Optimal Operation of a CO_2 Capturing Plant for a Wide Range of Disturbances

Mehdi Panahi
Sigurd Skogestad

18.10.2011
AIChE Annual Meeting

NTNU
Norwegian University of Science and Technology

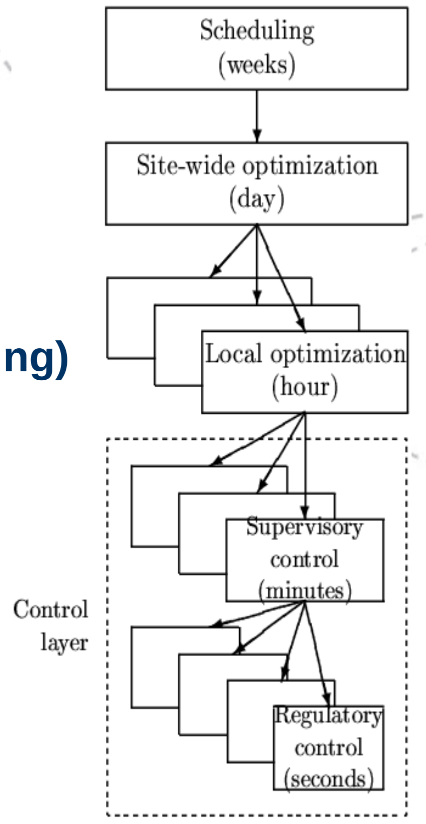
Skogestad plantwide control procedure*

I Top Down

- Step 1: Identify degrees of freedom (MVs)
- Step 2: Define operational objectives (optimal operation)
  - Cost function J (to be minimized)
  - Operational constraints
- Step 3: Select primary controlled variables **CV1s (Self-optimizing)**
- Step 4: Where set the production rate? (Inventory control)

II Bottom Up

- Step 5: Regulatory / stabilizing control (PID layer)
  - What more to control (CV2s; local CVs)?
  - Pairing of inputs and outputs
- Step 6: Supervisory control (MPC layer)
- Step 7: Real-time optimization



*Skogestad, S., 2004, Control Structure Design for Complete Chemical Plants, Computers and Chemical Engineering, 28, 219-234

NTNU
Norwegian University of Science and Technology

Optimal operation

Mode I: maximize efficiency

Mode II: maximize throughput

Self-optimizing control is when we can achieve acceptable loss with constant setpoint values for the controlled variables without the need to reoptimize the plant when disturbances occur

NTNU
Norwegian University of Science and Technology

Selection of CVs: Self-optimizing control procedure

Step 1: Define an objective function and constraints

Step 2: Degrees of freedom (DOFs)

Step 3: Disturbances

Step 4: Optimization (nominally and with disturbances)

Step 5: Identification of controlled variables (CVs) for unconstrained DOFs

Step 6: Evaluation of loss

NTNU
Norwegian University of Science and Technology

Economically optimal operation of CO_2 capturing

Step 1. Objective function:

min. (energy cost + cost of released CO_2 to the air)

Step 2. 10 steady-state degrees of freedom: 8 valves and 2 pumps
4 levels without steady-state effect: absorber 1,stripper 2,make up tank 1

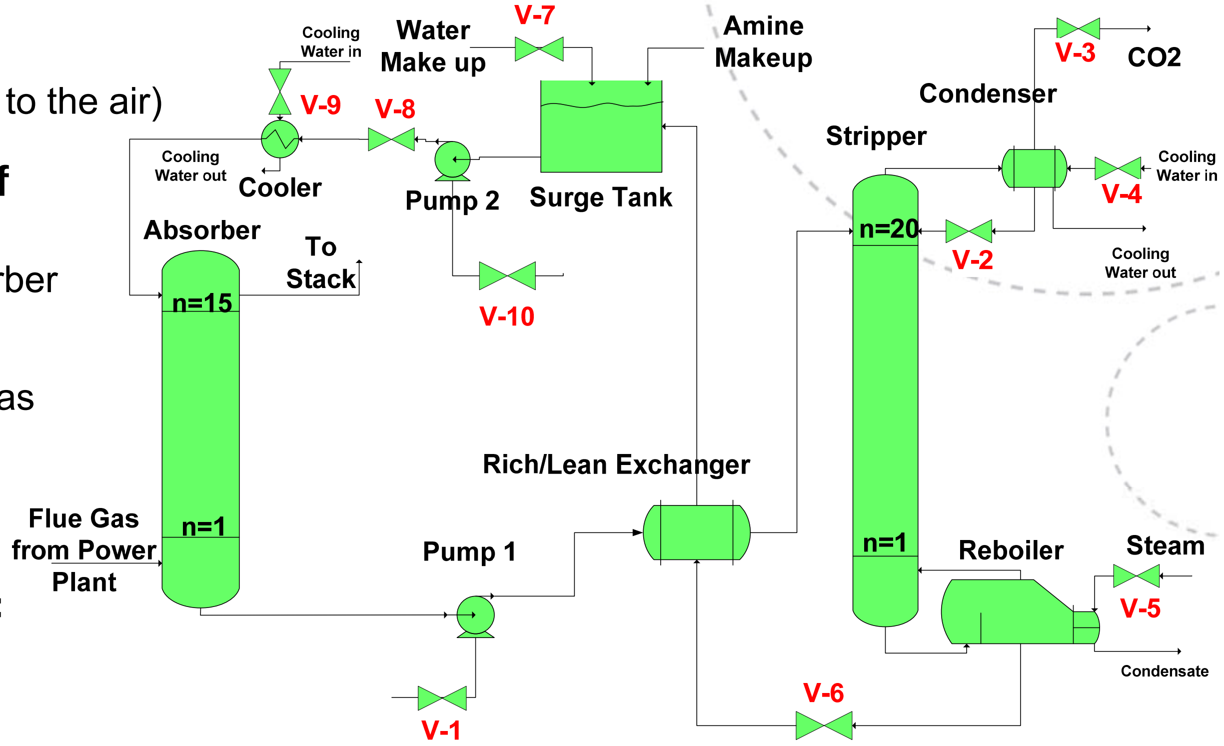
Step 3. 3 main disturbances: flue gas flowrate, CO_2 composition in flue gas + active constraint values

Step 4. Optimization

4 equality constraints and 2 inequality:

1. stripper top pressure, 1.8 bar
2. condenser temperature, 30°C
3. pump pressure of recycle amine, 4 bar
4. cooler temperature, 51°C
5. CO_2 recovery ≥ 80%
6. max. reboiler duty +20% from the nominal value

2 unconstrained degrees of freedom;10-4-4=2



Steps 5&6. Exact Local method: The candidate CV set that imposes the minimum worst case loss to the objective function

NTNU
Norwegian University of Science and Technology

Exact local method* for selection of the best CVs

Exact local method gives the maximum loss imposed by each candidate CV set

The set with the minimum worst-case loss is the best

$$\text{max. Loss}=\frac{1}{2}\bar{\sigma}(M)^2$$

$$M=J_{uu}^{1/2}G^{y^{-1}}(FW_d \;\; W_n)$$

$$F=G^y J_{uu}^{-1} J_{ud} - G_d^y$$

F is optimal sensitivity of the measurements with respect to disturbances; $F=\frac{\Delta y^{opt.}}{\Delta d}$

* I.J. Halvorsen, S. Skogestad, J.C. Morud and V. Alstad,

'optimal selection of controlled variables' *Ind. Eng. Chem. Res.*, **42** (14), 3273-3284 (2003)

NTNU
Norwegian University of
Science and Technology

Exact local method for selection of the best CVs

39 candidate CVs

- 15 possible tray temperature in the absorber
- 20 possible tray temperature in the stripper
- CO_2 recovery in the absorber and CO_2 content at the bottom of the stripper
- Recycle amine flowrate and reboiler duty

Applying a bidirectional branch and bound algorithm* for finding the best CVs

The best self-optimizing CV set in region I: CO_2 recovery (95.26%) and temperature of tray no. 16 in the stripper

These CVs are not necessarily the best when new constraints meet

* V. Kariwala and Y. Cao. Bidirectional Branch and Bound for Controlled Variable Selection, Part II: Exact Local Method for Self-Optimizing Control, Computers & Chemical Engineering, 33(2009), 1402-1412.

