



# Contrôle de paramètres dans un chémostat

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► **To cite this version:**

Jérôme Harmand. Contrôle de paramètres dans un chémostat. Colloque National d'Assimilation de Données, Dec 2014, Toulouse, France. hal-01090655

**HAL Id: hal-01090655**

**<https://hal.inria.fr/hal-01090655>**

Submitted on 2 Jun 2020

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## Control of the chemostat model

*J. Harmand, SAMI research team, LBE-INRA & INRA-INRIA  
MODEMIC*

# Le LBE-INRA et MODEMIC



- INRA
- About 80 people



*Modemic*

Treating and valorize biomass within a biorefinery context

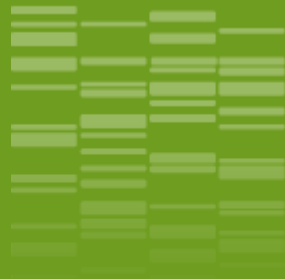


# CONTEXT

- ❖ An « explosion » of –omic data : a problematic of « big data »
- ❖ High computation capacity
- ❖ A (very) important deficit in modeling education within education in biology
- ❖ How available data and modeling may help in better understanding and controlling bioprocesses?

# CONTENT

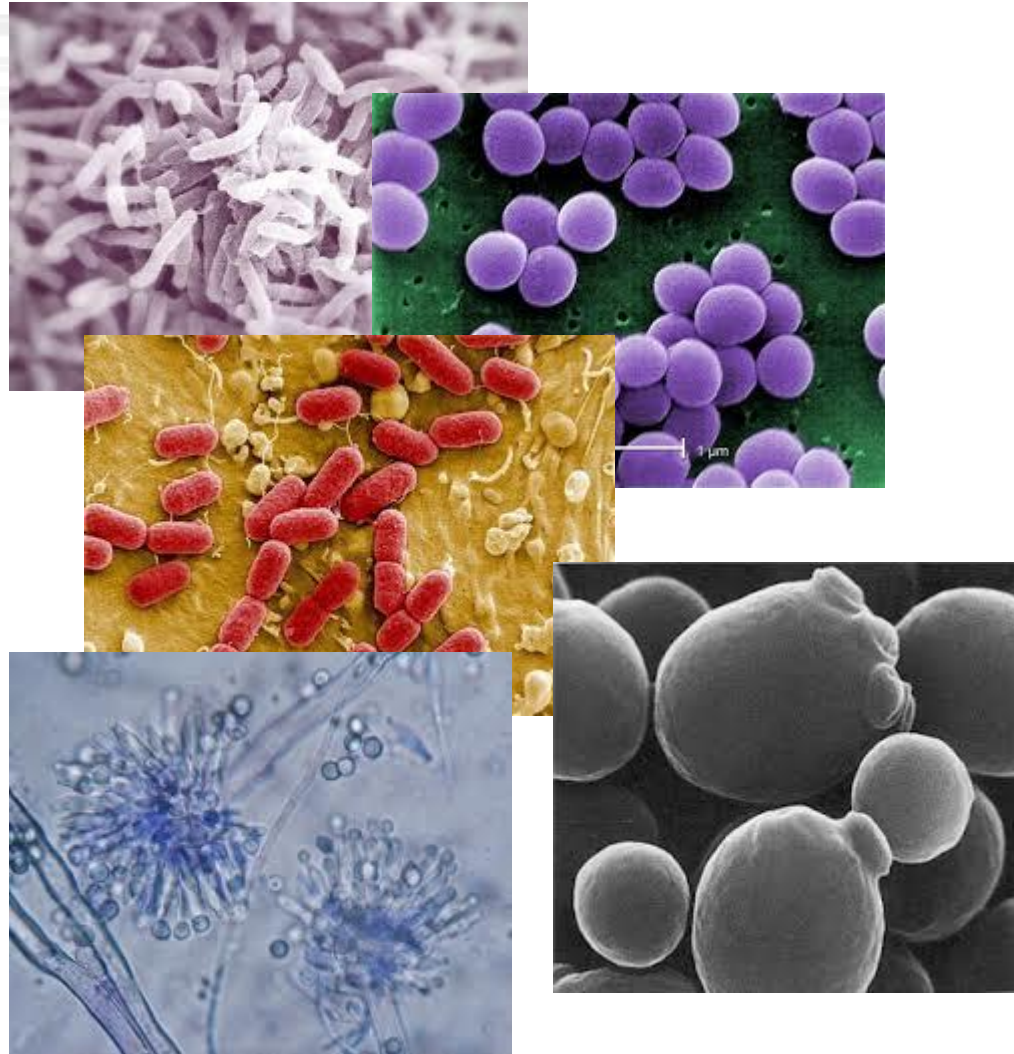
- ❖ Microbial ecosystems and the chemostat...
- ❖ Bioprocess modeling
- ❖ Observing and controlling the chemostat : a robust approach
- ❖ An example : control of the anaerobic digestion process



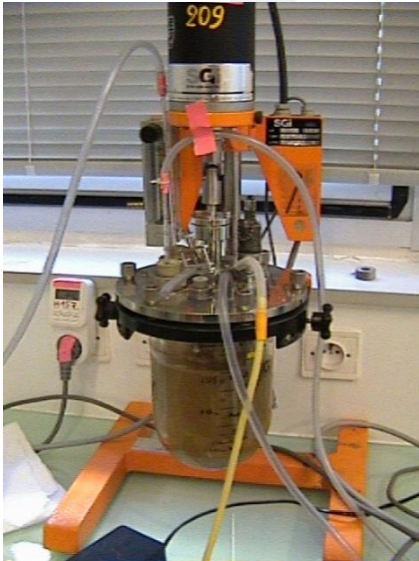
**\_01**

# Microbial ecosystems and the chemostat

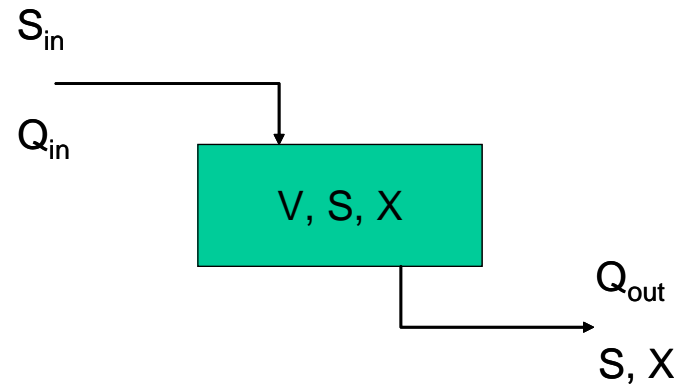
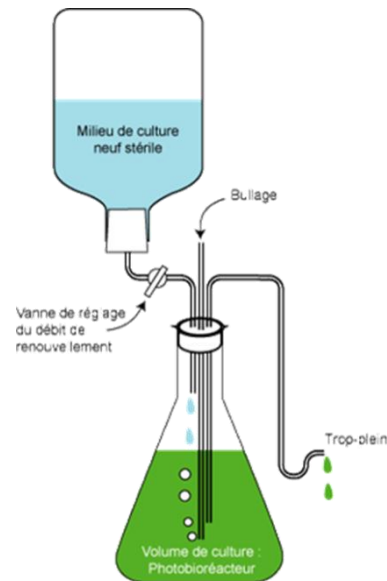
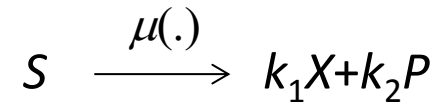
# Les écosystèmes microbiens



# The chemostat



« Chemostat »





