Towards a zerocost-biorefinery using a new nutrient recovery model library and global sensitivity analysis

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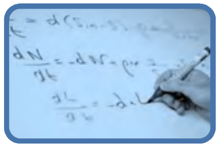
Outline

- Introduction

- Objectives



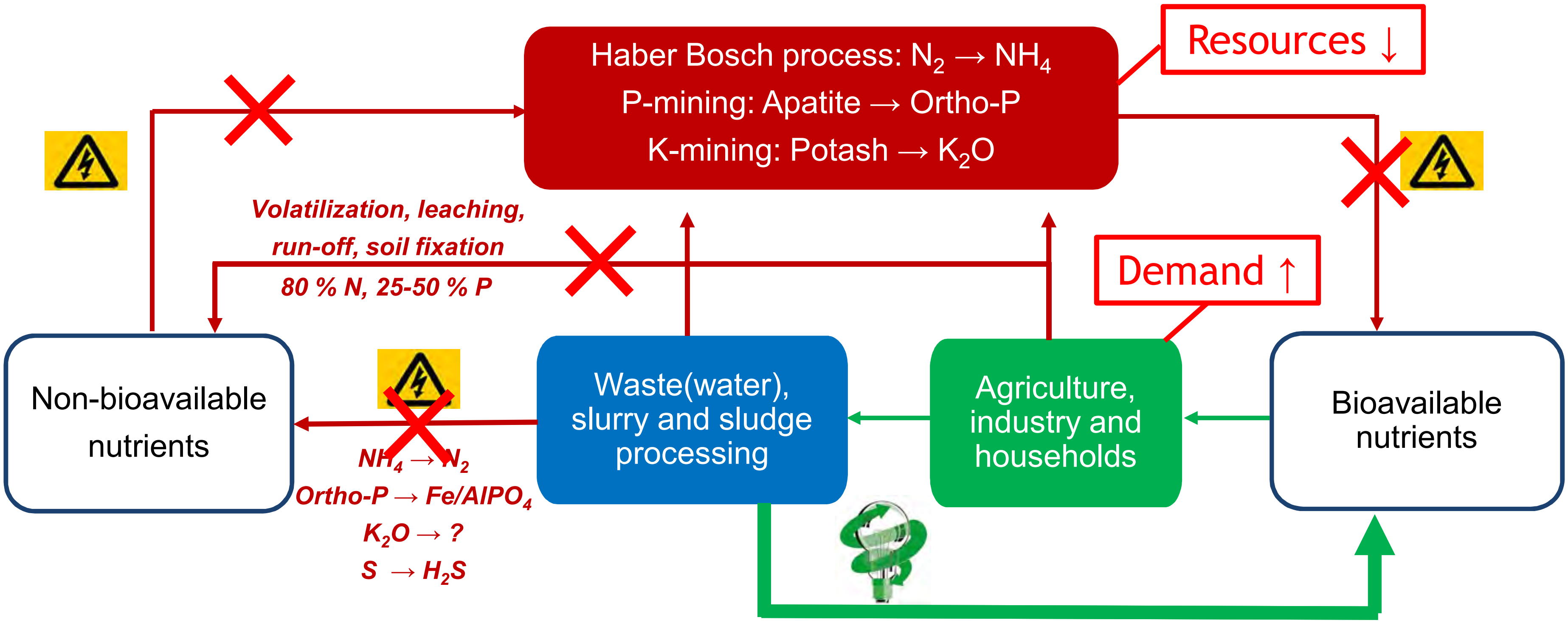
- Model development and validation

- Global sensitivity analysis and process optimization

- Conclusions

INTRODUCTION

Why recovering nutrients?



Waste Water Treatment Plant (WWTP)
→ Water Resource Recovery Facility (WRRF)

Nutrient recovery processes

- Precipitation → struvite, calcium phosphates
- Ammonia stripping → NH_3
- Acidic air scrubbing → ammonium sulfates
- tration → H_2O, N-K concentrates
- tion and harvest → biomass
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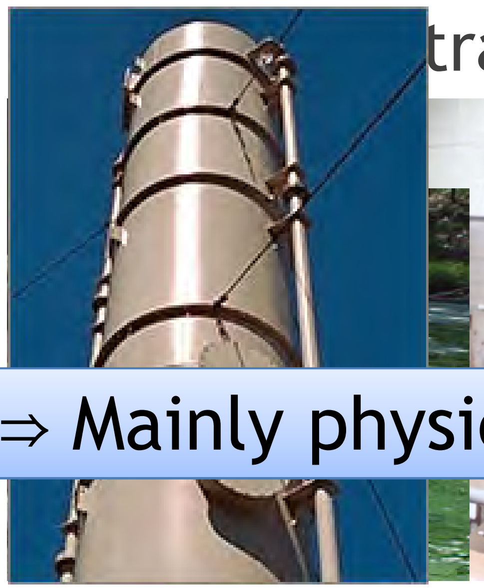
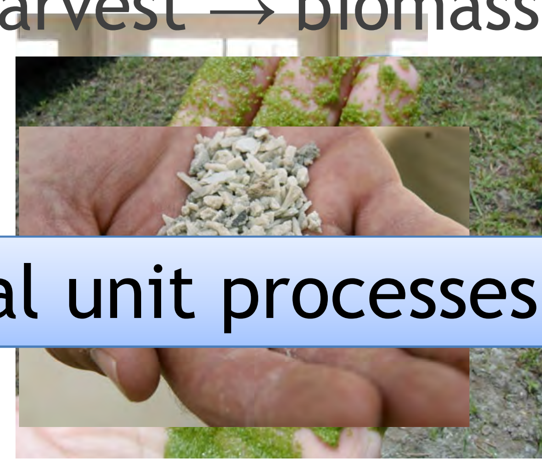




⇒ Mainly physicochemical unit processes!

Points of attention

- The nutrient recovery process must have equivalent treatment efficiency as conventional treatment
- The process must be cost-effective
- The process must be simple to operate and maintain
- There must be a market for the recovered nutrient products

