

# Designing for minimal N<sub>2</sub>O emissions at the new Kalmarsundsverket - Water Recycling Plant (Sweden)



## Case highlights:

- A ‘minimal N<sub>2</sub>O by design’ approach was adopted to minimize carbon footprint in design stage of a new treatment facility
- The AMNOXA™ model visualized plant performance and N<sub>2</sub>O hotspots in 3D and revealed two dominant N<sub>2</sub>O formation risks in the new plant’s designs
- Based on the modelling outcomes, critical design elements were adjusted: baffling wall modification, external carbon dosing location and aeration strategies
- Plant efficiency was maximized in parallel with N<sub>2</sub>O minimization
- Model outcomes will also be used for determination of future N<sub>2</sub>O monitoring spots

## Authors:



**Dr. Qing Zhao,**  
Process and Development Engineer,  
*Kalmar Vatten*



**Dr. Giacomo Bellandi**  
Tech Lead,  
*AM-Team*

## Introduction and problem statement

The Swedish water utility Kalmar Vatten is building Sweden's leading urban recycling plant—Kalmarsundsverket—as part of their mission to perform advance treatment of municipal wastewater and become climate-neutral while raising the status of water infrastructure. Beyond treating wastewater, this innovative facility will produce recycled water for future use in irrigation and industry, produce certified soil improvers, and generate biogas for heat and electricity. For Kalmar Vatten, addressing greenhouse gas emissions in the design stage represents a crucial step toward climate neutrality, as process emissions significantly impact their carbon footprint.

Kalmar Vatten engaged AM-Team to integrate minimal nitrous oxide (N<sub>2</sub>O) emissions into the design phase of their new Kalmarsundsverket wastewater treatment plant. The goal was to understand N<sub>2</sub>O formation mechanisms across different design variants and identify optimal bioreactor configurations that would minimize emissions while maximizing treatment efficiency—embodying the principle of 'minimal N<sub>2</sub>O by design.' AM-Team worked closely together with the equipment provider (Xylem) and engineering firm (Eliquo Malmberg Water) to find the feasible and effective mitigation solutions.

**"AMNOXA™ enabled us to test a multitude of design scenarios. We could see the exact effect of how different mixing options, aeration strategies, and carbon dosing locations would affect N<sub>2</sub>O formation and plant performance."**

- Dr. Qing Zhao, Process and Development Engineer,  
Kalmar Vatten



## Solution and Objectives

The forward-thinking digital engineering approach allowed virtual testing of multiple design configurations which are impossible to evaluate on-site in a non-existing plant. Optimal use of the model insights would reduce emissions and improve efficiency from day one of operation.

### The objectives were to:

- Understand N<sub>2</sub>O formation mechanisms in the new bioreactor designs
- Optimize mixer and aeration placement to minimize N<sub>2</sub>O production
- Test and compare mitigation strategies for various design options
- Determine optimal N<sub>2</sub>O sensor locations for future monitoring
- Integrate efficiency improvements alongside emission reductions

## Approach

AM-Team's AMNOXA™ modelling framework was used for comprehensive 3D assessment of the new plant. AMNOXA™ relies on specialised treatment data handling and a mixture of 3D and dynamic modelling. The 3D model, used in this project, consists of a physics-based Computational Fluid Dynamics (CFD) model with integrated biokinetics. Nutrient and carbon conversion and N<sub>2</sub>O production, transport and stripping are realistically taken into account.

### The modeling approach (Figure 1) included:

- Detailed reactor geometry including all zones, inlets, outlets, mixers, and diffusers
- Design data for two scenarios: 2027 commissioning conditions (18,000 m<sup>3</sup>/d) and 2050 future capacity (27,000 m<sup>3</sup>/d)
- Hydrodynamic analysis to identify mixing patterns and potential backflow issues
- N<sub>2</sub>O hotspot and root cause analysis pinpointing the local drivers for N<sub>2</sub>O production
- Virtual testing of mitigation scenarios including influent distribution, aeration strategies, and carbon dosing optimization

**"The 3D hotspot analysis is one of the key features of AMNOXA™, allowing to optimize biological treatment plants in a very effective manner."**

