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# Global Sensitivity Analysis of a Mathematical Model for AnMBR Systems Treating Municipal Wastewater

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**Abstract:** This study conducted a Global Sensitivity Analysis (GSA) of a mathematical model for simulating urban wastewater treatment in anaerobic membrane bioreactors (AnMBRs) at ambient temperatures. The Anaerobic Digestion Model ADM1 was modified and implemented in Matlab/Simulink, comparing three sensitivity analysis methods: One At a Time (OAT), Morris and Fourier Amplitude Sensitivity Test (FAST)..Experimental data from an AnMBR operating on municipal wastewater during summer and winter periods were used for model calibration and verification. The AnMBR had a 40L laboratory membrane bioreactor with a submerged flat sheet membrane and a 40L biogas collection tank. Experiments covered temperatures of 14-26°C and three hydraulic retention times (HRTs): 2 days, 1 day, and 12 hours. Performance evaluation included parameters such as COD effluent, total nitrogen effluent, biogas production, and volatile suspended solids concentrations. The primary aim was to compare the effectiveness of the OAT Morris and FAST sensitivity analysis methods in capturing the model's sensitivity to input parameters. This global sensitivity analysis enhances our understanding of the model's behavior and its applicability in designing and operating AnMBRs for urban wastewater treatment.

**Keywords: AnMBR; ultrafiltration; ADM1**

## 1. Introduction

Anaerobic membrane bioreactors (AnMBRs) have emerged as a promising technology for urban wastewater treatment due to their ability to combine the advantages of anaerobic digestion and membrane filtration(Dvořák *et al.*, 2015; Plevri, Mamais and Noutsopoulos, 2021). These systems utilize microorganisms to break down organic waste, while the membrane acts as a physical barrier for solid-liquid separation and biomass retention. Mathematical modeling plays a crucial role in understanding and optimizing the complex processes involved in AnMBRs.

The Anaerobic Digestion Model No.1 (ADM1), developed by the IWA Task Group for Mathematical Modeling of Anaerobic Digestion Processes, is a comprehensive framework widely used for simulating anaerobic digestion. However, the application of ADM1 to AnMBR systems requires modifications to incorporate the specific operational characteristics and membrane filtration aspects. These modifications are essential for accurate predictions and reliable design and optimization of AnMBR-based wastewater treatment processes.

In this study, we focus on the modification and calibration of the ADM1 model for AnMBR-based wastewater treatment(Batstone *et al.*, 2002). Our objective is to develop an accurate and reliable model that captures the intricacies of the AnMBR system and its interaction with the anaerobic digestion processes. By incorporating experimental data from a lab-scale AnMBR operating on municipal wastewater during different seasons, we aim to calibrate the model and validate its performance against real-world operational conditions.

Furthermore, to gain insights into the sensitivity of the model to input parameters, a global sensitivity analysis is conducted and also a compare with a local sensitivity analysis (OAT). This analysis utilizes three established sensitivity analysis methods: One At a Time (OAT), Fourier Amplitude Sensitivity Test (FAST), and Morris method. The comprehensive assessment provided by these methods will enhance our understanding of how variations in input parameters affect the model's predictions and guide us in identifying the most influential parameters.

The outcomes of this research have significant implications for the design and operation of AnMBRs for urban wastewater treatment. A calibrated and validated Anaerobic Digestion Model No.2 (BSM2) specific to AnMBRs will serve as a valuable tool for further investigations and optimization of these systems. The insights gained from the global sensitivity analysis will assist in identifying critical parameters and improving the overall efficiency and performance of AnMBR-based wastewater treatment processes.

## 2. Materials and Methods

The experiments consisted of three main simulated scenarios, each comprising a winter period and a summer period. Detailed experimental results can be found in Plevri et al., 2021. The lab-scale AnMBR research was conducted at the facilities of the Athens Water Supply and Sewerage Company (EYDAP). The setup included a 40 L anaerobic reactor with a flat sheet PVDF membrane (0.5 $m^2$ surface area) for ultrafiltration. Biogas produced was collected and measured using a 40L gas holder. To remove accumulated suspended solids, membrane cleaning involved recirculating biogas within the reactor.

To analyze global sensitivity, three established methods were employed:

- One at a Time (OAT) Analysis: OAT is a local sensitivity analysis that evaluates the influence of individual input parameters by perturbing them individually and assessing resulting changes in the model output.
- Fourier Amplitude Sensitivity Test (FAST): FAST decomposes the parameter space into frequency bands, quantifying the amplitude of the model response to identify influential parameters(Saltelli, Tarantola and Chan, 1999).
- Morris method: The Morris method assesses parameter influence by conducting elementary effect-based evaluations, examining the model's output response to small perturbations in each parameter(Morris, 1991; Campolongo, Cariboni and Saltelli, 2007).

These sensitivity analysis methods were applied to the modified ADM1 model to assess parameter sensitivity and understand their impact on model performance.

