

# Real-Time Kinetic Hard-Modelling for the Optimisation of Reaction Conditions and the Detection of Process Upset in Semi-Batch Reactors

Julien Billeter<sup>1</sup>, Yorck-Michael Neuhold<sup>1</sup>,  
Graeme Puxty<sup>2</sup>, Konrad Hungerbühler<sup>1</sup>

Contact: [julien.billeter@chem.ethz.ch](mailto:julien.billeter@chem.ethz.ch)

<sup>1</sup>ETH Zürich, Institute for Chemical and Bioengineering,  
Safety and Environmental Technology Group, Zürich, Switzerland.

<sup>2</sup>CSIRO Energy Technology, PO Box 330, Newcastle NSW 2300, Australia

# Motivation

- **Loss of productivity:** Fluctuations in reaction processes are partly due to variations in the concentration of initial reactants (sub-optimal operating conditions).

Another source of fluctuations comes from impurities present in the initial reactants causing unexpected side reactions.

- **Loss of time:** Initial concentrations are often determined by offline analysis (e.g. HPLC, spectroscopy) and can result in delaying the batch start.

# Trends in favour of online Kinetic Hard-Modelling (KHM)

- **Improving knowledge:** Fine chemical industries try to improve manufacturing by elucidating the underlying kinetic model (rate law) of processes whose patents have expired.
- **Multivariate on-line sensors:** Recent progress in Process Analytical Technology (PAT) allows now the monitoring of processes in real time using multivariate probes.

# KHM in Research phase

- Kinetic hard-modelling compares a measured signal with a modelled one obtained from a 1<sup>st</sup> principle hard model (rate law). The residuals are used as driving force for the least-square optimisation of the kinetic parameters.

Hard model = *function* (kinetic parameters, IC, CV, NCV)

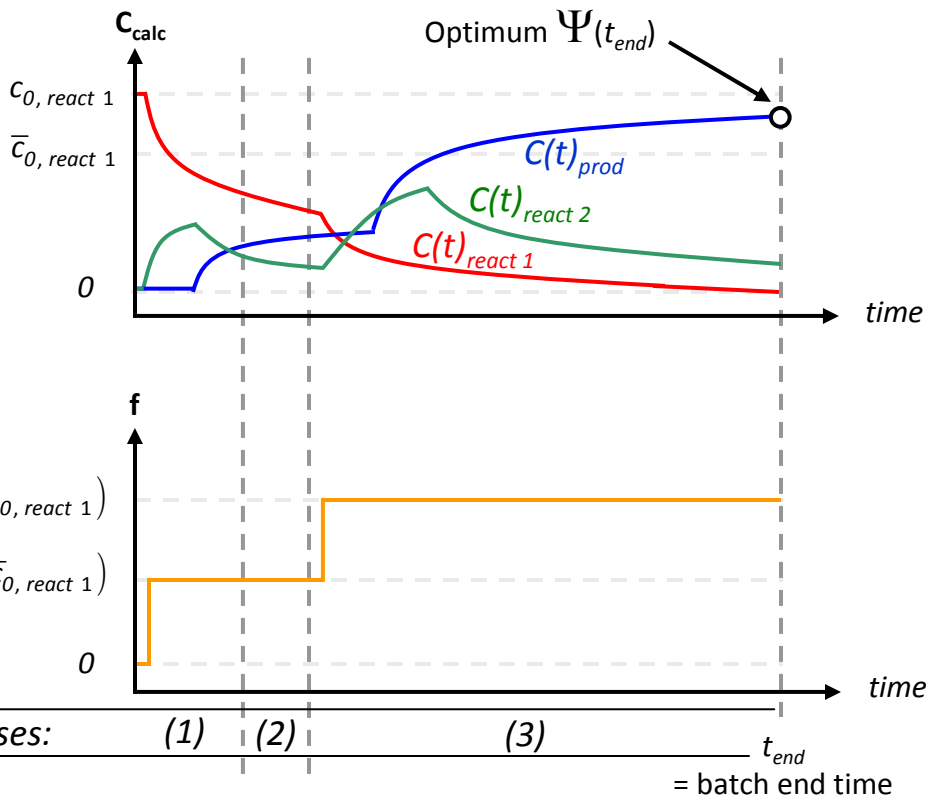
- |       |   |  |
|-------|---|--|
| ■ IC  | Initial <b>C</b> onditions                        | e.g. initial concentrations            |
| ■ CV  | <b>C</b> ontrol <b>V</b> ariables                 | e.g. dosing rate, temperature          |
| ■ NCV | <b>N</b> on- <b>C</b> ontrolled <b>V</b> ariables | e.g. concentration of the dosing agent |

