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Adapting WWTP performance to seasonality and climate change: Temperature-driven strategies for enhanced nitrogen removal

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ABSTRACT

A Temperature Driven Control Strategy that combines modifications on DO set-point, external carbon dosage and Solids Retention Time (SRT) is proposed to address the effect of seasonal and abnormal variations of temperature in the operation of Wastewater Treatment Plants. The medium-sized municipal WWTP, represented by Benchmark Simulation Model No. 2 (BSM2) that includes a Nitrogen Removal Activated Sludge Process (N-Removal ASP) with Dissolved Oxygen (DO) control has been selected as reference plant. The objective is to formulate a control strategy that improves the efficiency of the N-Removal ASP despite seasonal and unexpected variations of temperature of the influent, considering the trade-offs between temperature effects and control action effects on dynamic behavior. Simulations were carried out to evaluate the temperature and control actions effects on global average and dynamic behavior over a 30 days operation window, considering the BSM2 range from 10°C to 20 °C. A comprehensive analysis is carried out to look for potential solutions to improve performance at different temperature scenarios through the proper adjustment of DO set-points, carbon addition and sludge retention time (SRT). At low temperatures, the control actions are selected to improve N-Removal balance, since nitrification and denitrification rates are slowed producing violations of effluent quality limits in the presence of strong disturbances in influent flowrate. At high temperatures operational goals are to reduce the electricity consumption and the use of chemicals (external carbon), maintaining satisfactory performance. The Temperature Driven Control Strategy with different settings was tested considering a one year operating period. The proposed strategy address satisfactorily the seasonal and unexpected changes of temperature modelled by the annual BSM2 influent profile, attaining an appropriated trade-off between effluent quality and electricity consumption. The violations of required total Nitrogen limits are reduced up to 50 % in frequency and 33 % in length, while violations of required ammonium limits are reduced up to 36 % in frequency and 40 % in length. Annual average ammonium levels are reduced up to 19 % and annual average total Nitrogen is reduced up to 11 %. All these improvements are attained together with a slight decrease on electricity consumption. The proposed strategy is evaluated in a simulation platform, but it can be the starting point for the formulation of temperature driven advanced control strategies able to face climate change effects in the operation of for full-scale WWTPs.

1. Introduction

The water treatment sector plays a fundamental role in the attainment of the objectives of the Sustainable Development Strategy (2030 Agenda). Wastewater treatment plants (WWTPs) are essential to address water scarcity and to improve water quality by reducing the pollution and hazardous compounds from of influent wastewater before it is discharged back into the environment. Moreover, in the sustainability context, the conception of the WWTPs as "end of pipe solutions" has changed, since wastewater is considered a source of energy and materials (Ganora et al., 2019; Guerra-Rodríguez et al., 2020), which motivates its incorporation into the Circular Economy framework as Water Resource Recovery facilities (WRRFs), considering the maximization of resources and energy recovery (Maktabifard et al., 2018). However, the transformation of WWTPs into WRRFs requires significant economic investment, to upgrade existing facilities and innovative technologies, that are still scarce, to recover resources from wastewater (Palatsi et al., 2021; Ruano et al., 2024). In these circumstances, the implementation of

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optimal operation strategies is a solution for the fulfillment of the strict standards imposed by the Sustainable Development Strategy in the transition from existing WWTPs to adapted WRRFs.

The implementation of efficient control systems is a cost saving strategy to achieve the sustainable operation of the WWTPs addressing effluent quality, energetic efficiency and Greenhouse Gases (GHG) emissions (Zaborowska et al., 2021; Palatsi et al., 2021; Ruano et al., 2024). Nevertheless, the design and implementation of adequate control strategies involve several difficulties due to the complexity of the biological and physicochemical processes that take place in the wastewater treatment, the interactions between the different processes of the plant, the trade-off between different aspects of the operation and the sensitivity to external disturbances associated with variations of the influent characteristics (Revollar et al., 2020a, 2020b, 2021).

The efficiency of WWTPs operation is affected by human activities and the climate conditions given by precipitations and temperature. The influent of the WWTPs displays a diurnal pattern of pollutants load and flow variations linked to daily human activities, but also exhibits weekly and seasonal fluctuations associated with households and industrial discharges. The influent is also affected by temperature variation and precipitation levels, that depends on the seasons and regional climate conditions. The temperature of the influent wastewater can vary widely, typically falling within the range of local ambient temperatures (approximately 6–27ºC), depending also on the specific characteristics of the wastewater sources. The biochemical processes within the WWTP are temperature-sensitive (Zhou et al., 2018; Arnell et al., 2021), then wastewater temperature plays a pivotal role in the effectiveness of biological treatment. On the other hand, precipitations affect the influent flow rate and pollutants concentration.

Recent works have focused on the impact of seasonality of human activities and climate change on WWTPs performance (Lawrence et al., 2024; Ranieri et al., 2024). Climate change, primarily induced by human activities, is a significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years (Hegerl et al., 2007). The impacts of climate change are global in scope and unprecedented in scale, affecting weather patterns and increasing the frequency and intensity of extreme weather events. This results in more intense storms, longer periods of drought and extreme environmental events, such as heat waves and floods. Specifically, Spain has experienced a severe, prolonged drought at the start of the 2020 s and floods in the present year. Over the preceding three years, the country saw a significant decrease in rainfall and a rise in temperatures, which had far-reaching effects on agriculture, water supply, and energy production, underscoring the urgent need for effective water management strategies and climate change mitigation efforts (Toreti et al., 2024). Regarding water management systems, the atypical temperature and precipitations patterns produced by climate change affect the biological processes and the energy balance of WWTPs, which can result in environmental and public health risk (Lawrence et al., 2024).

In practice, the operational parameters of the plant are adjusted according to the operator's knowledge to deal with the expected disturbances produced by seasonal variations of the influent and the variations of the influent load and flowrate associated with meteorological events and population activities. These disturbances have been already considered in the design of the plant infrastructure, automation and operation strategies. Thus, it is possible to find several works focused on the control of WWTPs under varying influent conditions using classical and advanced control strategies applied to WWTPs dynamic simulators (Santín et al., 2016, 2022; Vega et al., 2014; Revollar et al., 2020b; Revollar et al., 2021) and to full-scale plants (Palatsi et al., 2021; Ruano et al., 2024). In some works, as Santín et al. (2022) and Revollar et al. (2020a), (2020b), (2021) the negative effect of temperature on the performance of Dissolve Oxygen control strategies has been identified (Revollar et al., 2023a, 2023b).

The main control drivers considered for biological treatment regulation in municipal WWTPs are the DO set-point to reject disturbances in flowrate and load, carbon addition to improve elimination of nitrogenated compounds and solids retention time (SRT) to address seasonal variations of temperature, and the main objectives of the operation and control strategies are to improve environmental performance, reducing emissions to water, and increase energetic efficiency (Hreiz et al., 2015; Palatsi et al., 2021; Ruano et al., 2024).

Nevertheless, climate change varies these conditions, then increased rainfall can lead to higher volumes of wastewater, elevating the energy demand for aeration and pumping, and overwhelming the capacity of the treatment plant. Prolonged periods of drought affect the composition of the influent and the balance between biomass and substrate in the biological processes and produce odor problems. The increase of temperature affects negatively the oxygen solubility and the microbial consortium in the aerobic biological treatments (Ranieri et al., 2024; Lawrence et al., 2024) and the increased rates of nitrification may require adjusted process controls to manage the associated oxygen demand, which increases significantly at higher temperatures.

In the search of adequate control strategies to meet the strict environmental regulations with the minimum consumption of resources, this work studies the effect of control actions on plant performance at different temperature scenarios under variable load and influent conditions. The different temperature scenarios could be associated with expected seasonal variations or with abnormal variations due to climate change. The main objective is the formulation of a Temperature Driven Control Strategy able to adapt the operation variables to seasonal variations of temperature and abnormal variations associated with climate change. Thus, this work contributes to the development of improved operational strategies to ensure adequate wastewater treatment and energetic efficiency in the face of variable weather conditions caused by climate change.

In the current context, where climate change affects influent conditions and stricter regulations are imposed on effluent quality, the development of control strategies that explicitly take into account temperature effects, including even long-term actions as SRT regulation and control actions to reject fast disturbances is necessary.

The study presented here focuses on WWTPs that employ the Nitrogen Removal Activated Sludge Process (N-Removal ASP) with Dissolved Oxygen (DO) control and external carbon source (chemicals addition) in the anoxic zone to facilitate denitrification, described by BSM2 platform. These processes are commonly implemented in medium-sized municipal WWTPs in Europe and the evaluated temperature range is representative of the wastewater temperature variations observed throughout the year in a European country. In a previous step, for the formulation of the Temperature Driven Control Strategy, performance and treatment efficiency indicators are evaluated to determine the temperature effects on the main operational variables, considering the dynamic response to influent variations at different temperature conditions. Then, potential solutions to improve the environmental performance and reduce consumption of resources through the proper adjustment of DO set-points, carbon addition and sludge retention time (SRT) are evaluated. Even though the proposed strategy is implemented in a simulation platform, it can be the starting point for a control strategy adapted to full-scale plants, providing a framework to formulate adequate advanced control solutions considering the temperature dependency of the N-removal process.

The remainder of this paper is organized as follows. Section 2 provides a detailed description of the reference scenario, and the methodology followed for the formulation of the control strategy. Section 3, presents the results of the preliminary evaluation of temperature effects on WWTP performance and the evaluation of the Temperature Driven Control Strategy in a year of operation under variable influent conditions exhibiting seasonal and unexpected variations. Conclusions are presented in Section 4.

2. Materials and methods

This section provides a description of the Benchmark Simulation Model 2 (BSM2) platform, which represents a municipal wastewater treatment plant (WWTP). It details the configuration and mathematical modeling of the plant, including the default control strategy applied in BSM2 and variation of default strategy described in Gernaey et al. (2014). These strategies are based on the regulation of dissolved oxygen (DO), sludge age (SA) and carbon dosage to enhance treatment efficiency. Relevant considerations associated with real plant operational aspects and temperature dependencies are also introduced in the BSM2 plant description. Then, the methodology followed to develop the control strategy tailored to address seasonal variations and unexpected variations of temperature, ensuring a balanced approach to treatment and energy efficiency is presented. Special attention is devoted to the description of the performance indicators to evaluate emissions to water, energy consumption and treatment efficiency, emphasizing the relationship between influent variability and plant performance.

2.1. Description of process represented by BSM2 platform including insights on temperature effect on process variables

The Benchmark Simulation Model 2 (BSM2) is selected to characterize a conventional urban wastewater treatment plant located in the Northern Hemisphere (Alex et al., 2021). This benchmark simulation model has been designed by IWA Task Group on Benchmarking of Control Strategies for Wastewater treatment Plants (WWTPs). It is the result of the combination of different sub-models used to represent the water line and the sludge line of a Municipal Wastewater Treatment Plant. These mathematical models are internationally accepted and well established (Gernaey et al., 2014): Activated Sludge Model 1-ASM1 (Henze et al., 2006) represents the N-Removal ASP, (Otterpohl and Freund, 1992) model is used for primary clarifier, Takács et al. (1991) model describes the secondary clarifier and Anaerobic Digestion Model 1 (Batstone et al., 2002) represent the anaerobic digestion. An influent generation tool (Gernaey et al., 2009) based on a combination of sub-models represents the typical annual phenomena observed in the influent of a full-scale WWTP. The BSM2 platform was conceived as a standard platform to evaluate plant-wide control strategies through realistic/dynamic computer simulations (Gernaey et al., 2014), however, it is an approximate modelling tool that cannot represent all the characteristics of a real plant. The operation and control strategies tested in the platform cannot be directly applied in a real plant, but they can provide relevant insights based on the approximated behavior and can be a starting point for the design of strategies adapted to real plants considering real instrumentation.

The plant represented by BMS2 platform is composed of a primary settler and a nitrogen removal activated sludge process (N-Removal ASP) for water line. The sludge line includes thickening, anaerobic digestion with biogas production, and dewatering units, together with a storage tank. The plant layout is shown in Fig. 1, the plant dimensions and relevant data are presented in Appendix 1, Table A.1.

Focusing on the N-Removal ASP, the elimination of nitrogenated compounds takes place through nitrification and denitrification processes. During the nitrification process, the microbial biomass transforms ammonium (S_{NH}) to nitrates (S_{NO}) under aerobic conditions (aerobic reactors). In the denitrification process the nitrates are reduced to nitrogen gas (N_2) under anoxic conditions (anoxic reactors).

Temperature significantly impacts the kinetics of biochemical reactions, microbial activity, oxygen transfer during aeration, and heating requirements for anaerobic digestion, as well as physical water properties like viscosity and density, which influence treatment efficiency (Gernaey et al., 2014; Alisawi, 2020). Higher temperatures increase microbial activity and growth rates, improving treatment efficiency, while lower temperatures lead to challenges such as reduced biomass and diminished nitrification and denitrification rates. Nitrification and denitrification are particularly sensitive to temperature. Low temperatures below 10ºC adversely affect these processes, while the optimal range for biological wastewater treatment lies between 20ºC and 35ºC. The rate of growth of nitrifying bacteria increases considerably with temperature over the range of 8ºC to 30 ºC (Gerardi, 2002). At temperatures below 15ºC, nitrification rates decline and cessation is observed at 5ºC (Gerardi, 2002; Zhou et al., 2018). Denitrification is similarly affected, with a 55 % decrease in rate when temperatures drop from 15ºC to 3ºC. These declines are attributed to reduced microbial activity and slower reaction kinetics, impacting nitrogen removal efficiency.