Potential flow diagram of **a WRRF**

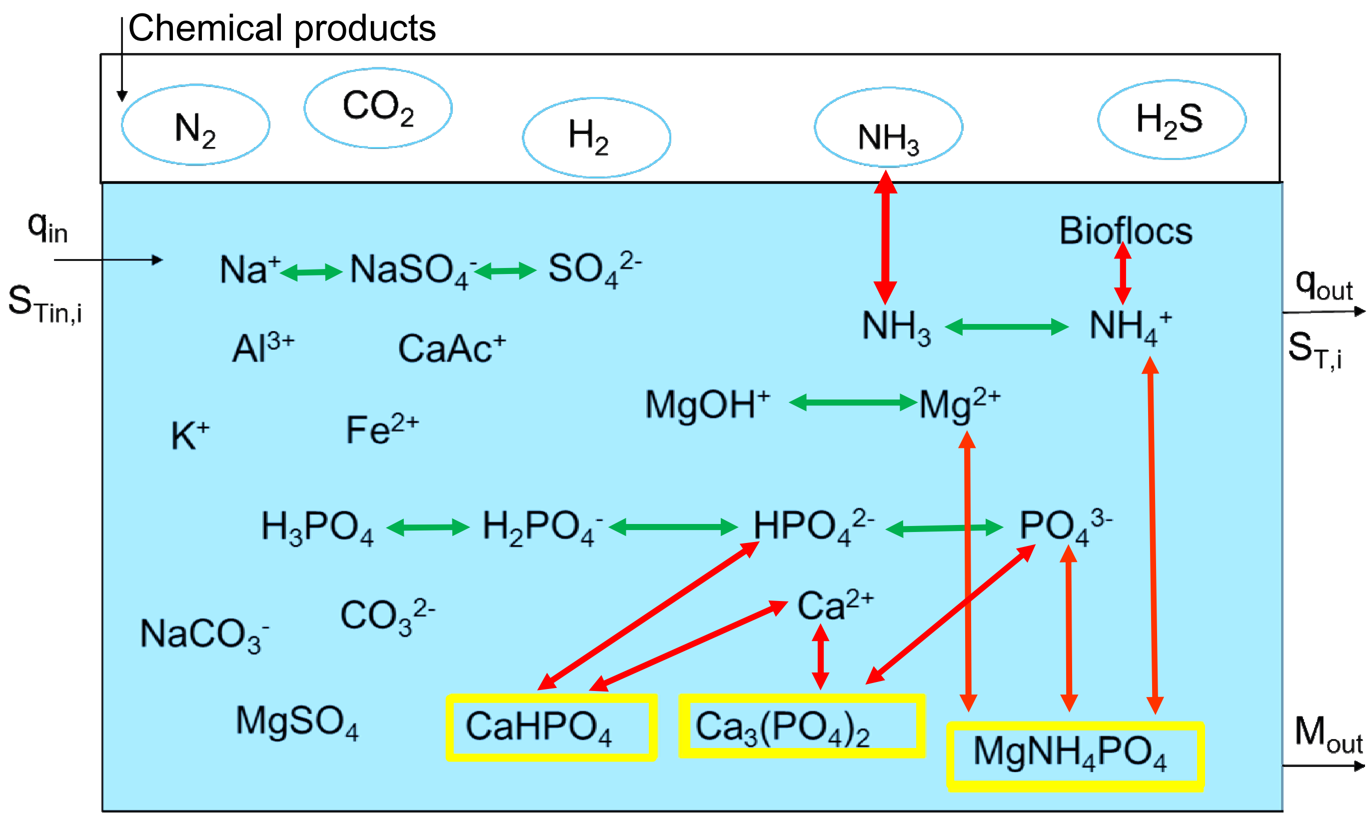
<u>Problem</u>: Optimal combination different for each waste flow

<u>Question</u>: What is the optimal combination of unit processes and operating conditions?

- Given: Particular waste stream
- Optimal:
  - Maximal resource recovery (nutrients, energy)
  - Minimal energy and chemical requirements

Approach = Mathematical models

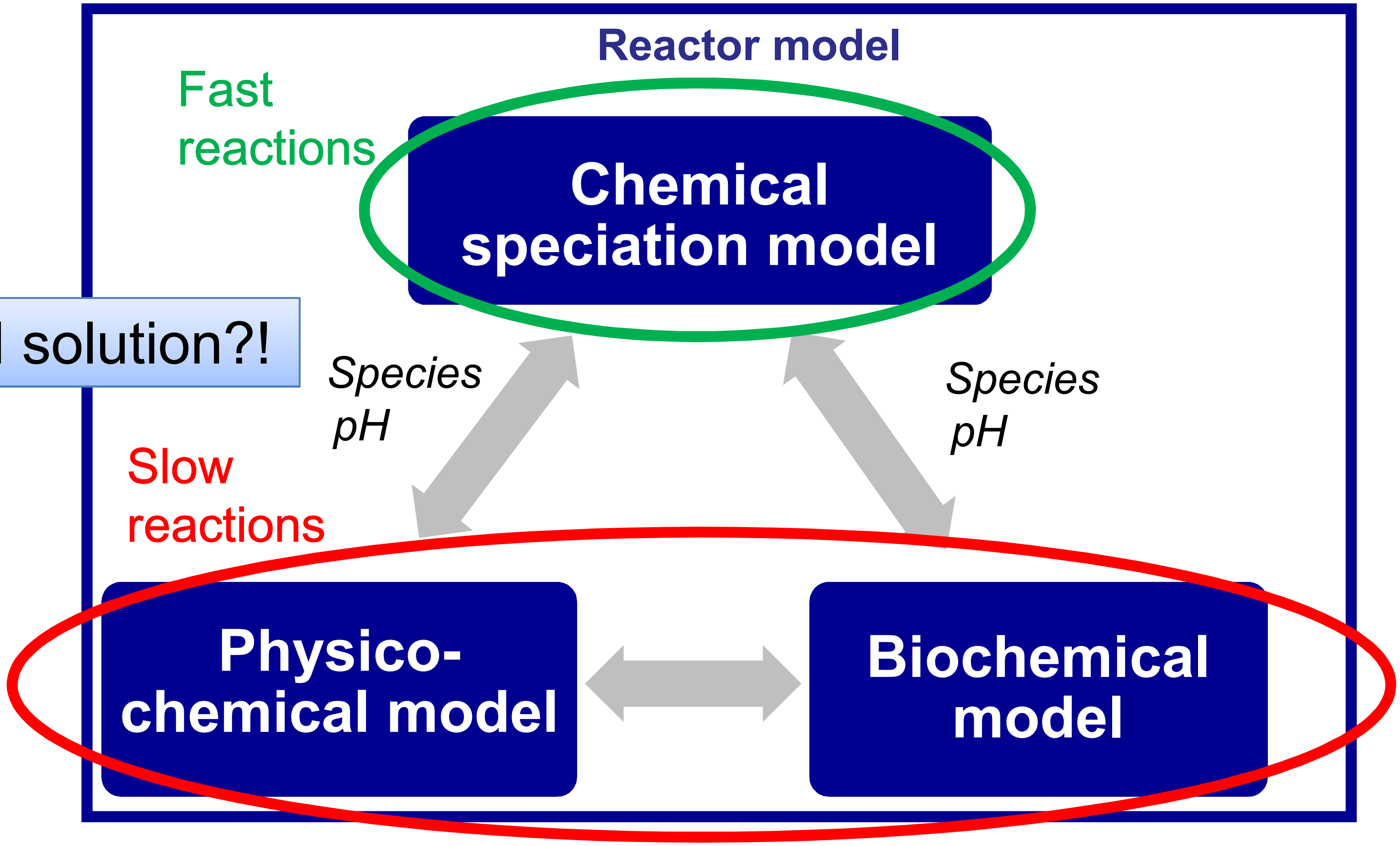
Modeling challenges



⇒ Insights in chemical speciation required for fertilizer quality optimization

Modeling challenges

Numerical solution?!