- Our kinetic hard-modelling approach is a calibration free method in the sense that the calibration (the absorptivity spectra) is nested into the non-linear optimisation and linearly fitted at each iteration.

# Online KHM in Production phase

- In production phase, differences between batches result from different IC and/or NCV that can be optimised in a non-linear way, setting the kinetic parameters to the values found during the research phase.
- Subsequently, Control Variables (e.g. dosing flow rate) can be optimised and/or the process can be monitored for detection of possible faults.

# Concept of online KHM



$\bar{C}_{0, react 1}$  = mean initial concentration,  
 $f_{opt}(\bar{C}_{0, react 1})$  = optimum dosing rate for  $\bar{C}_{0, react 1}$

## Phase 1: OPTIMISATION OF THE IC/NCV AND PROCESS UPSET DETECTION

Optimisation of IC/NCV (e.g.  $C_{0, react 1}$  and  $C_{dos, react 2}$ ) with kinetic parameters fixed.

Possible Process Fault is detected.

## Phase 2: OPTIMISATION OF THE CV

Extrapolation to a future time and optimisation of future **CV** under constraints to maximise  $\Psi$  (= Yield, Selectivity or Conversion).

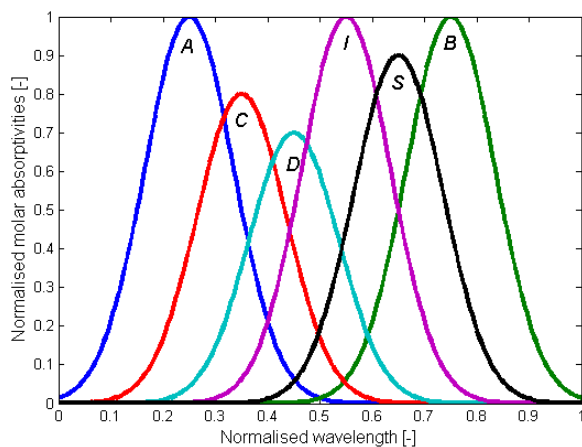
$$\begin{aligned} & \max_{f(t)} \Psi(t_{end}) \\ & \text{s.c. } V(t_{end}) \leq V_{max} \\ & \quad f_{min} \leq f(t) \leq f_{max} \end{aligned}$$

## Phase 3: OBSERVATION PHASE

Process running under optimal **CV**.

# Kinetic model

## Absorptivity spectra



## Heat released

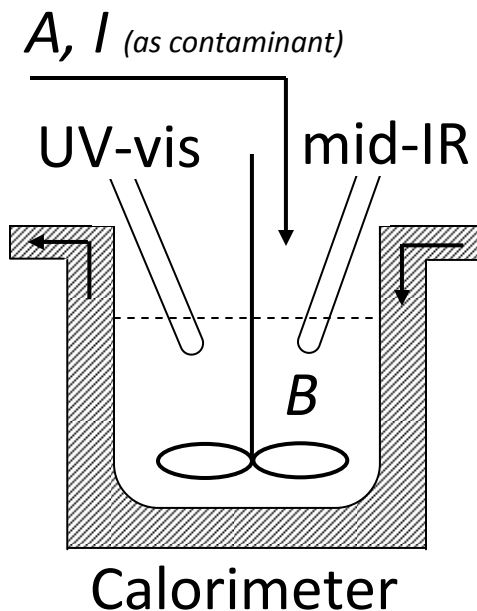
modelled:

