Modelling for Process and Control Design

Sten Bay Jørgensen

CAPEC, Department of Chemical Engineering
Technical University of Denmak,
DK-2800 Lyngby, Denmark

Nordic Process Control Workshop 15
29-30´th Januar 2009

Outline

- Motivation
    - Multipurpose Modelling, e.g.
      Integration of Process & Control Synthesis
      Exemplified through defining the Control Problem
- Modelling Paradigm for Process & Control Synthesis
    - Didactic Example (from food technology)
    - Workflow for Qualitative Process & Control Synthesis
- Application example on defining the Control Problem
    - Single cell Protein production in U-loop fermentor
- Other Application Examples of Modelling Paradigm
    - Alarm Design (Us et al.(2008))
    - HAZOP assistant (Rossing et al. (2008))
- Conclusions and Research challenges

Integration of Process and Control Design

Process design involves stages such as

1. conceptual process synthesis based upon requirement specifications
2. conceptual design
3. detailed design etc.

To integrate control design into these stages as early as possible involves dealing with control design already from the requirements level

Thus there is a need to be able to handle integration of process synthesis and control synthesis while devloping the process functionality to satisfy the process requirements

Since conceptual process design is qualitative. Then Integration of Process and Control design may be viewed from a qualitative viewpoint before handling the quantitative aspects.

Levels of abstraction

Representing System Requirements: Objective heteraki

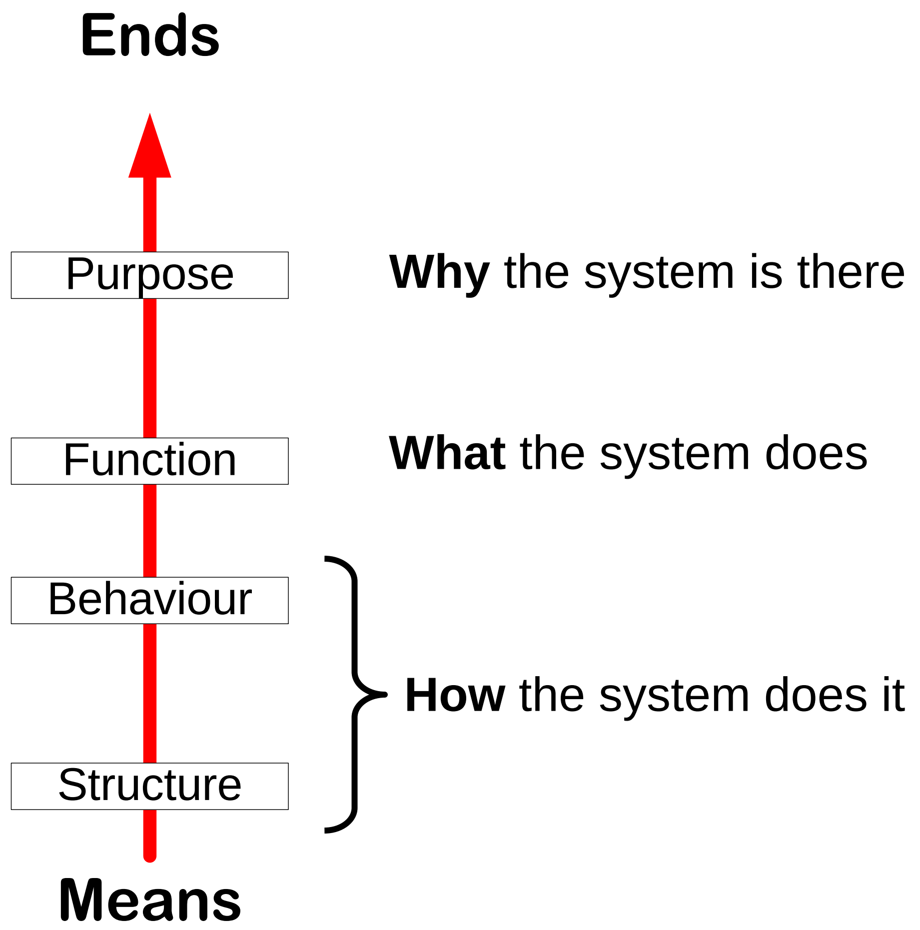
Representing System Knowledge:

- Selection of a proper level of abstraction plays an important role in model building:
  - Spatial structure (the anatomy), many levels of detail possible
  - Behaviour (dynamics), several levels of temporal resolution possible
- Alternatively, levels can be distinguished according to the functional organisation of a system

Modelling Paradigm

- To combine the process requirements to the functional behaviour points to a need for a suitable modelling paradigm!
- With such a modelling paradigm suitable workflows can be formulated!
- How is that accomplished?
  - What is there and what needs to be developed!
  - What else can such a modelling paradigm contribute to CAPE?