# Le chemostat

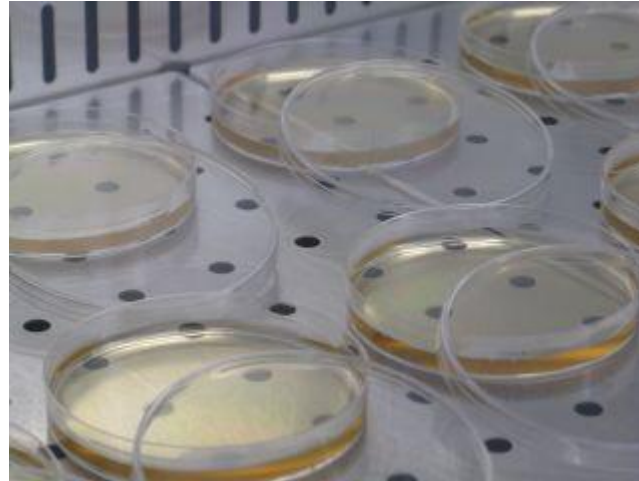
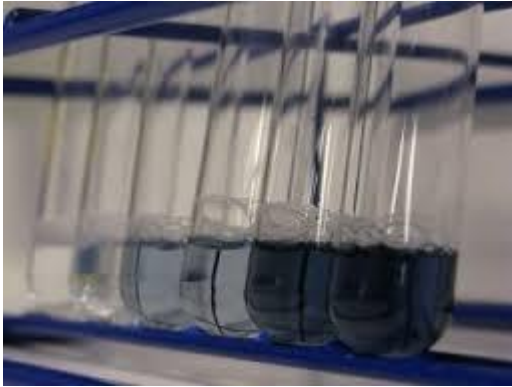
## The inventors of the chemostat

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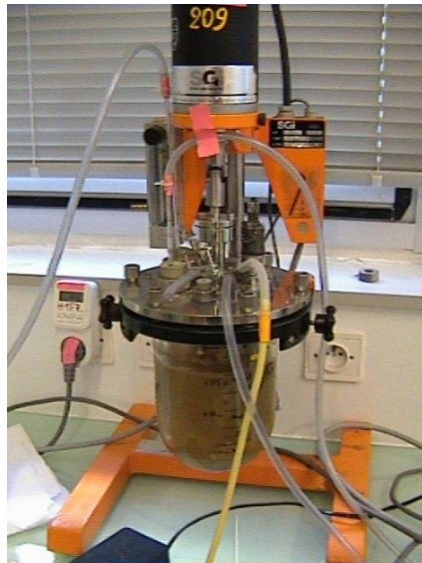
- Novick A. and Szilard L. (1950), *Description of the chemostat*. *Science*, 112, 715-716
- Monod, J., *La technique de culture continue theorie et applications*. *Ann. Inst. Pasteur*, 79, 390-410, 1950



# High diversity of scales



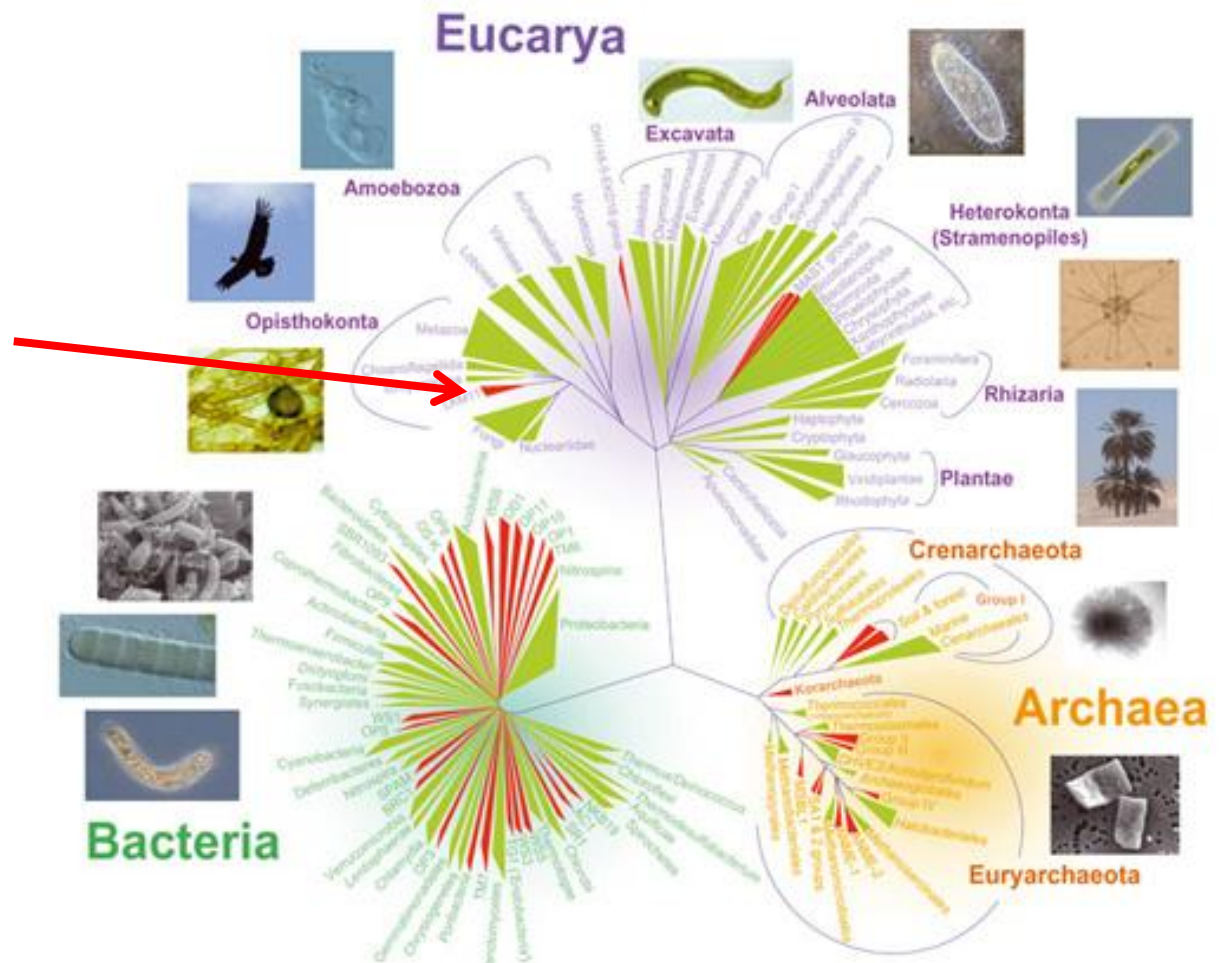
# How using microbial ecosystems



*Studying the functional heart of any bioprocess: a natural « complex » ecosystem*

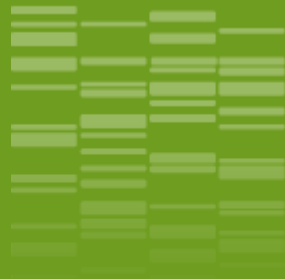
# An immense world...

You, your cat and your red fish...



# Conclusions

- ❑ Microbial ecosystems : complex systems;
- ❑ Used in a very high number of production/treatment fields
- ❑ The chemostat is only 60 years old;
- ❑ Important research effort...