Modeling challenges

Existing WWTP models → **WRRF models**

⇒ Lack of models to adequately put together optimal treatment trains for nutrient recovery and to select the optimal operating conditions

OBJECTIVES


problem
problem
solution
problem
problem
problem
problem
problem
problem

Project: Industrial Innovation Scholarship (BMP, 2013-2015)

- **Ph.D. Céline Vaneeckhaute (2015):**
  Nutrient recovery from bio-digestion waste:
  From field experimentation to model-based optimization

- **Supervisors:**
  Peter Vanrolleghem (model*EAU*),
  Evangelina Belia (Primodal),
  Filip Tack & Erik Meers (Ghent University)

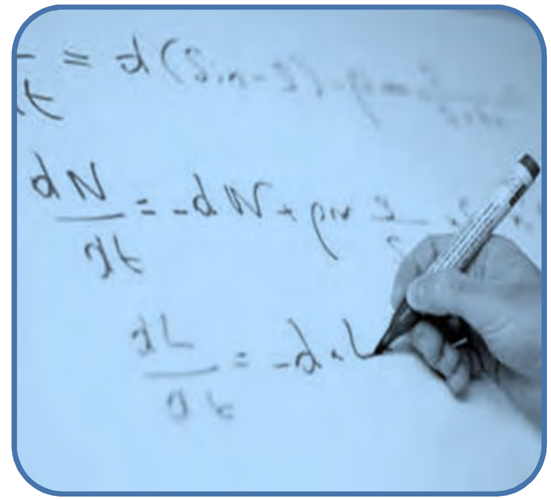
Project: Industrial Innovation Scholarship (BMP, 2013-2015)

- **Specific research objectives:**

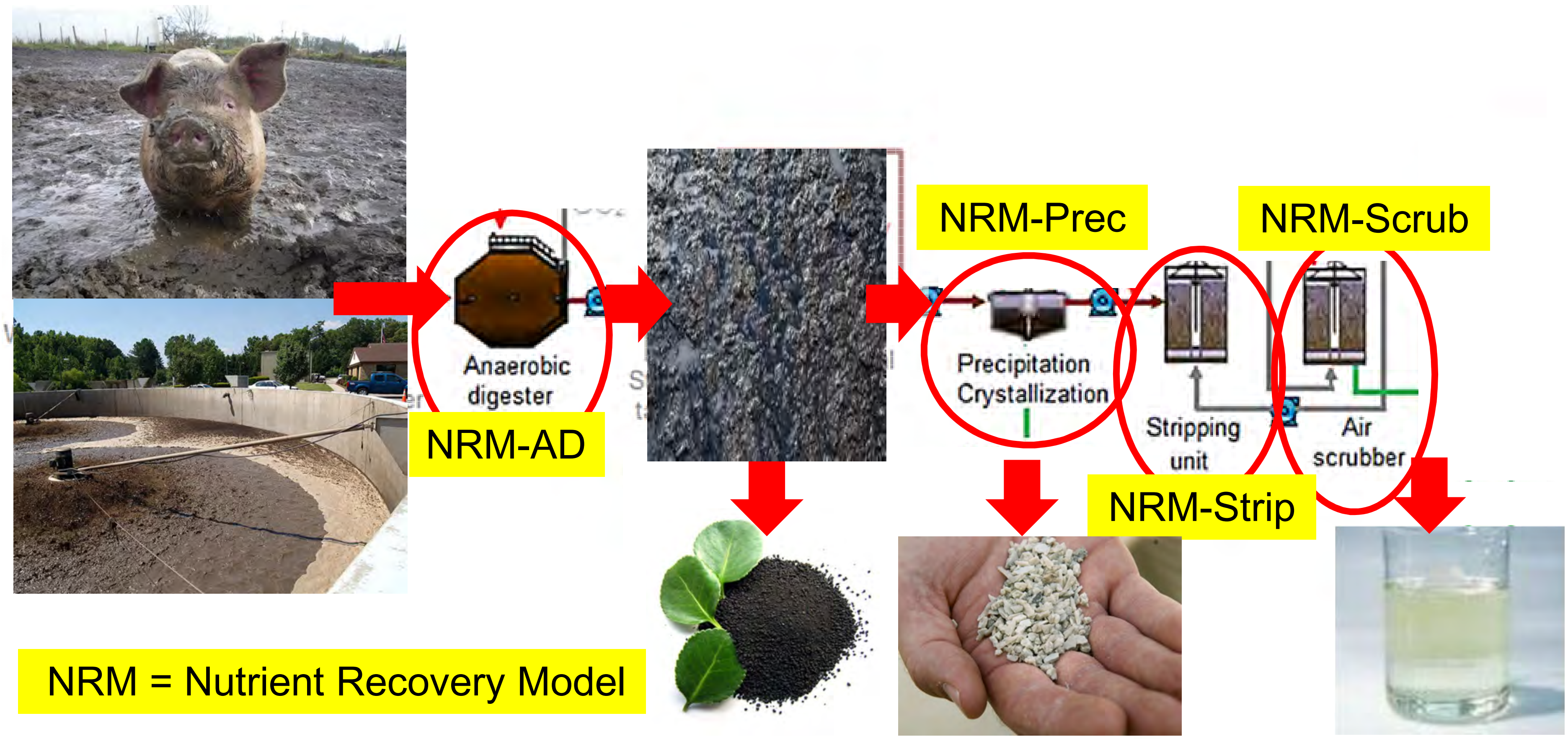
1. To develop generic models for the best available resource recovery systems including:
   - detailed chemical speciation
   - biological and physicochemical reaction kinetics
   - interactions between three phases (liquid-solid-gas)

2. To apply the models as a tool for optimization of single processes and treatment trains in order to:
   - maximize resource recovery (nutrients, energy) + product quality
   - minimize energy and chemical requirements