Optimal operational regions as function of feedrate

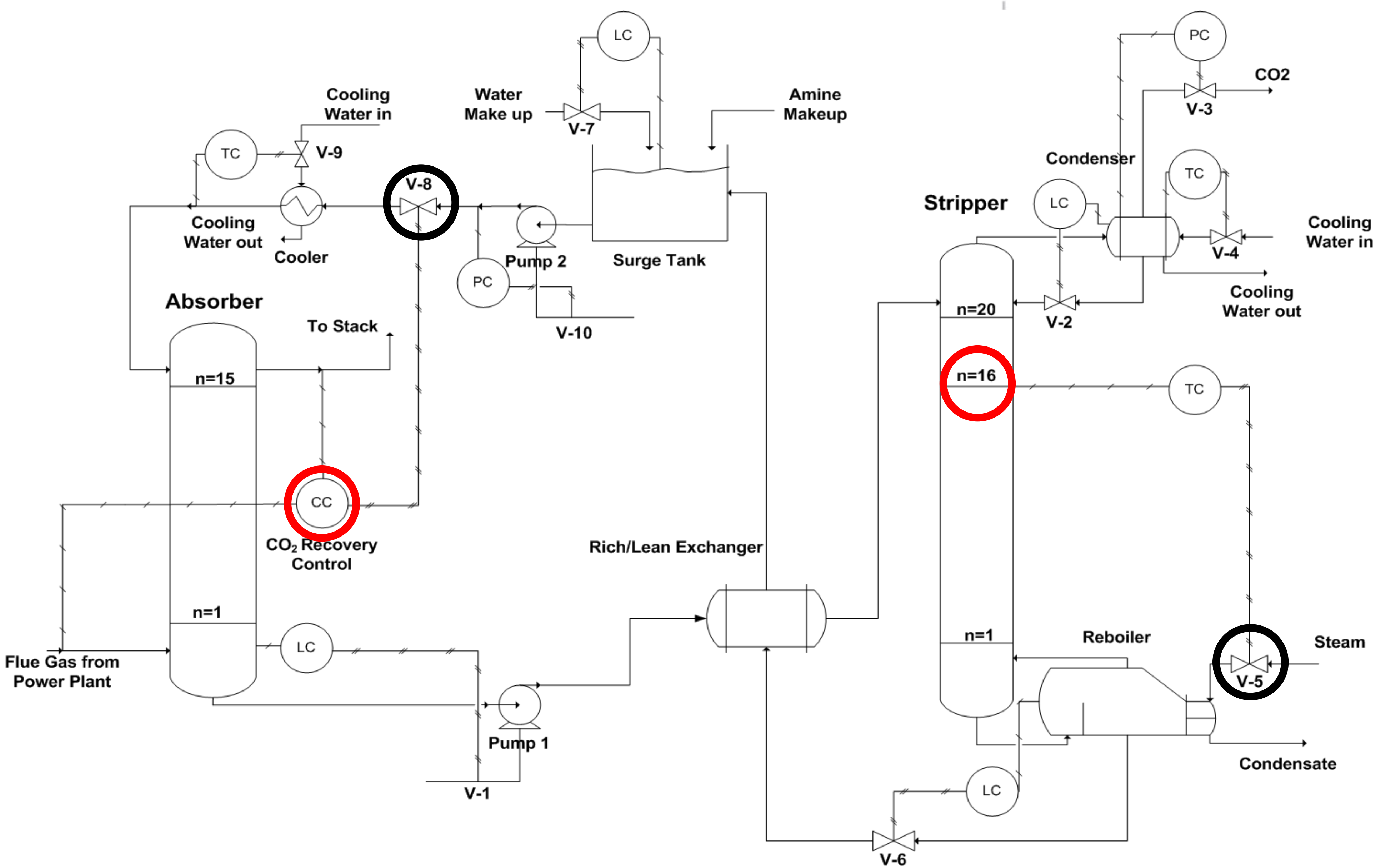
Region I. Nominal feedrate

Region II. Feedrate >+20%: Max. Heat constraint

Region III. Feedrate >+51%: Min. CO_2 recovery constraint

NTNU
Norwegian University of Science and Technology

Proposed control structure with given flue gas flowrate (region I)



Region II: in presence of large flowrates of flue gas (+30%)

	Flowrateof flue gas (kmol/hr)	Pumps duty (kW)	Self-optimizing CVs in region I		Cooler Duty (kW)	Reboiler duty (kW)	Objective function (USD/ton)
			CO_2 recovery %	Temperature of tray no. 16 °C			
Optimal nominal point	219.3	3.85	95.26	106.9	321.90	1161	2.49
+5% feedrate	230.3	4.24	95.26	106.9	347.3	1222	2.49
+10% feedrate	241.2	4.22	95.26	106.9	371.0	1279	2.49
+15% feedrate	252.2	4.64	95.26	106.9	473.3	1339	2.49
+19.38% feedrate, reboiler duty saturates	261.8	4.56 (+18.44%)	95.26	106.9	419.4 (+30.29%)	1393 (+20%)	2.50
+30% feedrate (reoptimized)	285.1	4.61	91.60	103.3	359.3	1393	2.65

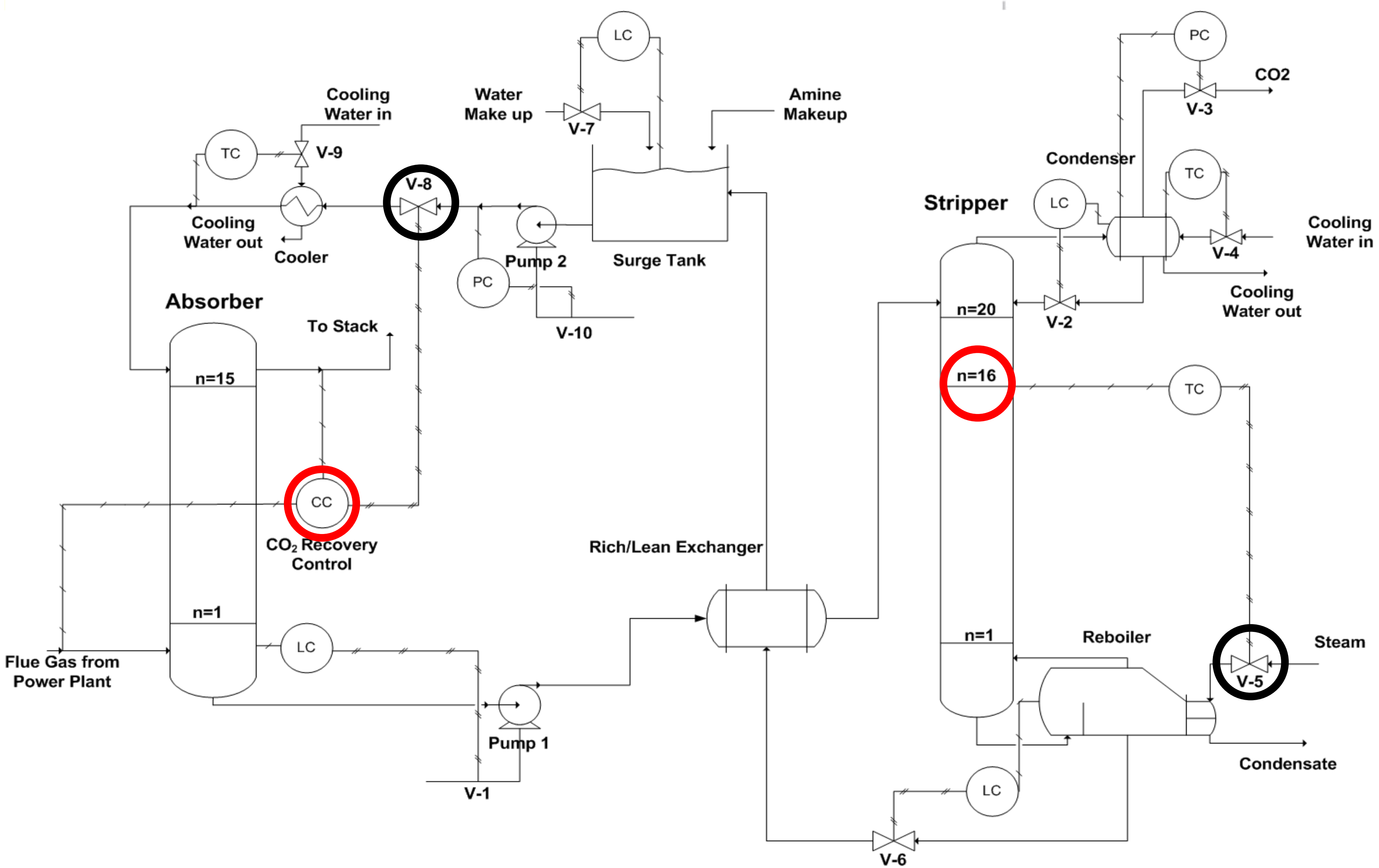
Saturation of reboiler duty (new operations region, region II); one unconstrained degree of freedom left