The biological processes and temperature dependencies are adequately represented by the ASM1 (Henze et al., 1987) that represents this process in BSM2 plant. The ASM1 takes into account 13 state variables and 8 biological processes. ASM1 explicitly assumes that all nitrogen is accounted for within the system through mass balance

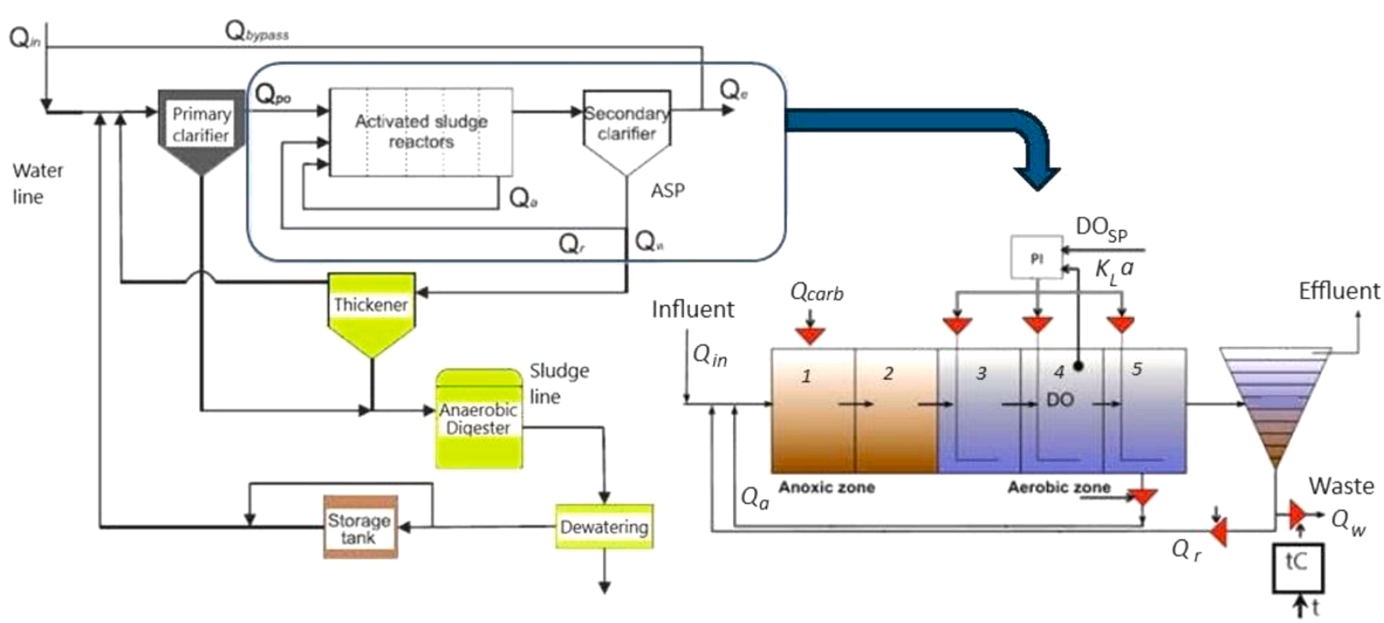

Fig. 1. Benchmark Simulation Model 2 (BSM2) layout and detail of Activated Sludge Process (ASP) based water line.

dynamics (Henze et al., 2006), including the processes of ammonification, nitrification, denitrification, and potential formation of nitrogen gases (e.g., N_2 and N_2O). Generally, in the ASP the kinetic parameters are sensitive to temperature variations, while stoichiometry remains unaffected by temperature changes (Vanrolleghem et al., 2009). A modified Arrhenius equation in the BSM2 to represent temperature dependency of the rate coefficients of growth, decay, and hydrolysis for both heterotrophs and autotrophs (Vanrolleghem et al., 2009; Gernaey et al., 2014). A comprehensive description of parameters, biochemical reactions, and dynamic equations of the ASM1 model, which is utilized to represent the N-Removal ASP in BSM2, can be found in Alex et al., (2021). This includes pertinent processes and reactions associated with Nitrogen removal, the variables considered in ASM1 and their influence in process rates are presented in Appendix 1, Tables A.2 and A.3.

Regarding the system structure, in the BSM2 plant, the N-Removal ASP occurs in a sequence of five perfectly mixed bioreactors (Fig. 1). The first two reactors are anoxic but perfectly mixed, while the subsequent three reactors constitute the aerobic zone. In these aerobic reactors, the aeration system maintains the DO concentration required for nitrification. The internal recirculation (Q_a) transfer the nitrates produced in the aerobic zone to the anoxic one for denitrification. The output of the reactor system flows to the secondary clarifier where treated water (Q_e) is separated from the sludge (Gernaey et al., 2014). The external recirculation (Q_r) and the waste flow (Q_w) are used to regulate two relevant parameters for the operation of the ASP. The external recirculation (Q_r) regulates the Food to Mass ratio (F/M), that measures the relation between the pollution to be removed and the number of microorganisms available in the system. The waste flow (Q_w) regulates the Sludge Age (SA) or Sludge Retention Time (SRT) that is a measure of the length of time that biomass remains in the reactor system. Then, most of the sludge is recycled back to the first reactor through Q_r to maintain an adequate F/M and a small amount of sludge is withdrawn from the ASP to keep a suitable SA.

In the sludge line, the sludge in excess Q_w is thickened and combined with primary settler underflow (Q_{PO}) to be treated at the Anaerobic Digestion (AD) unit reducing the amount of sludge for disposal. The sludge is stabilized while part of the organic matter is transformed into biogas. In BSM2 plant, biogas is used to increase the temperature of the sludge fed to the digester and to produce electricity. Biogas is composed of methane (CH_4), carbon dioxide (CO_2) and hydrogen (H_2). The gas line, that includes the equipment for biogas conditioning, it is not considered in the BSM2 plant.

2.1.1. Influent characteristics and BSM2 representation of influent variations

In real WWTPs variations in the influent act as disturbances, particularly affecting the processes in the water line. From a holistic plant-wide perspective, the propagation of these disturbances through the various units of the water and sludge line can significantly impact the overall performance of the plant. Specifically, the wastewater temperature typically ranges between 6ºC and 27ºC, influenced by local climate conditions, seasonal variations, and diurnal changes caused by domestic and industrial discharges (Arnell et al., 2021). Seasonal changes produce gradual temperature shifts, while diurnal variations can cause more abrupt changes. Wastewater temperature throughout the plant is further affected by factors like solar radiation, wind, and heat exchange between process streams.

The BSM2 plant represents facilities located in the Northern Hemisphere, where the warmer season occurs from April to September, while the colder season corresponds to the period between October and March. It is designed to represent a year of operation starting on July 1st. The BSM2 dynamic influent model represents typical phenomena observed in a year of operation as seasonal variations of temperature and precipitations, and variations of flowrate and load associated with domestic and industrial discharges (Gernaey et al., 2009, 2014).

Specifically, the influent model represents (Vanrolleghem et al., 2009; Gernaey et al., 2014):

- Diurnal variations of load and influent flowrate associated with population activities, distinguishing normal weekdays from weekends and holidays. The plant receives mixed domestic and industrial wastewater, then flowrate and pollutants decrease during weekends and holidays.
- Rainy and dry season effects observed in full-scale WWTPs, as increased infiltration in the rainy periods and "first flush" and dilution phenomena during rains and storms.
- Annual variations of temperature ranging between 10ºC and 20ºC, with an average of 15ºC. The variation is modeled using a sinusoidal function with an average value of 15ºC, an amplitude of 5ºC and a period of 364 days.
- Daily variations of temperature are also represented as a sinusoidal function with an amplitude of 0.5ºC.

2.1.2. BSM2 default control strategy including insights on real WWTP control

The control problem focuses on the regulation of N-Removal ASP variables that directly affect effluent characteristics. The BSM2 plant employs a default control strategy that includes a Dissolved Oxygen (DO) control in the 4th reactor (aerobic zone), a timer control of the waste flow (Q_w) to regulate the sludge age (SA) or Solids Retention Time (SRT) and an external carbon source (Q_{carb}) added at a fixed flow rate to the anoxic zone (Gernaey et al., 2014; Santín et al., 2016). The default BSM2 control strategy is included in the ASP layout presented in Fig. 1, and the default control system parameters are shown in Appendix 1, Table A.4.

As BSM2 platform is designed to test control strategies, several control handles are available for N-Removal ASP. Some of the available control actions are commonly applied in real practice such as DO regulation in the aerobic zone, Q_w adjustment to modify SRT, external carbon dosage, regulation of internal recirculation (Q_a) and external recirculation (Q_r). This work focuses on DO control, SRT regulation and external carbon dosage. All these actions are interdepended, but they are also related to wastewater temperature effects as detailed below.

2.1.2.1. DO control. DO control in the aerobic zone ensures the availability of oxygen for the nitrification process. Aeration control is used to attain the desired DO set-point. Diffused aeration systems are commonly used for oxygen transfer in aerobic reactors at municipal Wastewater Treatment Plants (Reifsnyder et al., 2020). A blower system is used to provide the air that flows through a valve before it is diffused into the aeration basin, producing bubbles with diameters ranging from 2 to 5 mm depending on the airflow (Baquero-Rodríguez et al., 2018). In real plants, the key manipulated variable to the aeration process is the valve position (Åmand et al., 2013b).

IWA Group decided to use Oxygen Transfer Coefficient (K_La) as the manipulated variable that regulates the aeration intensity in BSM2 plant although it is not a realistic control handle. Thus, the BSM2 default DO control strategy considers an anti-windup PI controller and an ion sensitive sensor for DO monitoring to keep the DO concentration in the 4th reactor (S_{O4}) at a set-point value (DO_{SP}) of 2 g O_2/m^3 by manipulating the K_La of the aerobic reactors: K_La_3, K_La_4 and K_La_5 (where K_La_5 is set to half of K_La_3 and K_La_4 values) as shown in Fig. 1. The time constant of the loop is about 30 min (Ammand et al., 2013b).

K_La encompasses the effects of the airflow rate, the formation of air bubbles and the air diffusion. In the BSM2 plant a Degrémont aeration system with DP230 porous disks at an immersion depth of 4 m is considered for aeration energy estimation from the value of the oxygen transfer coefficient (K_La) (Alex et al., 2021).

The K_La depends on air flow rate, aerator immersion depth, reactor volume, and air properties among other parameters including temperature, viscosity, density, diffusivity, and surface tension that collectively determine the efficiency of oxygen transfer in the system (Vanrolleghem et al., 2009). Details about the temperature dependency of K_La in BSM2 model can be found in Varolleghem et al. (2009). These authors express that higher K_La is required to achieve a specific oxygen concentration at low temperatures, that also implies larger energy requirements compared to conditions at higher temperatures. However, in the Oxygen Transfer Rate (OTR) described by Eq. (1) the driving force for oxygen transfer in bioreactors is the difference between oxygen saturation concentration (S_O^{sat}) and dissolved oxygen concentration (S_O). S_O^{sat} increases as temperature decreases while K_La increases with temperature, consequently, temperature produces opposite effects on the variables that determine the Oxygen Transfer Rate.

$$OTR = K_La \bullet \left(S_O^{sat} - S_O\right) \tag{1}$$

Regarding the selection of the DO set-point, this value is given by the operator with values usually ranging between 1 and 2 g/m^3(Åmand et al., 2013b; Åmand et al., 2013a). Oxygen consumption depends on the wastewater load and the effect of temperature. During the periods of lower load and higher temperature it is possible to attain the desired ammonium removal efficiency with lower DO levels. However, low DO concentrations are linked with larger emissions of nitrous oxide and sludge settleability problems, then a lower limit of DO set-point of 1.5 g/m^3 is considered in some cases (Åmand et al., 2013b). On the other hand, higher DO concentrations could be necessary to compensate the loss on nitrification rate at low temperatures. However, when elevated DO concentrations are applied in aerobic zone, high levels of oxygen could be transferred to the anoxic zone, and oxygen is an inhibitor of denitrification. Regarding the higher DO limit, it is reported that DO concentrations above 2 g/m^3 have a minor effect on the rate of nitrification while increases energy consumption (Metcalf and Eddy Inc, 2013; Åmand et al., 2013b). However, in some works that study real plant implementation of ammonium control, DO concentrations between 3.5 and 4 g/m^3 are allowed for short periods to reject ammonium peaks, especially during winter season (Åmand et al., 2013a; Ruano et al., 2024).

2.1.2.2. SA-SRT control. Sludge Age (SA) or Solids Retention Time (SRT) controlled through sludge wasting (waste flow Q_w) is the single most important design and operating parameter affecting the performance of ASP (Metcalf and Eddy Inc, 2013; Smith et al., 2014). The SRT is the average time that any particle remains in bioreactors, that it is also the time available for microorganisms to reproduce. An SRT longer than microorganisms' regeneration time allows its proliferation, but shorter SRT produces sludge wash out. The SA or SRT is computed as the ratio between the total suspended solids in bioreactors (TSS) and the amount of solids coming out the bioreactors each day (Eq. 2).

$$SRT = \frac{\sum_{1}^{5} TSS_i \bullet V_i}{Tss_{e\bullet} Q_e + Tss_{w\bullet} Q_w} \tag{2}$$

Regarding the relation between nitrification efficiency, temperature and minimum SRT, at a temperature of 20 C, at least four days are required for nitrifiers to regenerate at a faster rate than they are wasted from the system. The minimum SRT at low temperatures (10ºC) is ten days (Smith et al., 2013), since microorganisms' activity and biochemical reactions decelerate and larger residence time in the reactor system is necessary to remove pollutants. However, long SRT can produce poor settleability of the sludge, then recommended SRT ranges between 4 and 35 days (Hreiz et al., 2015).

In BSM2 plant, the timer control of waste flow (Q_w) adjusts the SRT according to seasonal variations of temperature that affect biomass activity (Gernaey et al., 2014). In BSM2, Q_w is set to 450 m^3/d the warmer period, but in the colder period Q_w is reduced to 300 m^3/d to increase SRT (Sludge Age) in order to compensate the deterioration of microbial activity.

2.1.2.3. Carbon dosage. Denitrification requires a sufficient supply of organic matter to serve as an electron donor, otherwise, the denitrifying bacteria are unable to perform this reduction process efficiently, leading to incomplete nitrogen removal. Denitrification is often carried out after most of the organic matter in wastewater has been consumed aerobically, then an external carbon source is needed (Sanjrani et al., 2022). Low temperatures also produces a deterioration of the denitrification process, and the addition of external carbon have a positive effect on denitrification rate. Thus, the addition of an external carbon source (Q_{carb}) plays a critical role in ensuring effective denitrification by supporting microbial activity and facilitating the conversion of nitrate (S_{NO}) to nitrogen gas (N_2).

In BSM2, the external carbon source is fed to the first anoxic reactor at a constant flow rate of 2 m^3/day and COD concentration of 400,000 g/m^3 (Gernaey et al., 2014; Santín et al., 2016). This strategy provides organic matter in the form of a readily biodegradable carbon source to be used as substrate in the denitrification process.

2.1.3. Alternative control strategies proposed for BSM2 model

An alternative control strategy, named CL1, modifies the BSM2 default strategy, controlling the DO_{SP} in the 4th reactor at 2 g O_2/m^3 by manipulating K_La_3 and K_La_4, while another PI loop regulates DO in reactor 5–1 g O_2/m^3 by manipulating K_La_5 (Gernaey et al., 2014). The Sludge Age control and external carbon dosage remain as in the default strategy.

2.2. Procedure for the formulation of the temperature driven control strategy

The objective of the study is the formulation of a control strategy for the N-Removal WWTP to address seasonal and unexpected changes of temperature while faces moderated disturbances in the influent flow and load. The default control strategy implemented in BSM2 plant combines control actions commonly applied in real practice such as DO control in the aerobic zone, SRT control, external carbon dosage, regulation of internal and external recirculation. This work focuses on the first three actions, thus the proposed General Control strategy for Temperature Variation (GCTV) result from the combination of actions on DO set-point, SRT and carbon dosage.

For the formulation of the control strategy to address seasonal and abnormal variations of temperature, employing the BSM2 as reference WWTP, the next steps were followed:

1. **Definition of default control strategy, temperature scenarios and operation window**

   Default BSM2 control strategy: The default BSM2 control strategy was described in the previous subsection, but it is necessary to specify the definition to avoid ambiguousness.

   The BSM2 default control strategy consists on the combination of DO control in the 4th reactor, timer control of Q_w to regulate SRT to the warm and the cold season, and an external carbon source (Q_{carb}) added at a fixed flow rate to the anoxic zone, with fixed Q_a and Q_r (see Table A.1).

   The default conditions for BSM2 default control strategy in this work are: DO set point in the 4th reactor (DO_{SP}) set at 2 g/m^3, Qw set at 300 m^3/d (SRT is 17 days) and Q_{carb} set at 2 m^3/day.