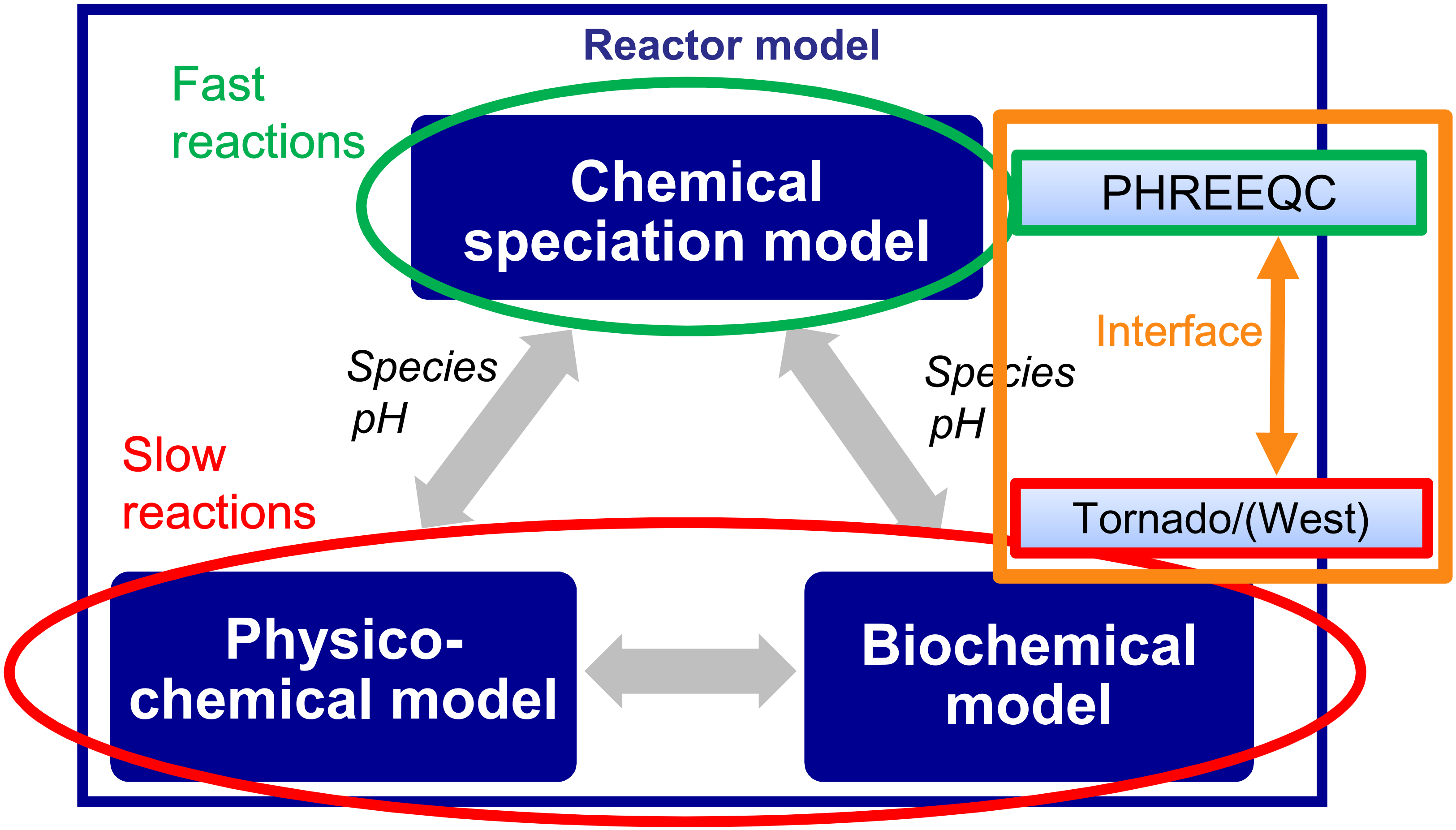
MODEL DEVELOPMENT AND VALIDATION



Model development
Generic nutrient recovery model library



Model development
Numerical solution



Model development
Important findings & contributions

- **Geochemical databases incomplete:**
  ➔ Extended database for nutrient recovery, e.g., $(NH_4)_2SO_4$, $AlPO_4$, … *(Nutricover.dat)*
- **Speed-up of model simulations:**
  - Selective database reduction
    ⇒ Speed X 4-5
  - Tight model coupling
    ⇒ Speed X 10

⇒ Highly efficient and practically implementable models!