Maximum gain rule for finding the best CV: 37 candidates

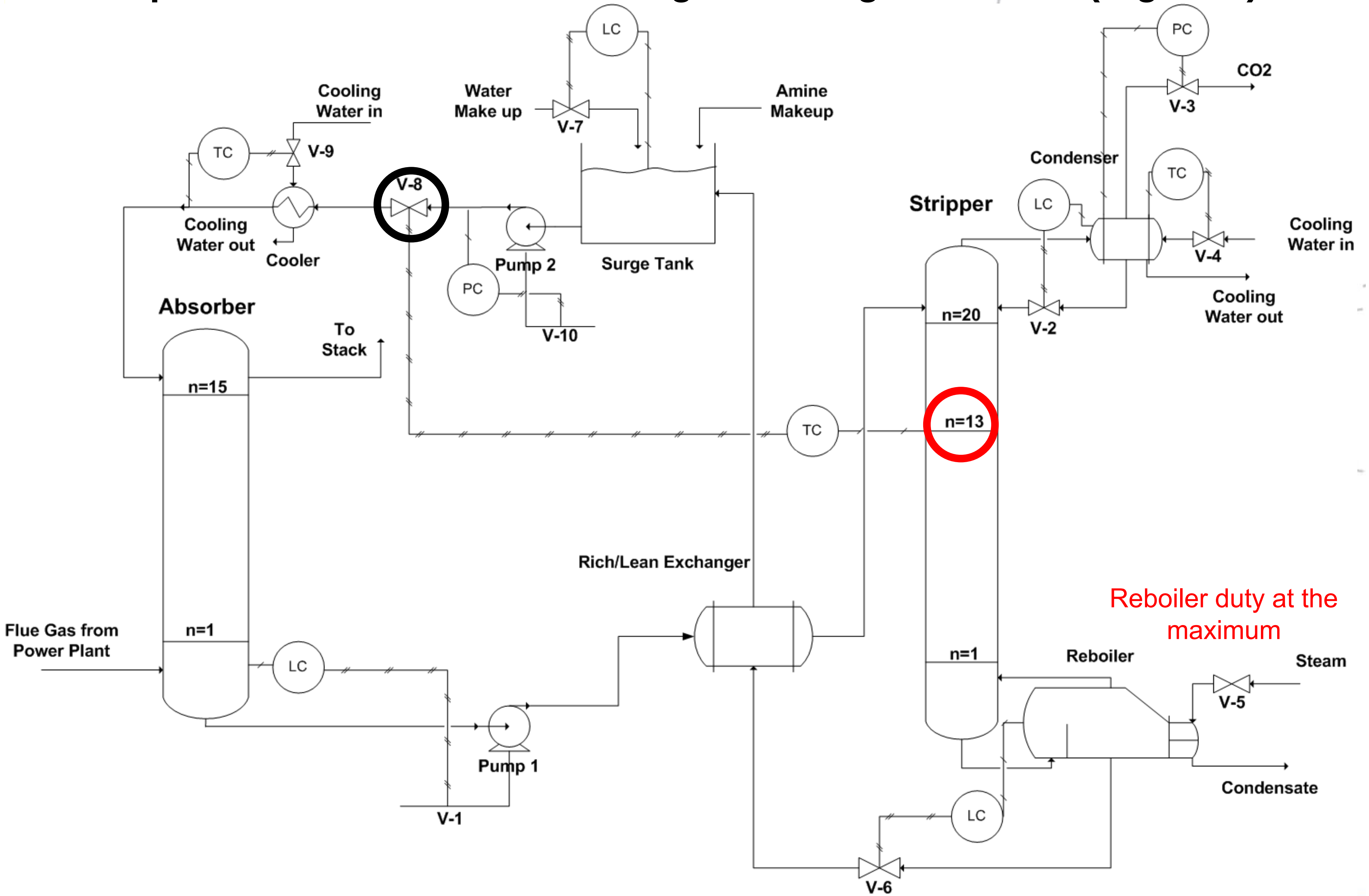
Temp. of tray no. 13 in the stripper: the largest scaled gain

NTNU
Norwegian University of Science and Technology

Proposed control structure with given flue gas flowrate (region I)



Proposed control structure with given flue gas flowrate (region II)



Region III: reaching the minimum allowable CO_2 recovery

	Flowrate of flue gas (kmol/hr)	Pumps Duty (kW)	CO_2 recovery %	Self-optimizing CV in region II Temperature of tray 13 °C	Cooler Duty (kW)	Reboiler Duty (kW)	Objective function (USD/ton)
Optimal nominal case in +30% feedrate	**285.1**	**4.61**	**91.60**	**109**	**359.3**	**1393**	**2.65**
+40% feedrate	**307.02**	**4.58**	**86.46**	**109**	**315.5**	**1393**	**2.97**
+50% feedrate	**328.95**	**4.55**	**81.31**	**109**	**290.3**	**1393**	**3.31**
+52.78% feedrate, reach to minimum CO_2 recovery	**335.1**	**4.54**	**80**	**109**	**284.6**	**1393**	**3.39**

A controller needed to set the flue gas flowrate

NTNU
Norwegian University of Science and Technology

Design of the control layers

Regulatory layer: Control of secondary (stabilizing) CVs (CV2s), PID loops

- Absorber bottom level,
- Stripper (distillation column) temperature,
- Stripper bottom level,
- Stripper top level,
- Stripper pressure,
- Recycle surge tank: inventories of water and amine,
- Absorber liquid feed temperature.

Supervisory (economic) control layer: Control of the primary (economic) CVs (CV1s), MPC

- CO_2 recovery in the absorber,
- Temperature at tray 16 in the stripper,
- Condenser temperature.

NTNU
Norwegian University of
Science and Technology

RGA analysis for selection of pairings

1. Dynamic RGA

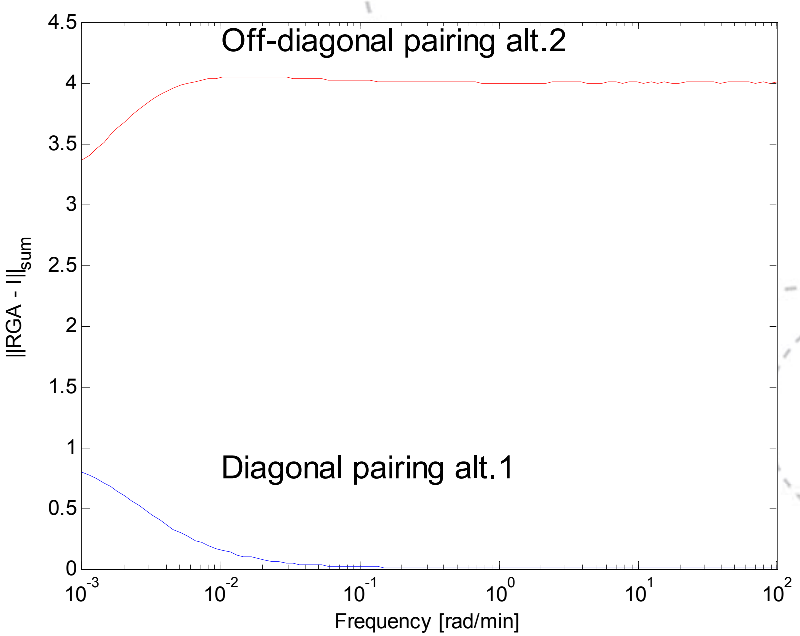
Recycle amine | Reboiler duty

CO_2 recovery

Temp. no.16 in the stripper

$$G_{dyn.}(s)=\begin{bmatrix} \frac{6.85s+1.74}{19.7s^2+11.4s+1} & \frac{-0.76s+0.038}{2400s^2+107s+1} \\ \frac{(-9.51s-1.02)e^{-2s}}{218s^2+17.3s+1} & \frac{0.45s+0.0754}{205s^2+18.8s+1} \end{bmatrix}$$