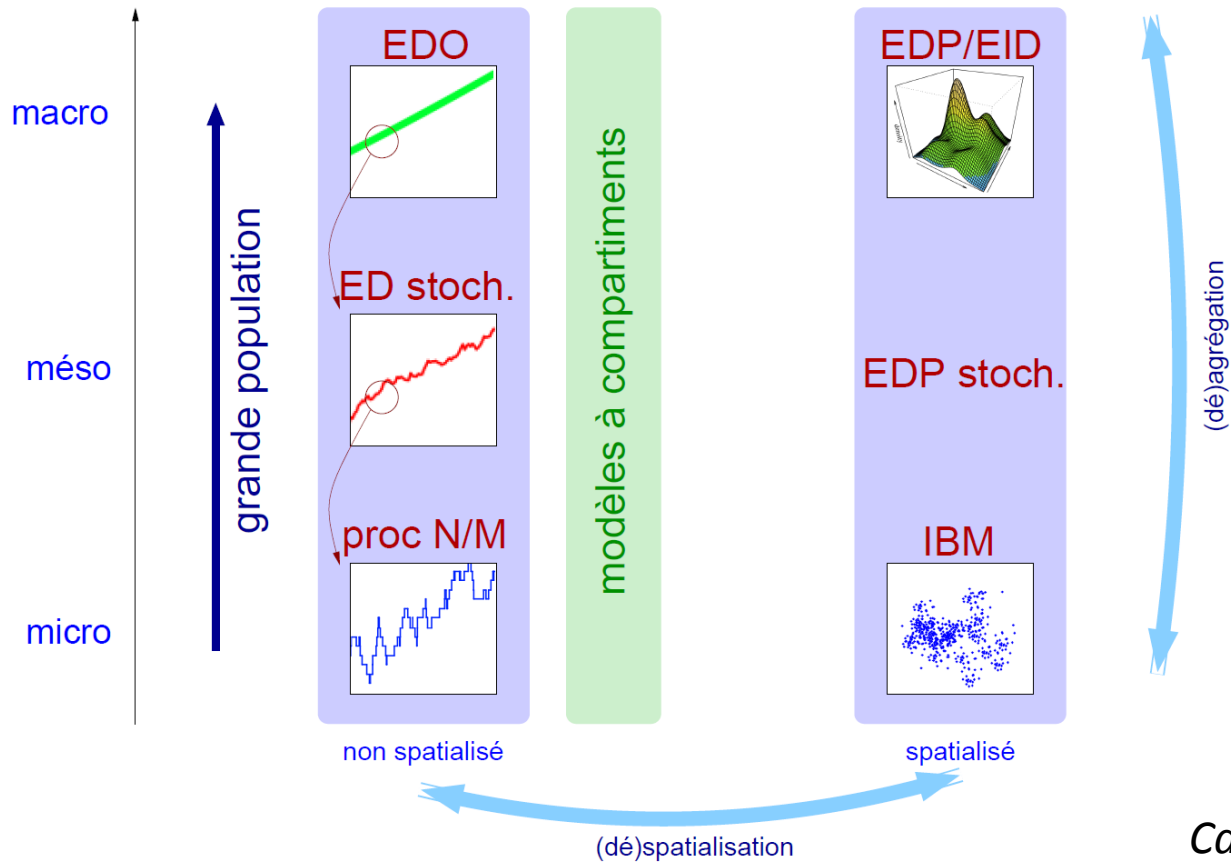


**\_02**

# Modeling

# Lots of model!

Deterministic continuous dynamical models vs stochastic IBM



Campillo, 2011

# Which model : the viewpoint of microbiologist...

Usually, they only know the two extreme cases : EDO-based and IBM (used for describing space)!

Then use of a model instead of another depends essentially of their collaboration and of their own modeling culture!

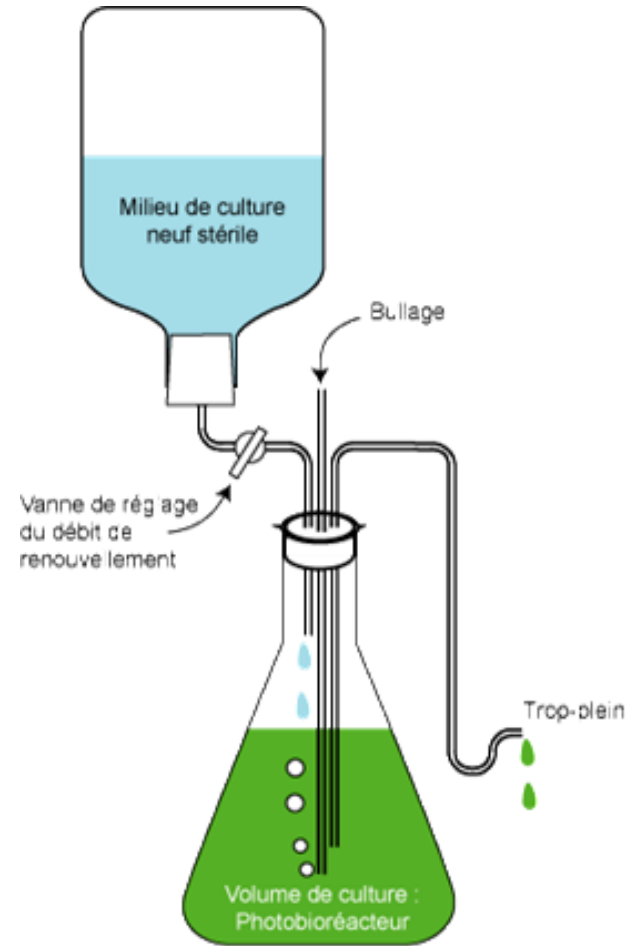
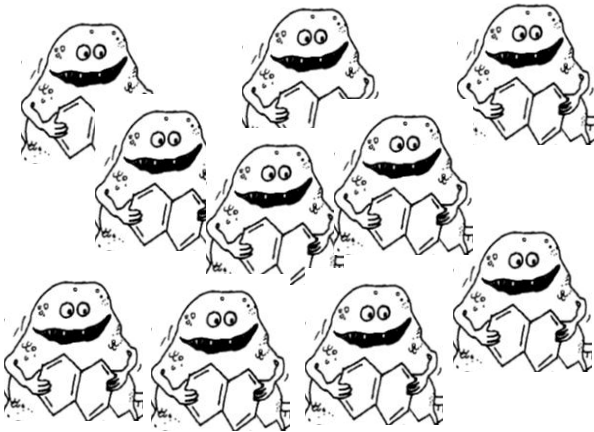


# Which model : the viewpoint of modelists/mathematicians...

Such nonlinear models may be usefull for my research to be applied...

