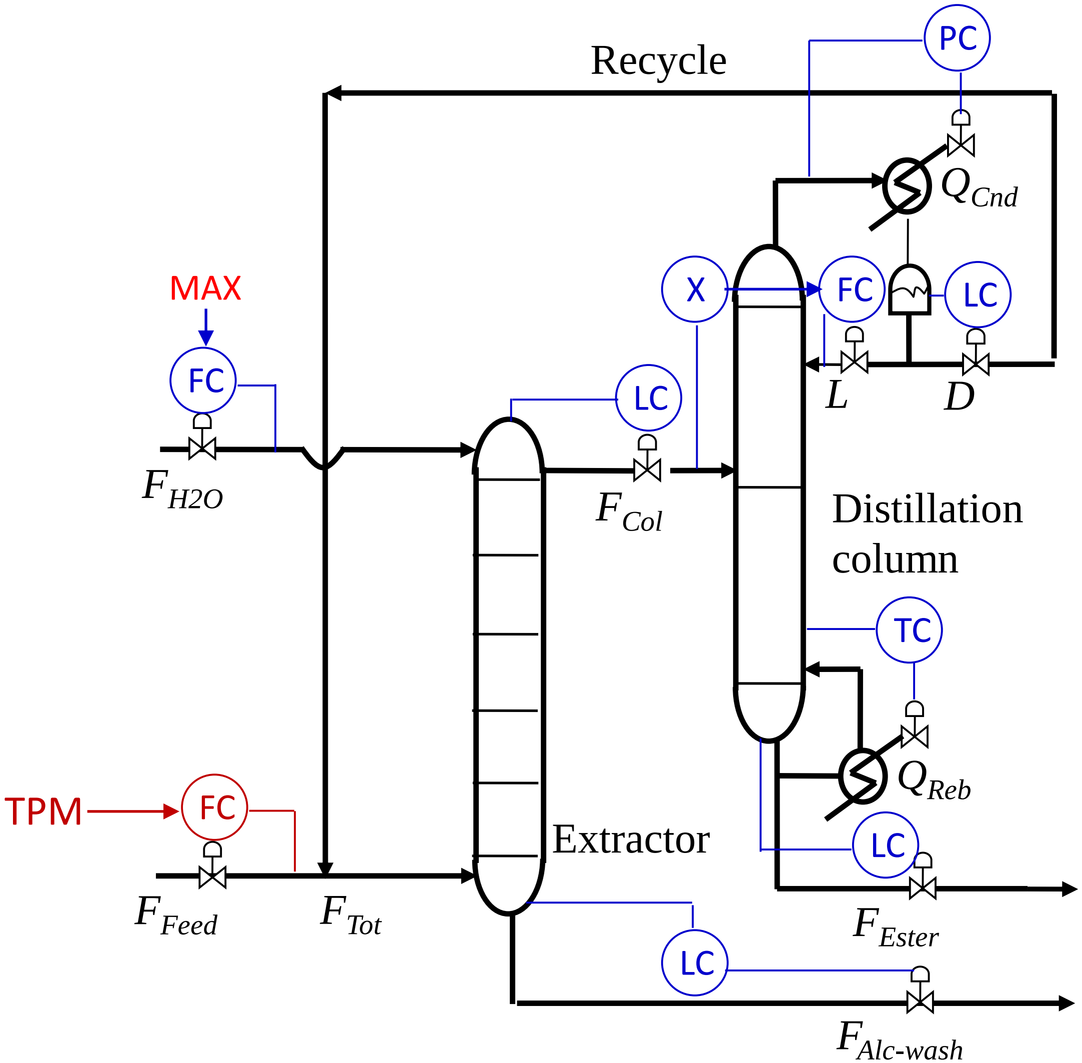
CS1: TPM at Bottleneck Feed



CS1: TPM at Bottleneck Feed