Functional modelling



This type of system analysis is means-end analysis or functional modelling which enables causal reasoning
It is based upon theory of actions!

Lind (1994)

Elementary action types

The elementary action types (Von Wright, 1963)

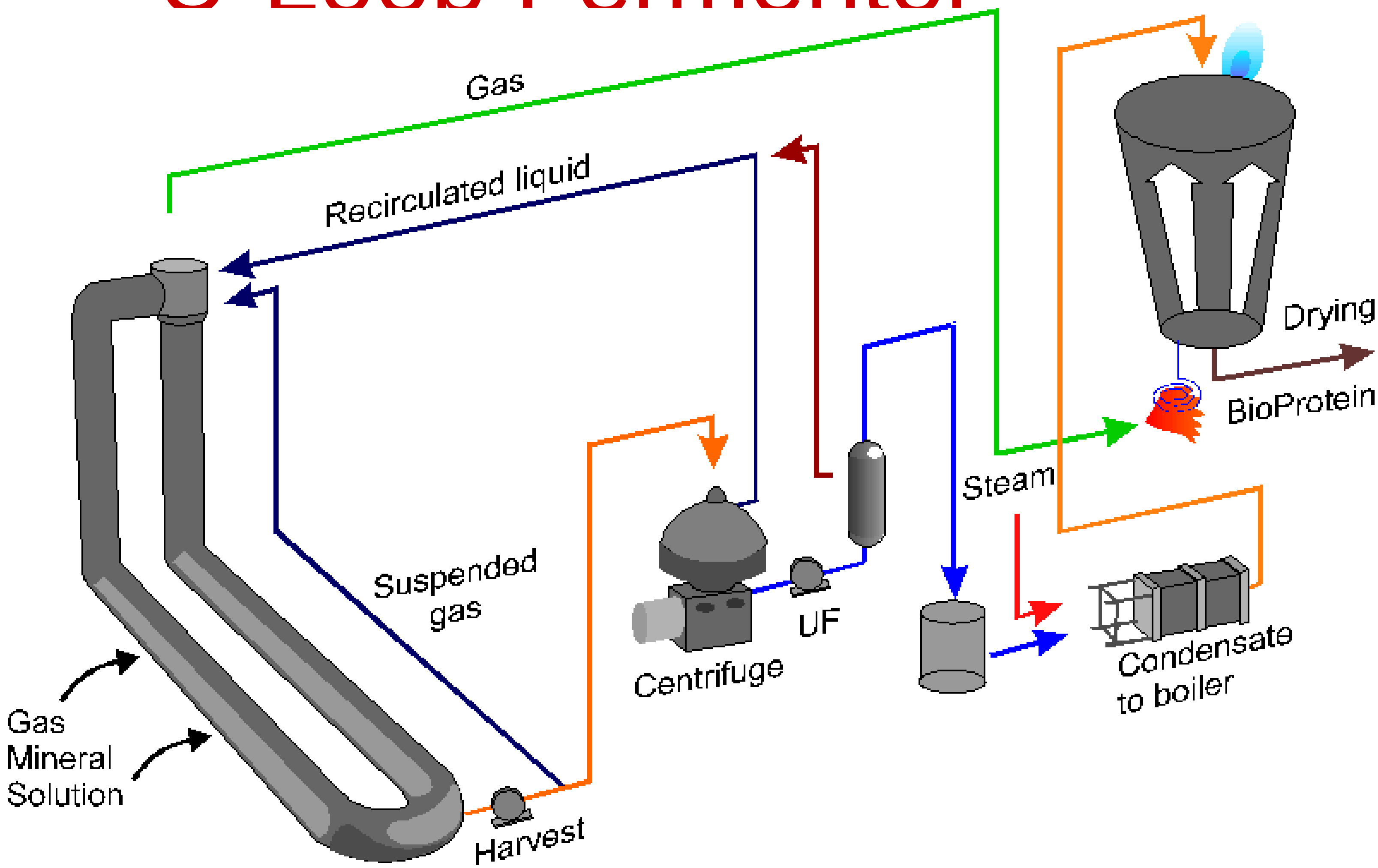
- an attractive basis for the definition of concepts for modelling action functions, e.g control!
- in direct correspondence to the types of action functions used in control engineering

Elementary action	Control action
Produce	Steer
Maintain	Regulate
Destroy	Trip
Suppress	Interlock