$$\Delta H_{r1} = -10.0 \text{ kJmol}^{-1}$$

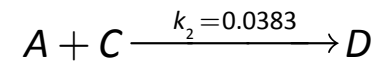
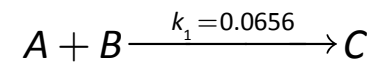
$$\Delta H_{r2} = -5.0 \text{ kJmol}^{-1}$$

unmodelled:

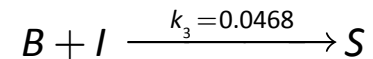
$$\Delta H_{r3} = -10.0 \text{ kJmol}^{-1}$$



modelled:



unmodelled:



*A* : dosed

*C* : wanted product

*D* : side product

*I* : contaminant in *A*

# Base Case simulation

## Mean IC / NCV

### No process fault

$$\text{IC: } \bar{c}_0 = \begin{matrix} & A & B & C & D & I & S \\ \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

$$\text{NCV: } \bar{c}_{dos} = \begin{matrix} & A & B & C & D & I & S \\ \begin{bmatrix} 2 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

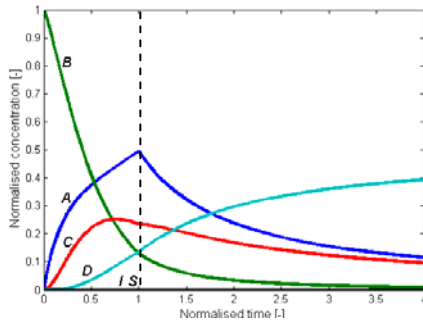
$$f_{opt}(\bar{c}_0, \bar{c}_{dos}) = 0.025$$



# Base case

$$\begin{array}{c}
 A \quad B \quad C \quad D \quad I \quad S \\
 IC: \bar{c}_0 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \\
 \\
 A \quad B \quad C \quad D \quad I \quad S \\
 NCV: \bar{c}_{dos} = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}
 \end{array}$$

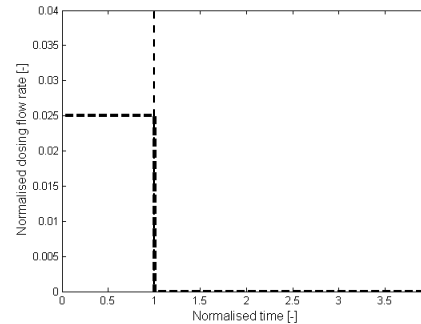
## Concentration profiles



$$V_0 = 0.3, V_{end} = 0.6 \quad (V_{max} = 1)$$

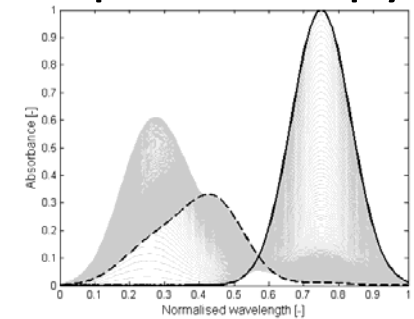
Time normalised to normal batch duration  
(1: one normal batch duration)

## Dosing rate (a CV)



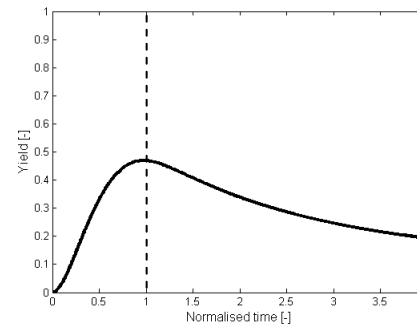
$$f_{opt}(\bar{c}_0, \bar{c}_{dos}) = 0.025 \quad (f_{max} = 1)$$