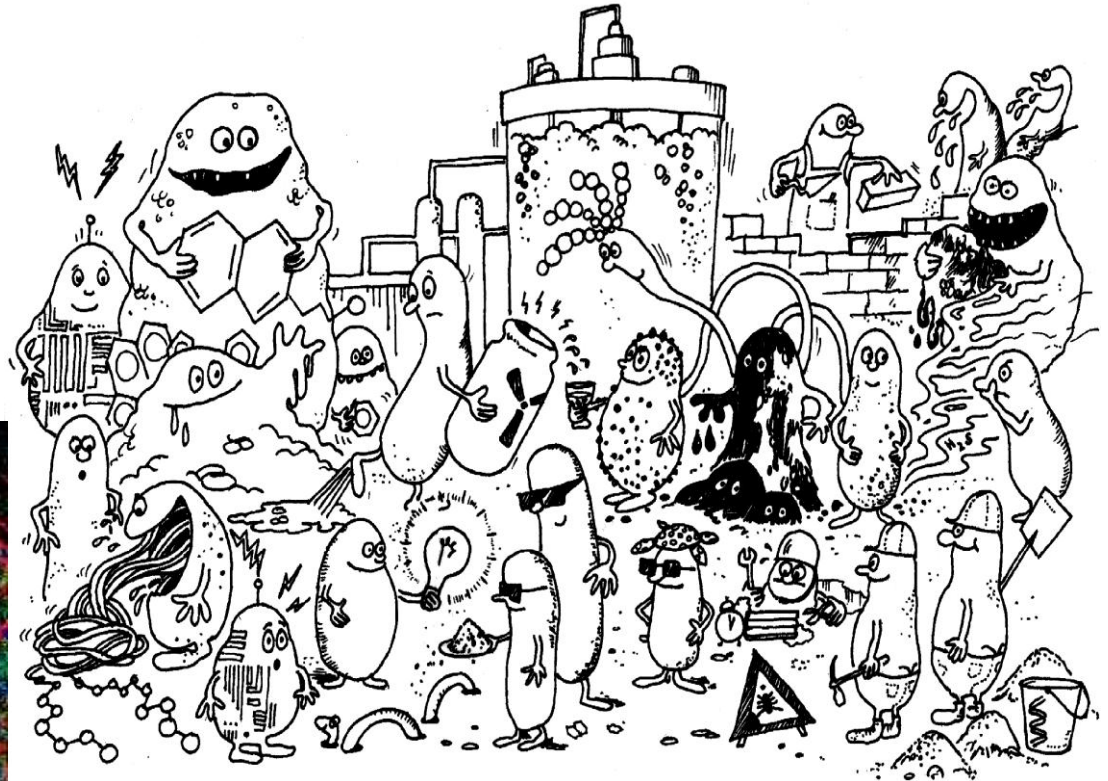
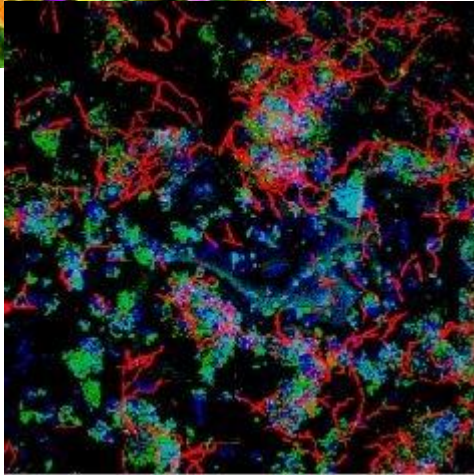
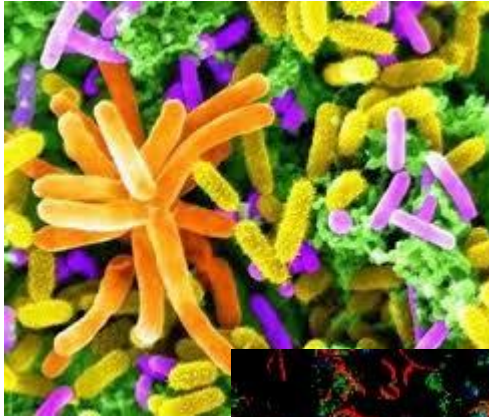
# How modeling an ideal bioprocess?

□ Until recently...



# How modeling an ideal bioprocess?

□ Modern biological tools reveal rather...



# The chemostat model

- The associated continuous deterministic model

$$\frac{d(SV)}{dt} = \text{"Input mass of S"} - \text{"Output mass of S"} \dots$$

...+ "production" - "consumption"

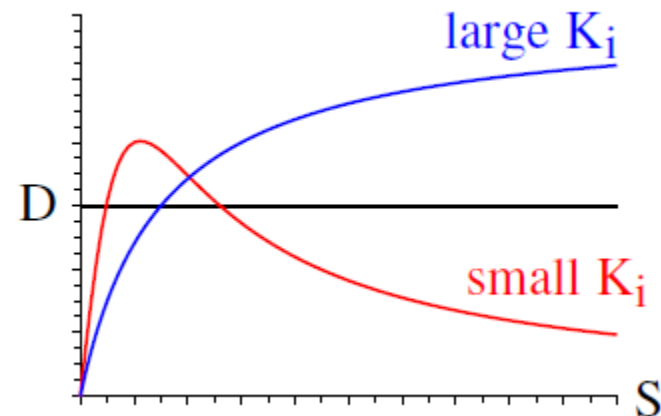
$$\begin{cases} \frac{dS}{dt} = S_{in} \frac{Q}{V} - S \frac{Q}{V} - \frac{\mu(S)}{Y} X = (S_{in} - S) D - \frac{\mu(S)}{Y} X \\ \frac{dX}{dt} = \mu(S) X - \frac{Q}{V} X = (\mu(S) - D) X \end{cases}$$

# The chemostat model

## □ Kinetic modeling

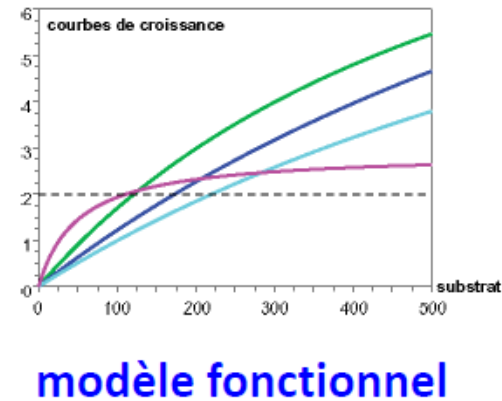
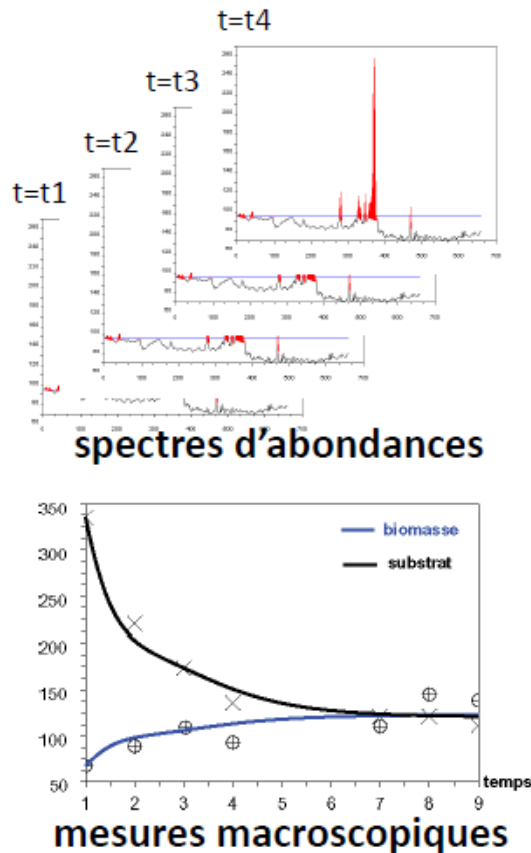
$$\begin{aligned}\dot{s} &= -\mu(s)x + D(s_{in} - s) \\ \dot{x} &= \mu(s)x - Dx\end{aligned}$$

$$\mu(s) = \frac{\bar{\mu}s}{K + s + s^2/K_i}$$



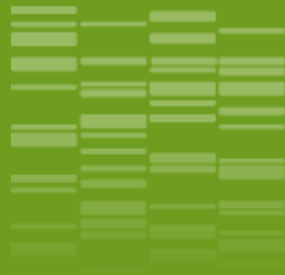
# The chemostat model

□ Matching data : identifying yields and kinetics coefficients



# Conclusions

- ❑ Important research on chemostat modeling;
- ❑ To study microorganism growth (ecological questions);
- ❑ To optimize its functioning...