- Dr. Giacomo Bellandi, Tech Lead, AM-Team



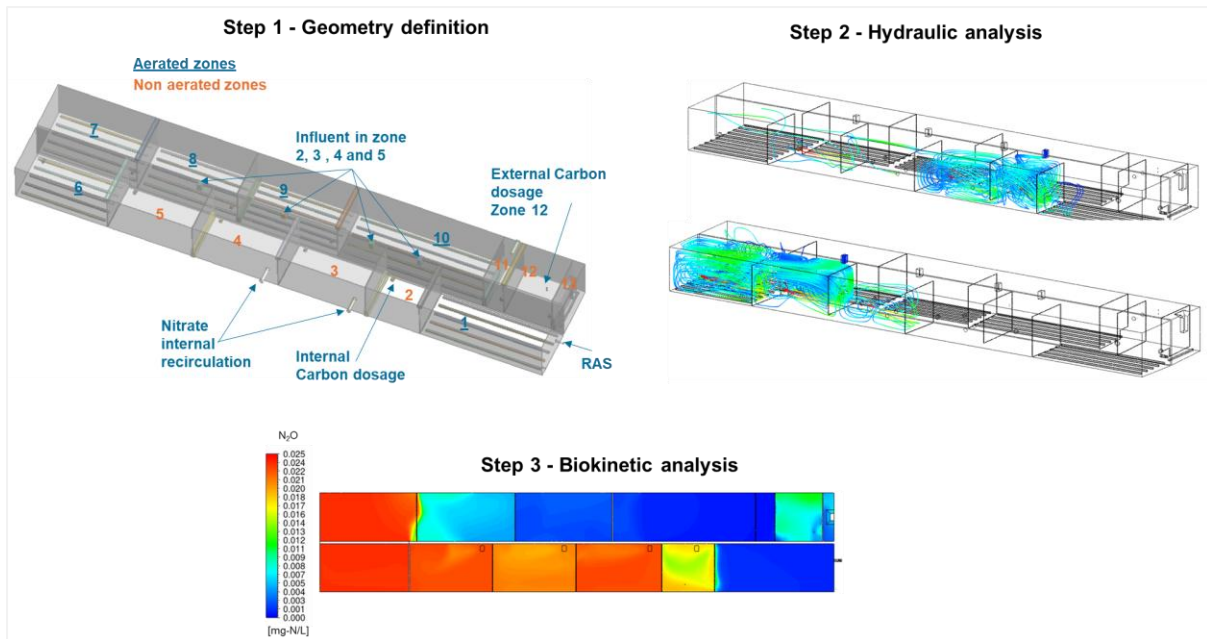


Figure 1. In a first step, 3D models of the existing designs were set up, followed by a general hydraulic analysis (step 2) and a biokinetic analysis (step 3). The latter visualized plant performance and  $N_2O$  production and emission in full 3D.

## Results and Findings

### Root Cause Analysis: understanding $N_2O$ formation mechanisms

AMNOXA™ revealed the specific biochemical pathways driving  $N_2O$  formation in the new reactor design. As shown in the  $N_2O$  heatmap in Figure 2, two primary mechanisms creating local ' $N_2O$  production hotspots' were identified:

**AOB Denitrification:** At the start of aerobic zones, low dissolved oxygen (DO) combined with high ammonia levels would trigger ammonia-oxidizing bacteria (AOB) to produce  $N_2O$  through the denitrification pathway<sup>1</sup>. This was particularly evident in zones (Figure 1) where the transition from anoxic to aerobic conditions created a zone where DO levels struggled to reach setpoint quickly, providing ideal conditions for this pathway.

**Heterotrophic Denitrification:** In anoxic zones where the carbon/nitrogen (C/N) ratio was suboptimal, incomplete denitrification led to  $N_2O$  accumulation as an intermediate product<sup>2</sup>. The initial design showed incomplete denitrification particularly in zones where external carbon dosing had not yet been fully mixed and utilized by heterotrophic bacteria, creating hotspots of  $N_2O$  production.