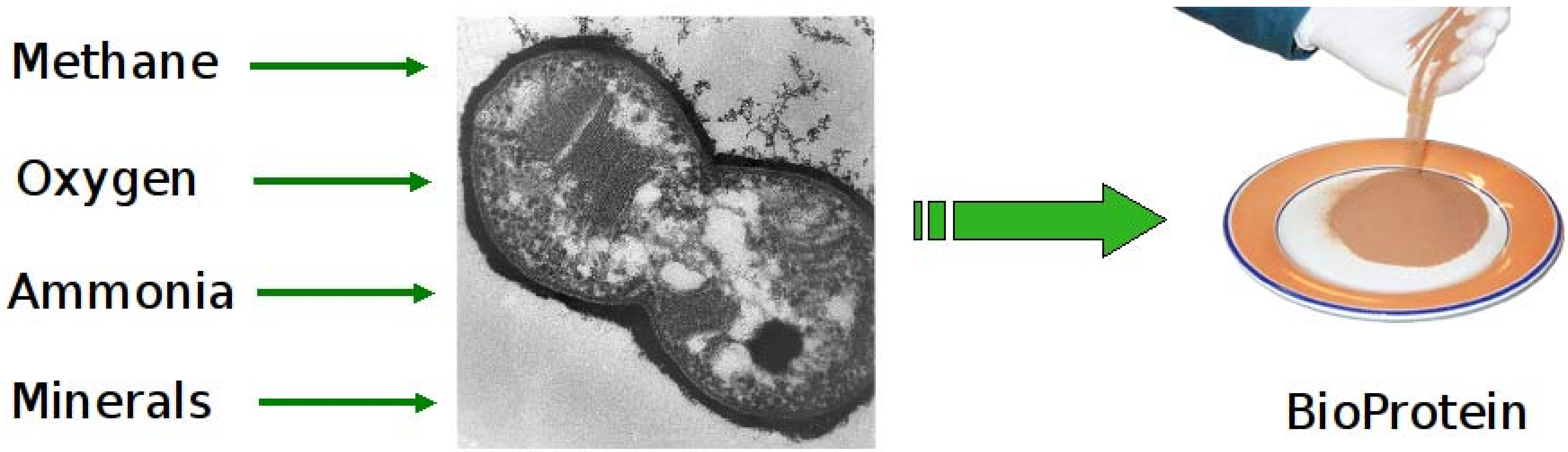
Defining the Control Problem

- State the goal(-s), i.e. the functionality for process/plant
- Determine the degrees of freedom (DOF) available in the plant
  - DOF for goal achievement, i.e. actuator variables
  - DOF as disturbances or unassigned
- DOF used for goal achievement become the actuator variables and defines the operating window for the process/plant
- Desirable measurements are pinpointed by considering information provided concerning goal achievement
- Couplings between measurements and actuators is designed, e.g. though inventory control

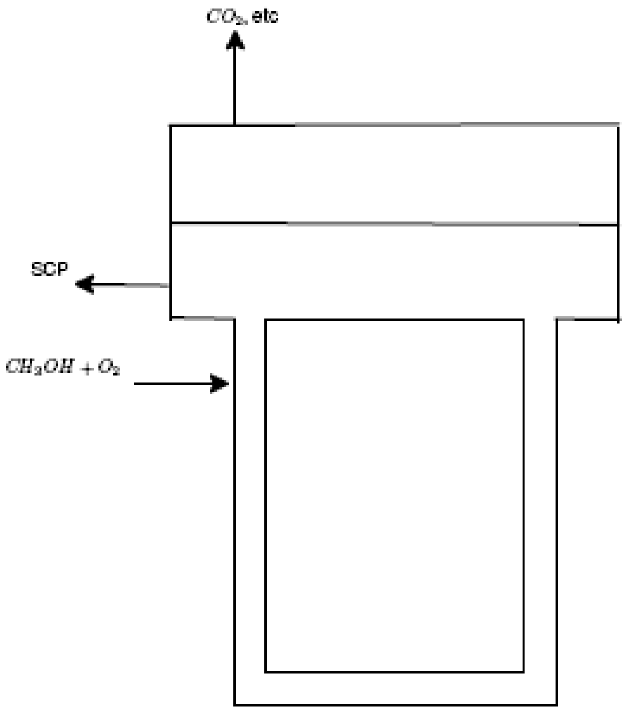
U-Loop Fermentor



Methylococus capsulatus



U-Loop representation



Desired Functionality

- Control goal: To achieve high productivity of biomass with high protein content

- This implies that the bioreactor should produce biomass without too high a biomass concetration which would limit oxygen transfer

Degree of Freedom Analysis

Equation	No.
PFR equations	$14 \cdot N_d$
CSTR equations	7
Mixer equations	5
Sum	$14 \cdot N_d + 12$

Variable	No.
PFR variables	$14 \cdot N_d$
CSTR variables	7
Mixer variables	5
Operation variables	$F_{f,l}, F_{f,g}, F_{res}$
	c_{f,O_2}, c_{f,CH_3OH}
Sum	$14 \cdot N_d + 17$

- Thus five degrees of Freedom

DOF Analysis

- $F_{f,l}$ $c_{f,CH3OH}$ Substrate feed rate and Concentration
- $F_{f,g}$ c_{O2} Gas feed rate and concentration
- F_{res} Recirculation rate

c_{O2} constant nearly pure Oxygen

F_{res} is nearly constant to maintain the effect of the static mixers

Thus three degrees of freedom $F_{f,l}$ $c_{f,CH3OH}$, $F_{f,g}$ define the operating window

Note the above analysis is based upon qualitative model information. Npow let us use a quantitative model to understand the process behaviour.