## 3. Results and Discussion

### 3.1 Experimental Scenarios Description

A total of six different scenarios were investigated to evaluate the performance of the AnMBR system. The operational temperature ranged from 14°C to 26°C, with an average temperature of 18°C during the winter period and 24°C during the summer period. Table 1 presents the specific conditions of interest for each scenario and its corresponding sub-scenario.

*Table 1 Operating Characteristics of the Six Different Scenarios*

| Parameters | Scenarios 1 a/b | Scenarios 2 a/b | Scenarios 3 a/b |
|---|---|---|---|
| T (°C) | 18/23 | 19/24 | 19/24 |
| Q (L/d) | 20 | 40 | 80 |
| HRT (d) | 2 | 1 | 0.5 |
| SRT (d) | 50 | 50 | 50 |

The experimental scenarios were carefully designed to capture the variations in temperature and corresponding system performance. The present study examines a GSA for 25 parameters with a total of 10 output parameters (COD, VSS, Qgas, TN,S_but, S_pro , S_ac ,$X\_C_4$,X_ac, $X\_H_2$).

### 3.2 Sensitivity analysis results

A comparison has been made between the results of all the methods as well as between the global and local sensitivity analyses. The local sensitivity analysis method was chosen for its simplicity and speed of implementation. Therefore, the results need to be validated and compared to the more accurate global methods. Additionally, the usefulness of the local sensitivity analysis method will be evaluated, considering its limitations.

The "one-at-a-time" method is a local sensitivity analysis approach and therefore has the corresponding advantages and disadvantages. The FAST method is a global sensitivity analysis method, while Morris method serves as a hybrid between the two. Thus, the comparison between these methods should be based on appropriate criteria that are applicable to all three methods. Specifically, the following aspects were compared: 1) the number of significant and non-significant parameters produced by each method, 2) the ranking order and differences among the parameters, 3) which parameters are deemed significant or non-significant, and 4) the number of iterations performed by each method.

Below is the sensitivity analysis for the COD output of the model. Figures 1 and 2 present the parameter prioritization using the OAT method and the FAST method, respectively.

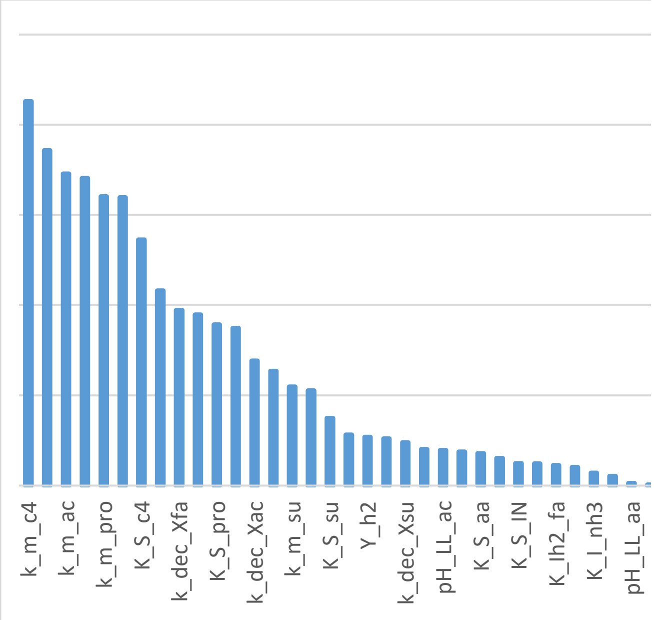


*Figure 1 Parameter prioritization for COD outlet using the 'one-at-a-time' method*

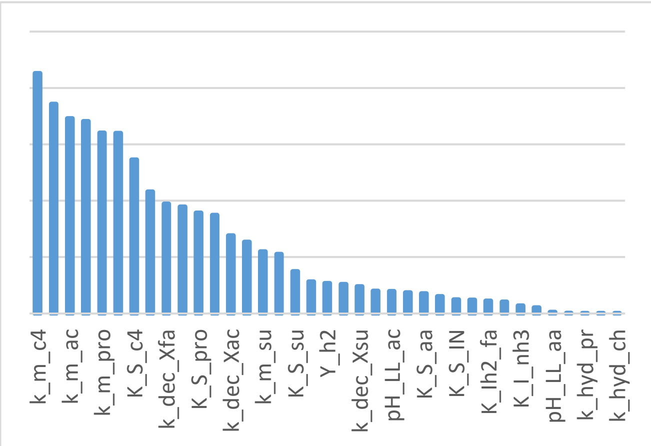


*Figure 2 Parameter prioritization for COD outlet using the FAST method*

Figure 3 presents the scatter plot diagram for the sensitivity indices of the parameters concerning COD outlet. The method also offers the capability of precise parameter prioritization based on their sensitivity index values.