<sup>1</sup> AOB denitrification: while AOBs are supposed to nitrify ( $NH_4 + O_2 \rightarrow NO_2$ ), they can also create  $N_2O$  under high ammonia, low dissolved oxygen conditions:  $NO_2 + NH_4 \rightarrow N_2O$  ('AOB denitrification')

<sup>2</sup> Incomplete denitrification: while heterotrophic bacteria are supposed to denitrify completely ( $NO_3 + C \rightarrow N_2$ ), they can stop at  $N_2O$  under C limiting circumstances ( $NO_3 + C \rightarrow N_2O$ )

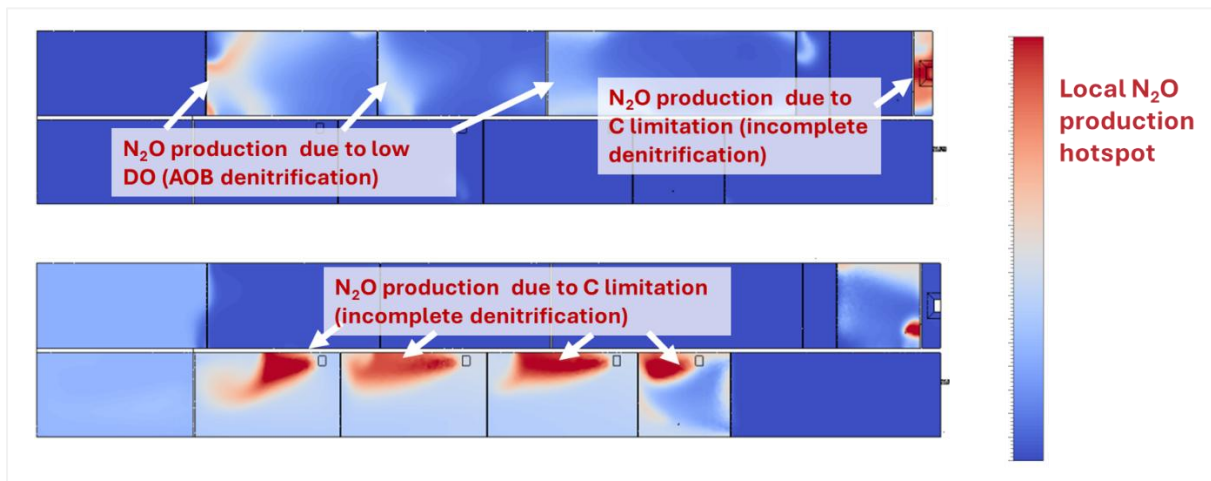


Figure 2. Top view of the reactor with **N<sub>2</sub>O hotspot analysis**. N<sub>2</sub>O production by AOB denitrification (top) indicates potential improvement of the aeration distribution and strategy. The hotspots caused by heterotrophic denitrification (bottom) shows high N<sub>2</sub>O production activity in the vicinity of the inlet pipes.

“AMNOXA™ is a solution that uniquely allows 'minimal N<sub>2</sub>O by design'. This is crucial, as there is no monitoring data available in the design stage, but important decisions still need to be made. We wanted to achieve a design that had minimal N<sub>2</sub>O baked in.”

- Dr. Qing Zhao, Process and Development Engineer,  
Kalmar Vatten



## Design Optimization: Minimal N<sub>2</sub>O by Design

The power of minimizing N<sub>2</sub>O in the design stage became clear when testing various reactor configurations. Each design modification could be evaluated for its impact on both N<sub>2</sub>O formation and overall plant efficiency:

**Mitigating undesired backflows:** Hydrodynamic analysis revealed significant backflows in some anoxic zones. The model revealed that adjusting mixer orientation or baffle walls could potentially reduce backflows by 70-80% without compromising mixing efficiency. This design change improved flow patterns and minimized risk of undesired oxygen recycling to anoxic zones, which would have exacerbated N<sub>2</sub>O production through the AOB denitrification pathway. In the end, the project consortium selected the baffle wall adjustment as most feasible option to implement in the final design.

**Carbon Dosing Location:** Results showed that relocating the external carbon dosing pipe improved C distribution and denitrification completeness (Figure 3). This uniform C distribution —achievable only through virtual testing—improved both N<sub>2</sub>O mitigation (by ensuring complete denitrification) and operational efficiency (by optimizing carbon usage).