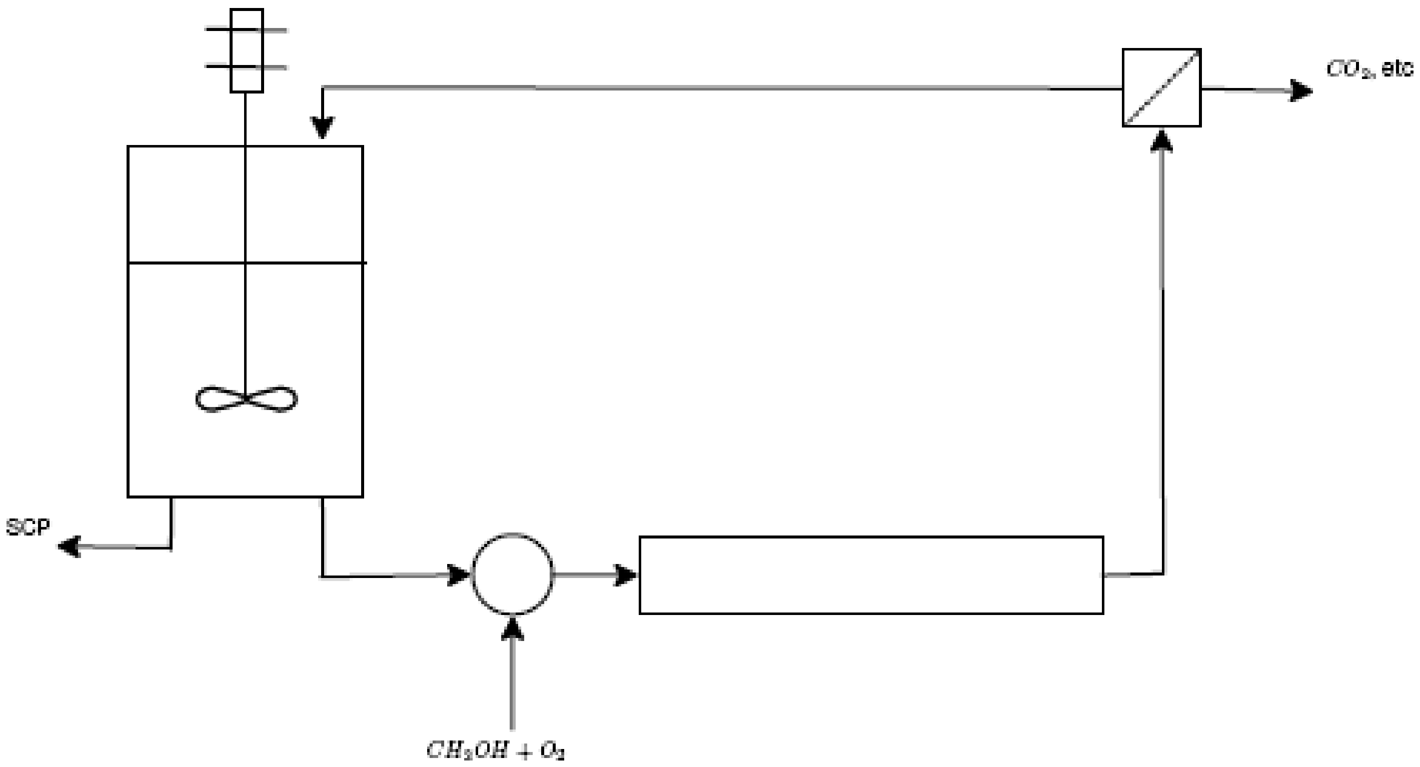
Stoichiometry

$$CH_3OH + Y_{SN}\ HNO_3 + Y_{SO}\ O_2 \rightarrow Y_{SX}\ X + Y_{SC}\ CO_2 + Y_{SW}\ H_2O$$