**\_03**

## Observing and controlling the chemostat...

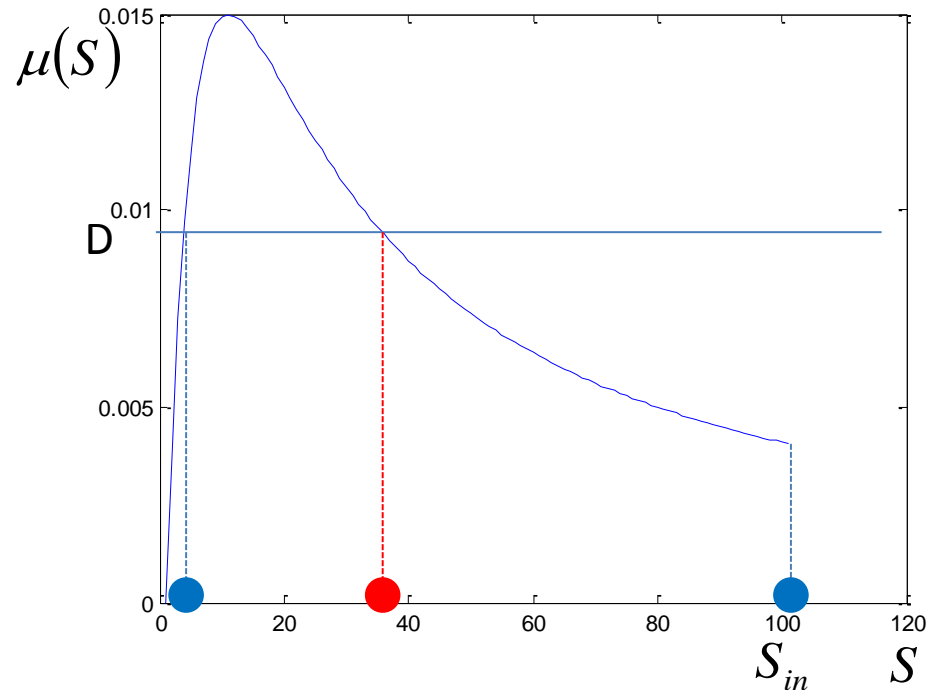


# The chemostat model

## □ Chemostat with inhibition

$$\begin{cases} \frac{dS}{dt} = (S_{in} - S)D - k\mu(S)X \\ \frac{dX}{dt} = (\mu(S) - D)X \end{cases}$$

$$\mu(S) = \frac{\bar{\mu}S}{S + K_S + \frac{S^2}{K_I}}$$



$$\bar{\mu} = 0.045, K_S = 10, K_I = 10$$

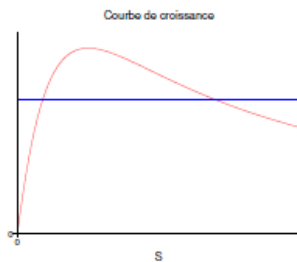
# The chemostat model

## Qualitative properties of the model



$$D > \max_{s \in [0, S_{in}]} \mu(s)$$

1 equilibrium : washout



$$\mu(s_{in}) < D < \max_{s \in [0, S_{in}]} \mu(s)$$

3 equilibria : bistability

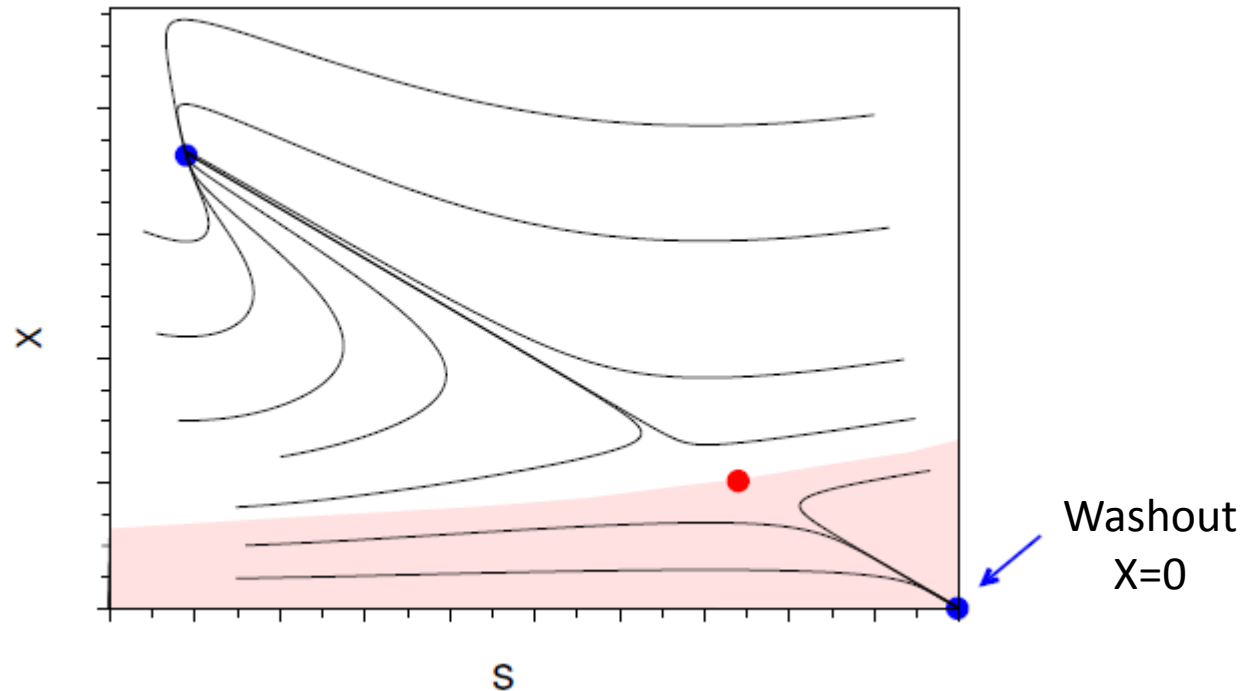


$$D < \mu(s_{in})$$

2 equilibria : 1 stable and one unstable (washout)

# The chemostat model

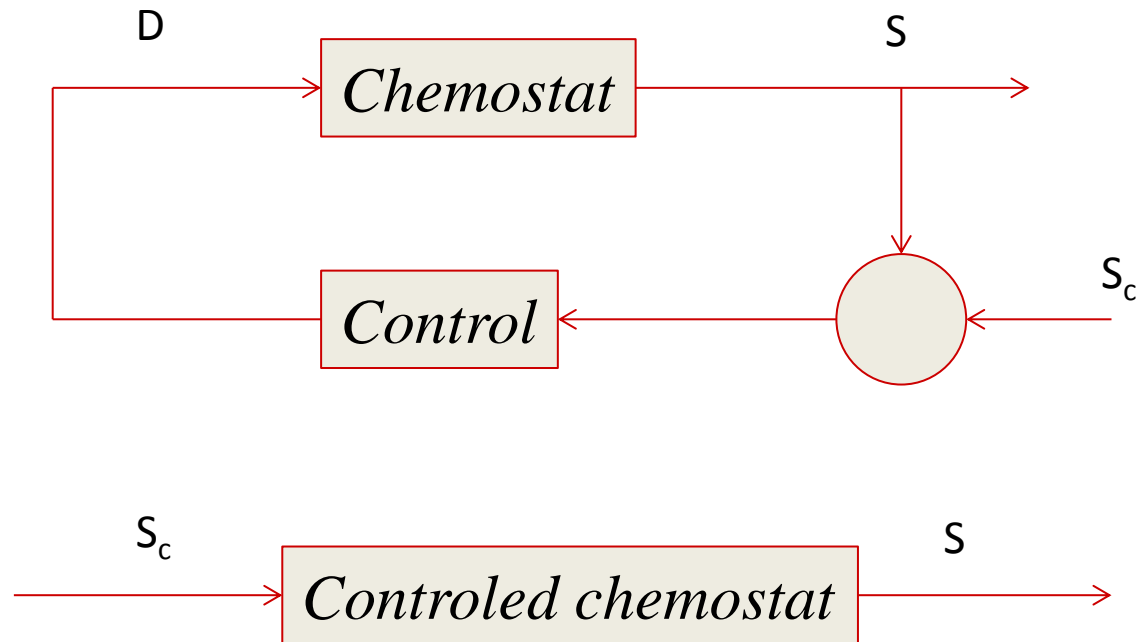
## □ State space representation



Cas #2 : Under the condition  $\mu(s_{in}) < D < \max_{s \in [0, S_{in}]} \mu(s)$

# Controlling the chemostat

## □ Closing the loop



# Stabilizing the chemostat

## □ Solution : Output Feedback

*Example #1* : Linearizing feedback control

$$D(s, x) = \frac{\mu(s)x - \lambda(s - s^*)}{s_{in} - s}$$

Cf. Bastin et Dochain 1986

*Example #2* : PI Controller

$$D(s) = G_1(s - s^*) + G_2 \int_0^t (s(\tau) - s^*) d\tau$$

Cf. Alvarez Lopez-Arenas 2012 (and many others)

*Example #N* : ...