$$RGA_{dyn.}(0)=\begin{bmatrix} 0.77 & 0.23 \\ 0.23 & 0.77 \end{bmatrix}$$



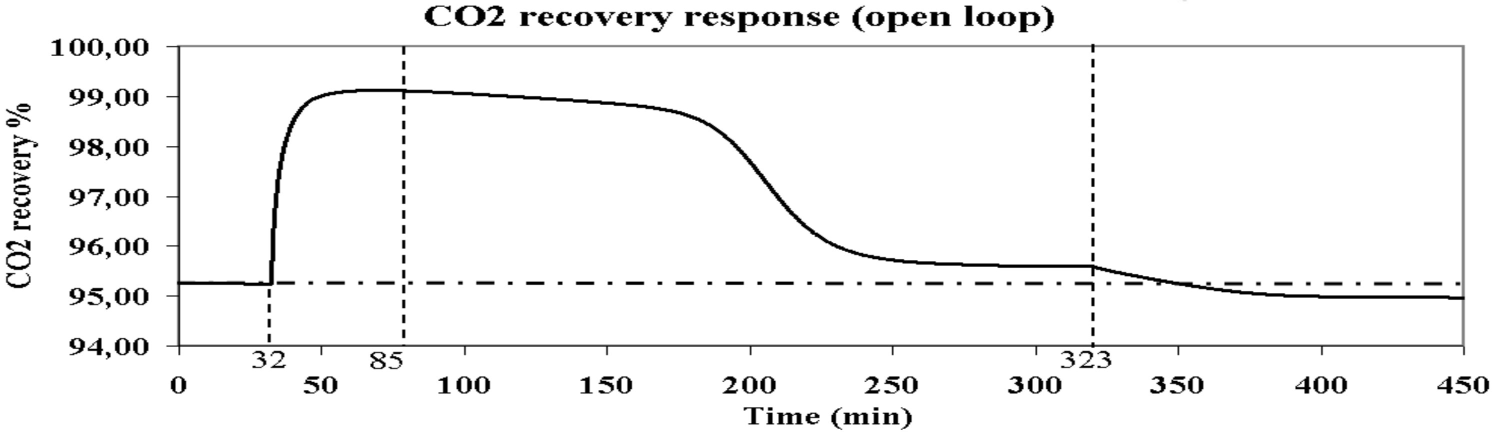
2. Steady-State RGA

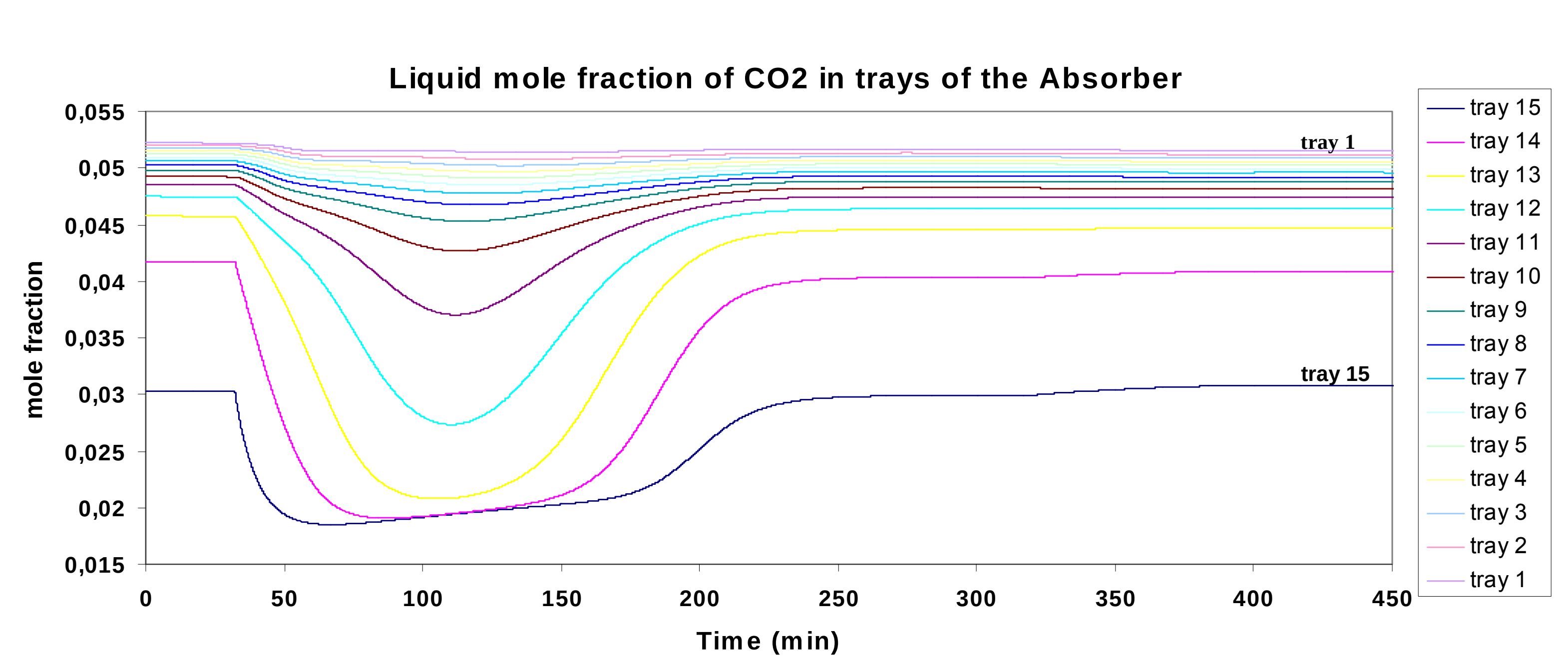
$$G_{SS}=10^{-2}\times\begin{bmatrix} -0.5232 & 1.48 \\ -8.47 & 5.17 \end{bmatrix}$$

$$RGA_{SS}=\begin{bmatrix} -0.27 & +1.27 \\ +1.27 & -0.27 \end{bmatrix}$$

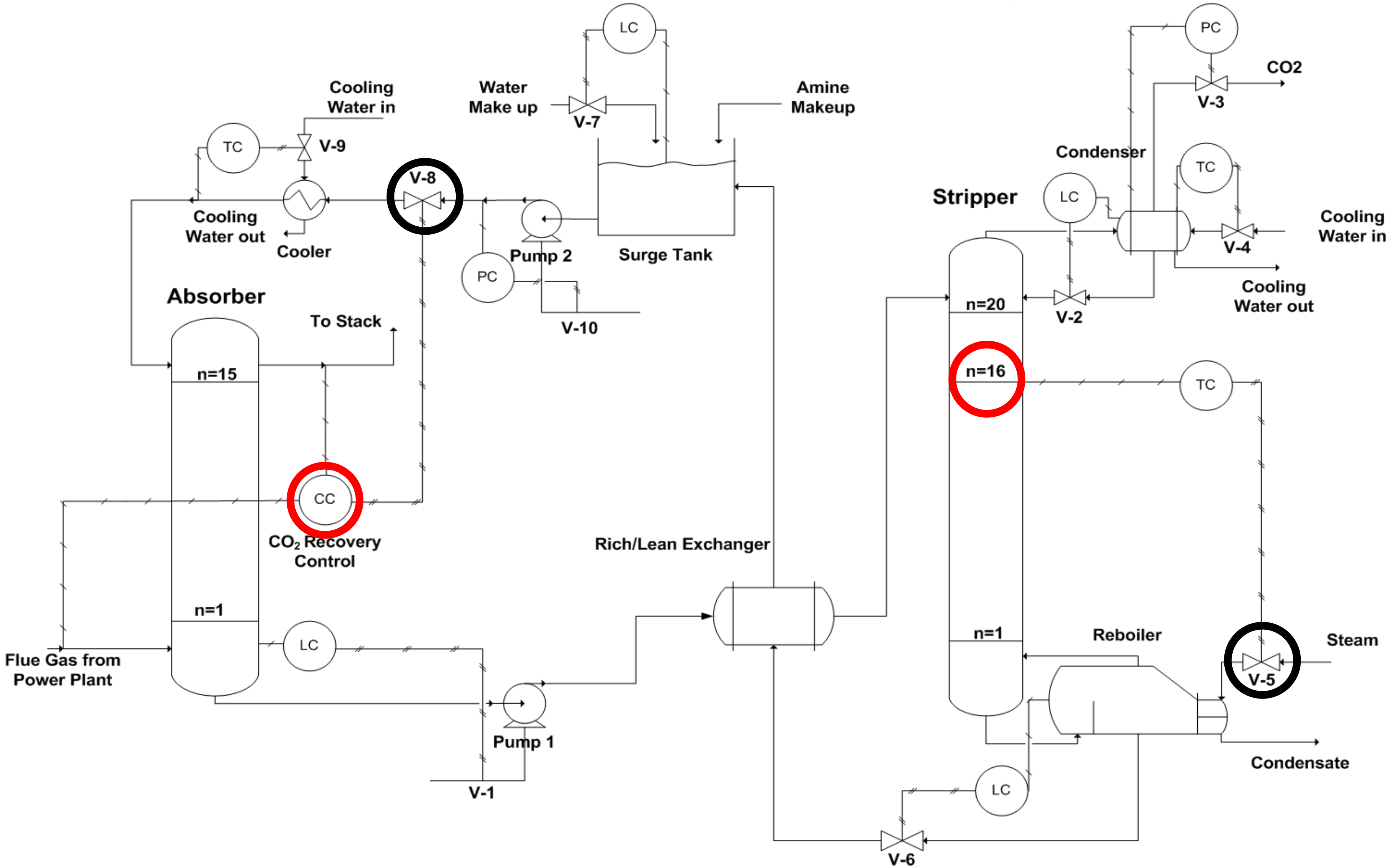
NTNU
Norwegian University of Science and Technology

"Break through" of CO_2 at the top of the absorber (UniSim simulation)

