WOOSU: Waste Water Treatment Optimal Operation and Symbiotic Upgrade

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***Abstract*—Wastewater Treatment Plants (WWTPs) are crucial for addressing water scarcity, but presents high energy consumption and also accounts for up to 6% of global water sector greenhouse gas (GHG) emissions. Current optimization approaches lack a holistic sustainability perspective, ignoring resource recovery and industrial symbiosis. To address these gaps, this work introduces the WOOSU project, which proposes a new paradigm shift by transforming WWTPs into circular economy resource recovery facilities. The project utilizes a framework that implements an edge-cloud microservices architecture, virtual sensors, and online Life Cycle Assessment (LCA) metrics. This proposed approach intends to achieve a $\geq$ 20% increase in operational eco-efficiency and a $\geq$ 20% reduction in GHG emissions.**

***Index Terms*—Wastewater treatment, industrial symbiosis, virtual sensors, circular economy, optimization.**

I. Introduction

Climate change and population growth, which reached 8 billion in 2022, aggravates water scarcity, while consumption is projected to rise 20 - 30% by 2050 [1], [2]. Sustainable Wastewater Treatment Plants (WWTPs) are vital to address water scarcity and achieve United Nation's 6th Sustainable Development Goals (UN-SDG). However, WWTPs are complex, non-linear systems highly affected by external factors, such as rainfalls, storms and droughts. Current operations achieve high-quality treated water at the expense of high energy consumption and chemical use. Furthermore, WWTPs account for 5% - 6% of global greenhouse gas (GHG) emissions from the water sector, and 3% - 5% of energy use [3]. Therefore, this highlights that optimizing operational efficiency while aiming for carbon neutrality is an urgent priority.

In the literature, several scientific studies proposed computational methodologies to optimize WWTPs via different approaches. However, they lack a holistic approach to sustainability, ignoring industrial symbiosis. The same happens with commercial tools, whose focus is exclusively on operational control without incorporating broader sustainability concepts. Therefore, the analysis on current studies shows gaps: lack of multi-objective perspectives within contextual systems, failure to integrate CO_2/CH_4 neutrality with the three sustainability pillars and circular economy concepts. Although digital twins are promising for optimization, difficulties still persist with respect to synchronous data access [4].

To bridge these gaps, the WOOSU project introduces a new paradigm shift, transforming WWTPs into resource recovery facilities within a circular economy, increasing sustainability. Assisted by Artificial Intelligence (AI) and systems engineering, WOOSU optimizes intra, inter, and cross-sector industrial symbiosis to reuse previously unwanted waste compounds. Using digital representation and Life Cycle Assessment metrics, it provides an overall better WWTP performance.

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II. Strategic Objectives

This project is guided by strategic objectives that provide a holistic solution for operational optimization, digitalization, and CO_2/CH_4 neutrality in WWTPs. They are briefly described in Table I.

TABLE I
Strategic Objectives.

ID	Focus Area	Goals
SO1	Advanced Monitoring	Edge-cloud microservices, virtual sensors, non-intrusive load tracking.
SO2	Modeling	Fusing differential first-principle equations with data-driven learning methods.
SO3	Industrial Symbiosis	Modular water, energy, and material framework for systemic regional circularity.
SO4	Multimodal Evaluation	Real-time, online assessment of multi-regime sustainability KPIs.
SO5	Advanced Control	Interpretable degradation models, real-time setpoint optimization, dashboards.
SO6	Test & Validation	Pilot validation to reach $\geq 20\%$ eco-efficiency, $\geq$ 10% energy save, $\geq$ 20% GHG cut (CO_2, CH_4), $\geq 20\%$ fewer errors.

III. Workplan Structure

The implementation of the WOOSU project aims to develop an innovative solution for the digitalization, monitoring, control and optimization of WWTPs, which will reduce energy and chemical consumption, while increasing sustainability through GHG emissions mitigation, being structured in a sequence of activities and deliverables.

A. Case Study

A core activity of the project is with respect to the integration and validation stage of the WOOSU framework in a real-world pilot WWTP operated by AGR, namely Nelas III. The WWTP of Nelas III is located in the municipality of Nelas, in Portugal, with a total area of 15,065 $[m^2]$ and is responsible for collecting, draining and purifying the effluent. It has an operational regime of 365 days and treats around 1,756 $[m^3/d]$ of wastewater, which corresponds to approximately 14,633 population equivalent [5]. An aerial view of the Nelas III WWTP can be seen in Figure 1. A more detailed description of its operation and structure will be presented below.

The treatment process consists of a single line of wastewater treatment. It is based on a secondary treatment using activated sludge in an extended aeration regime, with a biological reactor with nitrogen and phosphorus removal with a carousel oxidation ditch configuration, including UV disinfection and sand filtration. The effluent can be discharged at the ribeiro de Travassos, which flows in the Mondego river. Part of the treated water can be destined for reuse. The excess sludge which comes from the biological reactor and physico-chemical treatments are subjected to a thickening process, which is then followed by dewatering in a centrifuge.

Fig. 1. Aerial view of the Nelas III WWTP, located in the municipality of Nelas.

IV. Consortium Structure

The WOOSU project brings together a consortium composed of two industrial companies (ONCONTROL, AGR) and two R&D Institutions, namely University of Coimbra (UC) and the Institute for Systems and Computer Engineering, Technology and Science (INESC TEC). This consortium guarantees excellent collaboration between them: ONCONTROL and AGR act as technology adopters, converting research into a viable commercial product, while UC provides deep expertise in AI, control systems, and virtual sensors. INESC TEC provides experience in complex eco-efficiency and circular economy frameworks. They form a complete consortium, bringing together R&D capabilities and companies that develop technological solutions with the ability to include business entities at the critical stages of the value chain.

V. Expected Impacts

The proposed project is expected to transform WWTPs into resource recovery entities of unwanted waste, aiming at a CO_2/CH_4 neutrality. Through a holistic and multi-objective optimization approach, the WOOSU project intends to achieve a $\geq$ 20% increase in operational eco-efficiency, $\geq$ 10% reduction in energy consumption and $\geq$ 20% decrease in GHG emissions. The inclusion of circular economy and sustainability elements in this project enables WWTP-management that reduces resource waste and maximizes the reuse of treated water, nutrients included in biofertilizers, and biogas.

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