# Stabilizing the chemostat

## □ Solution : Output Feedback

*Exemple #1 : Linearizing feedback control*

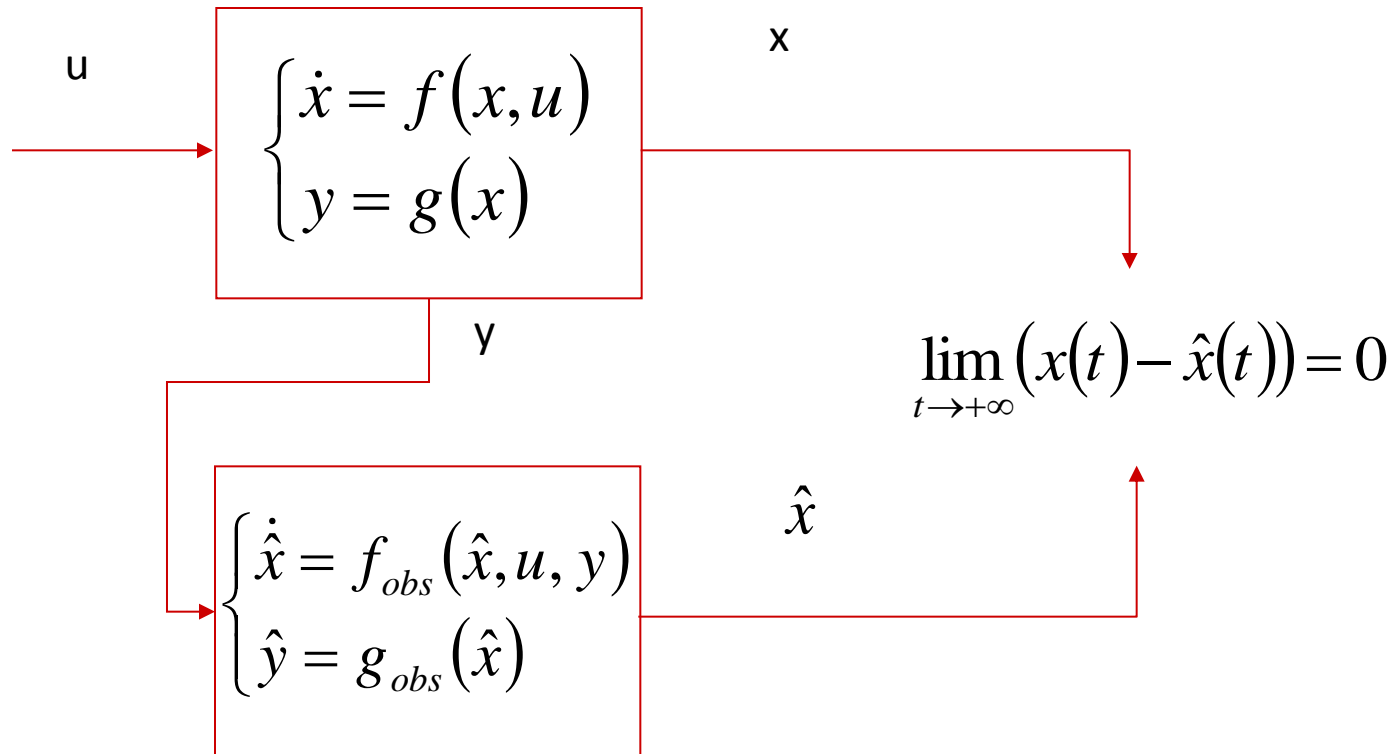
$$D(s, x) = \frac{\mu(s)x - \lambda(s - s^*)}{s_{in} - s}$$

***Drawback : We must know everything! (mu + sin, s and x...)***

*Assuming we only know s and we have uncertainty on others input and parameters, how stabilizing the system with guaranteed performances?*

# Stabilizing the chemostat

- Solution : A robust observer scheme



# Stabilizing the chemostat

- Solution : An interesting change of variables

$$\left\{ \begin{array}{l} \frac{d\hat{Z}(t)}{dt} = (S_{in} - \hat{Z}(t))D(t) \\ \hat{Z}(0) = \hat{Z}_0 \\ \hat{X}(t) = Y(\hat{Z}(t) - S(t)) \end{array} \right.$$

$$\lim_{t \rightarrow +\infty} Z(t) = S_{in}$$



# Stabilizing the chemostat

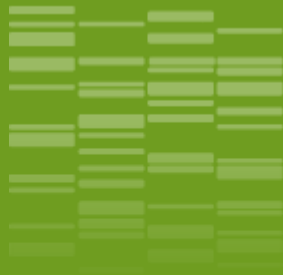
- Robustifying the asymptotic observer with respect to uncertainty (inputs + measurements + parameters)

$$\left\{ \begin{array}{l} \frac{d\hat{Z}^-(t)}{dt} = (S_{in}^- - \hat{Z}^-(t))D(t) \\ \hat{Z}^-(0) = \hat{Z}_0^- \\ \hat{X}^-(t) = Y(\hat{Z}^-(t) - S(t)) \end{array} \right.$$

$$\left\{ \begin{array}{l} \frac{d\hat{Z}^+(t)}{dt} = (S_{in}^+ - \hat{Z}^+(t))D(t) \\ \hat{Z}^+(0) = \hat{Z}_0^+ \\ \hat{X}^+(t) = Y(\hat{Z}^+(t) - S(t)) \end{array} \right.$$

