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# Nutrient Recovery Treatment Train Set-Up Using a New Model Library and Global Sensitivity Analysis

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### Summary of key findings

- A generic nutrient recovery model (NRM) library was created
- Insights obtained through global sensitivity analysis of the models allowed setting up an optimal treatment train configuration
- The NRM library was successfully used for treatment train (cost) optimization

### Background and relevance

In the transition from waste(water) treatment plants (WWTP's) to waste(water) resource recovery facilities (WRRF's), mathematical models are becoming important tools to fasten nutrient recovery process implementation and optimization. Indeed, models may aid in technology development, process operation, optimization and scale-up in a cost-effective way (Rieger et al., 2012). Although to date many processes for the recovery of nutrients from waste(water) have been proposed and applied to varying degrees, no generic models for nutrient recovery aiming at the construction and optimization of treatment trains for resource recovery are currently available. Moreover, existing model libraries for WWTP's, e.g. activated sludge models (ASM's), do not allow the integration of nutrient recovery unit processes and/or the coupling of a nutrient recovery treatment train. This is due to the omission of key fundamental physicochemical components and transformations that are essential to describe nutrient recovery.

Thus, a generic nutrient recovery model (NRM) library has recently been developed and validated at steady state (Vaneeckhaute, 2015). The proposed models are dynamic mathematical models, based on detailed solution speciation and reaction kinetics. To facilitate numerical solution, a highly efficient PHREEQC-WEST/Tornado interface has been established and verified. Model simulation outputs were found very sensitive to input waste stream characteristics through their direct effect on pH, which is adequately determined by means of the integrated chemical speciation calculation. Moreover, new data needs appeared, especially related to the physicochemical kinetic precipitation/dissolution and liquid-gas/gas-liquid transfer coefficients.

The NRM library was subjected to a global sensitivity analysis so as to find the main factors that impact a wide range of 25 performance indicators of a nutrient recovery treatment train, including methane and biogas production, digestate composition and pH, ammonium sulfate recovery, struvite production, purity, particle size and density, air and chemical requirements (acid, base), scaling potential, etc. With the obtained insights, an optimal treatment train consisting of several unit processes was developed and assessed in terms of nutrient recovery performance and operating costs. Using model-based optimisation the operating conditions and certain design variables have been optimized in view of maximized revenue.

### Methods

Global sensitivity analyses (GSA) were performed, providing information on how the model outputs are influenced by factor (parameter and model input) variation over the whole space of possible factor values (Saltelli et al., 2008). Three factor classes were considered: 1) Input waste characteristics at WRRF's; 2) Process operational factors; 3) Kinetic rate parameters specific to the NRM's.

Among the different sensitivity analysis methods available, the standardized regression coefficient (SRC) method was used for factor prioritization in this research (Vanrolleghem et al., 2015). One limitation of this method is its disability to detect synergistic or cooperative effects among factors, i.e. problems related to multicollinearity (Kutner et al., 2005; Saltelli et al., 2008). Due to the large number of model factors considered in the NRM library and the complex nature of the input waste matrices, i.e. manure and WWTP sludge, the model variance contribution due to multicollinearity may be significant. To overcome this potential problem, model quality was assessed by determination of variance inflation factors (VIF's), a widely accepted detection-tolerance for multicollinearity, next to common coefficients for evaluation of model linearity ($R^2$).

If multicollinearity was high, the linear models were reduced by eliminating overlapping factors until acceptable VIF and $R^2$ values were obtained (Kutner et al., 2005). When the quality of the linear model was found to be sufficient, model factors were ranked according to the significance of their effect on the different performance indicators.

### Results and Discussion

Based on an extensive literature review (Vaneeckhaute, 2015) four unit processes were selected to set up a nutrient recovery train: an anaerobic digester (NRM-AD), a precipitation/crystallization unit (NRM-Prec), a stripping unit (NRM-Strip) and an acidic air scrubber (NRM-Scrub). Manure and WWTP sludge were used as input to the NRM-AD, whereas digestate was used as input to the NRM-Prec and NRM-Strip. The output gas flow resulting from the NRM-Strip was used as input to the NRM-Scrub for ammonia recovery into a sulfuric acid solution.

For the NRM-AD and NRM-Prec units, a continuously stirred tank reactor (CSTR) design was assumed, with continuous biogas and precipitate extraction. The NRM-Strip and NRM-Scrub units were modelled using a stirred bubble tank design. Default (average) design parameters were obtained by distributing a technical questionnaire to key technology suppliers in the field.