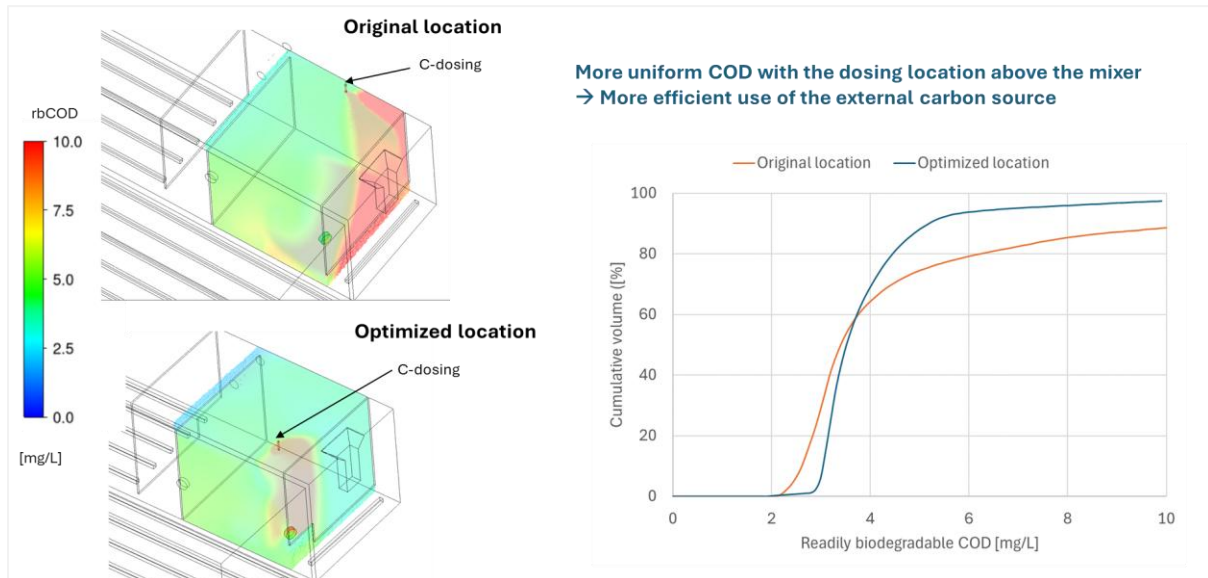


Figure 3. Chemical dosing distribution with original (top left) and optimized (bottom left) carbon dosing location. On the right the volume distribution curves of the optimized configuration shows an evident improvement in reaching an quasi-complete mixing (vertical curve)

**Aeration Strategy:** Virtual testing revealed that increasing aeration in the first aerobic zone (zone 8) reduced AOB denitrification activity by 70% (Figure 4a). However, this also increased overall nitrification, leading to higher nitrate levels and subsequent heterotrophic N<sub>2</sub>O production in aeration zones. The net impact on N<sub>2</sub>O was hence negative (Figure 4b). This demonstrated the importance of balanced system design rather than isolated optimizations—a key insight that guided the final recommendations for operational control strategies.

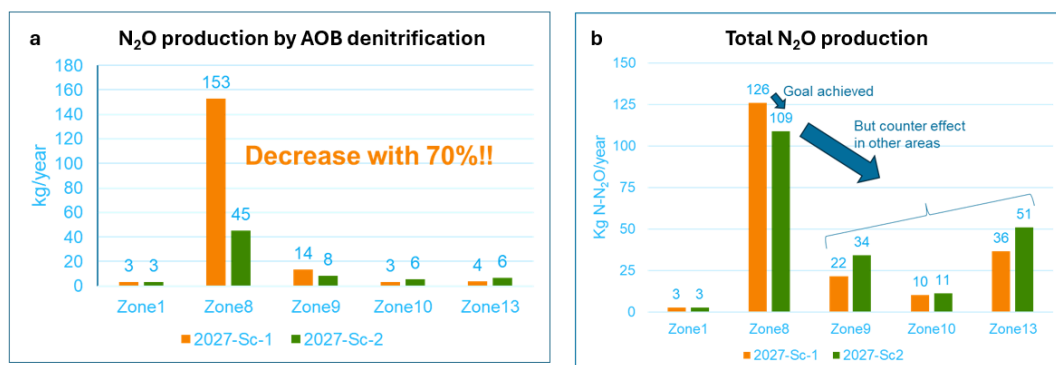


Figure 4. After general system optimization, AMNOXA™ was used to further pinpoint specific pathways to push N<sub>2</sub>O even lower. Adjusting aeration decreased the AOB production with 70% (a), yet negatively impacted N<sub>2</sub>O production by denitrification, leading to a net increase of N<sub>2</sub>O (b). This measure was hence not implemented.