$$\lim_{t \rightarrow +\infty} Z^-(t) = S_{in}^-$$

$$\lim_{t \rightarrow +\infty} Z^+(t) = S_{in}^+$$

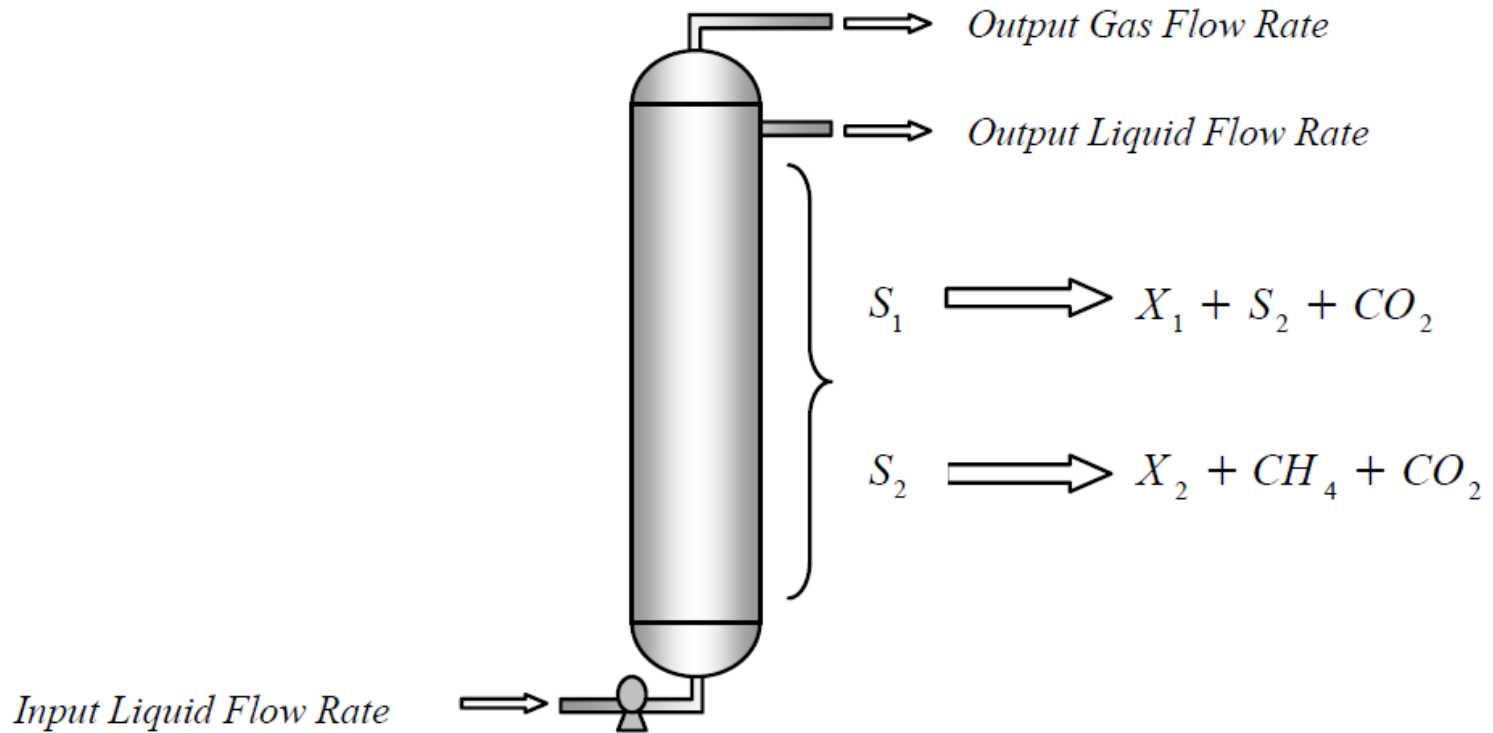


**\_04**

**An exemple : controlling the  
anaerobic digestion process**

# Stabilizing the chemostat

## □ Application



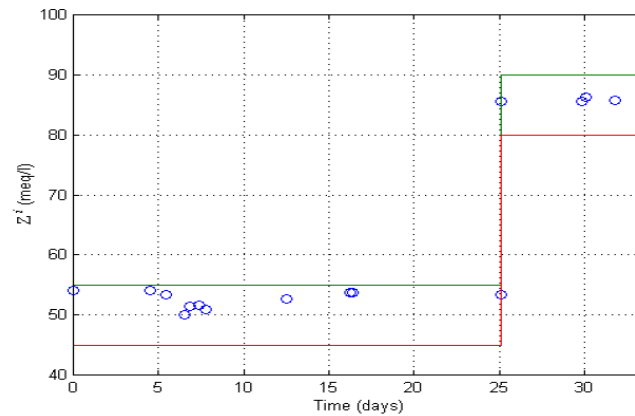
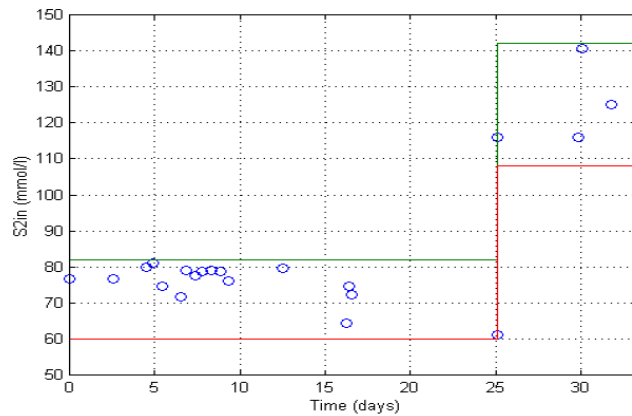
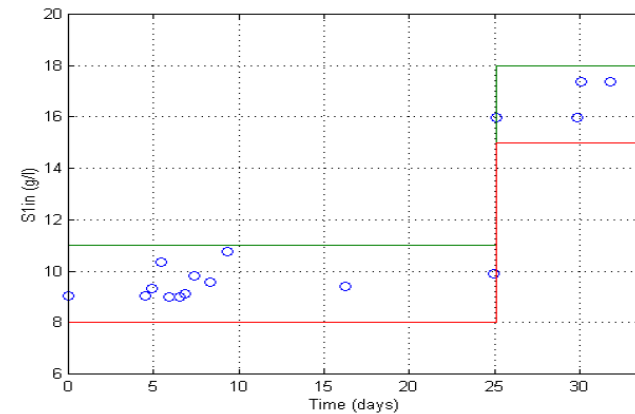
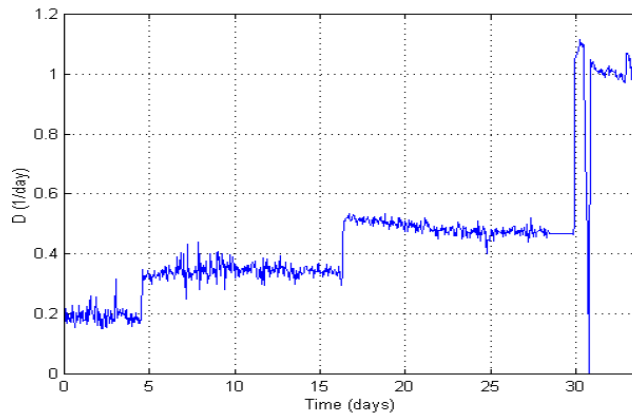
# Stabilizing the chemostat

## □ The model

$$\left\{ \begin{array}{l} \dot{X}_1 = (\mu_1 - \alpha D)X_1 \\ \dot{X}_2 = (\mu_2 - \alpha D)X_2 \\ \dot{Z} = D(Z^i - Z) \\ \dot{S}_1 = D(S_1^i - S_1) - k_1\mu_1 X_1 \\ \dot{S}_2 = D(S_2^i - S_2) + k_2\mu_1 X_1 - k_3\mu_2 X_2 \\ \dot{C}_{\text{TI}} = D(C_{\text{TI}}^i - C_{\text{TI}}) + k_4\mu_1 X_1 + k_5\mu_2 X_2 - Q_{\text{CO}_2} \end{array} \right.$$

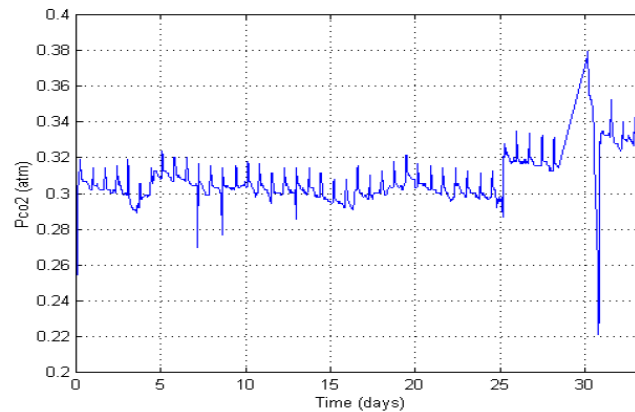
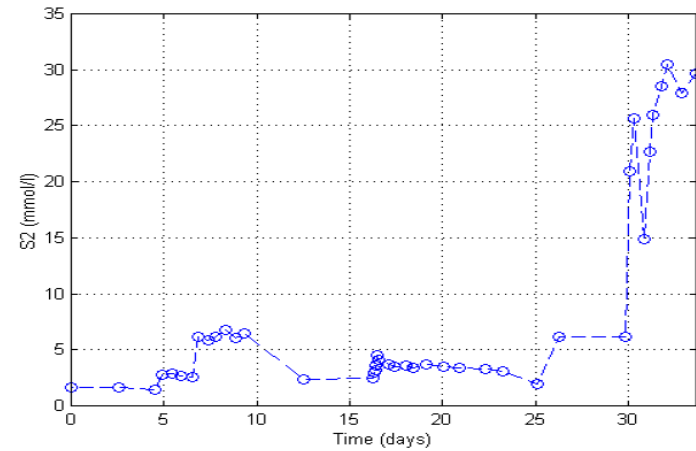
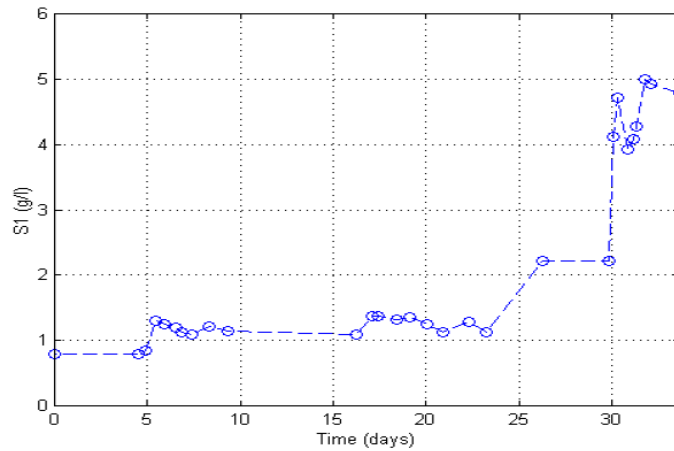
# Stabilizing the chemostat