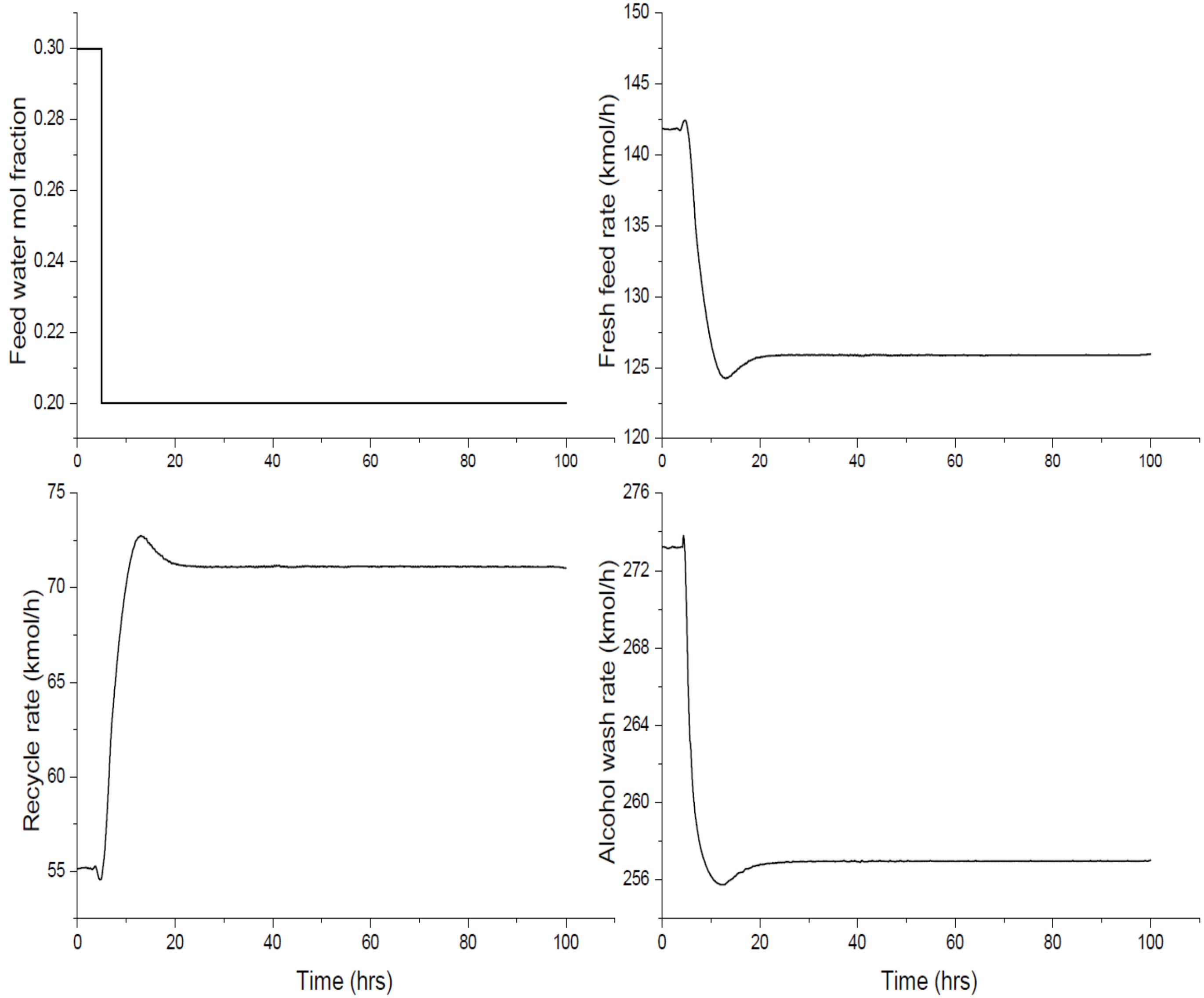


CS2: TPM at Fresh Feed



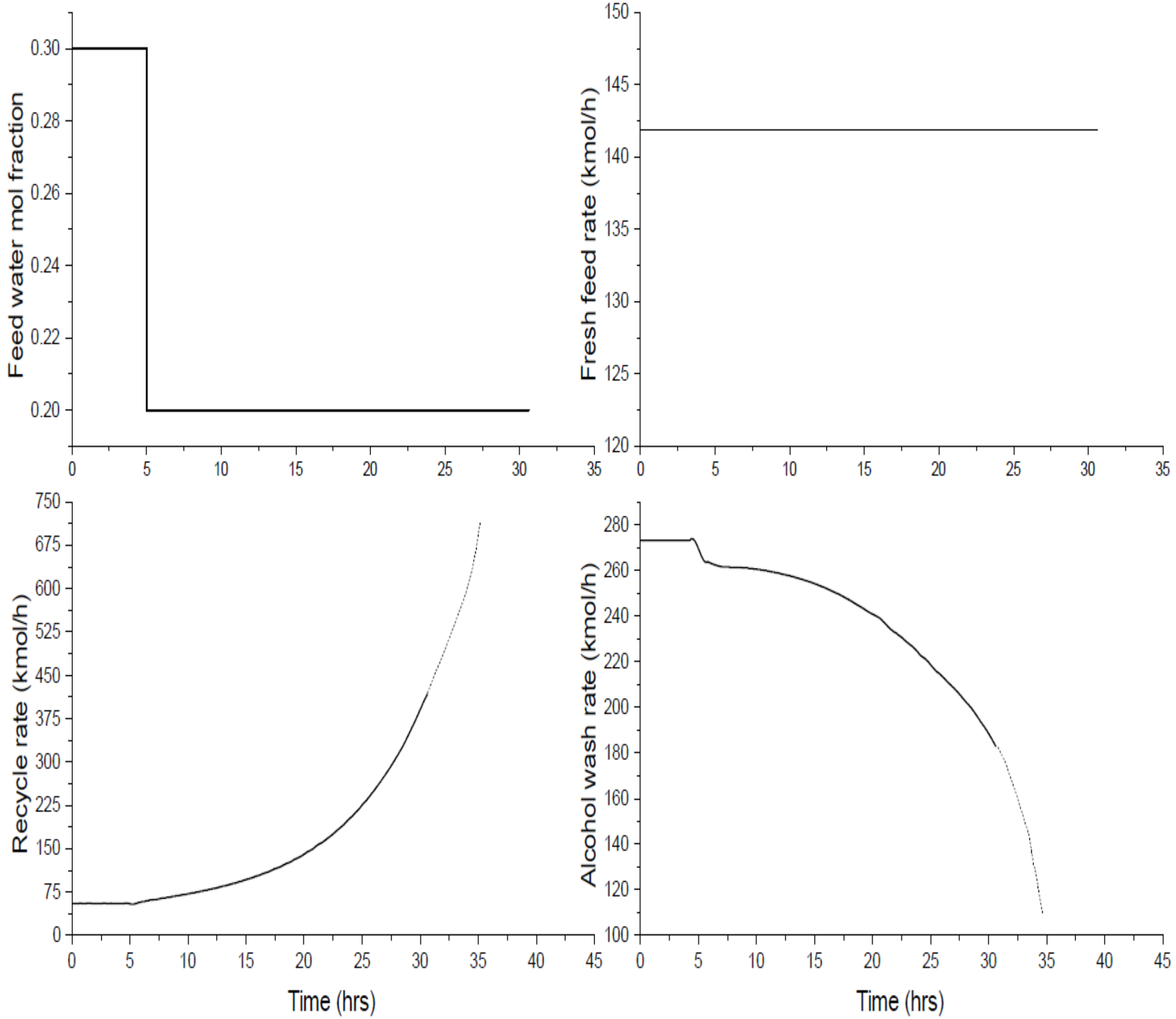
CS1 Closed Loop Transients