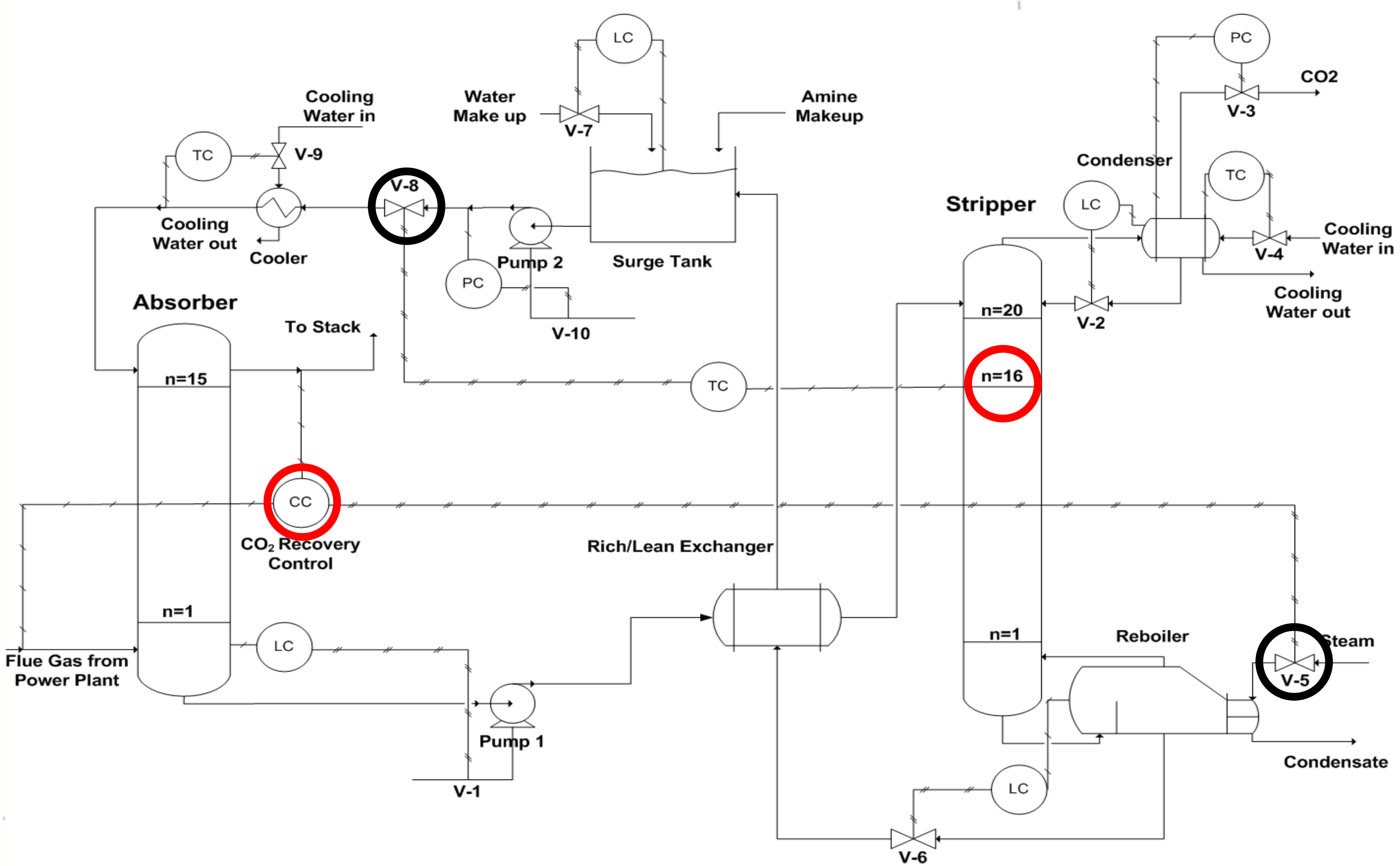




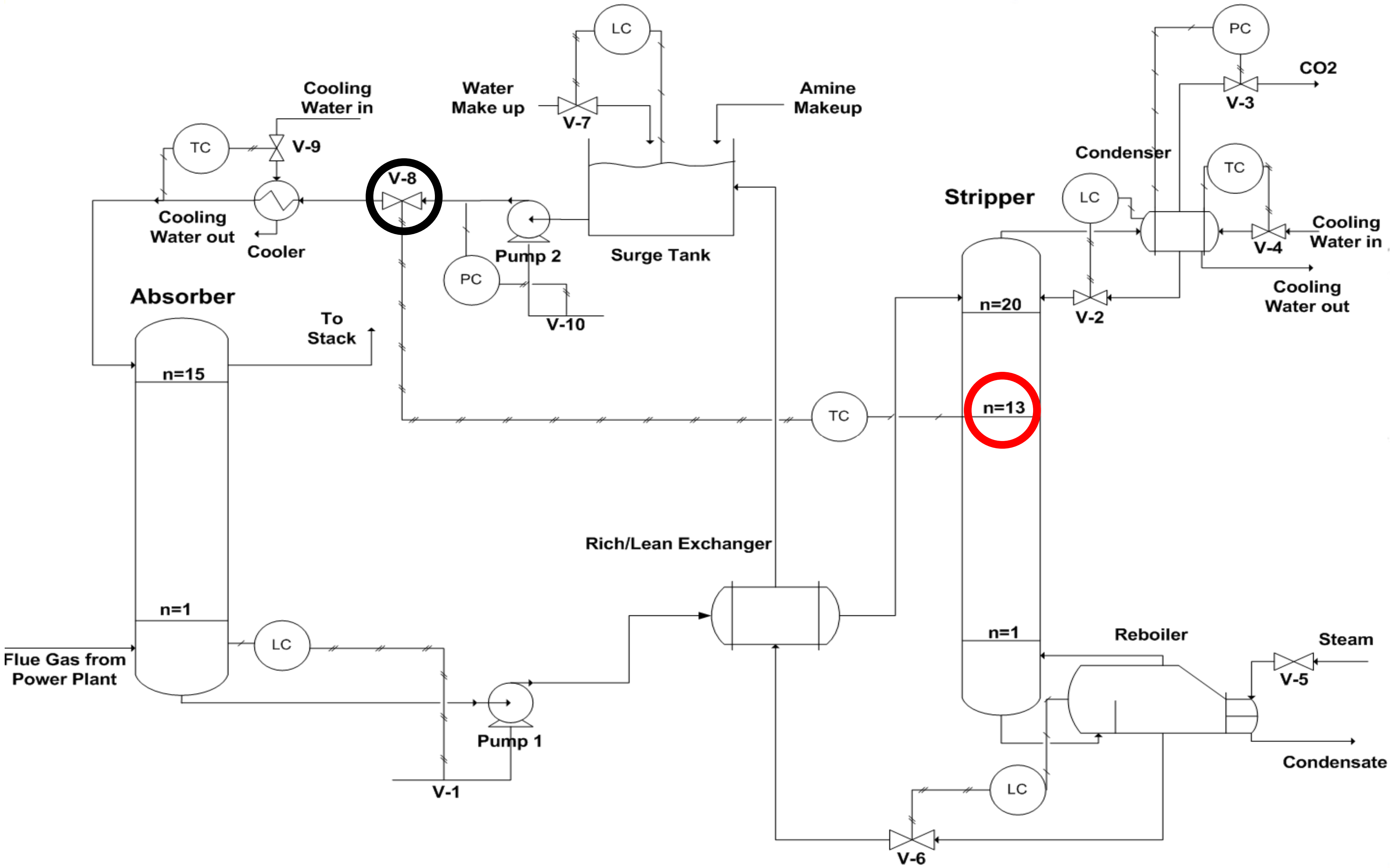
Proposed control structure with given flue gas flowrate, Alternative 1



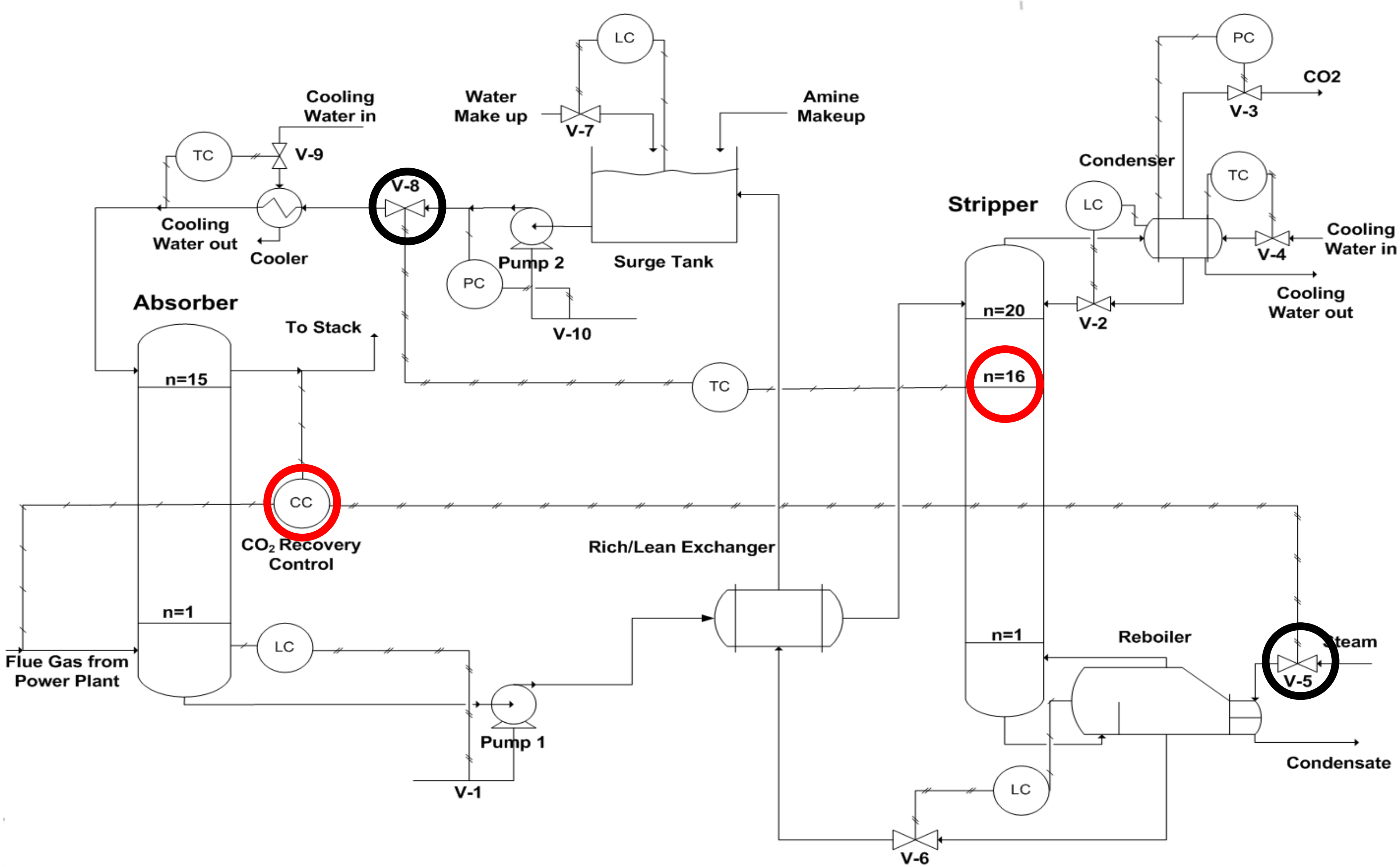
Proposed control structure with given flue gas flowrate, Alternative 2 (reverse pairing)