## Spectroscopy



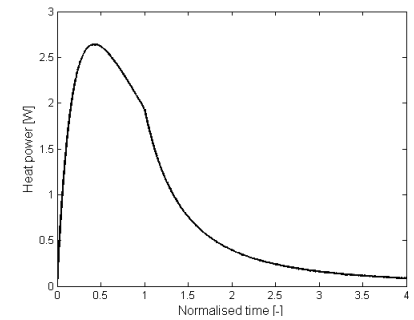
Added noise:  $10^{-4}$

## $\Psi = \text{Yield}$



$$\Psi(t_{end}) = \text{Yield}_{C/A, opt}(\bar{c}_0, \bar{c}_{dos}) = 46.98\%$$

## Calorimetry



Added noise:  $10^{-3}$

# Optimisation of the Initial **IC** and Non-Controlled **Variables (NCV)**

and subsequent optimisation of the  
**Control Variables (CV)**

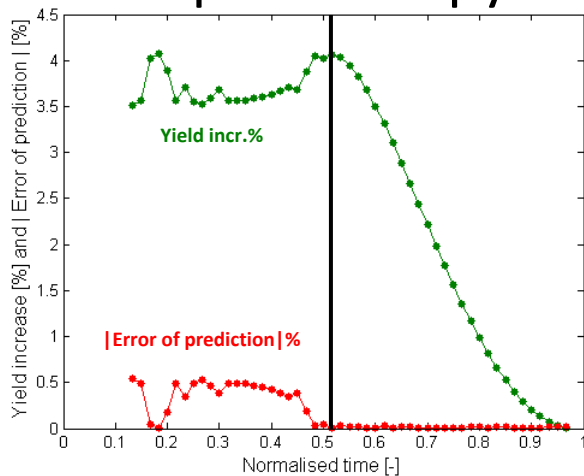
$$\text{IC: } \bar{c}_0 - 15\% = \begin{matrix} & A & B & C & D & I & S \\ \begin{bmatrix} 0 & 0.85 & 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

$$\text{NCV: } \bar{c}_{dos} + 15\% = \begin{matrix} & A & B & C & D & I & S \\ \begin{bmatrix} 2.30 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

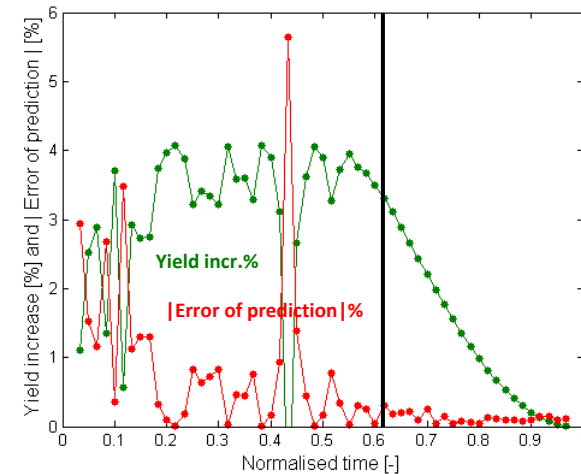
$$f_{opt}(\bar{c}_0 - 15\%, \bar{c}_{dos} + 15\%) = ?$$

# Optimisation of the Control Variables (CV)

## Spectroscopy



## Calorimetry



	UV-vis	Calorimetry
Time of calculation	0.516	0.616
$\sigma_p/p$	$\leq 0.20\%$	$\leq 1.70\%$
Calculated dosing rate	0	0
Yield increase	+4.05%	+3.30%
Maximum Yield increase	+4.08%	+4.08%

Extrapolation time = 0.0167

# CV optimisation and comparison with offline analysis

<i>IC</i>	<i>NCV</i>	Signal	Yield increase	Error of prediction	Time criterion for online KHM to be more efficient than offline analysis
0% (base case)	0% (base case)	Spectroscopy	0.09%	+0.00%	always
		Calorimetry	0.09%	+0.00%	always
		Offline	0.09%	-	-
-15%	+15%	Spectroscopy	4.05%	+0.02%	0.02%
		Calorimetry	3.30%	+0.30%	0.75%
		Offline	4.08%	-	-
-30%	+30%	Spectroscopy	11.06%	+0.15%	3.30%
		Calorimetry	8.47%	+0.45%	5.76%
		Offline	14.72%	-	-