## □ The robust observer : the inputs



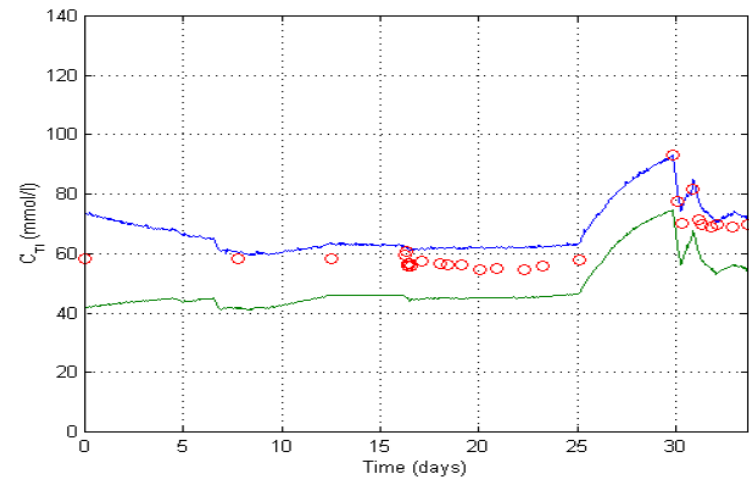
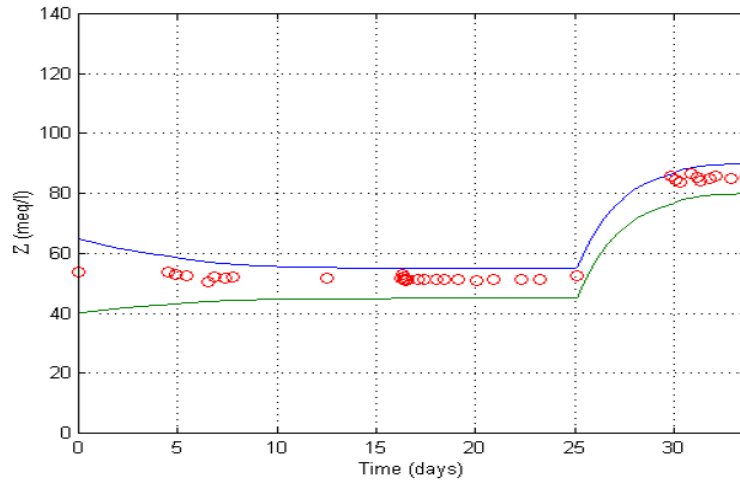
# Stabilizing the chemostat

## □ The robust observer : the measurements



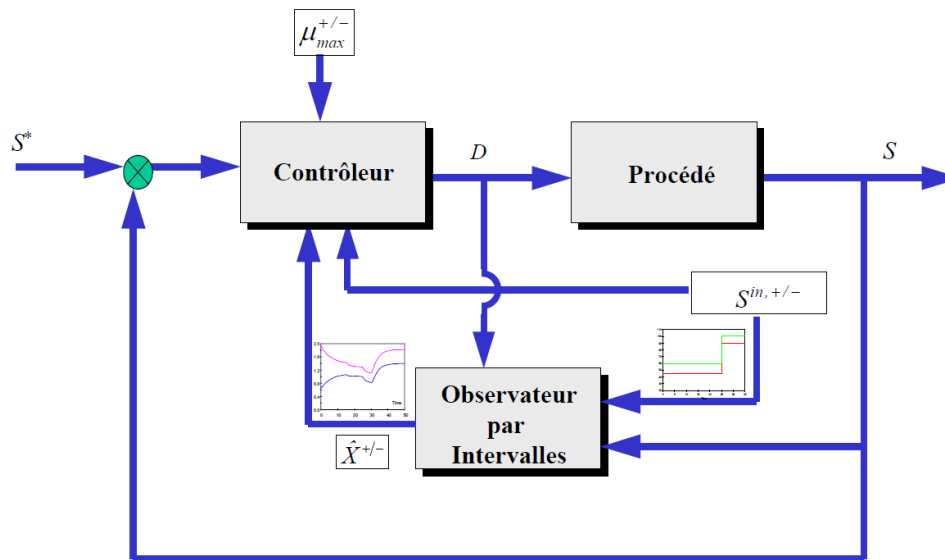
# Stabilizing the chemostat

## □ The robust estimations



# Stabilizing the chemostat

- Coupling the robust observer with the robust control design : application to the anaerobic digestion

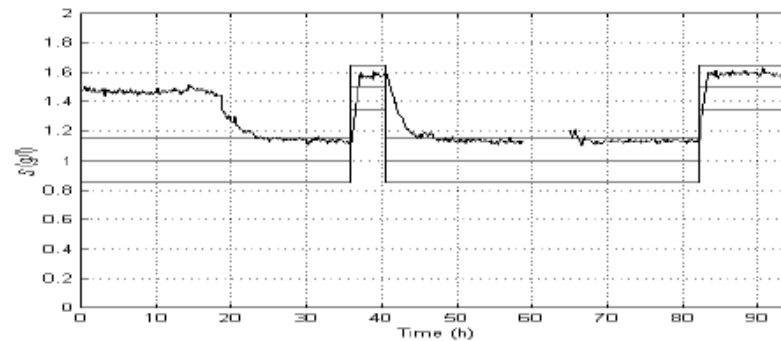
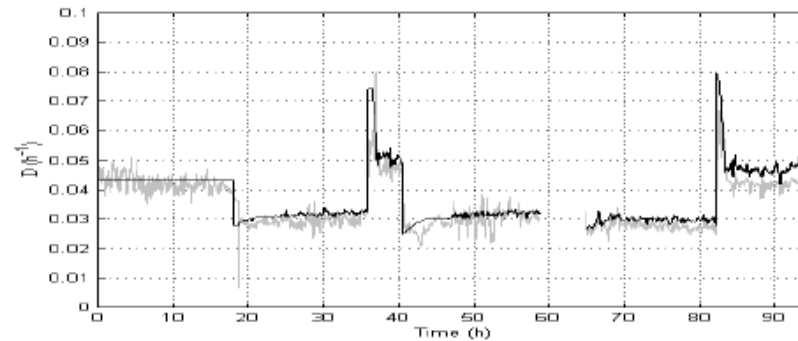


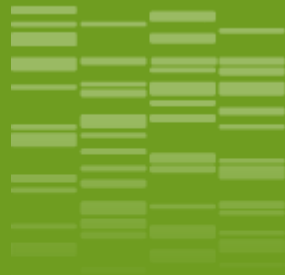
$$D(t) = \text{sat}_{[0, \bar{D}]} \left( \frac{k\mu^{+/-}(t)\hat{X}^{+/-}(t) - \lambda(S(t) - S^*)}{S_{in}^{+/-}(t) - S(t)} \right)$$



# Stabilizing the chemostat

## Results : control and controlled variable





**\_04**

# Conclusions and perspectives

# Conclusions and perspectives

- Model of the chemostat
- Stabilizing robustly the chemostat
- Towards biocontrol approaches...



Thank you for your attention!