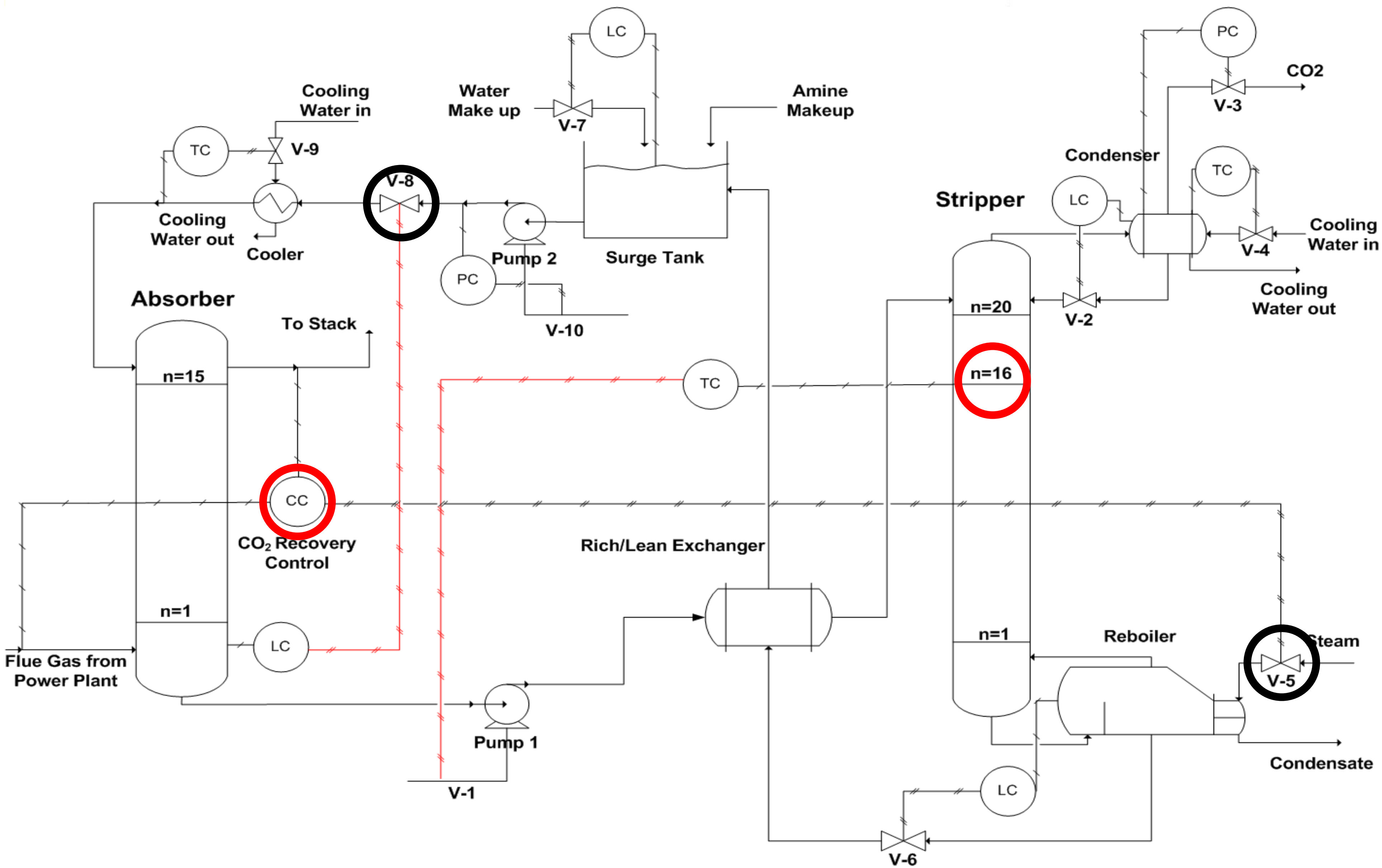
Proposed control structure in region II, Alternative 3



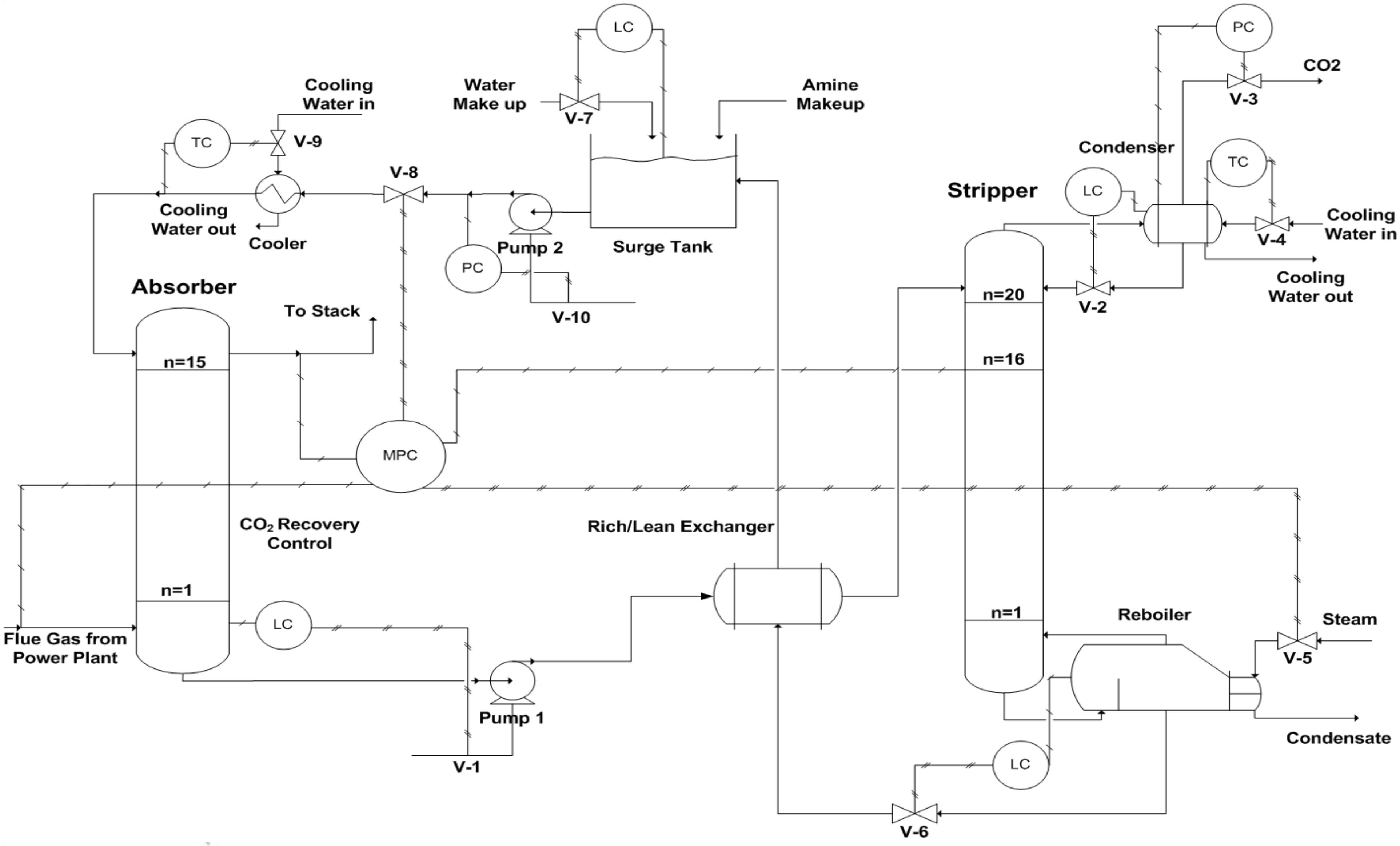
Proposed control structure with given flue gas flowrate, Alternative 2