# Optimisation of the CV

- For this particular mechanism and these pure component spectra, spectroscopy can be used to optimise online the CV.
- Due to its univariate nature, **calorimetry** produces a low improvement in yield when used in online KHM.
- For **extreme variations in the IC/NCV**, online KHM is only better than offline analysis if the time required for the offline analysis largely delays the batch start.
- For this particular mechanism, the concentration of the dosing agent has the most impact on the yield.

# Process Fault Detection (PFD) or Process Upset Detection

$$\text{IC: } \bar{c}_0 = \begin{matrix} & A & B & C & D & I & S \\ \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

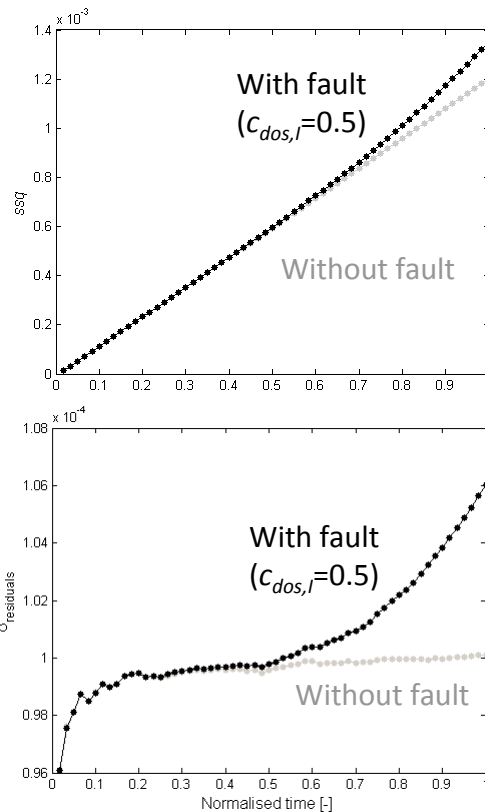
$$\text{NCV: } \bar{c}_{dos} + I = \begin{matrix} & A & B & C & D & I & S \\ \begin{bmatrix} 2 & 0 & 0 & 0 & c_{dos,I} & 0 \end{bmatrix} \end{matrix}$$

$$f_{opt}(\bar{c}_0, \bar{c}_{dos}) = 0.025$$

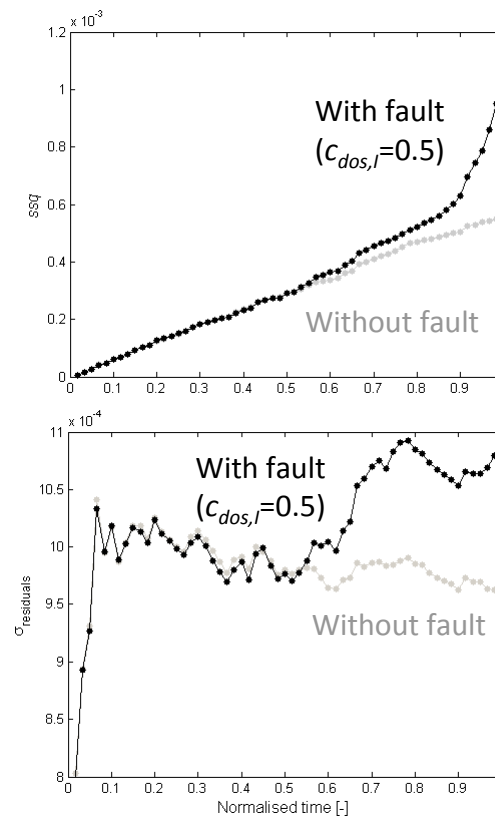
# SSQ and Standard deviation of the residuals as Process Fault indicators