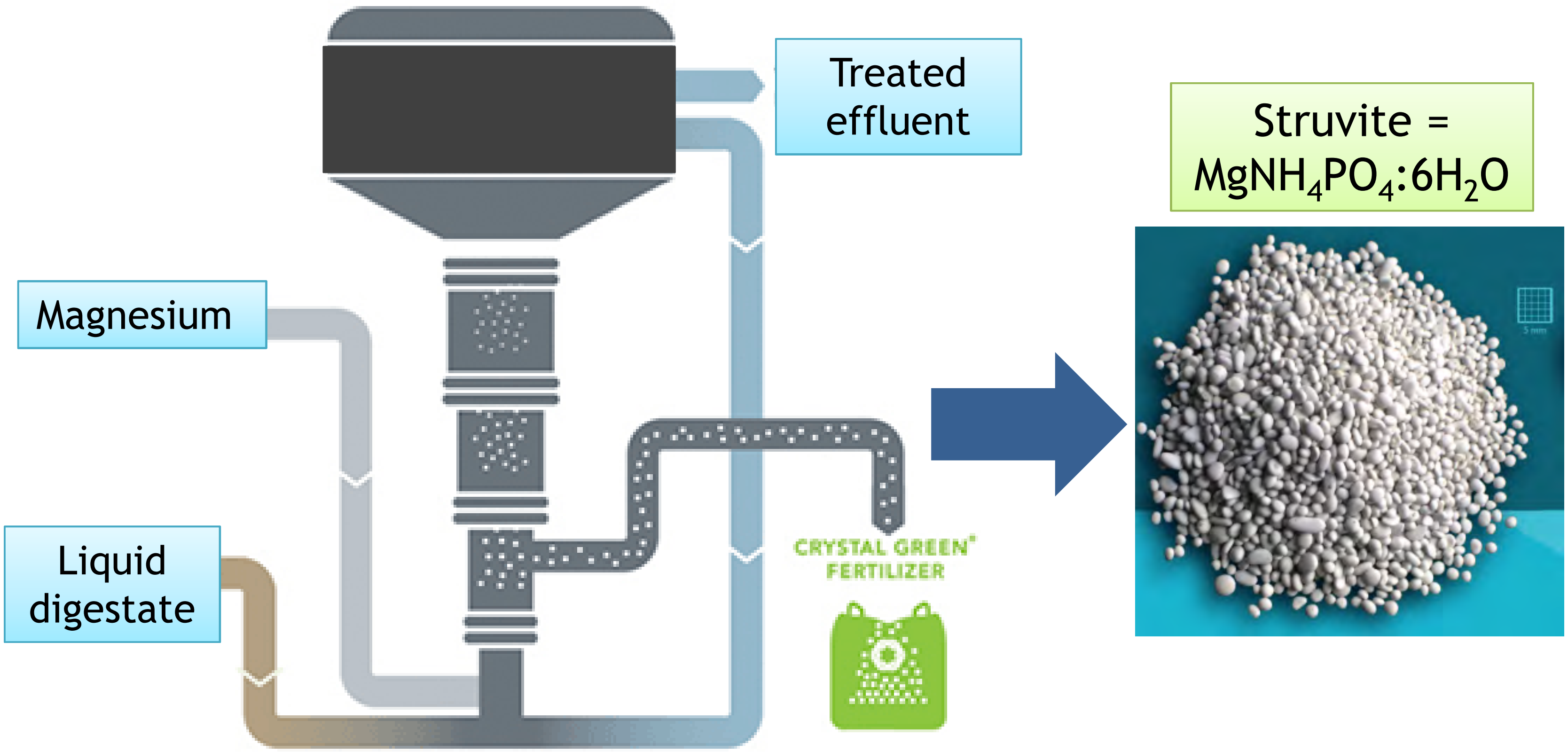
Model calibration & validation

Experimental results

Simulation results

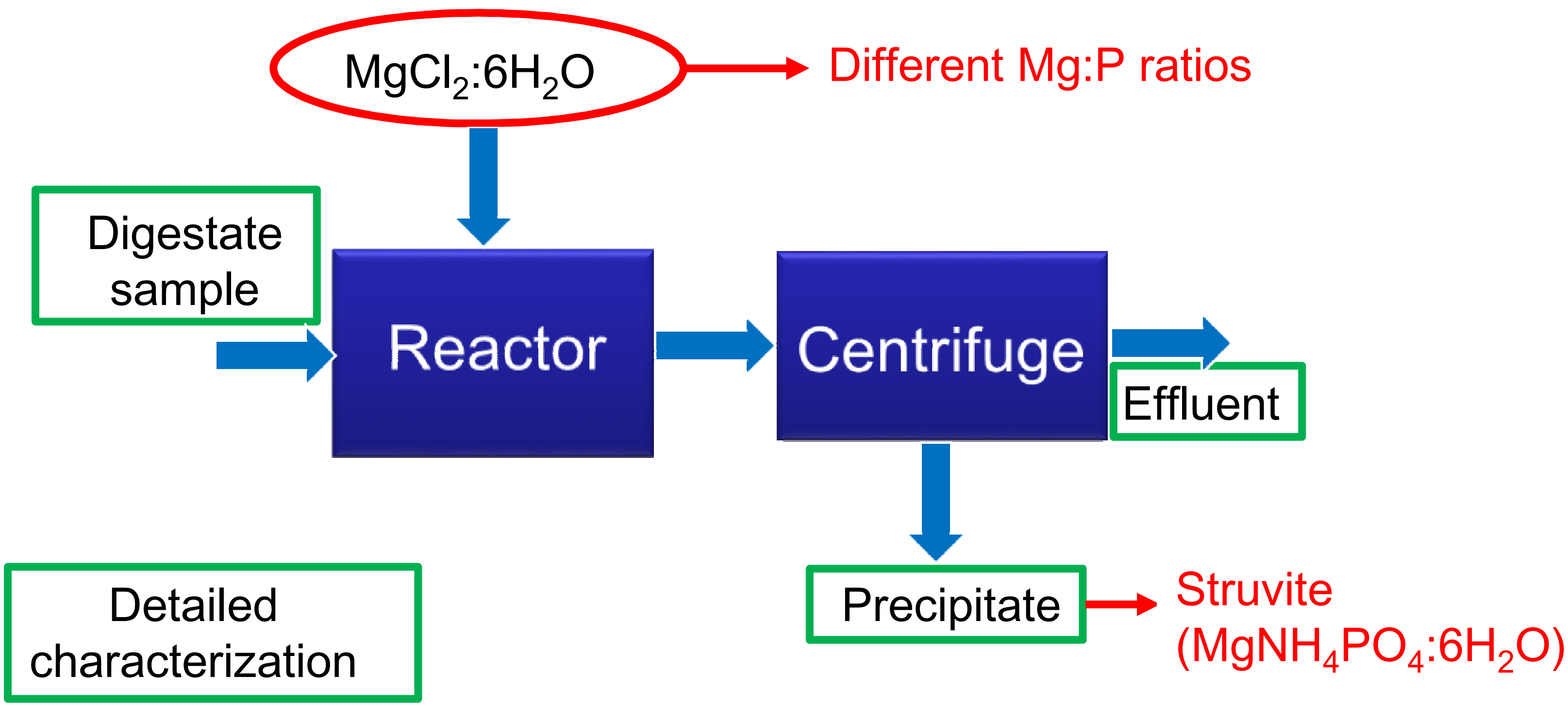
Model validation: NRM-Prec

Process lay-out



Source: adapted from Ostara (2015)

Model validation: NRM-Prec
Lab-scale experiments



Model validation: NRM-Prec

Experimental vs. simulation results (12 h)

Mg:P	Digestate 1 % P-recovery			Digestate 2 % P-recovery	
	Experim.	Original PHREEQC	Extended PHREEQC	Experim.	Extended PHREEQC
1:1	41	95.60	41.32	28	27.76
2:1	44	97.91	43.62	29	29.29

?

⇒ Very good prediction of P-recovery at steady state

⇒ Importance of a detailed chemical solution speciation and accurate input characterization!

Scenario analyses: NRM-Prec

- Main components precipitated: Al, Ca, Fe, K, Mg, N, P

Digestate 1:
very high Fe and Al in influent
→ optimal P-recovery = 56.2 %

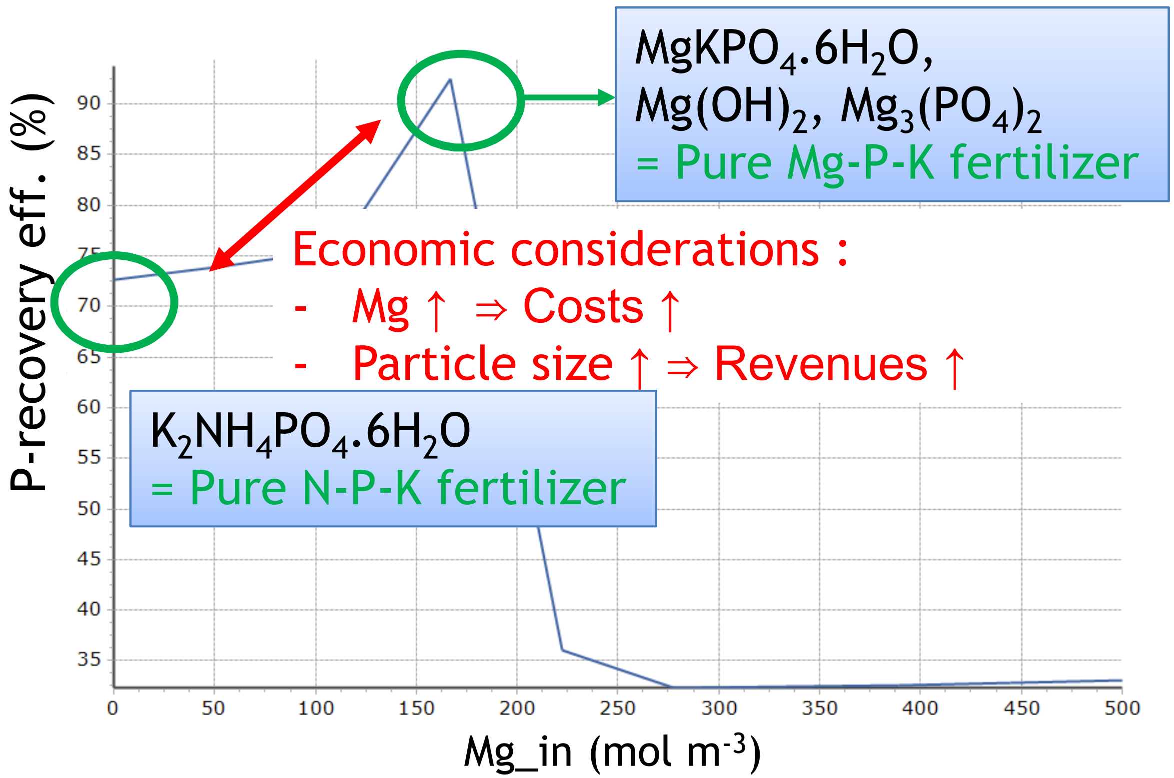
Digestate 2:
low Fe and Al in influent
→ optimal P-recovery = 90.7 %

(Co-)precipitate	Digestate 1	Digestate 2
$FeAl_2O_4$	+	-
$AlPO_4$	-	+
$Fe_3(PO_4)_2{:}8H_2O$	-	+

How to maximize nutrient recovery and guarantee fertilizer purity?