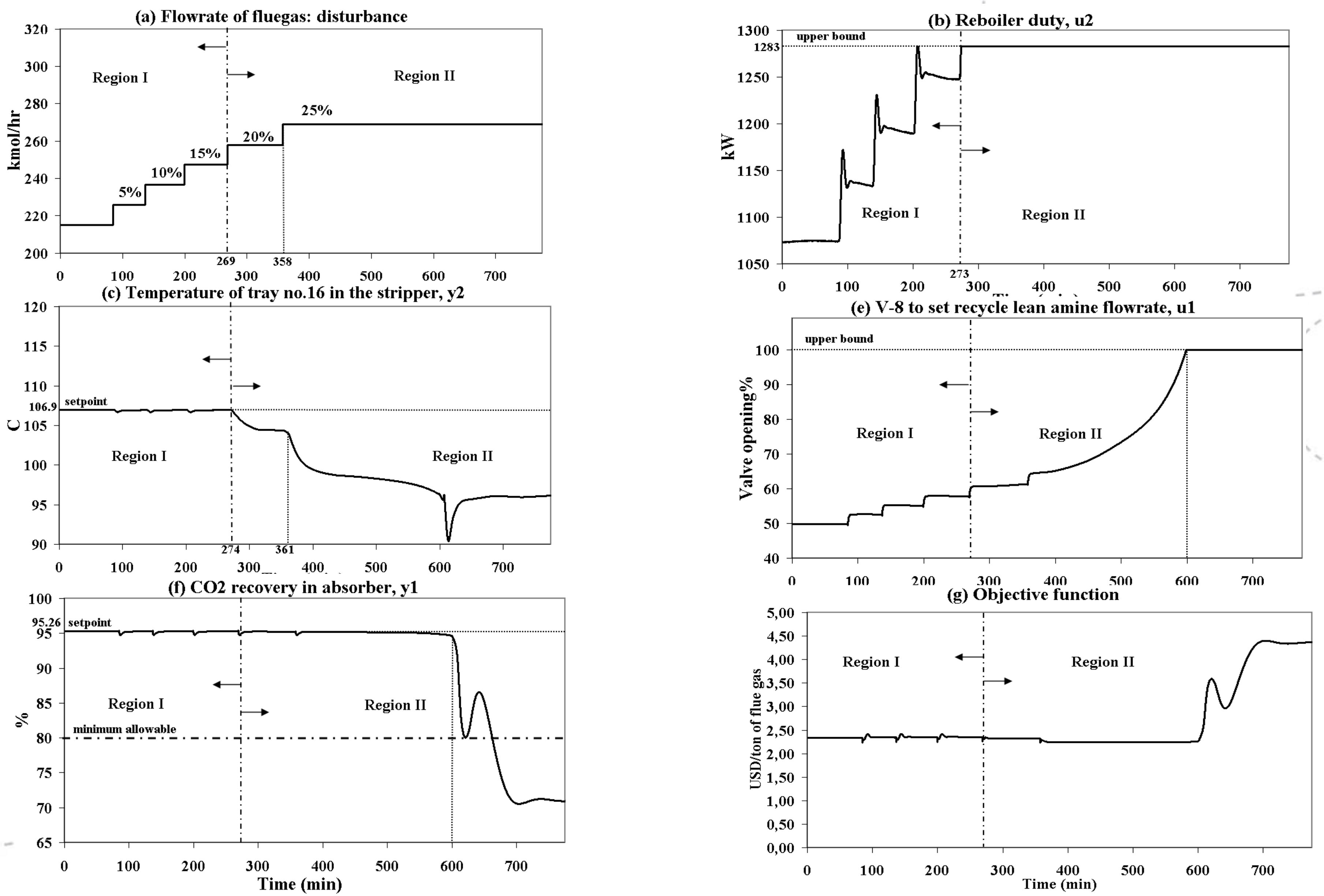
Modified Alternative 2 = Alternative 4



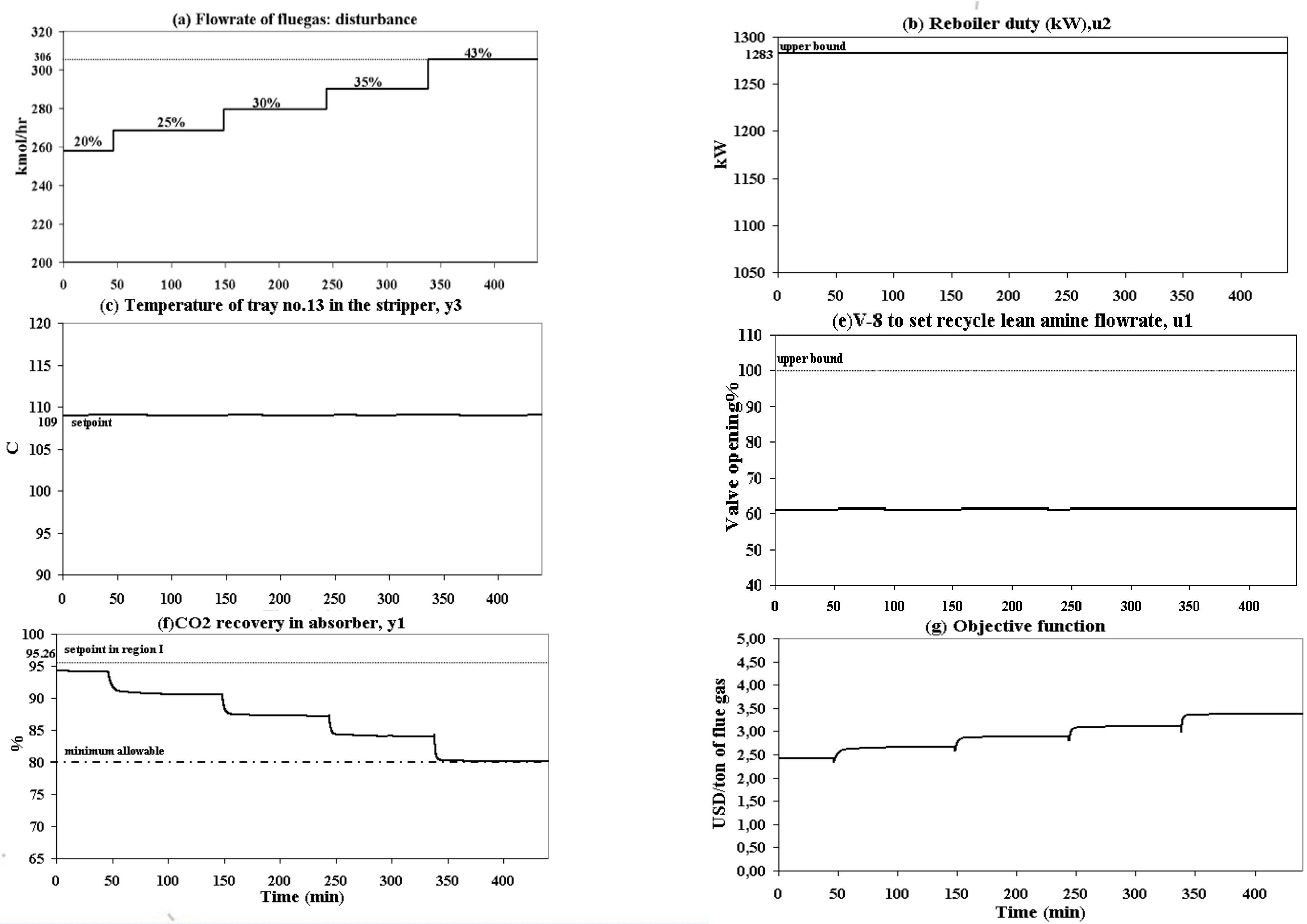
Control of self-optimizing CVs using a multivariable controller



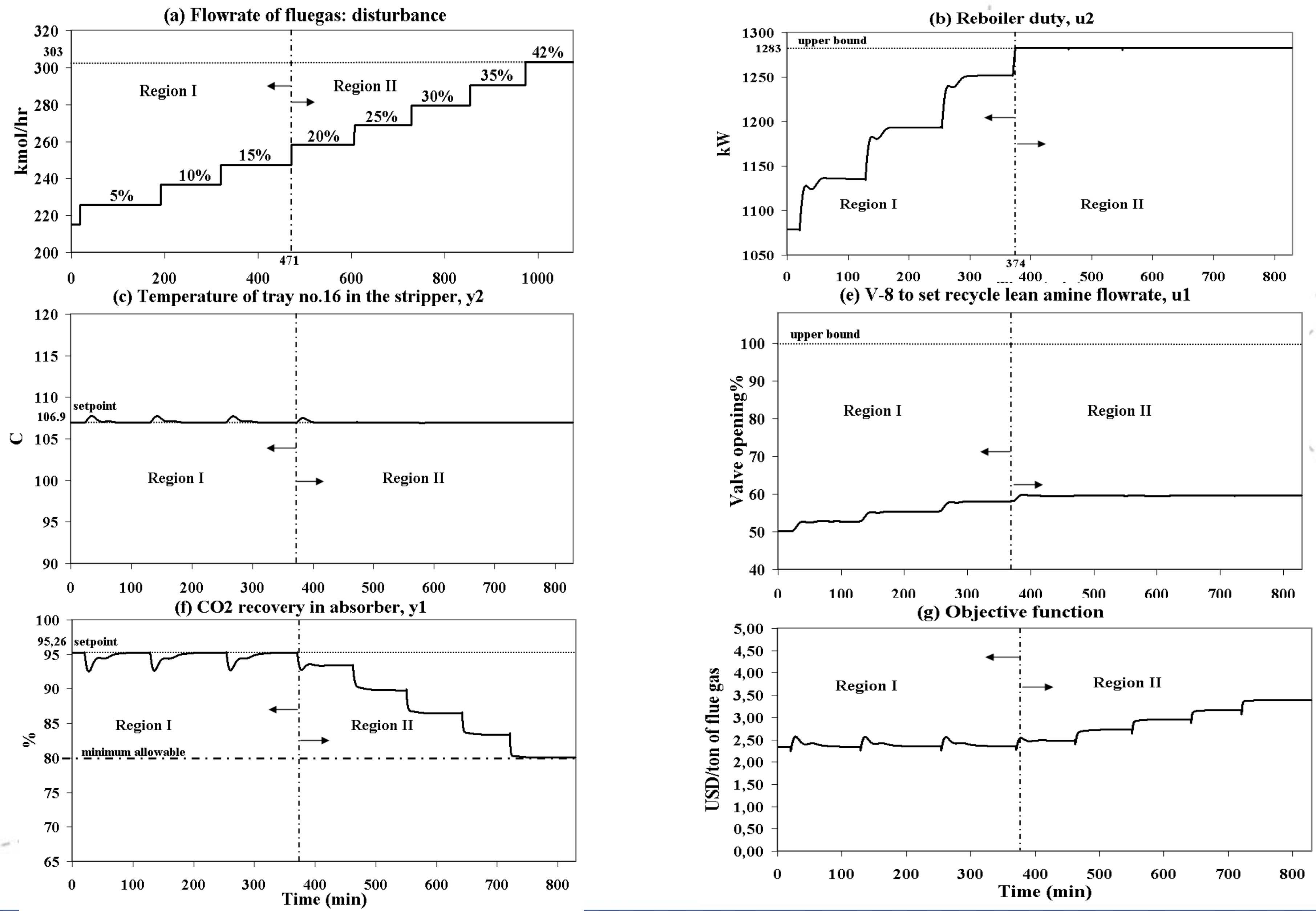
Performance of the proposed control structure, Alternative 1