Symbol	Value
Y_{SC}	0.268
Y_{SN}	0.146
Y_{SO}	0.439
Y_{SW}	1.415
Y_{SX}	0.732

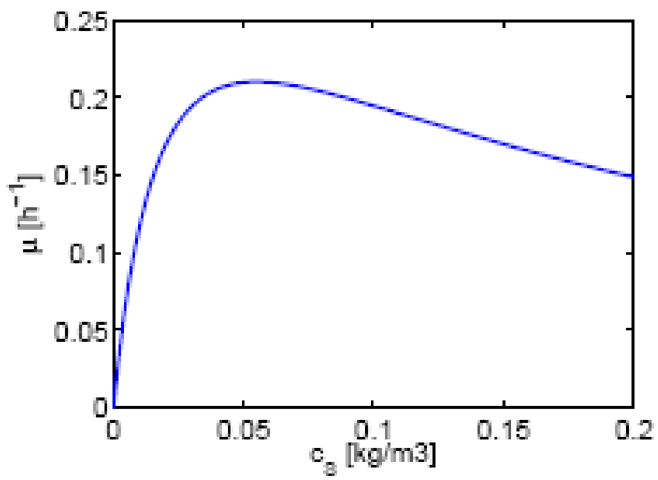
Table: Yield coefficients

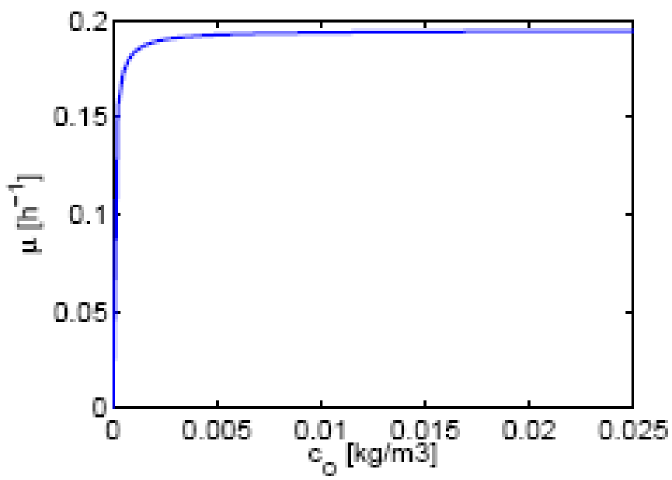
U-Loop representation



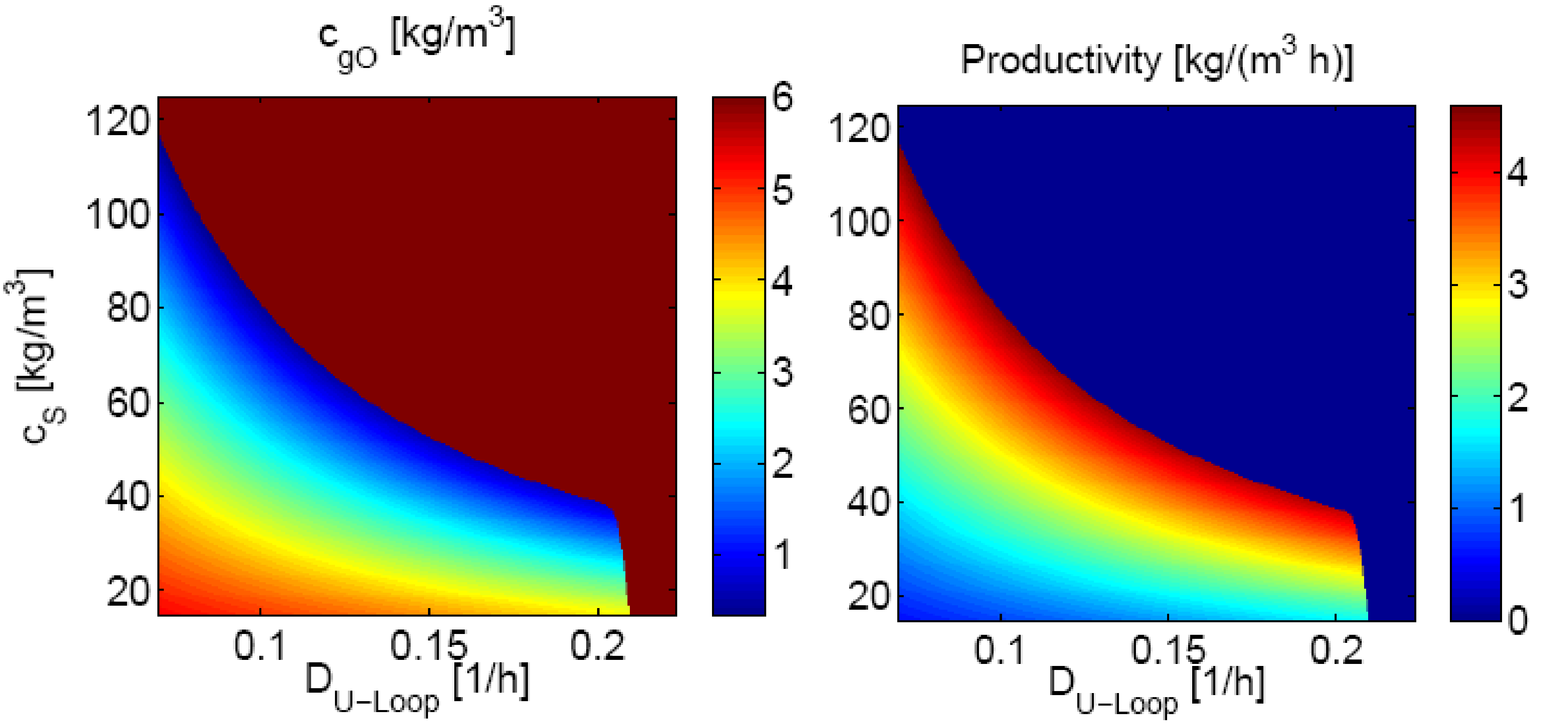
Kinetics

$$\mu = \frac{\mu_{max}\ c_{CH_3OH}}{K_S + c_{CH_3OH} + \left(\frac{c_{CH_3OH}}{K_I}\right)^2} \cdot \frac{c_{O_2}}{K_O + c_{O_2}}$$