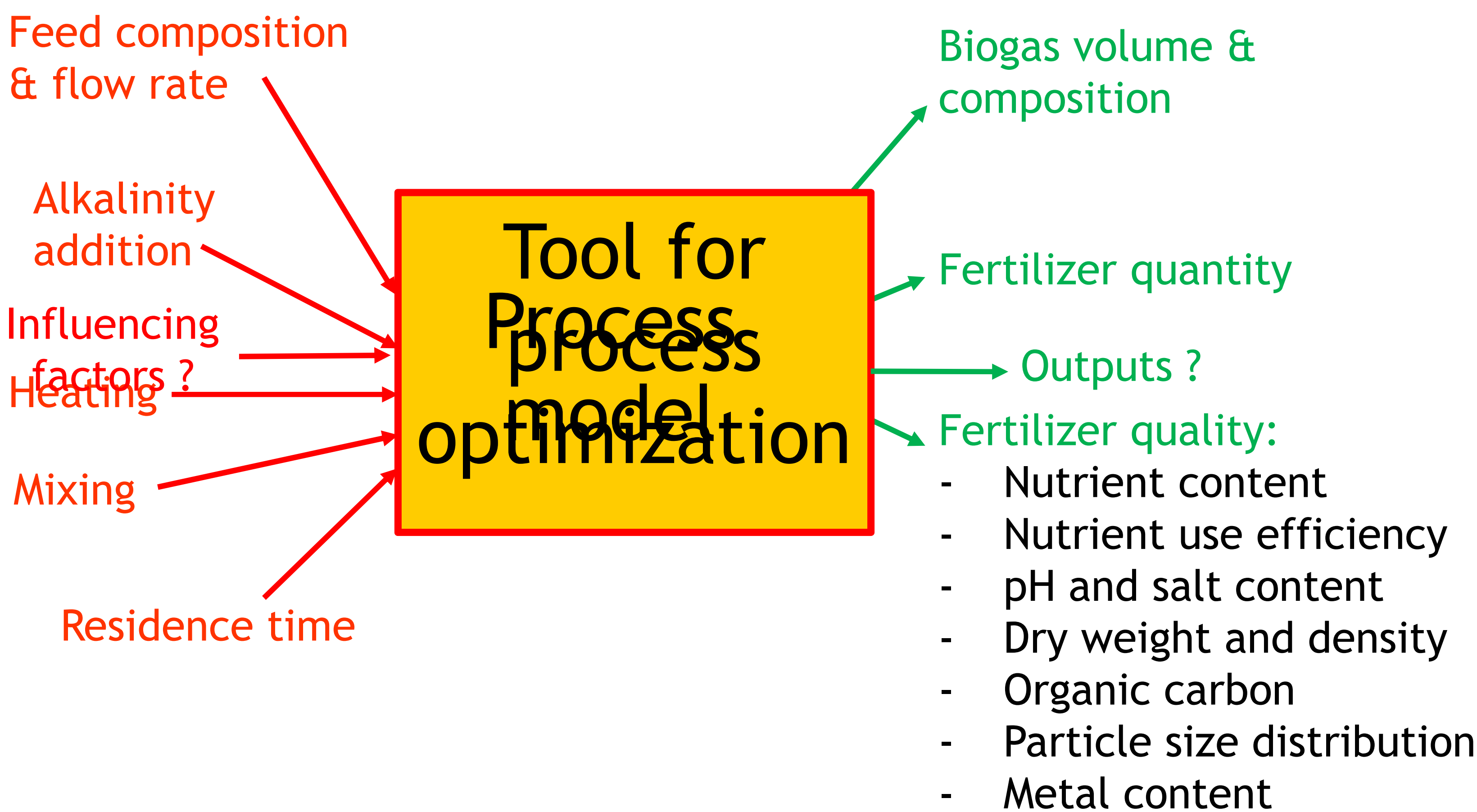
Scenario analyses: NRM-Prec

- Practical recommendations (if struvite is target):



GLOBAL SENSITIVITY ANALYSIS AND PROCESS OPTIMIZATION

Model application for process and treatment train optimization



Global sensitivity analysis (GSA)

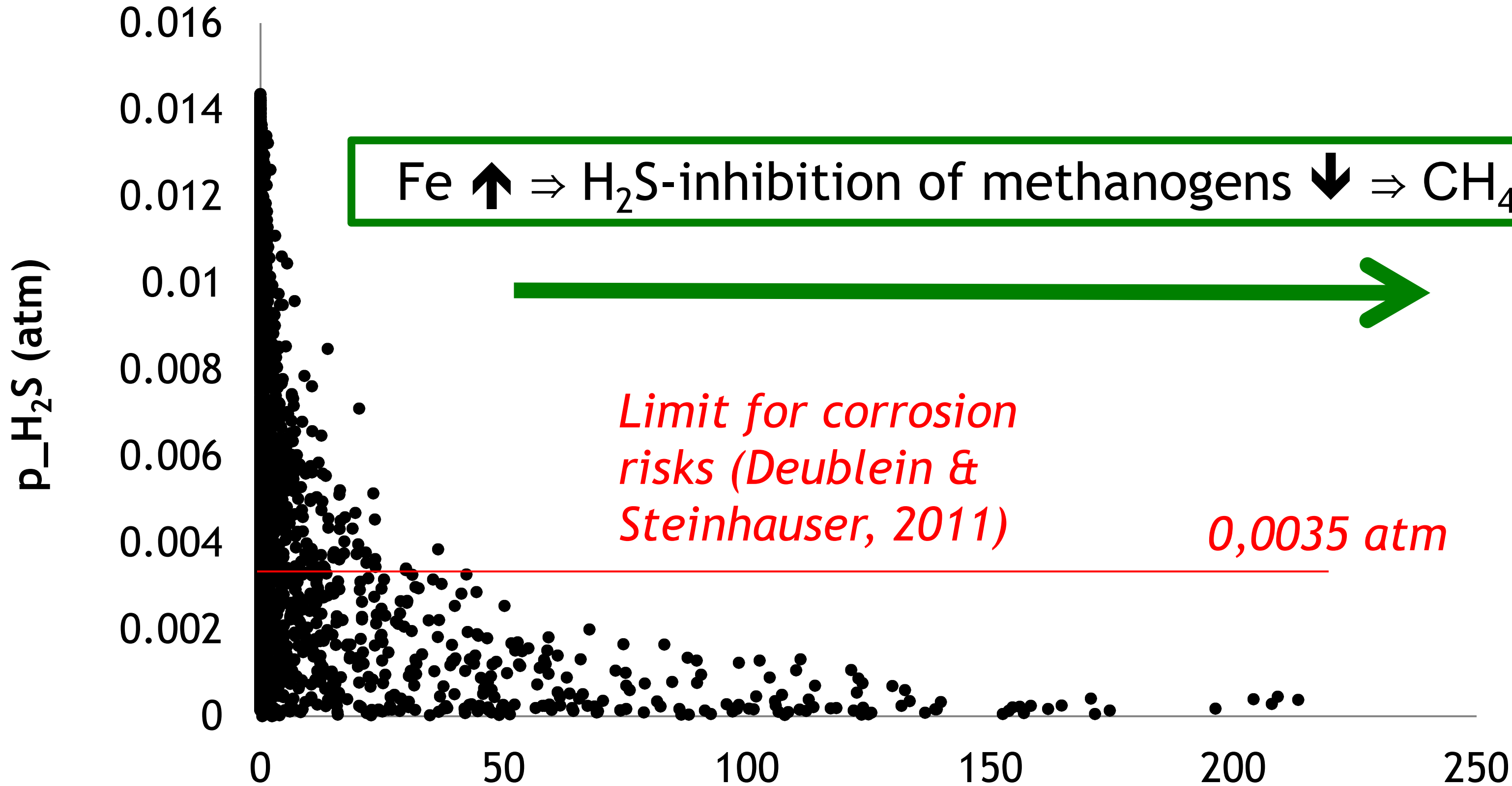
- Selection of factors with highest impact on model outputs (= objective for further study)