   Temperature scenarios: BSM2 influent temperature ranges between 10ºC and 20ºC. Then:

   – The lower limit (10ºC) is the worst-case scenario.
   – The upper limit (20 ºC) is the best-case scenario.
   – The middle point (15ºC) is the reference scenario. It is assumed that acceptable performance is attained in BSM2 plant at 15ºC employing default control strategy. It can be corroborated in previous works that have used BSM2 platform (Revollar at al., 2023a, 2023b).

– Intermediate scenarios between 10ºC and 20ºC are considered for the evaluation of global performance. Variations of ± 0.2ºC are observed on each scenario, due to the sinusoidal representation of temperature variations along the day in BSM2 influent model.

Operation window: An operation period of 30 days is selected for the evaluation of dynamic and global performance, even simulations are carried out for a full year of operation at each temperature scenario. This operation window is selected from the examination of the annual influent profile of BSM2, it corresponds to the month of January, from the 226–256 simulation days.

The BSM2 influent includes seasonal variations of temperature, influent flowrate and load, but the aim of this work is to study the temperature effects. To concentrate on the effect of temperature, large variations on load and precipitations are avoided. Then, the annual influent profile was examined to identify an operation period where influent pollution load per m^3 of incoming wastewater (Q_{in}) exhibits variations close to the annual mean value that is 3.62 kg/ m^3. The influent pollution load is described by Influent Quality Index (IQI), the average influent flowrate in the selected operation period is denoted as Q_{inavJ}, so the influent pollution load per m^3 of incoming wastewater is IQI/ Q_{inavJ}.

The characteristics of the selected operation window are:

– Length = 30 days.
– Simulation period: January, between the 226–256 simulation days.
– Q_{inavJ} = 22066 m^3/d. IQI/Q_{inavj} = 3.59 kg/m^3.

2. **Evaluation of the influence of temperature on global and dynamic plant performance employing default BSM2 control strategy**.

Simulations of BSM2 plant behavior in a given operation period are carried out to observe the effect of disturbances on influent load and flowrate at different temperature scenarios.

Objective: Evaluation of global performance of the plant in the selected operation window allows to quantify the magnitude of the temperature effects on the different performance indicators. The observation of dynamic behavior allows detecting the trade-offs between temperature variations and disturbances in the influent flowrate and load.

3. **Evaluation of control actions to improve WWTP efficiency**

The following control actions are applied to observe the effect on global performance and dynamic behavior of the plant.

– Modification of Q_w to vary SRT
– Modification of DO set point in the 4th reactor (DO_{SP}).
– Modification of carbon dosage (Q_{carb}).
– Incorporate regulation of DO in the 5th reactor, that is applying CL1 alternative strategy described in the previous subsection.

Objective: Analyze the benefits, drawbacks and possible trade-offs with temperature effects of the individual control actions based on their impact on global and dynamic performance indicators. Propose individual and combined actions that improve performance at the different temperature scenarios to formulate a more elaborate temperature dependent control strategy.

The problem is divided into:

a) Find individual or combined actions to improve treatment efficiency at low temperature scenarios (below 14ºC)

b) Find solutions to take advantage of the outstanding performance at high temperature scenarios (above 16ºC).

4. **Formulation of the Temperature Driven Control Strategy to address seasonal and abnormal variations of temperature for whole range of temperature variation**

The optimal actions that improve performance according with the low temperature requirements and the high temperature opportunities are combined to obtain a Temperature Driven Control Strategy able to address seasonal variations of temperature and abnormal variations associated with climate change in long operation periods. The strategy is evaluated considering the full BSM2 influent profile for a year of operation.

2.3. *Performance assessment*

Performance indicators are evaluated in different stages for the formulation of the Temperature Driven Control Strategy. The performance assessment of N-Removal BSM2 plant involves evaluating environmental and economic performance indicators, which often conflict with each other.

The BSM2 platform provides a systematic protocol to evaluate plant performance under various operating conditions and control strategies. The evaluation period in BSM2 plant is one year of operation between, 245 and 609 simulation days, however, the evaluation tool allows shorter operation windows. In this work an operation period of 30 days is considered between 226 and 256 simulation days.

For the evaluation of the different temperature scenarios, this study modifies the correspondence between the temperature profile and the other influent variables defined in BSM2 for benchmarking purposes. However, the performance assessment method proposed in BSM2 and some of the performance indicators are considered to evaluate the efficiency of the proposed control actions at different temperature scenarios.

2.3.1. *Computing method*

The data obtained from BSM2 simulations is generated at 15 min interval along the 30 days selected operation window. This data is used to compute:

– The average values of operation variables and performance indicators in the evaluation period as a measure of global performance under disturbances presented in that operation window.

The BSM2 performance assessment method computes the average indicators based on the rectangular integrals of flow rates $\overline{Q}$ and concentrations $\overline{Z}_K$ for the evaluation of the simulation results on a given evaluation period (t_{obs}) (Gernaey et al., 2014):

$$\overline{Q}(m^3/d) = \frac{\int_{t0}^{tf} Q(t)dt}{t_{obs}} \tag{3}$$

$$\overline{Z_K}(kg/m^3) = \frac{\int_{t0}^{tf} Z_K \bullet Q(t)dt}{\int_{t0}^{tf} Q(t)dt} \tag{4}$$

– The dynamic evolution of operation variables and performance indicators to get insight into process behavior regarding the effect of influent load and flowrate variations at different temperature scenarios. Even instantaneous values are obtained with a sampling time of 15 min, for the observation of dynamic performance hourly and daily average values, computed as shown in Eqs. (3) and (4) are considered. Annual average indicators are computed for the evaluation of the final Temperature Driven Control strategy.

2.3.2. *Performance indicators*

The performance assessment provides relevant metrics to quantify influent and effluent quality, emissions to water, violations of effluent quality limits, nitrification and denitrification efficiency and operational cost index (OCI) that contemplates energy costs, external carbon addition, biogas production and sludge production.

2.3.2.1. Effluent and influent quality indicators. Effluent Quality Index, EQI (kg/d): it is a measure of the total pollution load of the plant discharge for a given operation period (i.e. one year). It includes the following measurements of pollutants in the effluent: total Nitrogen (N_{tote}), ammonium (S_{NHe}), nitrates (S_{NOe}), total Chemical Oxygen

Demand (COD_e), total Suspended Solids (TSS_e) and Biological Oxygen Demand (BOD_{5e}).

Influent Quality Index, IQI (kg/d): it is a measure of the total pollution load of the influent for a given operation period (i.e.one year). It includes N_{totin}, S_{NHin}, S_{NOin}, COD_{in}, TSS_{in} and BOD_{5in} load in the influent.

The volume of incoming wastewater (m^3) is used as a functional unit for the analysis to express some of the performance indicators relative to an average Q_{in} in the evaluation period (Q_{inavJ}), then IQI/Q_{inav} and EQI/Q_{inavJ} are also computed.

Emissions to water: it is measured in terms of the concentration of nitrogenated compounds (g/m^3) in the effluent (S_{NHe}, N_{tote}, S_{NOe}).

Violations of effluent requirements: Deviation of the levels of pollutants in the effluent from desired limits are quantified in terms of number of events, extension of time of the infringements (absolute and relative), and magnitude of the violation.

The limits of pollutants in the effluent given in the BSM2 platform, that are considered in this work are:

- Total nitrogen $N_{tot} \leq 18\ gN/m^3$
- Ammonium concentration $S_{NHe} \leq 4\ gN/m^3$
- Total Chemical Oxygen Demand (COD) CODe $\leq 100\ gCOD/m^3$

These values were arbitrarily chosen, then they are not in concordance with current effluent requirements in any known location. These limits are compared with the instantaneous values of the effluent variables generated by simulations with a 15 min interval, so they are not related to daily, monthly or yearly average considered in real regulations (Gernaey et al., 2014). The European Wastewater Directive (90/271/EC) imposes a 10 mg/L TN limit over a 12-month average. The annual average is considered for compliance purposes, however, shorter time periods, such as days or weeks, are subject to higher variability due to operational fluctuations, particularly during periods of cold temperature or transient conditions.

2.3.2.2. N-Removal efficiency indicators. Some other indicators are computed as nitrification, denitrification and ammonium removal efficiency, named N-Removal efficiency indicators. These indicators are not considered in the BSM2 evaluation protocol, but the same methodology is used to obtain their values.

NO-production: It indicates nitrification effectiveness. The amount of nitrates produced in the aerobic zone (S_{NO5}) of the ASP is computed with respect to concentration of nitrates in the second anoxic reactor (S_{NO2}):

$$NO-production = \frac{SNO_5 - SNO_2}{SNO_5} x100 \tag{5}$$

Nitrification trend with temperature is as follows (Gerardi, 2002): at 16 ºC nitrification decreases approximately 50 % respect to nitrification rate at 30 ºC, at 10ºC the nitrification rate is approximately 20 % of rate at 30ºC, and nitrification ceases below 5ºC.

NO-removal: It is an indication of the effectiveness of denitrification process. It is a measure of the amount of nitrates incoming to ASP bioreactors that are converted to N_2. $S_{NOASPin}$ represents the incoming nitrates measured after recirculation and influent mixing point (Fig. 1), while S_{NO2} is the nitrates concentration in the second anoxic reactor.

$$NO-removal(NO\ toN_2) = \frac{SNO_{ASPin} - SNO_2}{SNO_{ASPin}} x100 \tag{6}$$

NH4-removal: It is an indication of the effectiveness of the ammonium elimination in ASP. Measures the amount of ammonium that is removed from ASP reactor system, starting from $S_{NHASPin}$, that is the ammonium concentration measured after recirculation mixing point (Fig. 1). S_{NH5} is the ammonium concentration in the fifth reactor.

$$NH_4 - Removal = \frac{SNH_{ASPin} - SNH_5}{SNH_{ASPin}} x100 \tag{7}$$

2.3.2.3. Operational costs indicators. The indicators associated with operating costs, that include electricity consumption as a fundamental issue.

Operational Cost Index (OCI): it is defined in BSM2 as the weighted sum of different costs:

$$OCI = AE + PE + 3SP + 3EC - 6MET_{prod} + HE_{net} \tag{8}$$

Electricity consumption indicator: The Electricity consumption of the ASP, *E_{ASP} (kWh/d)* includes the aeration energy (AE), the pumping energy (PE) and the mixing energy (ME). Electricity consumption per m^3 of incoming wastewater in the evaluation period; E_{ASP}/Q_{inavJ} is also computed.

$$E_{ASP} = PE_{ASP} + AE + ME_{ASP} \tag{9}$$

While a brief description is presented here, and a general overview of the indicators is presented in Appendix 1, a more detailed description, including equations, can be found in the works of Jeppsson et al. (2007) and Alex et al. (2021).

3. Results

3.1. Evaluation of the influence of temperature on global and dynamic plant performance employing default BSM2 control strategy

Simulations are performed for each temperature scenario to obtain the operation variables and compute the performance indicators throughout the selected operation period (30 days between 226 and 256 simulation days) following the methods presented in the previous section. The same variation patterns of influent load and flowrate are applied for each temperature scenario and the default control strategy at default conditions is employed.

To determine a general trend regarding the temperature effect on plant operation variables and performance on each scenario, the following data is observed and analyzed:

- Average performance indicators in the selected operation window (30 days average) as a measure of global performance under the variable influent conditions (Table 1 and Fig. 2).
- Dynamic evolution of control variables and N-Removal efficiency in the selected operation window. Daily average values of relevant inputs (influent variables), outputs (control variables) and removal efficiency indicators are used to simplify the representation (simulations produce data for each 15 min). In some cases, hourly averages are presented to highlight interesting events (Fig. 3).
- Dynamic evolution of emissions to water and electricity consumption indicators in the selected operation window, also considering daily and hourly averages (Fig. 4).

Table 1 shows the performance indicators for the different temperature scenarios from 10ºC to 20ºC with an interval of 2ºC. A color code is used to illustrate the quality of performance: black is used for 15ºC, where satisfactory performance is assumed, red is used for the worst performance, green is used for the best performance, and intermediate colors are used to represent the transitions. In the last column, the metric $\frac{\Delta Index}{\Delta T}$ (ºC^{-1}) is used to quantify the effect of the temperature span variation on each performance indicator, it is computed as:

$$\frac{\Delta Index}{\Delta T} (ºC^{-1}) = \frac{Index(10ºC) - Index(20ºC)}{Index(20ºC)} \bullet \frac{1}{\Delta T},\ \Delta T = 10ºC \tag{10}$$

Table 1
Temperature effect on selected performance indicators. Average values in the selected operation period.

IQI/Q_{inavJ} (kg/m^3): 3.59 kg/m^3	10°C	12°C	14°C	15°C	16°C	18°C	20°C	ΔIndex /ΔT (°C^{-1})
EQI/Q_{inavJ} (kg/m^3)	0.28	0.27	0.26	0.25	0.25	0.24	0.23	0.021
S_{NHe} (gN/m^3)	0.73	0.43	0.27	0.22	0.19	0.15	0.12	0.511
S_{NOe} (gN/m^3)	11.3	11.0	10.5	10.3	10.0	9.44	9.00	0.025
N_{tote} (gN/m^3)	14.0	13.4	12.8	12.5	12.1	11.6	11.1	0.027
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.23	0.24	0.24	0.24	0.25	0.25	0.25	−0.008
(S_{NO5}-S_{NO2})/S_{NO5}%	62.6	64.5	67.2	68.8	70.4	73.7	76.8	−1.42
(S_{NORin}-S_{NO2})/S_{NORin} %	53.3	55.6	59.0	61.0	62.8	67.1	70.9	−1.75
(S_{NHRin}-S_{NH5})/S_{NHRin} %	91.3	94.7	96.6	97.1	97.5	98.1	98.4	−0.67
N_{tote} violation (% operation time)	0.10	0	0	0	0	0	0	
N_{tote} violation (events)	1.00	0	0	0	0	0	0	
N_{tote} violation (time d)	0.03	0	0	0	0	0	0	
S_{NHe} violation (% operation time)	0.87	0.31	0	0	0	0	0	
S_{NHe} violation (events)	2.00	1	0	0	0	0	0	
S_{NHe} violation (time d)	0.26	0.09	0	0	0	0	0	
COD_e violation (% operation time)	0	0	0	0	0	0	0	

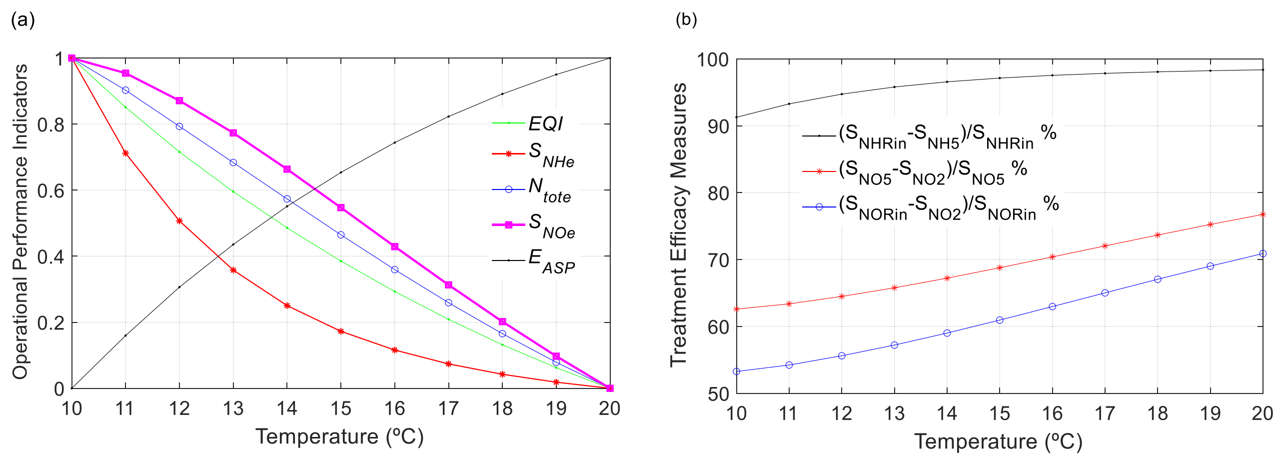

Fig. 2. Operational performance indicators (normalized values) and N-Removal efficiency measures trend with temperature.

$$\frac{\Delta \text{Index}}{\Delta \text{T}}\left(^{\circ}\text{C}^{-1}\right) = \frac{\text{Index}(10^{\circ}\text{C}) - \text{Index}(20^{\circ}\text{C})}{\Delta \text{T}} \text{for treatment efficiency metrics}$$

Positive values of $\frac{\Delta Index}{\Delta T}$ (°C^{-1}) indicates deterioration of performance with temperature descend for EQI/Q_{inavj}, S_{NHe}, S_{NOe}, N_{tote}. Negative values of $\frac{\Delta Index}{\Delta T}$ (°C^{-1}) indicates deterioration of performance with temperature descend in the case of N-Removal efficiency indicators NO-production, NO-removal, and NH4-removal. In the case of electricity consumption (E_{ASP}/Q_{inavj}) negative $\frac{\Delta Index}{\Delta T}$ (°C^{-1}) indicates improvement with temperature descend.