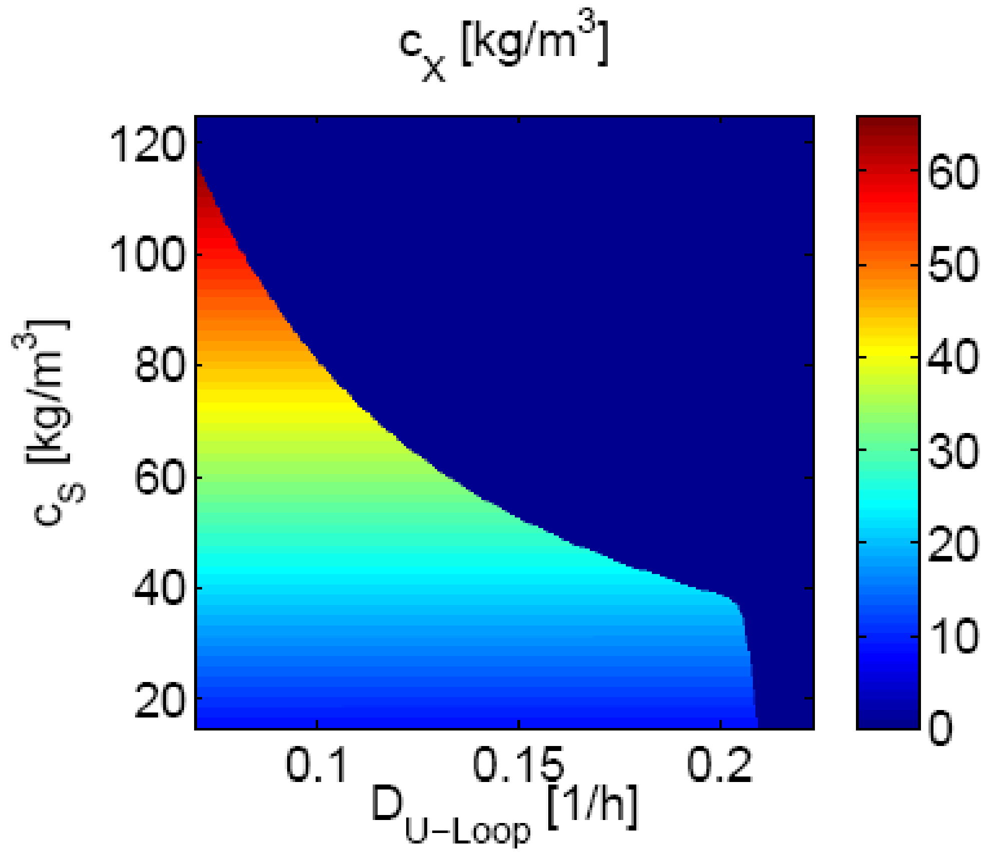




Operating Window



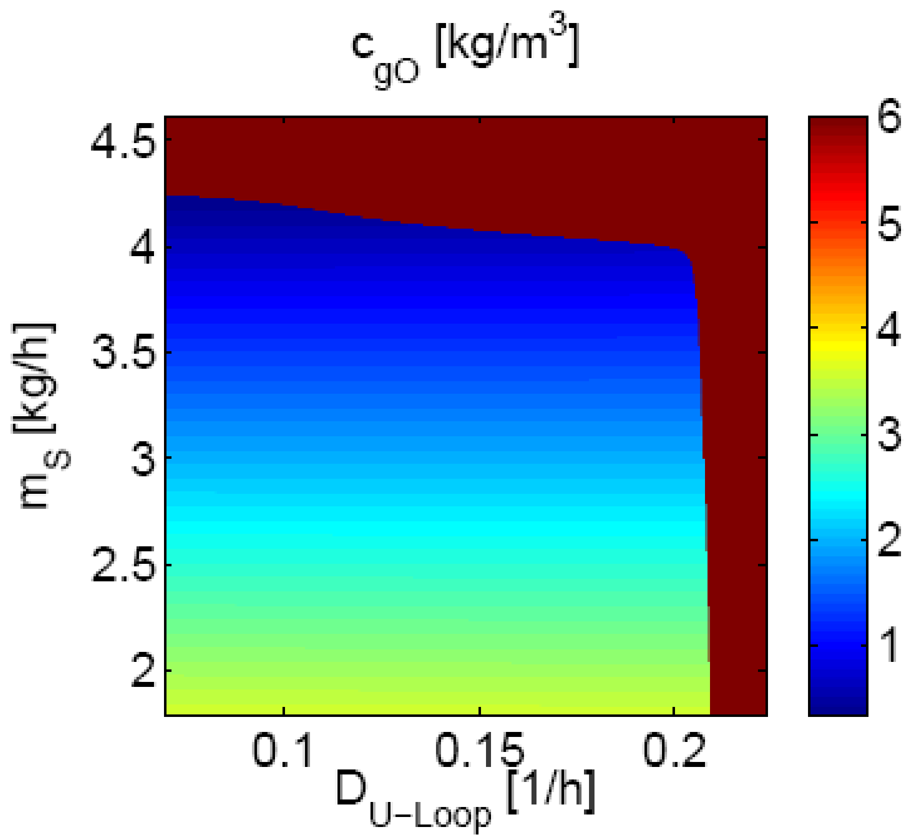
Biomass range



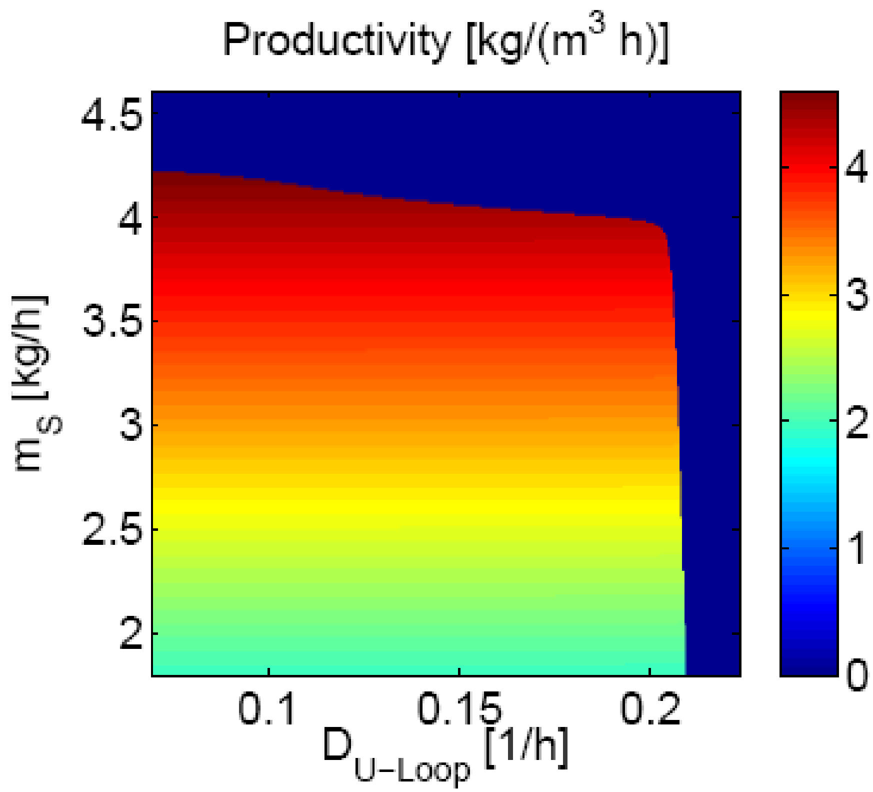
- Desig for optimal biomass concentration

Redefine feed variables

$$
\begin{aligned}
m_{f,S} &\in [1.8000; 4.6033]\frac{kg}{h} \\
D_{ULoop} &\in [0.0697; 0.2231]\frac{1}{h} \\
F_{f,l} &\in [0.0360; 0.1152]\frac{m^3}{h} \\
m_i &= c_i \cdot F
\end{aligned}
$$