The GSA provided important generic insights in the interactions between process inputs and outputs for the three different waste streams under study. For all unit processes, the variation related to the input waste composition resulted in a major effect on the output variation through its direct effect on the operational pH and ionic strength. Major findings involve, among others, the impact of chloride (Cl) inhibition on ammonia removal in the stripping unit (so, MgO or $Mg(OH)_2$ is to be preferred over $MgCl_2$:$6H_2O$ for preceding phosphorus (P) precipitation), the impact of calcium (Ca), iron (Fe) and aluminium (Al) inhibition on P recovery in the precipitation unit (suggesting the inclusion of a Ca/Fe/Al precipitate separator after the anaerobic digester), and the interaction between Fe/Al, sulfur (S) and methane ($CH_4$) production in the anaerobic digester. By using MgO/ $Mg(OH)_2$ in the struvite precipitation unit, pH is increased which is also beneficial for a subsequent ammonia stripper and thus reduces the need for base addition. Finally, if struvite is to be recovered, the implementation of the precipitation unit after digestion is also beneficial as the GSA showed that higher temperatures increase struvite purity.

Based on the results, it was possible to propose an optimal treatment train configuration for nutrient recovery aiming at the production of high-quality fertilizers at minimal cost (Figure 1). Next to the input characterization, it was found that also local fertilizer legislations and markets may greatly influence the optimal configuration.

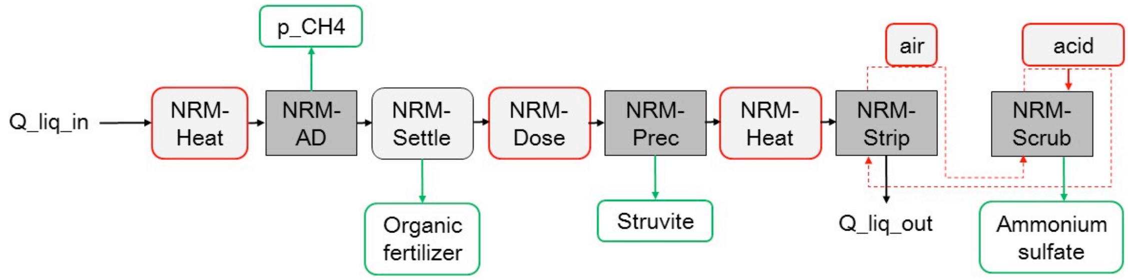


**Figure 1 Proposed treatment train configuration targeting struvite and ammonium sulfate fertilizer; red = consumable (= cost); green = recovered resource (= revenue). AD = anaerobic digestion; Dose = chemical dosing; Heat = heat exchanger; Prec = precipitation/crystallization; p = partial pressure in the biogas; Q_liq = liquid flow rate; Scrub = scrubber; Strip = stripper.**

Finally, the use of the NRM library to establish the operational settings of a sustainable and cost-effective treatment scenario with maximal resource recovery and minimal energy and chemical requirements was demonstrated for pig manure as a case study. Under the optimized conditions and assumptions made, potential financial benefits for a large-scale anaerobic digestion and nutrient recovery project were estimated at 2.8-6.5 USD $m^{-3}$ manure based on net variable cost calculations, or an average of ± 2 USD $m^{-3}$ $y^{-1}$, equivalent with 40 USD $ton^{-1}$ total solids $y^{-1}$, over 20 years when also taking into account capital costs. Hence, it is likely that in practice a full-scale 'ZeroCostWRRF' can be constructed. Nevertheless, subsidies and heat balances were found to play a crucial role in determining the feasibility of resource recovery projects.

It can be concluded that the NRM library and GSA strategy developed in this study provide a valuable and cost-effective framework for increased process understanding, treatment train configuration, and optimization of region-specific nutrient recovery applications. Starting from the obtained results and insights, a generic roadmap for setting up nutrient recovery strategies as function of fertilizer markets and input characteristics was proposed. The roadmap involves: 1) an overview of bio-based fertilization recommendations as function of fertilizer legislations, 2) guidelines for determining the feasibility of nutrient recovery based on operational experience, and 3) an algorithm for configuration and optimization of nutrient recovery treatment trains as function of input waste characterization and fertilizer markets. As such, the roadmap provides useful guidance for waste(water) processing utilities considering the implementation of nutrient recovery practices. This, in turn, should stimulate and hasten the global transition from traditional WWTP's to WRRF's.

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