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# Plantwide Control and Multi-Objective Optimization for Sustainable Wastewater Treatment Plants

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**Abstract:** The concept of plantwide control, initially developed to enhance process control in the chemical industry, has seen limited application in wastewater treatment plants (WWTPs). However, the need for multi-objective optimization and control in WWTPs has grown significantly due to stricter regulations, such as the Urban Wastewater Treatment Directive, and rising costs for energy and operational resources (e.g., precipitants, flocculants, external carbon sources). Recent advancements, including unified communication protocols (e.g., OPC UA and Ethernet-APL), more affordable and robust online sensors, and AI-driven closed-loop control systems, have created new opportunities for implementing plantwide control solutions in WWTPs. In response, the DWA[3] working group on plantwide control is developing operational strategies to address these challenges. This paper presents three strategies—focusing on nitrogen removal, COD harvesting, and plantwide energy management—while highlighting the challenges, conflicting objectives, and the critical need for prioritization in modern WWTP operations.

**Keywords**: plantwide-control, operating strategies, multi-objective optimisation

## Introduction

The concept of plantwide-control is well-known and was first introduced in 1973 (Foss, 1973) to improve process control in the chemical industry. Nevertheless, the concept is rarely applied to WWTP`s, although the challenges of multi-objective optimization and control are greater than ever due to stricter rules and requirements, such as the Urban Wastewater Treatment Directive (EU, 2024) and rising prices for energy and operating resources (precipitants, flocculants, external carbon sources, etc.), particularly in the European Union (Barjenbruch, Hartwig, 2024; EC, 2024). One could argue that plantwide-control is not well-known in the wastewater treatment industry, but Olson mentioned it in 2014 in his review of ICA in wastewater over the last 40 years, highlighting the necessity as well as its benefits (Olsson et. al, 2014). Why then, are plantwide-control strategies are not applied at a broader scale?

The reasons are multifaceted. On the one hand, the development of dedicated control solutions for one or two processes is easier than considering the dynamic effects on multiple process units with maybe even contradicting objectives and on the other hand access to existing proprietary control systems used in different process units as well as comprehensive data acquisition and analysis has proven to be a hassle on long-standing plants. Thus, closed-loop control systems developed during the last ten years focus mostly on the optimization of aeration control as it is the main energy consumer. Drewnowski (2019) developed an aeration and recirculation control using a WWTP-simulation model as a soft-sensor for $NH_4$-concentration in the nitrification tank to reduce energy consumption, describing the solution as an advanced supervisory control system. Similarly, Revollar et al. (2020) designed a two-state $O_{DO}$-setpoint control based on a global performance indicator being the ratio of nitrogen removal (kg N) and energy consumption (kWh). Considering multiple objectives, Santín et al. (2018) developed a fuzzy logic plantwide-control system

optimizing DO-setpoints and recirculation reducing Greenhouse Gas (GHG) emissions, nutrient removal and operational costs, which are evaluated using Effluent Quality Index and Operational Cost Index (EQI and OCI). But interdependencies between process units and a prioritization was not considered. A real plantwide-control system for the activated sludge treatment stages as well as sludge treatment of the same WWTP was developed and implemented by Palatsi et al. (2021) and Romero-Güiza et al. (2022). Nevertheless, a prioritization of conflicting objectives is not considered, and plant operation remains conventional.
Fortunately, recent developments in unified communication protocols, i.e. OPC UA[1] or Ethernet-APL[2], reduced prices and higher robustness of online sensors for WWTP and advances in AI-supported closed loop control systems facilitate the implementation of plantwide-control solutions. Therefore, the working group for plantwide control of the DWA[3] is currently developing operating strategies for WWTPs of which three will be presented, ranging from simple (nitrogen removal) to complex (energy management) strategies.

**Objectives and priorities**

In the course of the planning process, the various objectives of the networked process control system must be prioritized depending on the local and temporary boundary conditions and anchored accordingly in the functional design specification. Drawing up the catalog of objectives is a complex task and is part of the planning process, considering the advantages and disadvantages of each solution. At the same time, it must be possible for the operator to easily adapt prioritizations according to the current circumstances.

- Reliable compliance with the requirements of the water permit is essential.
- The reduction of total emissions from the sewer network (combined system) by optimal utilization of stormwater overflow basins, adjustment of throttle discharges and, if necessary, use of storage basins upstream of the WWTP is becoming increasingly important but requires investment in sensor and automation technology.
- Minimizing the use of operating resources has long been a key objective of automation solutions to ensure the desired stability of sewage fee.
- Energy management aspects are crucial for the operation of WWTP. The main objective of operators is no longer “just” balance sheet energy self-sufficiency but a synchronous balance between generation and consumption or even a surplus.
- The minimization of the greenhouse gases nitrous oxide ($N_2O$) and methane ($CH_4$) emitted from WWTP - up to so-called climate neutrality - is increasingly mentioned as a further possible operational goal of WWTP operation. Legal requirements for this are not yet foreseeable at either the European or national level. With cost-efficient operation and simultaneous assurance of high effluent quality, conflicts of objectives in energy-intensive and GHG-emitting process stages such as primary clarification (sludge storage times) and aeration (aeration times, DN efficiency) may well intensify in the future.