Low temperatures effects. As expected, all the performance indicators shown in Table 1, except electricity consumption per m^3 of incoming wastewater (E_{ASP}/Q_{inavj}), attain their worst value at 10°C. Among the indicators of emissions to water, the ammonium concentration (S_{NHe}) is the most affected by low temperatures changing from 0.12gN/m^3 at 20°C to 0.73gN/m^3 at 10°C. The change of S_{NHe} with temperature $\frac{\Delta Index}{\Delta T}$ is 0.511°C^{-1} while EQI/Q_{inavj}, S_{NOe}, N_{tote} exhibits a $\frac{\Delta Index}{\Delta T}$ ranging between 0.027 and 0.021°C^{-1}.

The *NO-production* and *NO-removal* indicators exhibit the larger variation for the studied temperature span with $\frac{\Delta Index}{\Delta T}$ of 1.42°C^{-1} and 1.75 °C^{-1}, respectively. The temperature effect on *NH4-removal* is smaller with a $\frac{\Delta Index}{\Delta T}$ = 0.67°C^{-1}, but produces a deterioration close to 8 % on ammonium removal efficiency. The severe deterioration of *NO-production* and *NO-removal* indicators reported for low temperatures reflects the decrease of nitrification and denitrification rates. This is a relevant operational problem to be addressed by control strategies since the actions to improve nitrification produce an increase of nitrates levels (S_{NO}) that could not be effectively eliminated by denitrification, since it is also slowed by low temperatures. This situation could increase the levels of total Nitrogen in the effluent (N_{tote}), producing violations of the N_{tote} limits.

Table 1 shows that violation of total Nitrogen limits (N_{tote} violation) occurs at 10°C for a brief period of time, while short violations of ammonium levels in the effluent (S_{NHe} violation) occurs at 10°C and 12°C. These negative events are a consequence of the deterioration of the N-Removal processes low temperatures, reducing the ability of the system to reject influent disturbances.

High temperature effects. Except for E_{ASP}/Q_{inavj} indicator, a outstanding performance above 16°C is observed in all indicators of performance shown in Table 1, attaining the best values at 20°C. The electricity consumption per m^3 of incoming wastewater (E_{ASP}/Q_{inavj}), is the only performance indicator affected favorably by temperature

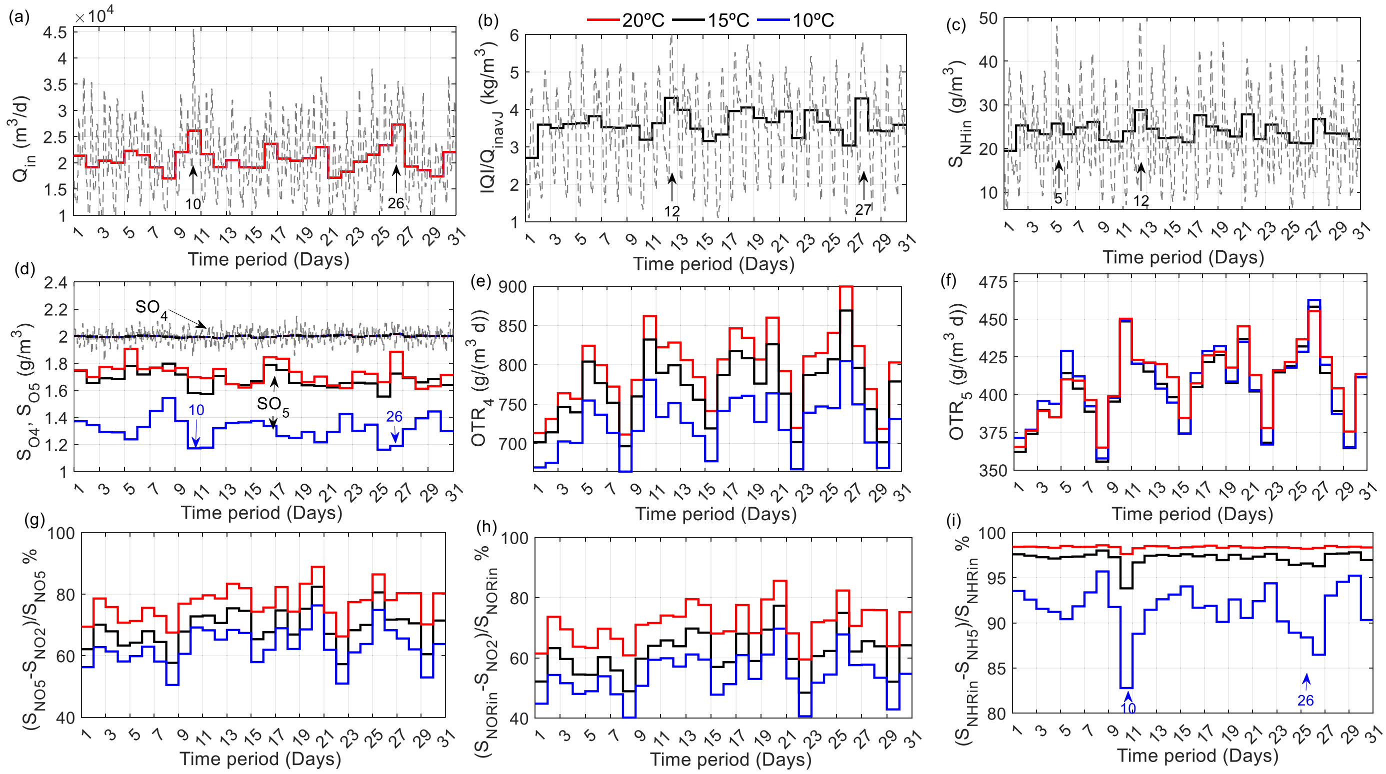

Fig. 3. Impact of dynamic variation of inputs on control variables and N-Removal efficiency indicators at different temperature scenarios. Controlled variable: S_{O4}.

descend, but this effect is also the less significant with a $\frac{\Delta Index}{\Delta T}$= -0.008ºC^{-1}.

Fig. 2 presents the variation of the indicators with respect to temperature. The indicators EQI/Q_{inavj}, S_{NHe}, S_{NOe}, N_{tote} and E_{ASP}/Q_{inavj} are normalized, with respect to the maximum values observed in the temperature range to facilitate visualization. The normalized indicators are denoted EQI/Q_{inavj}, S_{NHe}, S_{NOe}, N_{tote} and E_{ASP}/Q_{inavj}. Normalization was not necessary for the N-Removal efficiency indicators as they are expressed as percentages.

S_{NHe} and N-Removal efficiency indicators (*NO-production*, *NO-removal* and *NH4-removal*) exhibit changes of different magnitudes between the different temperature scenarios, these changes are larger as temperature decreases. This nonlinearity can be observed in Fig. 2 and can be also deduced from Table 1 information:

- S_{NHe} varies 0.30 gN/m^3 between 10ºC and 12ºC.
- S_{NHe} varies 0.04 gN/m^3 between 16ºC and 18 ºC.
- *NH4-removal* varies −3.4 % between 10ºC and 12ºC.
- *NH4-removal* varies −0.6 % between 16ºC and 18 ºC.

Fig. 2.a it is possible to notice the nonlinear variation of S_{NHe} with temperature: S_{NHe} decreases abruptly as temperature increases between 10ºC and 14ºC, this trend is moderated between 14ºC and 16ºC, and minor above 16ºC. A slight nonlinear tendency is observed in EQI/Q_{inavj} and S_{NOe}, while the relation N_{tote} vs T is almost linear. The indicators E_{ASP}/Q_{inavj}, exhibits an exponential increase from 10ºC to 20ºC.

Regarding N-Removal efficiency, in Fig. 2.b ammonium elimination, described by *NH4-removal* indicator, exhibits an exponential increase with temperature, starting from 91.3 % at 10ºC until saturation around 98 % above 16ºC. On the other hand, nitrates production in the aerobic zone (*NO-production*) and elimination in the anoxic zone (*NO-removal*), start from 62 % and 53 %, respectively, at 10ºC, and increase with temperature. At 14ºC the efficiency is 68 % and 60 % for *NO-production* and *NO-removal*, respectively, and change in the slope is observed. At 16ºC, efficiencies are 70 % *NO-production* and 63 % for *NO-removal*. Below 14ºC nonlinear trend is observed and efficiency changes are greater as temperature decreases, but above 14ºC minor changes are appreciated and trend approximates to linearity. This tendency can be associated with nonlinear relation between nitrification and temperature, that exhibits a larger variations below 14ºC and smaller variations at higher temperatures.

The dynamic evolution of relevant variables and performance indicators at different temperature scenarios, namely reference scenario (15ºC), worst-case scenario (10 ºC) and best-case scenario (20ºC) is presented in Figs. 3 and 4. For the observation of dynamic performance, hourly and daily average values are computed for the selected operation window. The hourly profile shows the real frequency and magnitude of the disturbances throughout the day, which makes possible to detect extraordinary events, as peaks on influent variables with strong impact on N-Removal performance.

Fig. 3 shows:

- Variation of the influent variables (Q_{in}, IQI/Q_{inavJ}, S_{NHin}).
- The system states, in this case S_{O4} and S_{O5}. SO4 is the DO concentration in the 4th reactor, that is the controlled variable.
- Oxygen Transfer Rates in reactors 4 and 5 (OTR_4 and OTR_5)

The first row of Fig. 3 shows relevant influent variations in the selected evaluation horizon. The daily and the hourly average profiles of Q_{in}, IQI/Q_{inavJ}, S_{NHin} are presented in subfigures (a), (b) and (c), respectively. The specific days when these events occur are pointed out in the subfigures. The events detected are summarized in Table 3.

The second row of Fig. 3 shows the relevant variables for DO control, for the three temperature scenarios. The DO concentration in reactors 4 and 5 (S_{O4} and S_{O5}) is presented in subfigure (d), including the hourly profile of S_{O4} at 15ºC. Daily average S_{O4} response exhibits an accurate tracking of the desired DO set-point (DO_{SP}=2 g/m^3) independently of the temperature scenario, with a neglectable effect of disturbances and peaks on influent variables. Hourly S_{O4} profile shows minor fluctuations close to the set-point due to the variable nature of the inputs.

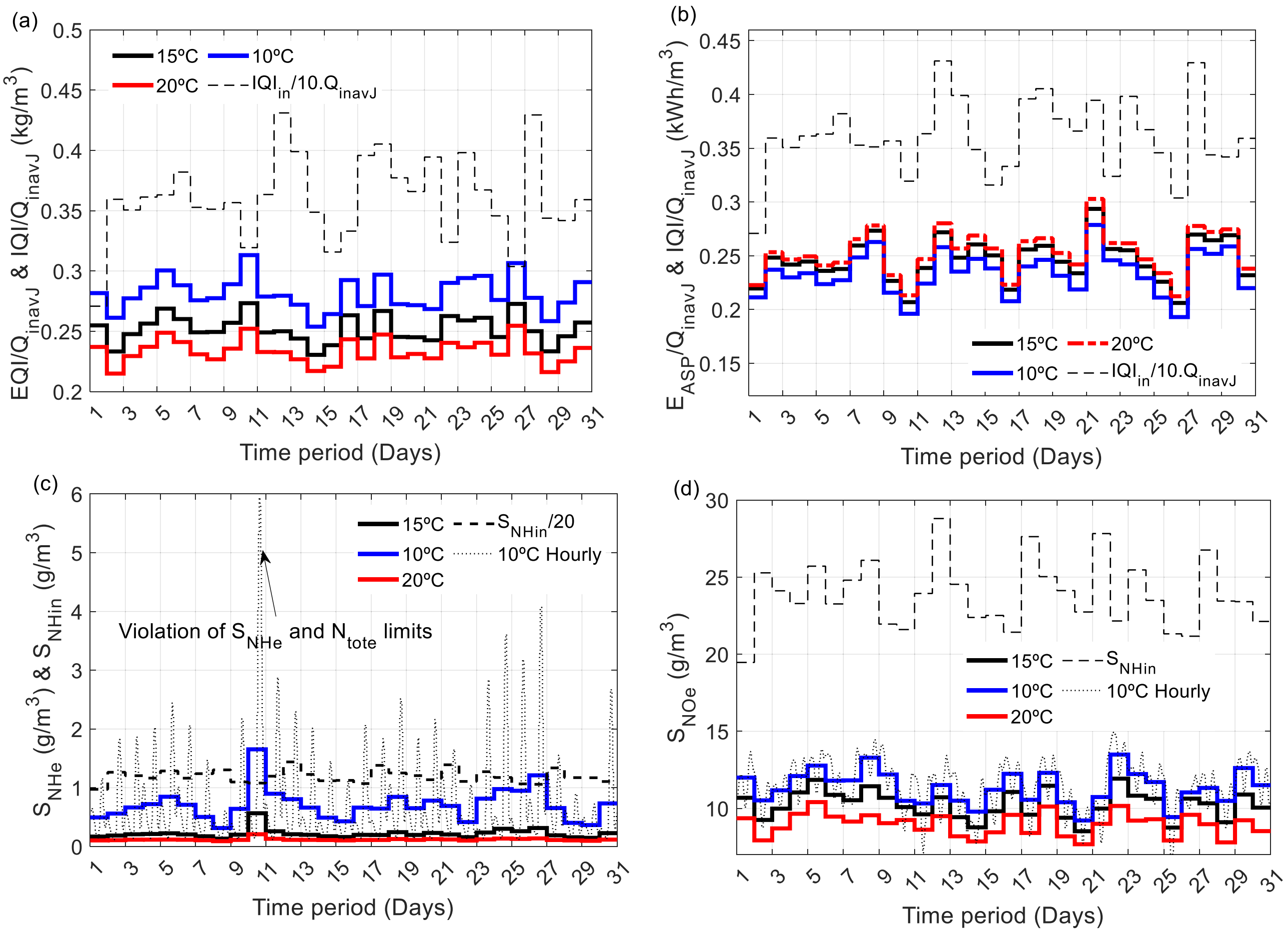

Fig. 4. Dynamic behavior of performance indicators (EQI/Qin_{avJ}, E_{ASP}/Qin_{avJ}, S_{NHe} and S_{Noe}) at different temperature scenarios compared with the levels of influent pollutants.