Acquired understanding

Optimal treatment train configuration

GSA results: NRM-AD

Effect of Fe on H_2S- and CH_4-production

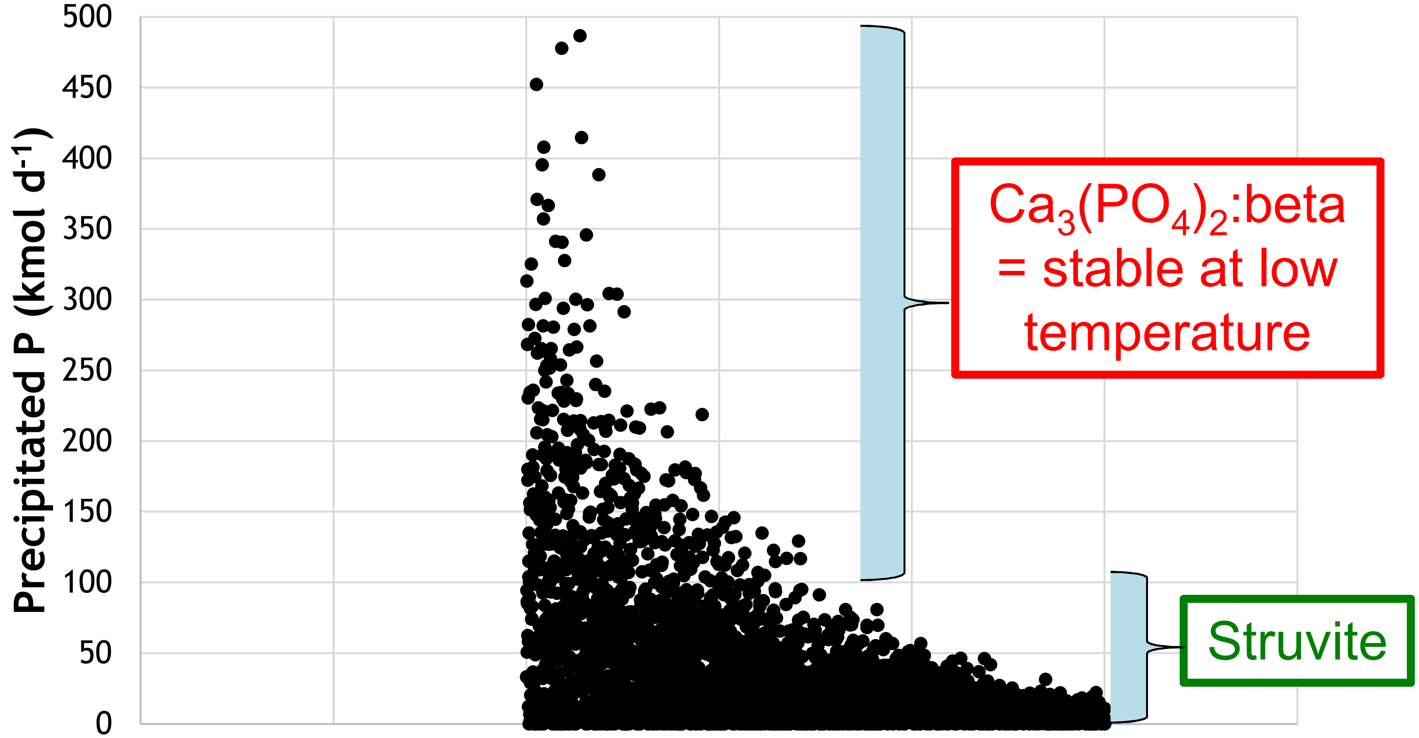


⇒ Use of models for process and product quality optimization & control

⇒ Importance of species and precipitate modeling + input characterization!

GSA results: NRM-Prec

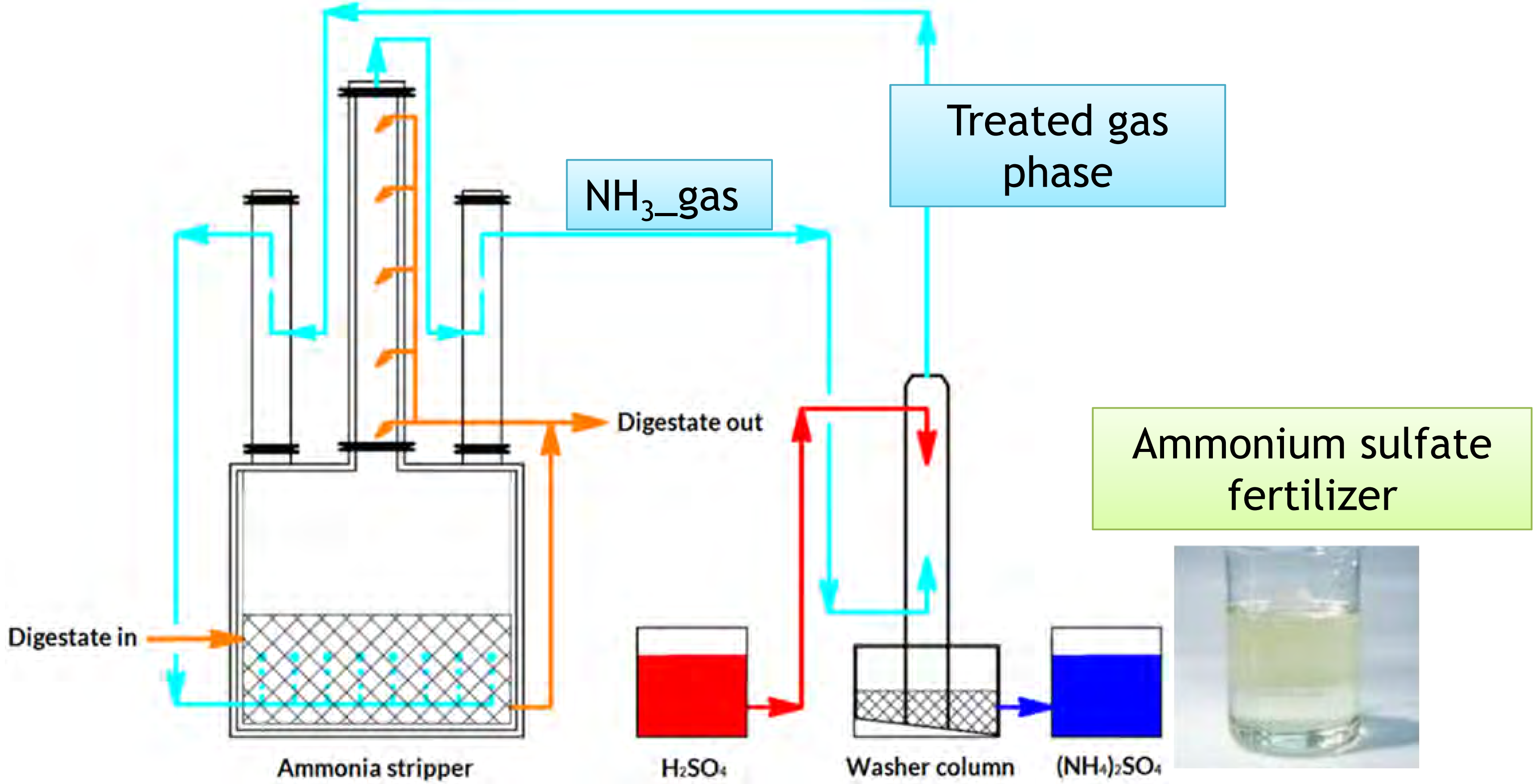
Effect of temperature on P-precipitation