Economic objectives or overriding objectives can conflict with water-oriented objectives, and the objective of reducing GHG emissions can also compete with others in individual cases. In particular, if no legally objectives are to be achieved, but rather objectives that are pursued for overriding reasons, a corresponding prioritization (as well as compromise solutions) are not only debatable, but necessary. The simple possibility of changing the initial, well-established approaches and thus adjusting the system flexibly is pointed out once again. This means that a plantwide control system goes far beyond local and process-related automation solutions. The operator alone is responsible for defining the objectives and priorities; planners and authorities

[1] OLE for Process Control Unified Architecture
[2] Advanced Physical Layer
[3] DWA-German Association for the water industry, wastewater and waste

only have an advisory role. Compliance with legal requirements and the overriding demands of water protection are a prerequisite.

**Plantwide-control strategies**

**1. Nitrogen removal**

Nowadays, the control of internal recirculation during pre-denitrification by measuring the $NO_3$-N-concentration in the effluent of the anoxic zone is common practice in larger WWTPs in Germany. The advantages of a closed-loop control are the minimisation of oxygen carryover from nitrification and the maximisation of the contact time in the denitrification (DN) zone. In the case of additional dosing of external carbon sources (such as acetic acid), which is controlled depending on the nitrate concentration in the DN zone, this control loop must be properly linked to the control of the internal recirculation (carbon dosing only at maximum recirculation $Q_{R,max}$, which equals a maximum nitrate load $NO_{3,max}$). The goal of this plantwide control strategy is to increase the conversion of $NO_3$ to $N_2$ while minimising the use of external carbon sources by optimising the internal recirculation rate $Q_R$, making it a multi-objective optimization problem.
In the event of any temporary use of the treated wastewater for agricultural purposes, the discharge value of the WWTP can be adjusted in accordance with §15 of the EU Urban Wastewater Treatment Directive (UWWTD) (EU, 2024) to ensure sufficiently high nitrate loads (for fertilisation) in the process water. In this case, the regulation of the nitrogen turnover in the wastewater treatment plant becomes significantly more complex, as the effluent target value for nitrate will become dynamic.

**2. COD-harvesting**

The targeted management of the primary treatment to achieve COD-harvesting is another example of a multi-objective plantwide-control problem that should consider the following important operational goals:

- further increase of nitrogen removal regarding the increased requirements according to the EU Urban Wastewater Treatment Directive (EU, 2024),
- the consistent increase in generated energy from biogas onsite utilising primary sludge,
- the functionality of the primary treatment in case of a storm water inflow to minimise the solids and COD loads to the biological stage

The first two are conflicting objectives, as denitrification and anaerobic digestion 'compete' for the COD that is removed in the primary treatment stage, requiring a prioritization or a Pareto approach. Several control options are available whose successful implementation is made more difficult by the following boundary conditions: the fixed volume of the primary clarifiers, complex and thus expensive measurement technology (COD, TOC), unclear significance of substitute parameters (SAC), long dead times ($NO_3 - N$ measurement in the effluent or at the end of the DN zone) and different inflow conditions. A typical reference variable is then the $NO_3 - N$ concentration in the effluent of the DN zone. If an external carbon source must also be used to ensure extensive denitrification, prioritization has to be defined in terms of economic, operational and, if applicable, climate aspects ($CO_2$-emissions from the production of the external carbon source).

**3. Energy management**

When generating energy, which at WWTP primarily comes from renewable source, the future goal will increasingly be to provide sufficient energy in advance at predictable times so that the amount of energy purchased externally is as low as possible (approaching energy neutrality (EU, 2024). At the same time, however, attention has to be paid to economic viability, as the feed-in of electricity and heat is often not sufficiently considered from the perspective of WWTP operators.

The automated coupling of electricity generation from renewable energy (photovoltaics, wind power, possibly hydropower) and the WWTP's own CHP in case of onsite anaerobic stabilisation, the storage of heat and electricity based on prediction models for generation and consumption, while at the same time ensuring high-quality wastewater treatment processes, requires complex automation solutions with higher-value components. Building blocks for these complex solutions are state-of-the-art open, standardised communication protocols such as OPC UA and Ethernet-APL that allow the aggregation of process data and their meta-data in centralized data platforms that check for data plausibility automatically and preprocess data for the use in AI-services. Those are needed to accurately predict energy generation and consumption in electricity accounting grids as these predictions are a prerequisite for a complex electricity balancing optimization. Due to the high number of electricity sources and sinks, evolutionary optimization algorithms (i.e. genetic and swarm-based algorithms) are well suited to solve these high-dimensional, non-linear optimization problems to decide how much electricity is produced at which point in time and whether it is for own use or supplied to the grid. When it comes to WWTP operation, demand can only be regulated to a limited extent by process units with a high electricity consumption that can be controlled (such as aeration and dewatering). Loads that follow seasonal, weekday or daily patterns can be determined comparatively easily. In any case, there are many, diverse influencing variables that can only be calculated with sufficient accuracy in advance by using model-predictive controllers that require simulation- or AI-based process models (digital twins).

## Conclusion

In conclusion, the implementation of plantwide-control strategies in WWTP presents a promising yet complex opportunity to enhance process efficiency and meet stringent regulatory requirements. Despite the historical challenges and the multifaceted nature of these systems, recent advancements in communication protocols and AI-supported control systems are paving the way for more integrated and effective solutions. The ongoing efforts by the DWA working group to develop and present various operating strategies, from nitrogen removal and COD harvesting to energy management, highlight the potential benefits of adopting a holistic approach for WWTP operation.

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