On the other hand, S_{O5} is not regulated to a reference value, then, at 15ºC and 20ºC scenarios daily S_{O5} profile exhibits a natural descend of 12.5 % with respect to S_{O4} (2 g/m^3), with moderate fluctuations around 1.75 g/m^3. However, at 10ºC the S_{O5} profile decreases 35 % with respect to the controlled S_{O4}, with greater fluctuations around 1.3 g/m^3 approximately. Fluctuations of S_{O5} response are noticeable as temperature decreases suggesting that the effect of influent disturbances on DO is amplified at low temperatures. Noteworthy valleys in S_{O5} coincide with the peaks of influent flowrate (Q_{in}) the days 10–11 and 25–26.

According to Vanrolleghen et al. (2009) the contradictory effects of temperature on K_La and S_{Osat}, mitigate the temperature effect on the Oxygen Transfer Rate, as discussed in Section 2. For simplicity, the Oxygen Transfer Rates in reactors 4 and 5 (OTR_4 and OTR_5) are presented as manipulated inputs instead of K_La_4 and K_La_5, that are the control handles of DO control loop of BSM2 default control strategy. The dynamic response of control variables, including the K_La_4 and K_La_5 control movements, is shown in Figure A.1.

Oxygen transfer rates in reactor 4 and reactor 5 (OTR_4 and OTR_5) are presented in the second row of Fig. 3, subfigures (e) and (f) respectively. It is interesting to observe that OTR_4 profiles attain lower values as the temperature of the scenarios decreases, even though S_{O4} attaches the same set-point value in all cases. This situation suggests that a smaller amount of oxygen is transferred at low temperatures to attain the same DO concentration ($DO_{SP} = 2$ g/m^3), resulting in lower electricity consumption for DO regulation at lower temperatures. However, in reactor 5, where S_{O5} is not enforced to a reference value, and lower DO levels are attained at 10ºC, the OTR_5 profiles approximately coincide in shape and magnitude, indicating that approximately the same amount of oxygen is being transferred at different temperatures.

In the third row of Fig. 3, the dynamic variations of the N-Removal efficiency indicators are presented. *NO-production*, *NO-removal* and *NH4-removal* indicators are presented in subfigures (g), (h) and (i), respectively. Deterioration of nitrification and denitrification at low temperatures translates into lower main values of the dynamic profiles as temperature of the scenarios decreases. Regarding the effect of disturbances, it is observed that *NO-production* and *NO-removal* exhibits similar variation patterns for the three temperature scenarios (subfigures (g) and (h)). But, in the case of *NH4-removal*, the profile at 10 ºC exhibits amplified variations with respect to the other temperature scenarios (subfigure (i)). Significative variations (valleys) are observed at 10ºC, which coincide with the peaks observed on influent flowrate (Q_{in}), days 10 and 26, being another evidence of the large effect of disturbances at low temperatures.

Another observation, regarding the results presented in Fig. 3, is that appropriate control performance at 10ºC scenario does not guarantee appropriate operation performance. DO control in the 4th reactor exhibits good tracking of DO_{SP}, with acceptable disturbance rejection, but a significant deterioration of ammonium removal efficiency (*NH4-removal* profile) is observed with a strong effect of disturbances. Then, in the formulation of the Temperature Driven Control Strategy this issue should be considered to improve performance at low temperatures.

Fig. 4 shows the dynamic behavior of the indicators of emissions to water: EQI/Q_{inavJ}, S_{NHe}, S_{NOe} and energy consumption E_{ASP}/Q_{inavJ}, compared with the corresponding influent profiles, for the different temperature scenarios. In subfigure (a) the EQI/Q_{inavJ} profiles exhibit symmetrical variation patterns, attaining higher values as the temperature of the scenarios decreases. The profile with the worst E_{ASP}/Q_{inavJ} corresponds to 10ºC scenario. The pattern of variation of EQI/Q_{inavJ} profiles differs from IQI/Q_{inavJ} pattern coinciding in some cases the valleys of IQI/Q_{inavJ} with the peaks of EQI/Q_{inavJ} (low load, poor elimination), indicating that the load of influent pollutants do not determine the removal efficiency.

In subfigure (b), daily average E_{ASP}/Q_{inavJ} profiles exhibit similar variation patterns for the three temperature scenarios, attaining higher mean values as the temperature of the scenario increases. In this case, some similarities, including simultaneous peaks and valleys, are observed between E_{ASP}/Q_{inavJ} and IQI/Q_{inavJ} profiles. This suggests that the load of influent pollutants has a significant impact on aeration requirements of ASP, that is the larger contributor to electricity consumption.

The daily average S_{NHe} profile and S_{NHin} profile are compared in subfigure (c). There are no similarities between S_{NHe} and S_{NHin} variation patterns. The strong nonlinear effect of temperature on S_{NHe} is reflected also in dynamic response, since the shape of the S_{NHe} profiles for the different temperatures are not symmetrical. Moreover, peaks and valleys of the profiles coincide in the different scenarios, but their amplitude increases as the temperature of the scenario decreases. The differences between the minimum valley and the maximum peak (days 8 and 10 respectively) using daily averages are:

- 0.11 g/m^3 at 20ºC
- 0.40 g/m^3 at 15ºC
- 1.35 g/m^3 at 10ºC

which evidences that effect of disturbances amplifies as temperature decreases. Then, the number of peaks and valleys in S_{NHe} response also increases at low temperatures. Two significant peaks are identified (days 10 and 26) at 10ºC using daily averages. The hourly average profile at 10ºC is also included to identify the cause of the violations of S_{NH} limits reported in Table 1. That is a peak on day 10 that trespasses in a large amount the required limits on S_{NHe} and coincides with a peak in Q_{in}.

In the case of S_{NOe} profiles shown in subfigure (d), the three temperatures scenarios present a similar pattern of variation. Some similarities with S_{NHin} profile are found, which is reasonable, since ammonium load is transformed to nitrates, through nitrification in the aerobic reactors. At low temperatures, the S_{NOe} profiles attain larger values although it has been observed that nitrification decreases as temperature decreases (Table 1, Fig. 3). These higher levels of S_{NOe} at low temperatures are a consequence of the accumulation of nitrates in the system due to the slower denitrification rate.

Regarding the impact of relevant events on plant behavior, Table 2 summarizes the cause-effect relationship between relevant influent disturbances and the consequences on dynamic evolution of operation variables and performance indicators.

Table 2
Relevant events observed in daily and hourly influent profiles and their consequences on performance indicators at low temperatures.

Day	Event	Consequence (at 10ºC)
5	Peak in hourly S_{NHin}	Very slight peak in hourly S_{NHe}
10	Peak in hourly Q_{in} Valleys (Dilution effects): IQI/Qin_{avJ} S_{NHin}.	Peaks: S_{NHe}, EQI/Q_{inavJ} Valleys: S_{O5}, *NH4-removal,* E_{ASP}/Q_{inavJ} Violation of S_{NHe} and N_{tote} levels
12	Peak in hourly IQI/Q_{inavJ} and S_{NHin}.	Peak in E_{ASP}/Q_{inavJ}
26	Peak in daily Q_{in} Valleys (Dilution effects): IQI/Qin_{avJ}, S_{NHin}.	Peaks: S_{NHe}, EQI/Q_{inavJ} Valleys: S_{O5}, *NH4-removal,* E_{ASP}/Q_{inavJ}
27	Peak in hourly IQI/Q_{inavJ}.	Valley in EQI/Q_{inavJ} Peak in E_{ASP}/Q_{inavJ}

3.2. *Proposing solutions to address the impact of temperature variations on performance*

Relevant considerations for the formulation of the Temperature Driven Control Strategy comes from the performance assessment of temperature effect on plant behavior carried out in the previous section. The most important issues associated with the effect of temperature on N-Removal WWTP operation are:

- An appreciable deterioration of performance indicators associated with ammonium removal below 14ºC, reaching their maximum at 10ºC.
- Strong nonlinear trend with temperature of S_{NHe} and N-Removal efficiency indicators (*NO-production* and *NO-removal*). The temperature impact on the indicators is greater as the temperature decreases.
- Negative effects of low temperature on performance noticeably below 14ºC:
  - ○ High levels of ammonium in the effluent (S_{NHe}).
  - ○ Deterioration of *NO-removal* and *NO-production* that lead to accumulation of nitrates in the system.
  - ○ Descend of DO levels in the 5th reactor.
  - ○ Peaks of S_{NHe} and valleys on S_{O5} and *NH4-removal* associated with strong disturbances in the influent flow (Q_{in}), leading to violations of the allowable limits of ammonium (S_{NHe}) and total nitrogen (N_{tote}) concentration in the effluent.
- Outstanding values of emissions to water indicators above 16ºC.
- Electricity consumption (E_{ASP}), decreases as temperature decreases, but the variation is not significant.

  Some other important observations derived from the evaluation of temperature effect on dynamic performance that are not directly considered in the formulation of the control strategy are:
- The trade-off between DO levels, OTRs and temperature in aerobic reactors
- The relation influent load and electricity consumption.

As a general comment, it is necessary to highlight that regardless of the good performance of the local DO control loop in reactor 4, the treatment objectives are not achieved in the range of low temperatures. The dynamic response shows excellent tracking of DO set-point and appropriate disturbances rejection at 10ºC, 15ºC and 20ºC (Fig. 3). However, violations of the effluent quality requirements occur at temperatures below 12ºC (Table 1), which is a meaningful operational and environmental problem.

3.2.1. *Considerations for the formulation of the temperature driven control strategy*

First, it is assumed that satisfactory performance operating under BSM2 default control strategy at default conditions is attained at 15ºC. The performance indicators for this reference scenario are average S_{NHe}= 0.22 gN/m^3, S_{NOe} = 10.3 gN/m^3, N_{tote}= 12.5 gN/m^3, ammonium removal efficiency (*NH4-removal*) 97.1 % and no violations of the required effluent quality limits.

The range of low temperatures is defined between 10ºC and 14ºC, since deterioration of performance and transitions in the nonlinear trend with temperature are appreciated below 14ºC. The range of high temperatures is between 16ºC and 20ºC. Reference scenario (15ºC) determines the limits of satisfactory performance.

The control problem is split to address different goals depending on the range of influent temperature variations to:

- Find individual or combined actions to improve treatment efficiency at low temperatures.
- Find solutions to take advantage of the outstanding performance at high temperatures

In general, the trade-off between environmental impact and electricity consumption is considered to take control decisions, however low temperature and high temperature operation goals might be different in some cases.

3.2.2. Low temperature goals

It is difficult to achieve significant improvement of treatment performance at low temperatures since kinetics of biological processes are determined by temperature. Then, the control decisions at low temperatures must attempt to minimize the S_{NHe} and N_{tote} peaks that produce violations of effluent quality limits, and then, to improve S_{NHe} and N_{tote} levels when is possible. Avoiding violations of effluent requirements is the priority in this situation, even if it implies increasing energy consumption in a short operation period. If it is possible to choose between multiple actions, the actions with lower electricity consumption are preferred.

3.2.3. High temperature goals

At high temperatures outstanding environmental performance is attained, then it is admissible to relax performance requirements to reduce the consumption of energy and chemicals, while treatment performance keeps at least as in reference scenario (15ºC).

The specific criteria to formulate the Temperature Driven Control Strategy are:

- Satisfactory performance limits are: S_{NHe}= 0.22 gN/m^3, S_{NOe} = 10.3 gN/m^3, Ntote= 12.5 gN/m^3, ammonium removal efficiency NH4-removal= 97.1 % and no violations of the required effluent quality limits. Conditions attained at 15ºC.
- Control objectives below 14ºC:
  - Minimize the peaks on S_{NHe} response to avoid violations of effluent quality limits.
  - Attain favorable conditions to N-Removal processes, balancing nitrification and denitrification processes to avoid accumulation of nitrates.
  - Ensure adequate levels of DO (S_{O4} and S_{O5}) in aerobic reactors.
- Control objectives above 16ºC:
  - Reduce electricity consumption (E_{ASP}/Q_{inavJ}).
  - Reduce consumption of chemicals (Q_{carb}).

The control actions considered in this work are:

- **Modification of Q_w to vary SRT.** Sludge age or SRT regulation is usually applied in practice to deal with seasonal variations of temperature. SRT is adjusted varying Q_w, it is set to 450 m^3/d (SRT 12.1 days) in the warmer period, and it is set to is set to 300 m^3/d (SRT 17.8 days) in the colder period in default BSM2 strategy (Table A.4). It is considered a long-term control action in BSM2 control strategy. Changes of Q_w below 300 m^3/d are proposed.
- **Modification of DO set-point in the 4th reactor (DO_{SP}).** Default BSM2 control strategy employs a fixed DO set-point to ensure the adequate DO levels in the 4th reactor to face influent disturbances. DO set-point can be modified between 1.5 and 4 g/m^3 to adjust DO levels to influent variations. The adjustment of DO set-point is a fast control action, that is selected to reject influent disturbances at low temperatures. A range of variation of DO set-point between 1.6 and 3.6 g/m^3 is considered.
- **Modification of carbon dosage (Q_{carb}).** Modification of carbon dosage (Q_{carb}) is included to promote denitrification at low temperatures. Even BSM2 control strategy employs constant Q_{carb} throughout the year, this is a fast control action that can be used to attain an adequate balance between nitrification and denitrification. Variations between 1 and 3 m^3/d are considered.
- **Incorporate regulation of DO in the 5th reactor.** A DO set-point (DO_{SP5}) between 1 and 1.5 g/m^3 in the 5th reactor is considered to deal with S_{O5} descend at low temperatures, that could produce deterioration of ammonium removal efficiency. This strategy, that combines DO control in the 4th and the 5th reactor is denoted CL1 strategy in Gernaey at al. (2014). The DO_{SP5} proposed in Gernaey et al. (2014) is below S_{O5} values attained at 10ºC with the default control strategy. Then, a variation of CL1 with DO_{SP5}= 1.5 g/m^3 is proposed here.

3.3. Evaluation of control actions to improve WWTP efficiency

First, the effect of SRT at relevant scenarios as a long-term action. Afterwards, the effect of DO set-point and Q_{carb} changes to reduce emissions to water below 14ºC, and to reduce energy and chemicals consumption above 16ºC is evaluated, considering the worst-case scenario (10ºC) and the best-case scenario respectively.

3.3.1. Modification of SRT

SRT or sludge age represents the time that wastewater remains in the system. In practice, it is increased at low temperatures to compensate the reduction of the rates of biological processes. The minimum SRT required for nitrification is 10 days at 10ºC and 4 days at 20ºC (Smith et al., 2013; Hreiz et al., 2015). Larger values, up to 35 days, are usually applied in practice to ensure the desired ammonium levels in the effluent (S_{NHe}), but increasing SRT reflects on greater energy consumption, moreover, high STRs can produce settleability problems.