$ssq$

## Spectroscopy



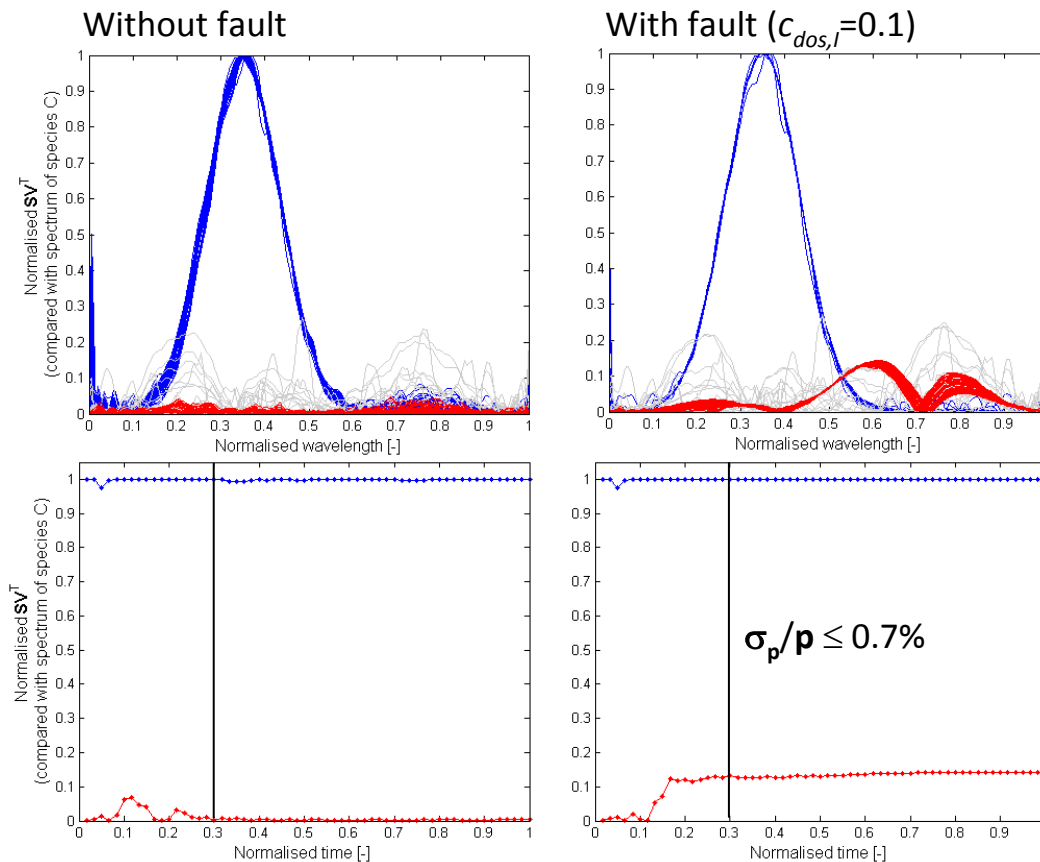
## Calorimetry



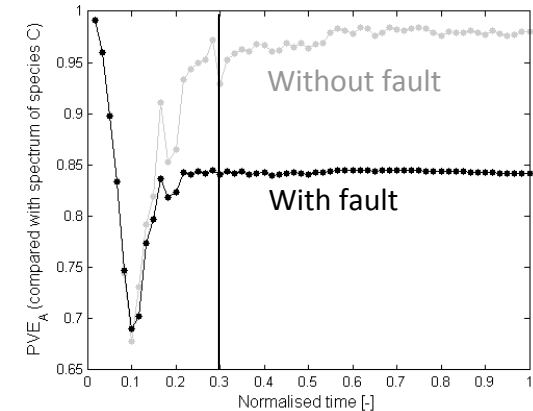
$\sigma_{residuals}$

# Known absorptivity spectra (in eigen-space) as Process Fault indicators

$\mathbf{SV}^T$  (benchmark: spectrum of  $C$ )