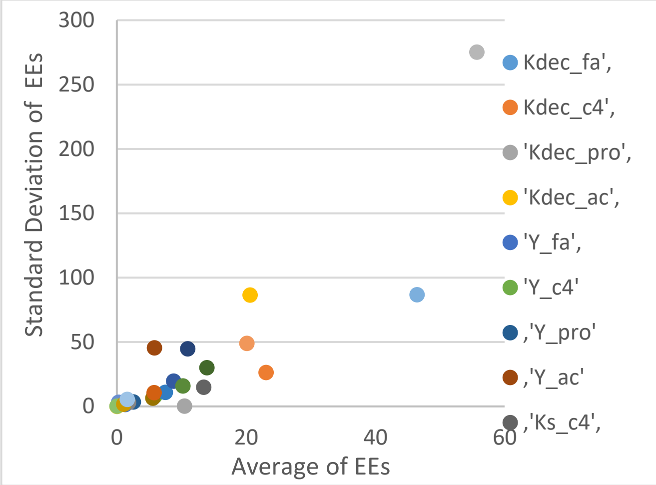


*Figure 3 Scatter plot (mean, standard deviation), Morris method.*

Furthemore, the convergence of the models has been further checked with a different number of iterations for all output parameters. The results are presented only for the COD as an indication in Figures 4 and 5.

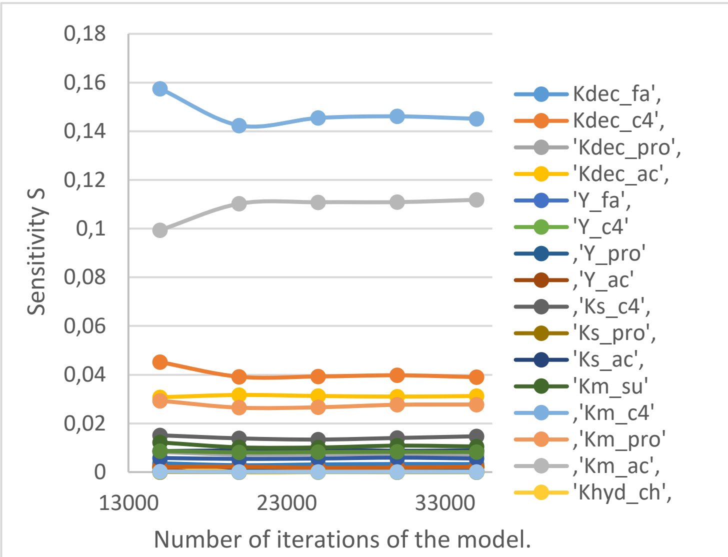


*Figure 4Convergence plot of parameters for COD outlet, FAST method*

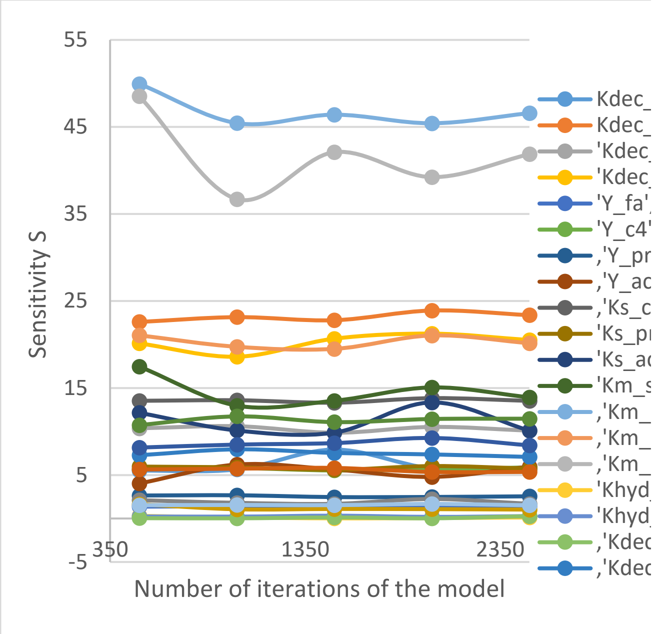


*Figure 5 Convergence plot of parameters for COD outlet, Morris method*

## 4. Conclusions

In the study, six different scenarios were examined, and the simulation results for key parameters such as CODout, Qgas, VSS, pH, and CH4 were found to closely match the experimental data. This successful development and validation of the modified ADM1 model in these scenarios indicate its effectiveness. Subsequent research could concentrate on extending the use of the modified model to other scenarios, thereby promoting the wider adoption of AnMBRs.
Regarding GSA , it is good practice to apply more than one sensitivity analysis method to the simulation model. This allows for a comprehensive comparison and evaluation of the methods. Additionally, behaviors and patterns are observed in the results of each method, which may be common to all or specific to one of the 114 methods. By comparing them, areas of agreement in the results are identified, which receive greater attention. Meanwhile, any extreme cases are excluded as isolated incidents of the respective method.

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