The SRT has been modified adjusting Q_w to observe its effect on N-Removal performance and electricity consumption at the different temperature scenarios. Results are presented in Table 3:

- At low temperatures (10ºC, 12ºC) Q_w is varied between 300 m^3/d and 250 m^3/d. It is observed that reducing Q_w, avoids the violation of N_{tote} limits and improves the emissions to water and treatment efficiency indicators. Violations of S_{NHe} limits are avoided at 12ºC, but they remain at 10ºC, even for the maximum SRT. However, the magnitude of the violation of S_{NHe} limits decreases with longer sludge ages. Increasing SRT by reducing Q_w from 300 m^3/d to 250 m^3/d, improves significantly average S_{NHe}, but a minor effect is observed on S_{NOe}, with a nonlinear trend in both variables.
- At 10ºC with Q_w= 275 m^3/d (SRT 19.3 days), average S_{NHe} decreases almost 20 % and S_{NOe} 1.4 % with respect to default conditions. For Q_w = 250 m^3/d (SRT 21 days) S_{NHe} decreases 14 % and S_{NOe} 2 %, with respect to Q_w= 275 m^3/d.
- At reference scenario (15ºC) Q_w is varied between 300 m^3/d and 450 m^3/d (SRT 12.1 days). Reducing SRT from 17.8 days to 12.1 days produce violations of S_{NHe} limits and duplicates average S_{NHe}. Then, it is not recommended to reduce SRT at 15ºC to save energy.
- Al best-case scenario (20ºC) Q_w is also varied between 300 m^3/d and 450 m^3/d (SRT 12.1 days). Satisfactory N-removal performance is attained in both cases, with no violations of effluent limits. Then SRT could be reduced to save energy, with a consequential increase of average S_{NHe}. In this case, S_{NHe} increment is within the acceptable tolerance.
- At 10ºC and 12ºC is observed that E_{ASP}/Q_{inavJ} increases linearly as SRT increases.

Then, increasing SRT is a potential alternative to be considered in the Temperature Driven Control Strategy to improve N-Removal performance at low temperatures. Increasing SRT improves treatment performance at low temperatures.

Energy consumption increases with SRT. At low temperatures the increment of E_{ASP}/Q_{inavJ} for using larger SRTs is an acceptable expense to improve S_{NHe} and avoid violations of effluent requirements. At 20ºC, increasing Q_w to 450 m^3/d (SRT 12.1 days), as defined in BSM2 timer control, reduces energy consumption with a minor impact on S_{NHe} and N_{tote}. However, reducing SRT at 15ºC, where adequate performance is attained, to reduce energy consumption produces significant

Table 3
Effect of SRT variations by Q_w adjustment on selected performance indicators at different temperature scenarios.

	10ºC			12ºC		15ºC		20ºC	
Q_w (m^3/d)	300	275	250	300	275	450	300	450	300
EQI/Q_{inavJ} (kg/m^3)	0.28	0.28	0.28	0.27	0.27	0.26	0.25	0.24	0.23
S_{NHe} (gN/m^3)	0.73	0.59	0.51	0.43	0.35	0.47	0.22	0.17	0.12
S_{NOe} (gN/m^3)	11.32	11.16	10.93	11.02	10.77	11.44	10.3	10.07	8.96
N_{tote} (gN/m^3)	14.04	13.77	13.49	13.43	13.13	13.78	12.5	12.14	11.07
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.232	0.234	0.236	0.238	0.240	0.236	0.244	0.245	0.251
$(S_{NO5}$-$S_{NO2})/S_{NO5}$%	62.6	63.6	64.8	64.5	65.9	62.2	68.8	69.6	76.8
$(S_{NORin}$-$S_{NO2})/S_{NORin}$ %	53.3	54.5	56.0	55.6	57.4	52.8	61.0	62.0	70.9
$(S_{NHRin}$-$S_{NH5})/S_{NHRin}$ %	91.3	92.8	93.8	94.7	95.6	94.3	97.1	97.8	98.4
N_{tote} violation (% operation time)	0.10	0	0	0	0	0	0	0	0
N_{tote} violation (events)	1.00	0	0	0	0	0	0	0	0
N_{tote} violation (time d)	0.03	0	0	0	0	0	0	0	0
S_{NHe} violation (% operation time)	0.87	0.59	0.49	0.31	0	0.35	0	0	0
S_{NHe} violation (events)	2	1	1	1	0	1	0	0	0
S_{NHe} violation (time d)	0.26	0.18	0.15	0.09	0	0.10	0	0	0
COD_e violation (% operation time)	0	0	0	0	0	0	0	0	0
SRT (d)	17.8	19.3	21.0	17.8	19.3	12.1	17.8	12.1	17.8

deterioration of S_{NHe} and violations of the required limits.

Temperature based Q_w control, could be used instead of timer control to adjust SRT to real conditions of the process. This strategy could be useful to ensure adequate performance when abnormal variations of temperature alter seasonal patterns.

3.3.2. Actions on DO and Q_{carb} to reduce emissions to water below 14ºC considering the worst-case scenario (10ºC)

3.3.2.1. Modification of DO in aerobic reactors and external carbon source. The fast actions to improve N-Removal efficiency, avoiding violations of effluent requirements, at low temperatures are evaluated in the worst-case scenario (10ºC). The idea is to observe the effect on system performance in the most severe conditions. The proposed actions are:

- Increase DO_{SP} to promote conversion of S_{NH} to S_{NO} through nitrification, considering:
  DO_{SP}= 2.2 g/m^3, DO_{SP} = 2.4 g/m^3 and DO_{SP} = 2.6 g/m^3.
- Increase Q_{carb} to promote conversion of S_{NO} to N_2 through denitrification, considering Q_{carb} = 3 m^3/d.
- Simultaneous increase of DO_{SP} and Q_{carb}. These combined actions are denoted CB:
  CB1: Q_{carb} = 3 m^3/d + DO_{SP}= 2.2 g/m^3, CB2: Q_{carb} = 3 m^3/day + DO_{SP}= 2.4 g/m^3.
- CL1 control strategy that regulates DO_{SP} in the 4th reactor to 2 g/m^3 and DO in the 5th reactor to DO_{SP5}:

DO_{SP5}= 1 g/m^3 (Gernaey et al., 2014), DO_{SP5}= 1.5 g/m^3 (S_{O5} levels attained at low temperatures with default BSM2 strategy).

The average and maximum values of the indicators of emissions to water (S_{NHe}, S_{NOe}, N_{tote}) and the average electricity consumption (E_{ASP}/Q_{inavj}) obtained for the proposed control strategies are presented in Table 4 and compared with default strategy. Average values of the performance indicators are used to evaluate the general effect of control actions on process behavior in the selected operation period, and the maximum values of the indicators, that are determined considering the full data set (measurements are obtained each 15 min), are used to detect violations of the effluent quality requirements.

In Table 4 is observed that the maximum S_{NHe} is above the desired limit (4 gN/m^3) in all cases, what means that none of the proposed control actions can attenuate the effect of the disturbance that causes the violation of the maximum allowable limit of S_{NHe} (Day 10 peak in Q_{in}). Increasing DO set point in the 4th reactor (First row, columns 2–4) produces a moderate improvement of average and maximum ammonium levels (S_{NHe}), but also causes a significant worsening of the levels of nitrates in the effluent (S_{NOe}) and, consequently, in N_{tote}. It is important to remember that nitrification and denitrification processes are at 62 %, and 53 % of efficiency at 10ºC. In this scenario, the

Table 4
Average and maximum values indicators of emissions to water (S_{NHe}, S_{NOe}, N_{tote}) and electricity consumption per m^3 of incoming wastewater (E_{ASP}/Q_{inavj}) for the control strategies applied in the worst-case scenario (10ºC) to improve performance.

	Default	DO_{SP} 2.2 g/m^3	DO_{SP} 2.4 g/m^3	DO_{SP} 2.6 g/m^3	Q_{carb} 3 m^3/d
S_{NHe} (gN/m^3)	0.73	0.65	0.60	0.55	0.76
Maximum S_{NHe} (gN/m^3)	6.03	5.70	5.41	5.15	6.14
S_{NOe} (gN/m^3)	11.3	11.9	12.4	12.9	9.3
Maximum S_{NOe} (gN/m^3)	14.9	15.5	16.0	16.5	12.8
N_{tote} (gN/m^3)	14.0	14.5	15.0	15.4	12.0
Maximum N_{tote} (gN/m^3)	18.1	18.3	18.8	19.3	17.2
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.23	0.24	0.24	0.25	0.24
	Default	CB1	CB2	CL1 DO_{SP5}= 1 g/m^3	CL1 DO_{SP5}= 1.5 g/m^3
S_{NHe} (gN/m^3)	0.73	0.68	0.61	0.71	0.62
Maximum S_{NHe} (gN/m^3)	6.03	5.80	5.50	5.49	5.07
S_{NOe} (gN/m^3)	11.3	9.72	10.1	10.9	11.7
Maximum S_{NOe} (gN/m^3)	14.9	13.3	13.7	14.5	15.3
N_{tote} (gN/m^3)	14.0	12.4	12.8	13.6	14.3
Maximum N_{tote} (gN/m^3)	18.0	17.3	17.4	18.0	18.4
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.23	0.24	0.25	0.23	0.23

Default: Q_{carb} = 2 m^3/day + DO_{SP}= 2 g/ m^3
CB1: Q_{carb} = 3 m^3/d + D_{OSP} = 2.2 g/m^3, CB2: Q_{carb} = 3 m^3/d + D_{OSP} = 2.4 g/m^3.

nitrification process that transforms ammonium to nitrates is slowed down by low temperatures, but it is aided by the increment of DO levels in the aerobic zone. However, oxygen is an inhibitor of denitrification and part of the oxygen in the aerobic zone, that increases with DO_{SP}, is transported through internal recycle (Q_a) to anoxic reactors producing a deterioration of nitrates elimination. Then, increasing DO set-point at low temperatures to reduce S_{NHe} levels produces a substantial increase of nitrates levels (S_{NO}) that lead to violations of N_{tote}. It is also observed that, in all cases, increasing DO_{SP} produces a moderated but insufficient improvement of S_{NHe} violations but worsen the violations of the desired N_{tote} limits.

The second proposed action is to increase the external source of carbon (Q_{carb}) to improve denitrification (First row, column 5 of Table 4). This action produces a notable decrease of average and maximum values of S_{NOe} and N_{tot}, avoiding the violation of the desired N_{tote} limits. The addition of organic matter by increasing Q_{carb} promotes denitrification, decreasing S_{NOe} levels, with a slight increment of S_{NHe} levels. This solution by itself is not relevant for improving performance, but a natural decision that arises from the observation of the effects of increasing DO set-point and Q_{carb} is to combine both actions to find a balance between nitrification and denitrification. The tests CB1: $Q_{carb} = 3\ m^3/d + DO_{SP} = 2.2\ g/m^3$ and CB2: $Q_{carb} = 3\ m^3/d + DO_{SP} = 2.4\ g/m^3$ increase simultaneously Q_{carb} and DO_{SP}. These actions (CB1 and CB2, presented in the second row of Table 4) produce a slight deterioration of the average and maximum S_{NHe}, but a noticeable enhance the S_{NOe} and N_{tote} average and maximum values. As a result, the favorable effects of increasing DO_{SP} on S_{NHe} are kept, while increasing Q_{carb} reduces S_{NOe} levels and avoids the violations of N_{tote} limits. However, these actions do not minimize the violations of S_{NHe}.

The idea of implementing CL1 strategy comes from the observation of a significant reduction of S_{O5} levels in the 5th reactor at 10ºC, that was thought to be a factor influencing the deterioration of the indicators of emissions to water. However, this strategy exhibits the same drawbacks that increasing DO_{SP}, increasing the oxygen levels in reactor 5 produces an accumulation of nitrates in the system, that reflects as high average and maximum levels of S_{NOe} and N_{tote}. Furthermore, the CL1 strategy do not address the violations of S_{NHe} and N_{tote} limits.

Increasing DO_{SP} implies increasing electricity consumption per m^3 of incoming wastewater (E_{ASP}/Q_{inavJ}). Energy consumption also increases when using higher external carbon source dosage (Q_{carb}). The strategy with the lower impact on electricity consumption among all tested actions is CL1 (Table 4).

The dynamic behavior of the system when applying the proposed control actions is also evaluated to corroborate observations from Table 4 adding information about dynamic behaviour. Fig. 5 presents the dynamic profiles of the S_{NHe} and S_{NOe} indicators, built using the daily average values of indicators on the evaluation period.

The main values of S_{NHe} profiles slightly increases as DO supply (DO_{SP}, DO_{SP5}) intensifies for all actions that involves DO_{SP} increase presented in subfigures (a), (b) and (c) respectively (Increase DO_{SP}, CB1, CB2, CL1). The profile for $DO_{SP} = 2.6\ g/m^3$ was not shown to avoid redundancy. In all cases, S_{NHe} (a, b, c subfigures) and S_{NOe} profiles (d, e, f subfigures) exhibits symmetrical patterns for DO_{SP} changes, even individual modification of Q_{carb} shown in subfigures (b) and (e). Likewise, the changes in the main values of the profiles per change of DO_{SP} are similar for each strategy, with a moderate difference for S_{NOe} in CB1 and CB2 actions. In subfigure (e), it is observed how the strong positive effect of increasing Q_{carb} displace the S_{NOe} profiles to lower values. In subfigures (d) and (f) is observed that S_{NOe} profiles with CL1 strategy attain lower values than those of the default control strategy, even though in both cases high levels of S_{NOe} are produced.

The dynamic profiles allow to observe the peaks of ammonium concentration (S_{NHe}) days 10 and 26 (Fig. 5(a), (b), (c)) that are a consequence of the abrupt peak on the influent flowrate (Q_{in}) pointed out in Fig. 3(a). In this worst-case scenario, the combined actions (CB1 and CB2) improve performance, producing a moderate reduction of the main values of S_{NHe} profiles while acceptable levels of S_{NOe} are maintained.