Large Feed Composition Change

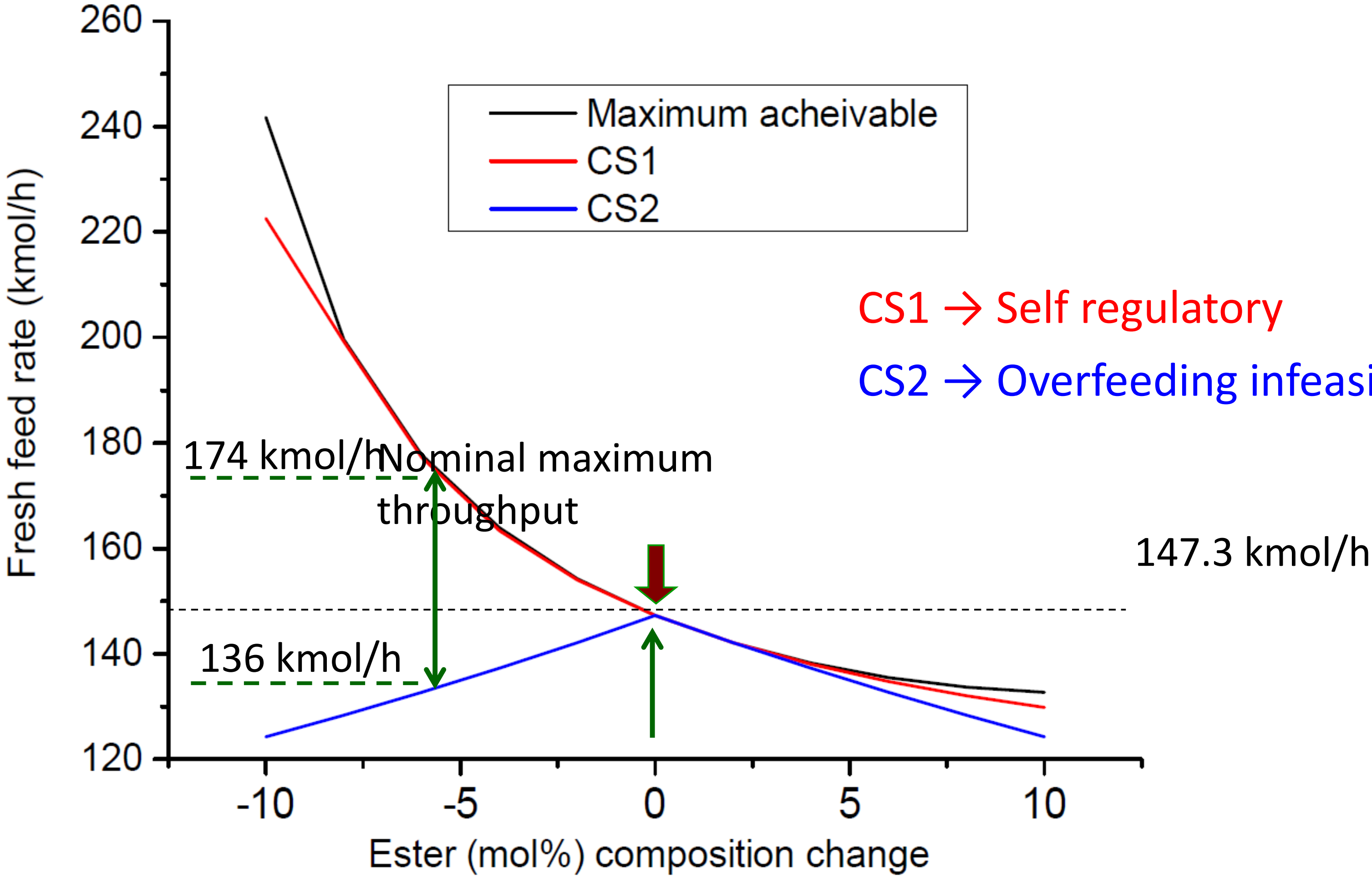


CS2 Closed Loop Transients

Large Feed Composition Change



Throughout Maximization Results



CS1 → Self regulatory

CS2 → Overfeeding infeasibility