## Efficiency Gains and Performance Improvement (3E: Emissions, Effluent, Efficiency)

The design optimizations delivered benefits beyond N<sub>2</sub>O mitigation. The principle of 'minimal N<sub>2</sub>O by design' inherently led to a more efficient plant:

**Improved Mixing Efficiency:** Reduced backflows and more uniform mixing patterns were achieved, improving overall treatment kinetics while preventing the oxygen recycling that would have contributed to N<sub>2</sub>O formation.

**Enhanced Carbon Utilization:** Optimizing carbon dosing location improved distribution efficiency, meaning the same amount of external carbon achieved better denitrification results. This translates to potential operational savings through more effective use of carbon sources while simultaneously reducing N<sub>2</sub>O emissions from incomplete denitrification.

**Better Effluent Quality:** The balanced aeration and carbon dosing strategies designed to minimize N<sub>2</sub>O also improved nitrogen removal efficiency. Complete denitrification means less nitrate breakthrough and better overall effluent quality—supporting Kalmar Vatten's goal to reduce effluent nitrogen and phosphorus by at least 35% compared to their old plant, while coping with future increasing influent loading.

**“AM-Team’s hotspot analysis revealed where and how N<sub>2</sub>O was likely to be produced. By pinpointing and tackling those root causes, we could mitigate N<sub>2</sub>O based on a scientifically sound methodology.”**

- Dr. Qing Zhao, Process and Development Engineer,  
Kalmar Vatten



### Sensor Placement for Future Monitoring

Given the complex and dynamic nature of the system with multiple swing aeration zones, the AMNOXA™ analysis identified optimal sensor locations for future N<sub>2</sub>O monitoring. The modeling revealed that emissions can vary significantly during transitions from anoxic to aerobic conditions and during peak loadings. For comprehensive monitoring, a dynamic model or digital twin approach was recommended to support ongoing optimization during plant operation.

## Conclusion and Impact

Kalmar Vatten, the consortium partners Xylem and Eliquo Malmberg Water and AM-Team successfully integrated climate-smart design principles into the new wastewater treatment plant through AMNOXA™ modeling. By identifying N<sub>2</sub>O formation mechanisms at the design stage, they could optimize reactor configurations before construction—embodying the principle of 'minimal N<sub>2</sub>O by design.'

### Key achievements include:

- Comprehensive understanding of N<sub>2</sub>O formation mechanisms specific to the new reactor design based on a 3D N<sub>2</sub>O hotspot analysis
- Practical design optimizations: 70-80% backflow reduction through refinement of partition wall, optimized carbon dosing locations, and balanced aeration strategies
- Identification of critical operational parameters (DO setpoint in first aerobic zone, COD/N ratio optimization) for ongoing N<sub>2</sub>O management
- Simultaneous improvements in emissions, effluent quality, and operational efficiency—the 3E approach that supports Kalmar Vatten's broader circular economy vision

**"While N<sub>2</sub>O often gets attention within existing treatment plants, significant mitigation impact can be made in the design stage prior to construction. AMNOXA™ is the only solution that allows minimal N<sub>2</sub>O by design, in combination with maximizing general plant performance."**

- Dr. Giacomo Bellandi, Dr., Tech Lead, AM-Team



AMNOXA™ allowed to thoroughly evaluate the plant before construction. Kalmar Vatten can now commission their new plant with confidence, knowing it's designed from the ground up to minimize N<sub>2</sub>O emissions while maximizing treatment performance and resource recovery. This project establishes a new standard for climate-conscious wastewater infrastructure: designing minimal emissions in, rather than retrofitting solutions later.

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Sint-Pietersnieuwstraat 11

9000 Gent (BE)

+32 480 64 70 76

[info@am-team.com](mailto:info@am-team.com)

[www.am-team.com](http://www.am-team.com)

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About AM-Team:

AM-Team provides globally unique modelling and data services and digital twin solutions to smartly design, optimise and digitalise municipal and industrial water and wastewater treatment plants. The company has worked on over 200 sites on 4 continents. AM-Team directly works with utilities and also partners with engineering firms, software companies and technology vendors.

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