Summarizing, the simple increase of DO_{SP} is not enough to improve N-Removal performance, since the reduction of S_{NHe} is accompanied by

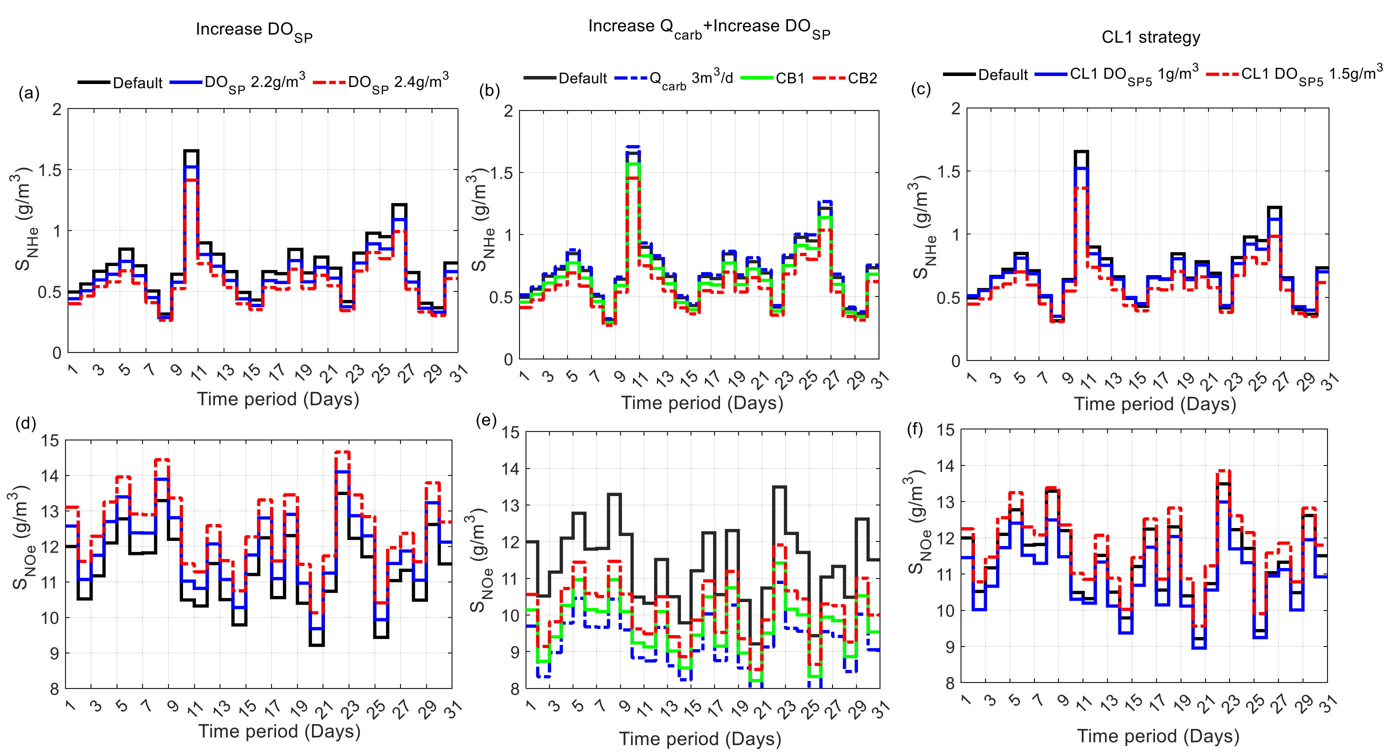

Fig. 5. Effect of the proposed actions to improve performance on ammonium and nitrates levels in the effluent (S_{NHe} and S_{Noe}) at low temperatures (10ºC). CB1: $Q_{carb} = 3\ m^3/d + D_{OSP} = 2.2\ g/m^3$ and CB2: $Q_{carb} = 3\ m^3/d + D_{OSP} = 2.4\ g/m^3$.

an increase of S_{NOe} to undesirable levels. CL1 strategy that fixes DO set-point in the 5th reactor, slightly improves this situation. However, none of the proposed actions has been able to minimize the S_{NHe} peak observed the day 10, that produce violations of S_{NHe} and N_{tote} limits, that is the most important problem associated with performance deterioration at low temperatures in the selected evaluation window.

3.3.2.2. Addressing the violations of required effluent limits due to strong disturbances. It is observed from previous results that among the fast control actions, increasing DO_{SP} improves nitrification which reduces ammonium levels in the effluent (S_{NHe}). However, this action produces an undesirable elevation of nitrates levels in the effluent (S_{NOe}) that reflects on the total Nitrogen concentration (N_{tote}). It is found that increasing the carbon dosage (Q_{carb}) is the solution to this trade-off, since it promotes denitrification, reducing nitrates levels in anoxic reactors.

The cause of the violation of the required limits on S_{NHe} and N_{tote} has been identified as a strong disturbance in Q_{in}. According with Table 3 results, this situation persists even with longer SRTs, then fast actions are necessary to reject the disturbance. DO levels must be severely increased for a brief period to facilitate nitrification when disturbance in Q_{in} is detected. This temporal DO set-point is denoted $DO_{RV.}$ The reactions associated with nitrification exhibits a saturation when DO is close to 4 g/m^3 (Ammand et al., 2013), then DO_{RV} mut be lower. Prolonged periods of intensive aeration are discarded due to the high consumption of electricity and the possible negative effects of excess of oxygen on denitrification, microorganisms' diversity and settleability of the sludge.

Then, the proposed control action to reduce or, preferably, avoid the violations of effluent quality limits is increasing DO set-point (DO_{SP}) up to 3.6 g/m^3 in the period where the disturbance in affecting the system. Q_{carb} mut be set at 3 m^3/d to prevent nitrates accumulation. Increasing the aeration to reach higher DO set-points implies higher energy consumption, however, in this situation, avoiding violations of effluent quality limits is a priority.

In the evaluated scenario, the Q_{in} disturbances that produce the S_{NHe} peaks were detected on days 10 and 26. However, in regular operation, it is not possible to predict the exact moment when such disturbances occur. Therefore, in the general control strategy, the parameter Q_{inL} is used as a trigger to intensify aeration in the presence of strong disturbances in Q_{inL}.

Then, the strategy proposed to reduce the impact of the large disturbances of influent flow on S_{NHe} and N_{tote} levels at low temperatures is composed of the following actions, that are tested to find the best conditions:

– Q_{carb}= 3 m^3/day to promote denitrification
– DO_{SP} between 2. 0 g/m3–2.2 g/m^3
– $DO_{SP} = DO_{RV}$ while $Q_{in} \geq Q_{inL}$ with DO_{RV} between 2.8 and 3.6 g/m^3 to reduce violations of effluent quality limits in the presence of strong influent disturbances.

The strategy is incorporated as a modification of default BSM2 control strategy and CL1 strategy with DO_{SP5}= 1.5 g/m^3.

In order to determine Q_{inL} the Q_{in} profile in the operation window is examined. The average influent flow in the selected operation period is Q_{inavJ} = 22066 m^3/day, in Fig. 3, subfigure (a), it is possible to distinguish normal fluctuations of Q_{in} around Q_{inavJ} and occasional strong disturbances with Q_{in} values above 28000 m^3 /d, that approximately corresponds with 85 % percentile. It is considered that the action to reject Q_{in} disturbances must be activated for disturbances of infrequent magnitude above 85 % percentile, then Q_{inL} values are selected between 85 % (28000 m^3/d) and 92 % (32500 m^3/d) percentile of Q_{in} profile depending on desired sensitivity to Q_{in} disturbances

The strategy has been tested in the worst-case scenario (10ºC) with different values of Q_{inL}, DO_{SP} and DO_{RV}. The following settings are considered:

– P1: DO_{SP}= 2.0 g/m^3, DO_{RV}= 3.2 g/m^3, Q_{inL}= 28000 m^3 /d.
– P2: DO_{SP}= 2.0 g/m^3, DO_{RV}= 3.6 g/m^3, Q_{inL}= 28000 m^3 /d.
– P3: DO_{SP}= 2.0 g/m^3, DO_{RV}= 3.6 g/m^3, Q_{inL}= 32500 m^3 /d.
– P2-SP: DO_{SP}= 2.2 g/m^3, DO_{RV}= 3.6 g/m^3, Q_{inL}= 28000 m^3 /d.
– CL1-P2: CL1 (DO_{SP5} =1.5 g/m^3) strategy with DO_{SP}= 2.0 g/m^3, DO_{RV}= 3.6 g/m^3, Q_{inL}= 28000 m^3 /d.

Table 5
Average and maximum values indicators of emissions to water (S_{NHe}, S_{NOe}, N_{tote}) and electricity consumption (E_{ASP}/Q_{inavj}) for the control strategy applied in the worst-case scenario (10ºC) to prevent violations of effluent requirement limits.

	Default	P1	P2	P3	P2-SP 2.2 g/m^3	CL1-P2
S_{NHe} (gN/m^3)	0.73	0.63	0.60	0.68	0.56	0.56
Maximum S_{NHe} (gN/m^3)	6.03	4.85	4.57	4.89	4.51	4.44
S_{NOe} (gN/m^3)	11.3	9.60	9.68	9.40	10.1	9.81
Maximum S_{NOe} (gN/m^3)	14.9	12.9	12.9	12.8	13.4	13.2
N_{tote} (gN/m^3)	14.0	12.2	12.3	12.1	12.6	12.4
Maximum N_{tote} (gN/m^3)	18.0	17.4	17.5	17.3	17.6	17.6
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.232	0.243	0.246	0.240	0.250	0.245

Default: Q_{carb} = 2 m^3/day + DO_{SP}= 2 g/ m^3
P1: DO_{SP}= 2.0 g/m^3, DO_{RV}= 3.2 g/m^3, P2: DO_{SP}= 2.0 g/m^3, DO_{RV}= 3.6 g/m^3, P2-SP: DO_{SP}= 2.2 g/m^3, DO_{RV}= 3.6 g/m^3, CL1-P2: CL1 strategy with DO_{SP}= 2.0 g/m^3, DO_{RV}= 3.6 g/m^3.

The results of the evaluation are shown in Table 5, and dynamic profiles of S_{NHe}, S_{NOe} and E_{ASP}/Q_{inavJ} are presented in Fig. 6. The maximum values of S_{NHe} and S_{Ntote} (considering full data, with samples each 15 min) in Table 5 are used to observe if the action has been successful to minimize the violations of effluent quality limits, while average values indicate the effect on global performance in the selected operation window. A reduction amongst 19 % and 23 % in the maximum values of S_{NHe} are attained with proposed strategy compared with Default BSM2 strategy. Even though it is still not possible to avoid the violations of required S_{NHe} limits, the magnitude of the peak is minimized. Violations of N_{tote} limits have been eliminated, an maximum S_{NOe} are reduced from 14.9 gN/m^3 to values around 12 gN/m^3. In all cases average S_{NHe} reduces from 6.8 % to 23 %, as well as nitrates levels (S_{NOe}) and total Nitrogen (N_{tote}), which indicates the positive effect of the proposed strategy in N-Removal performance. Regarding effects of each parameter:

– P1 vs P2 settings, that differs on DO_{RV}: An extra reduction of 6 % of S_{NHe} peak is reached with an increase of 1.2 % of electricity consumption (E_{ASP}/Q_{inavJ}) and a very slight increase of S_{NOe} and N_{tote}
– P2 vs P3 settings, that differs on Q_{inL}: S_{NHe} peak increases 7 % when Q_{Lin} is increased, with an increase of 1.23 % of E_{ASP}/Q_{inavJ}
– P2-SP 2.2 g/m^3 vs P2 settings, that differs on DO_{SP}: average and maximum S_{NHe} values are improved with increasing DO_{SP} to 2.2 g/m^3 in the whole operation period. Consequently, larger E_{ASP}/Q_{inavJ} (4 %) and worse S_{NOe} and N_{tote} average and maximum values are attained.
– CL1-P2 vs P2: average and maximum S_{NHe} values are improved, and the maximum reduction of S_{NHe} peak is attained, with larger E_{ASP}/Q_{inavJ} (4 %) and worse S_{NOe} and N_{tote} average and maximum values.

From these results it is noticed that increasing DO_{SP} in the whole operation window (P2-SP 2.2 g/m^3) strategy do not produce significant improvements with respect to other strategies. Average S_{NHe} and maximum S_{NHe} are moderately reduced compared with other strategies,

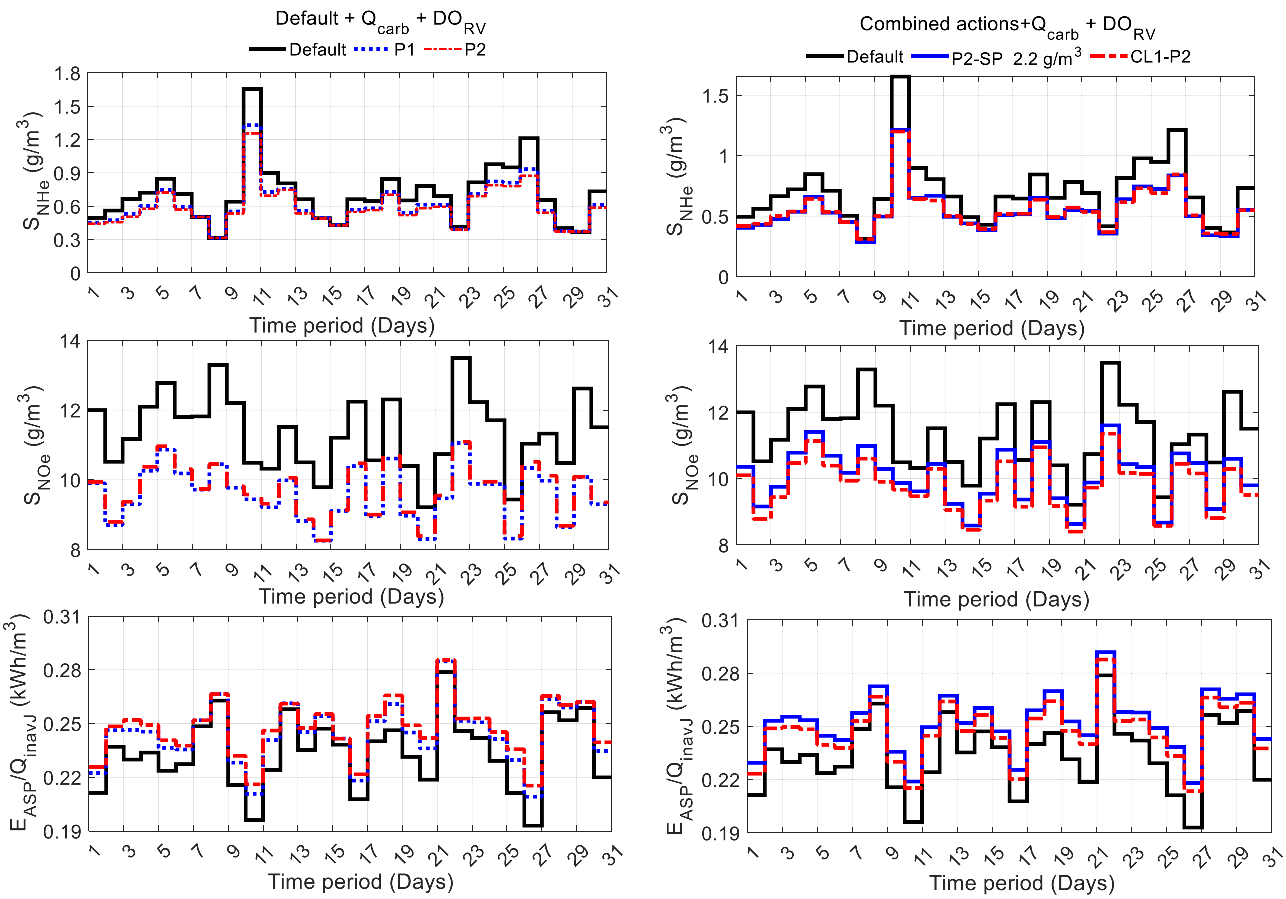

Fig. 6. Effect of the strategy proposed to reduce the peaks on ammonium in the effluent (S_{NHe}) on emissions to water indicators and electricity consumption E_{ASP}/Q_{invJ} at worst-case scenario (10ºC).

Table 6
Average and maximum values indicators of emissions to water (S_{NHe}, S_{NOe}, N_{tote}) and electricity consumption per m^3 of incoming wastewater (E_{ASP}/Q_{inavj}) for the control strategies applied at different temperature scenarios.