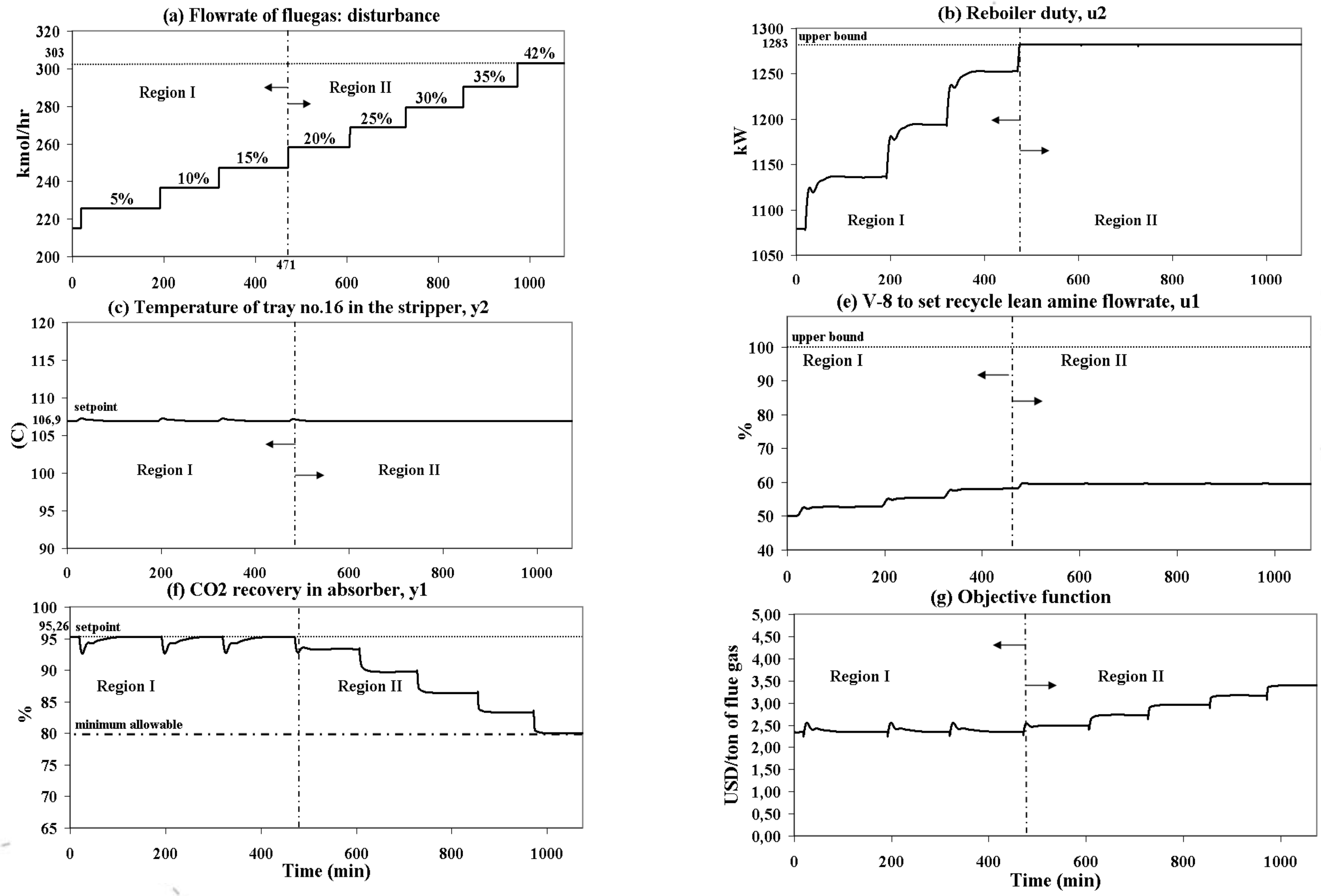
Performance of the proposed control structure, Alternative 3



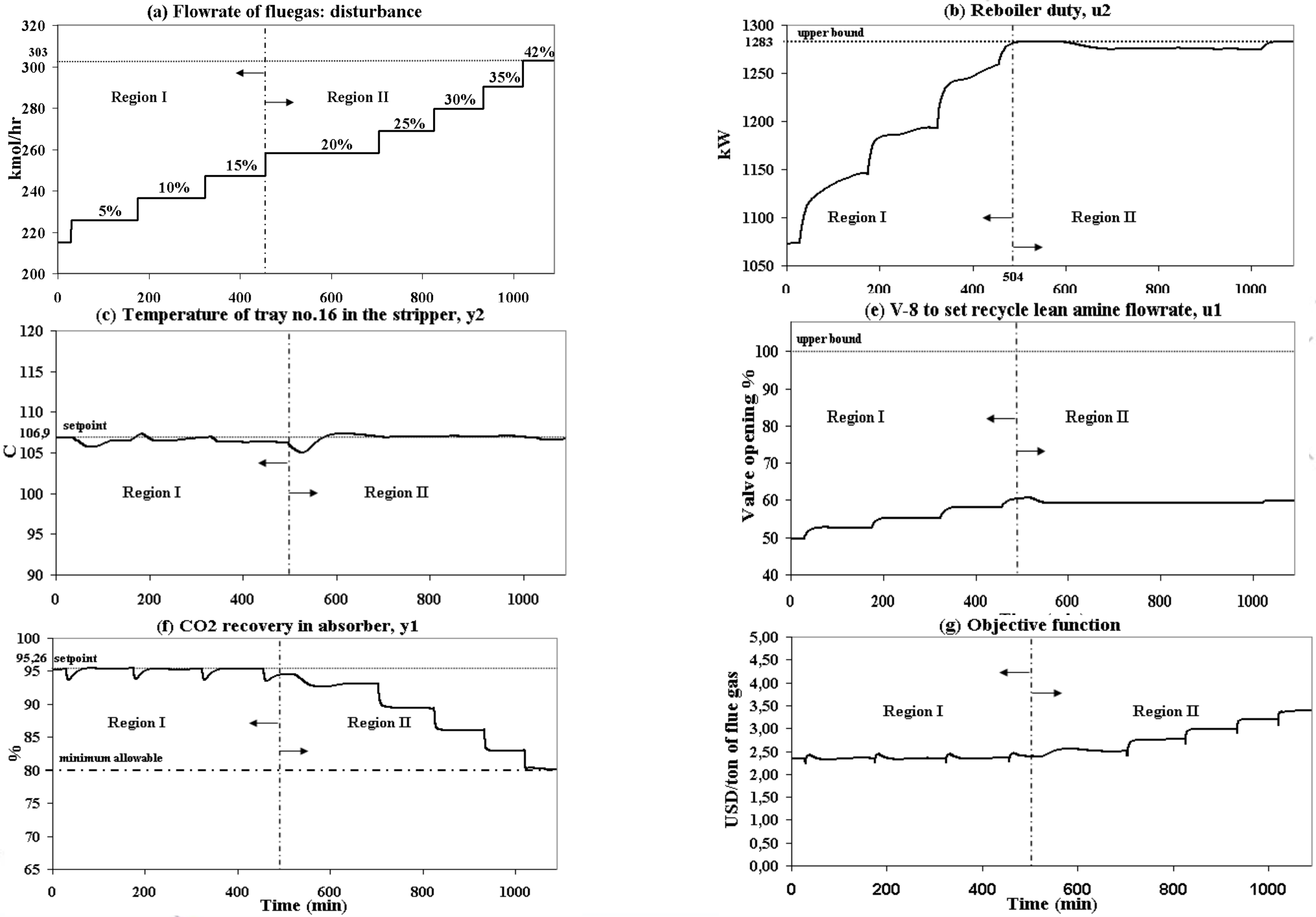
Performance of the proposed control structure, Alternative 2



Performance of the proposed control structure, Alternative 4



Performance of the proposed control structure, MPC



Conclusions

- Alternative 1 is optimal in region I, but fails in region II
- Alternative 2 handles regions I (optimal) and II (close to optimal), but more interactions in region I compare to Alternative 1. No need for switching
- Alternative 3 is optimal in region II. Need for switching
- Alternative 4 is modified Alternative 2 ,results in less interactions. No need for switching
- MPC, similar performance to Alternatives 2 & 4

Alternative 4 is recommended for implementation in practice

NTNU
Norwegian University of Science and Technology

Conclusions

- Alternative 1 is optimal in region I, but fails in region II
- Alternative 2 handles regions I (optimal) and II (close to optimal), but more interactions in region I compare to Alternative 1. No need for switching
- Alternative 3 is optimal in region II. Need for switching
- Alternative 4 is modified Alternative 2 ,results in less interactions. No need for switching
- MPC, similar performance to Alternatives 2 & 4

Alternative 4 is recommended for implementation in practice

Thank you for your attention

NTNU
Norwegian University of Science and Technology