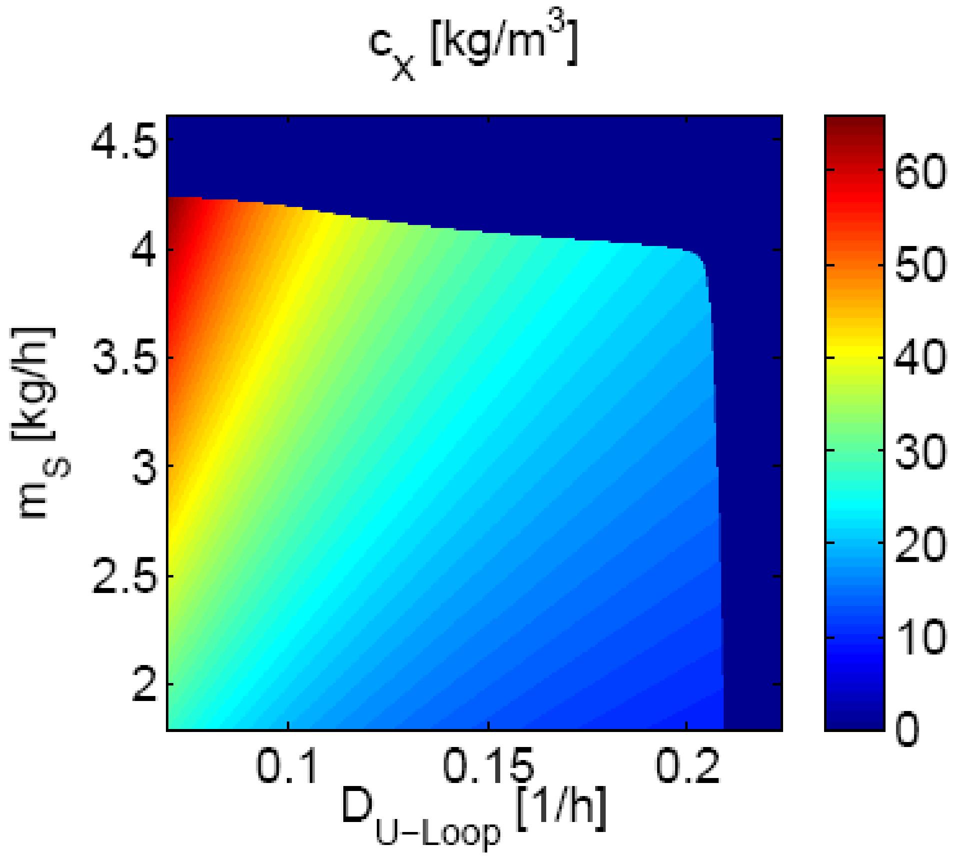


c_{gO} [kg/m^3]
4.5
4
3.5
3
2.5
2
m_S [kg/h]
0.1
0.15
0.2
D_{U-Loop} [1/h]
6
5
4
3
2
1



Productivity [kg/(m^3 h)]
4.5
4
3.5
3
2.5
2
m_S [kg/h]
0.1
0.15
0.2
D_{U-Loop} [1/h]
4
3
2
1
0

Design for optimal Biomass Concentration



- Biomass concentration around 20 kg/m^3

Control Problem

- Control around a total substrate feed flow rate of 4 kg/h
- Ratio gas addition rate to total substrate feed rate

In addition

- Investigate dynamic interactions and decide on control design paradigm
- Consider control or constraining other nutrient addition rates: Nitric acid and phosphate

Conclusions I

- The control definition procedure relies mainly on qualitative knowledge
- It is based upon the intended functionality of the process/plant
- A strong coupling is apparent between process design and control design

Conclusions II

CAPEC

Functional Modelling provides a unified framework for qualitatively combining:

Many levels of abstraction, incl. a multilayered granularity

Thus providing potential for Integration of Multiple tasks, incl.:

Control Problem Definition

Process & Control Synthesis

Process & product design incl. Process integration

Risk management (HAZOP-Assistant)

Alarm design

Operator communication etc.

To harvest these potentials then:

Research in functional modelling within the different engineering knowledge domains is necessary!

References

- Hamid, K.; Gani, R. (2008): ”A Model-Based Methodology for Simultaneous Process Design and Control for Chemical Processes” Presentation at CAPEC annual meeting 2008.
- Lind, M. (1994): “Modeling Goals and Functions of Complex Industrial Plant”. Applied Artificial Intelligence, 8(2):259-283, 1994.
- Rossing; N; Jensen,N.; Lind, M.; Jorgensen, S.B. (2008): ”A Goal Based Methodology for HAZOP Analysis” Accepted for presentation at CSPEC08, Harbin, China.
- Us, T.; Jensen,N.; Lind, M.; Jorgensen, S.B.(2008):”Fundamental Principles of Alarm Design”. Accepted for presentation at CSPEC08, Harbin, China.