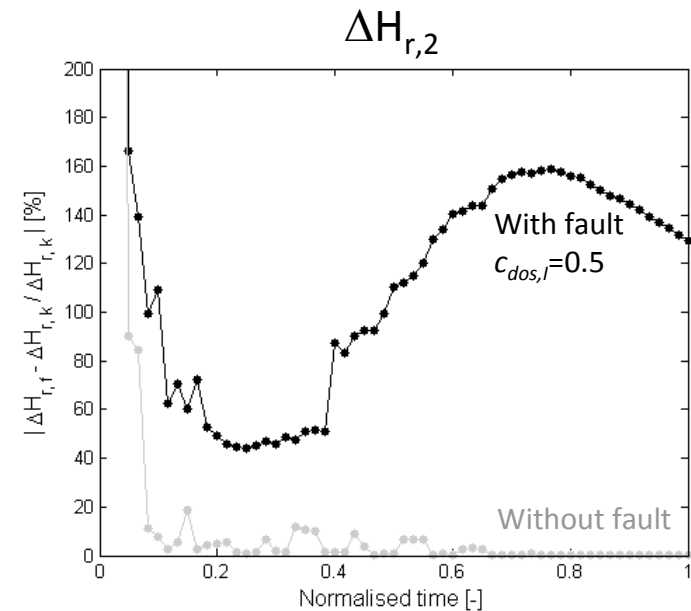
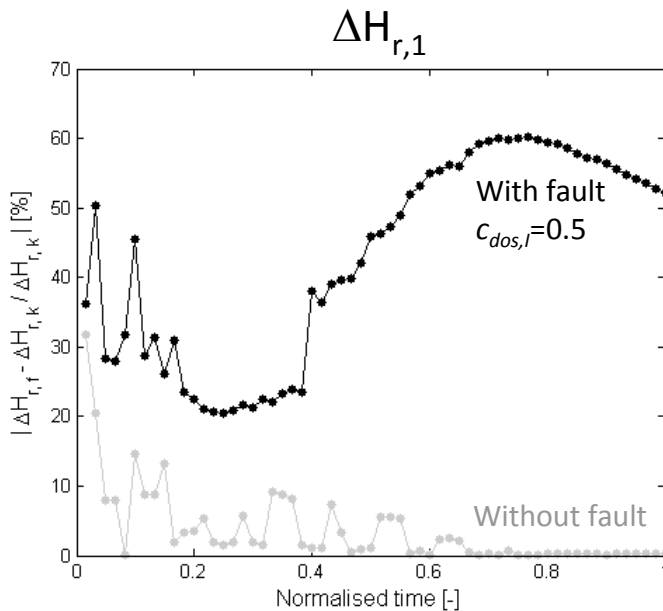
$PVE_A$



Spectrum selected for PFD	$PVE_A$ at $t_{end}$	
	With fault	Without fault
Spectrum of A	85.51%	98.68%
Spectrum of B	98.50%	99.47%
Spectrum of C	78.33%	97.57%
Spectrum of D	69.82%	96.62%



# Known reaction enthalpies as Process Fault indicator



# Process Fault Detection

- Spectroscopy and calorimetry can be used to detect Process Faults
- The best process fault indicators are generally the ones based on a priori information, i.e. the absorptivity spectra and the reaction enthalpies

# Conclusion

- The capabilities of online KHM have been demonstrated by:
  - Optimisation of the Initial Conditions (IC) and Non-Controlled Variables (NCV)
  - Subsequent optimisation of the Control Variables (CV)
  - And constant Detection of possible Process Faults (PFD)
- Next, online KHM will be applied on experimental data for a simple chemical system.

A blue-tinted banner image at the top of the slide showing a large, domed building, likely a part of the ETH Zurich campus, with mountains in the background.

**Thank you for  
your attention**