⇒ Struvite purity ↑ if temperature ↑

GSA results: NRM-Strip

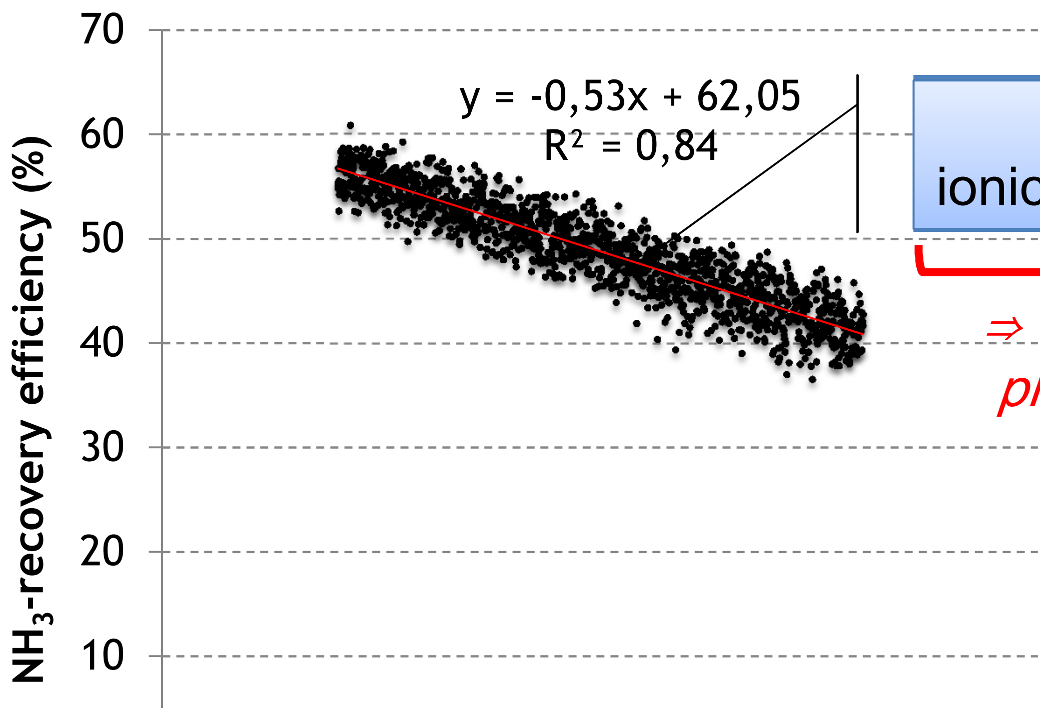
Process lay-out



Source: adapted from Colsen (2015)

GSA results: NRM-Strip

Impact of chlorides on NH_3-recovery efficiency



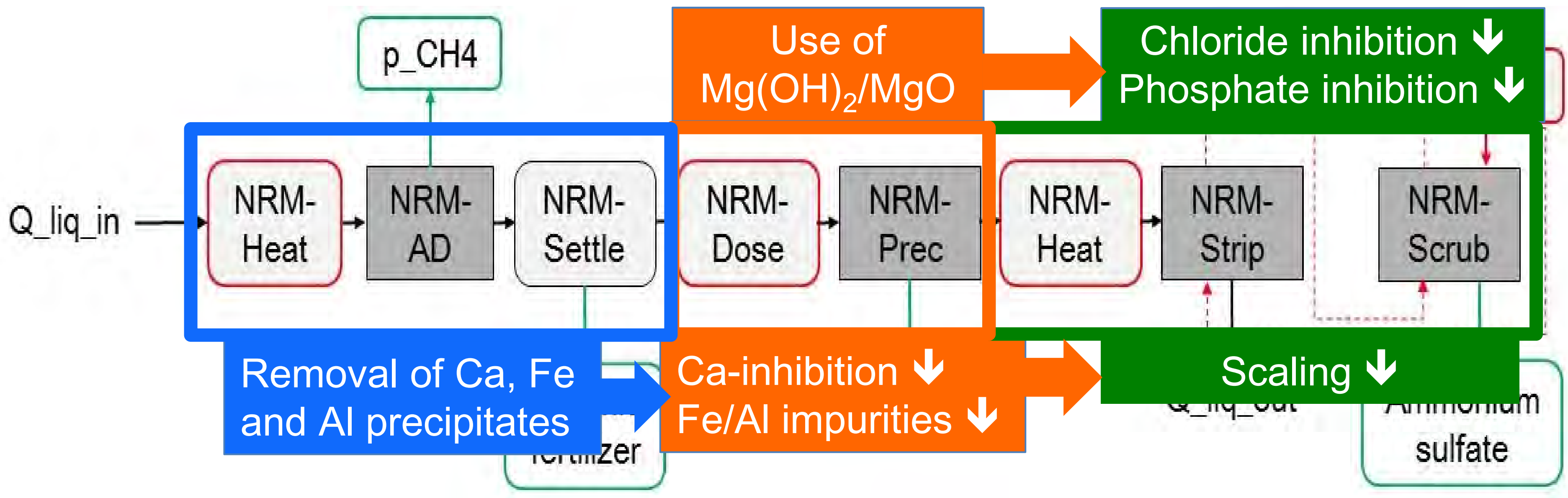
Chloride ↑ ⇒
ionic strength ↑ and pH ↓

⇒ Importance of accurate phys-chem calculations!

⇒ Practical implication for treatment train:
if preceding P-precipitation
use $Mg(OH)_2$/MgO instead of $MgCl_2$

Treatment train configuration

OPTIMAL OPERATING CONDITIONS?



Consumables → Costs

Recovered products → Revenues

Treatment train optimization

Treatment train optimization
Economic analysis

Variable costs & revenues	Capital costs

Variable costs & revenues

- Heat requirements ➔ worst & best case
- Chemicals
- Electricity
- Maintenance, material & labor costs
- Biogas production ➔ electricity and heat
- Fertilizer marketing ➔ worst & best case
- CO_2 emission reduction credits: 15 $ ton^{-1}

Capital costs

- Technology providers
- CAPDET software

Treatment train optimization
Case-study

Optimized WRRF

Financial benefits:

~ variable costs:
5 \$ m^{-3} manure y^{-1}
90 \$ ton^{-1} solids y^{-1}

~ variable + capital costs:
2 \$ m^{-3} manure y^{-1}
40 \$ ton^{-1} solids y^{-1}

Subsidies
Heat balances
Co-inputs

ZeroCostWRRF
(pay-back time: 7 years)

Note: If integration of nutrient recovery in existing WWTP
⇒ Need for overall optimization, e.g. aeration processes upstream, …

CONCLUSIONS

Conclusions

- **WRRF modeling challenges:**
  - Integration of detailed chemical speciation and physico-chemical reaction kinetics in existing (biological) models
  - Generic models for nutrient recovery technologies?
  - Numerical solution?

Conclusions

- **WRRF modeling advances:**
  - Generic nutrient recovery model (NRM) library created
  - Efficient numerical solution strategy developed
  - Default parameters + proper input characterization
    ➔ good agreement with steady state experimental results
  - Global sensitivity analysis
    ➔ optimal treatment train configuration
  - Treatment train optimization ➔ potential for ZeroCostWRRF

    BUT if integration in existing WWTP:
    need for overall optimization!

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DHI The expert in WATER ENVIRONMENTS

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THANK YOU FOR YOUR ATTENTION

QUESTIONS ?