	12ºC			14ºC		15ºC
	Default	P11	P12	Default	P22	Default
S_{NHe} (gN/m^3)	0.43	0.40	0.41	0.27	0.26	0.22
Maximum S_{NHe} (gN/m^3)	4.41	3.44	3.71	3.02	2.60	2.44
S_{NOe} (gN/m^3)	11.0	9.20	9.20	10.5	10.6	10.3
Maximum S_{NOe} (gN/m^3)	14.6	12.6	12.6	14.2	14.2	14.0
N_{tote} (gN/m^3)	13.4	11.6	11.6	12.8	12.8	12.5
Maximum N_{tote} (gN/m^3)	17.5	16.9	16.8	17.0	17.1	16.8
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.24	0.24	0.24	0.24	0.24	0.24

Default: Q_{carb} = 2 m^3/day + DO_{SP}= 2 g/ m^3
P11: D_{OSP}= 2. 0 g/m^3, D_{ORV}= 2.8 g/m^3 at 12ºC; P12: D_{OSP}= 2. 0 g/m^3, D_{ORV}= 3.2 g/m^3 at 12ºC; P22: D_{OSP}= 2. 0 g/m^3, D_{ORV}= 2.4 g/m^3 at 14ºC.

but it results in higher S_{NOe} levels and increases electricity consumption.

In Fig. 6, the dynamic profiles with the different settings of the proposed strategy are compared with default strategy, allowing to observe the significant improvement of S_{NOe} behavior, the significant reduction of the S_{NHe} peak, and the moderated improvement of the mean values of S_{NHe}. P1 vs P2 effects and P2-SP 2.2 g/m^3 and CL1-P2 are compared in different columns. P3 is excluded to facilitate comparison.

This strategy has been tested in 12ºC and in the 14ºC scenarios considering the following settings, with Q_{inL} = 32500 m^3/d (More relaxed than in the 10ºC scenario):

- P11: DO_{SP}= 2. 0 g/m^3, DO_{RV}= 2.8 g/m^3 at 12ºC.
- P12: DO_{SP}= 2. 0 g/m^3, DO_{RV}= 3.2 g/m^3 at 12ºC.
- P22: DO_{SP}= 2. 0 g/m^3, DO_{RV}= 2.4 g/m^3 at 14ºC.

From the results presented in Table 6, it can be verified that settings of DO_{RV} and Q_{inL} can be relaxed as temperature increases producing a relevant improvement of performance. From the comparison between different settings, it is stated that P11 and P12 strategies avoid violations of S_{NHe} limits at 12ºC, and improves the other indicators with no significant effect on electricity consumption. The S_{NHe} peak is lower with P11, that uses a lower DO_{RV}, compared with P12, but both strategies achieve similar performance in the other indicators. At 14ºC it is observed that performance indicators with Default and P22 strategy are not so different between them, and their values are close to the values obtained at reference 15ºC scenario. It is necessary to restate that curves of *NO-production*, *NO-removal* and *NH-removal* change from abrupt variations to soft variations close to 14ºC (Table 1, Fig. 2). Then, no significant deterioration of performance associated with temperature is observed at 14ºC with respect to 15ºC. The only underlining advantage of P22 strategy, compared with Default conditions, is the reduction of S_{NHe} peak.

3.3.3. *Actions on DO and Q_{carb} to reduce energy and chemicals consumption above 16ºC*

In the case of temperatures above 16ºC, two main actions are evaluated to reduce energy and chemicals consumption taking advantage of the enhanced performance observed at high temperatures. The actions are to decrease DO set-point in reactor 4 and to reduce carbon dosage

(Q_{carb}) on reactor 1.

These actions are tested in the best-case scenario (20ºC) and compared with Default BSM2 strategy (Q_{carb} =2 m^3/day + DO_{SP}= 2 g/m^3). Specifically, the variations are:

– Decrease DO_{SP} to lower aeration energy, considering: DO_{SP}= 1.8 g/m^3, DO_{SP} = 1.6 g/m^3.
– Reduce Q_{carb} to save chemicals, considering: Q_{carb} = 1 m^3/d.
– Simultaneous decrease of DO_{SP} and Q_{carb}:

CB3: DO_{SP}= 1.6 g/m^3, CB4: Q_{carb} = 1 m^3/day + DO_{SP}= 1.8 g/m^3.

The effect of the proposed individual (Decrease DO_{SP}, decrease Q_{carb}) and combined control actions (CB3, CB4) on average and maximum values of S_{NHe}, S_{NOe}, N_{tote} and E_{ASP}/Q_{inavj} for the best-case scenario (20ºC) are presented in Table 8. The proposed control strategy establishes that actions to reduce consumption of resources are suitable if environmental indicators values are below the attained at 15ºC (Admissible limits), that are also presented in the table.

At 20ºC scenario, average and maximum S_{NHe} are significantly below the ammonium levels attained at 15ºC for all tested control actions. When DO levels are reduced to 1.6 g/m^3 and 1.8 g/m^3 to decrease electricity consumption (E_{ASP}/Q_{inavj}), average ammonium concentration (S_{NHe}) exhibits a slight deterioration, compared with Default case, but average and maximum S_{NOe} shows a moderate improvement. Reducing DO levels in the aerobic zone reduces the available oxygen for nitrification, increasing S_{NH}, but the amount of oxygen transported by recirculation (Q_a) to the anoxic zone also decreases, which is favorable for denitrification, reducing the levels of S_{NO} in the system. Then, according with results shown in Table 8, these alternative DO_{SP} can be implemented to save electricity.

On the other hand, reducing external carbon dosage (Q_{carb}) to 1 m^3/d increases S_{NOe} levels since the substrate available for denitrification is reduced. In this case, S_{NOe} levels are greater than levels at 15ºC reference scenario, as shown in Table 7, which makes this action unfeasible due to an excessive deterioration of performance.

The combined actions (CB3 and CB4) are considered for the simultaneous reduction of electricity (E_{ASP}/Q_{inavj}) and chemicals consumption. Desired S_{NHe} is attained with a low DO_{SP} at 20ºC due to the positive effect of temperature on biological kinetics, furthermore, the low DO levels are favorable to eliminate nitrates in anoxic zone. In the case of CB3, the benefits of the lower DO set-points (1.6 g/m^3) on denitrification compensates the reduction of Q_{carb}, allowing the attainment of the desired levels of nitrates in the effluent (S_{NOe}). It makes possible to save electricity and chemicals simultaneously. In the CB4 case with higher DO_{SP}, the admissible limits of S_{NOe} (10.3 gN/m^3 at 15ºC) and N_{tot} (12.5 gN/m^3 at 15ºC) are infringed, making this action unfeasible at 20ºC, since positive effects of the low DO levels on denitrification are not enough to compensate the Q_{carb} reduction.

Table 7 shows the results for scenarios with temperatures between 16ºC and 20ºC. It is observed that reducing DO_{SP} = 1.6 g/m^3 that was effective at 20ºC, produces inadmissible deterioration of S_{NHe} at 16ºC where microorganisms are less active. CB3 strategy, that was effective at 20ºC to reduce electricity consumption (E_{ASP}/Q_{inavj}) and external carbon usage (Q_{carb}), causes a larger deterioration of the levels of S_{NHe}, S_{NOe} and N_{tot} compared with default strategy at 18ºC.

The effect of proposed actions on dynamic profiles of S_{NHe} and S_{NOe} at 20ºC are presented in Fig. 7. The dynamic profiles of valid solutions must be below the limits of acceptable performance given by profiles obtained at 15ºC with default BSM2 strategy. For individual and combined actions involving DO_{SP} reduction, the deterioration of nitrification due to the lower DO levels is evidenced as a reduction of the mean values of the N_{He} profiles, but the limits for acceptable performance are still being attained in the whole horizon for all cases (subfigures a,b). Regarding S_{NOe} levels, the favourable effect of decreasing DO_{SP} on nitrates elimination reflects on S_{NOe} dynamic profiles shown in subfigure (c). However, for the combined action of decreasing DO_{SP} and reducing carbon dosage (Q_{carb}), S_{NOe} dynamic profiles shown in subfigure (d) exceeds the allowable limits of acceptable performance (S_{NOe} at 15ºC) for all cases, except for CB3 combined actions, in the whole operation window.

These results evidence the sensitivity of the denitrification process to the availability of the organic matter provided by Q_{carb}, even in the favourable conditions promoted by higher temperatures. The only scenario possible to simultaneously reduce energy and chemicals consumption is at 20ºC. However, it is possible to decrease energy consumption reducing the DO_{SP} to 1.6 g/m^3 at 18ºC and to 1.8 g/m^3 at 16ºC.

3.3.4. Formulation of the temperature driven control strategy

A brief overview of the main aspects that arose from the evaluation of the selected control actions is presented in Table 8. The table summarize the pros and cons of the actions considered in this work to assess the impact of temperature on the performance of N-Removal process of the WWTP represented by BSM2 plant. It also presents the range of variation of the control variables involved in the different control actions to be

Table 7
Average and maximum values indicators of emissions to water (S_{NHe}, S_{NOe}, N_{tote}) and electricity consumption per m^3 of incoming wastewater (E_{ASP}/Q_{inavj}) for the control strategies applied in the best-case scenario (20ºC) and other temperatures in the higher temperature range.

Best case scenario 20ºC							15ºC
	Default	DO_{SP} 1.6 g/m^3	DO_{SP} 1.8 g/m^3	Q_{carb} 1 m^3/d	CB3	CB4	Default
S_{NHe} (gN/m^3)	0.12	0.14	0.13	0.11	0.13	0.12	0.22
Maximum S_{NHe} (gN/m^3)	0.74	1.03	0.85	0.70	0.96	0.80	2.44
S_{NOe} (gN/m^3)	8.96	8.22	8.59	10.9	9.92	10.4	10.3
Maximum S_{NOe} (gN/m^3)	13.6	13.0	13.3	15.1	14.1	14.6	14.0
N_{tote} (gN/m^3)	11.1	10.4	10.7	13.0	12.0	12.5	12.5
Maximum N_{tote} (gN/m^3)	16.2	15.7	15.9	17.2	16.5	16.8	16.8
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.251	0.239	0.245	0.246	0.234	0.240	0.244
	16ºC			18ºC			15ºC
	Default	DO_{SP} 1.6 g/m^3	DO_{SP} 1.8 g/m^3	Default	DO_{SP} 1.6 g/m^3	CB3	Default
S_{NHe} (gN/m^3)	0.19	0.23	0.21	0.15	0.17	0.16	0.22
Maximum S_{NHe} (gN/m^3)	1.93	2.55	2.20	1.17	1.64	1.55	2.44
S_{NOe} (gN/m^3)	10.0	9.08	9.54	9.44	8.63	10.5	10.3
Maximum S_{NOe} (gN/m^3)	13.9	13.0	13.5	13.8	13.1	14.6	14.0
N_{tote} (gN/m^3)	12.1	11.3	11.7	11.6	10.8	12.7	12.5
Maximum N_{tote} (gN/m^3)	16.6	16.1	16.3	16.3	15.8	16.9	16.8
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.246	0.235	0.240	0.249	0.238	0.233	0.244

CB3: Q_{carb} = 1 m^3/d + DO_{SP}= 1.6 g/m^3, CB4: Q_{carb} = 1 m^3/d + DO_{SP}= 1.8 g/m^3,

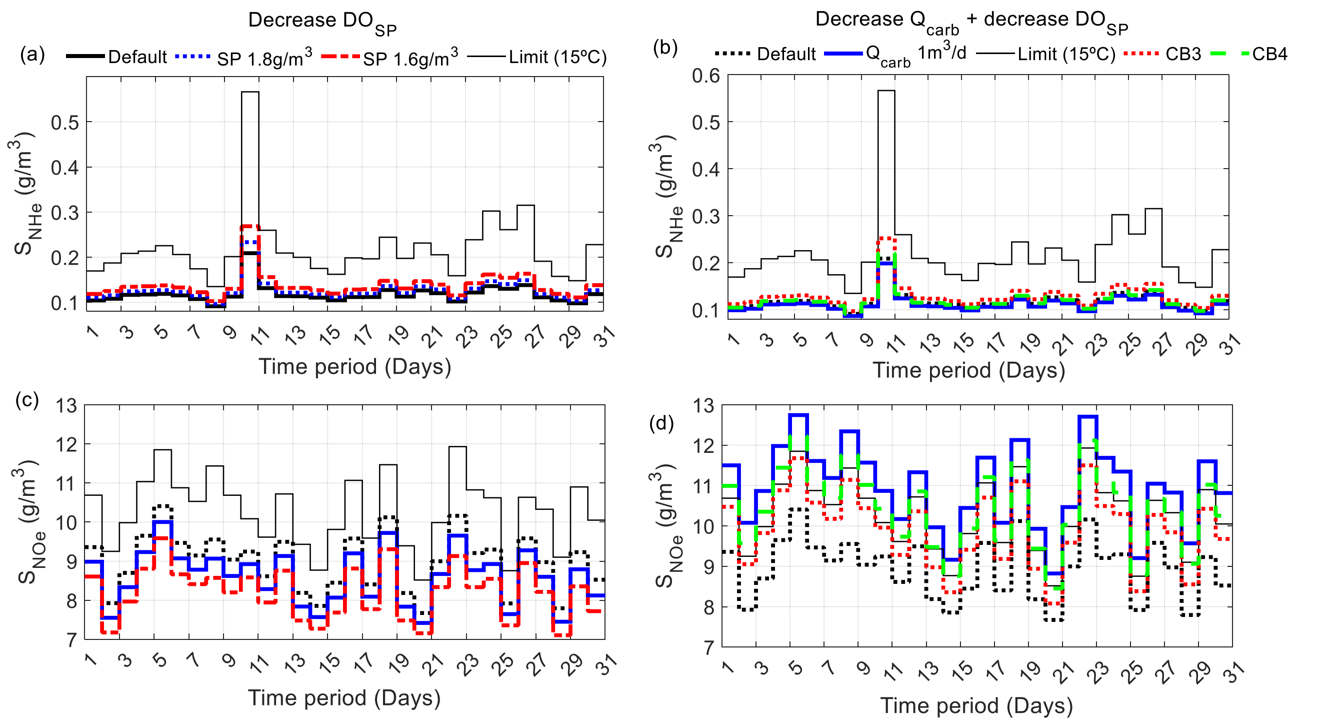

Fig. 7. Effect of reduction of the DO reference in R4 (DO_{SP}) and Q_{carb} on S_{NHe} and S_{NOe} and electricity consumption E_{ASP}/Qin_{avJ} in the best-case scenario (20ºC).

applied in the Temperature Driven Control Strategy. This range of variation have been selected from the analysis of the results discussed in Sections 3.3.1 to 3.3.2, with a conservative criterion with respect to the increase of DO levels (DO_{SP}, DO_{RV}). As shown in Table 8, actions with a negative impact on N-Removal performance at low temperatures, as single increase of DO_{SP} have been discarded, as well as, actions that are feasible only in a very limited range of temperature, as simultaneous decrease of DO_{SP} and Q_{carb} at high temperatures.

Regarding long-term SRT regulation, it was recommended in Section 3.3.1 that Q_w adjustments were executed considering influent wastewater temperature, but in the current version of the Temperature Driven Control Strategy, timer control from BSM2 default strategy is maintained for simplicity.

Founded on the analysis of the results presented in Sections 3.3.1 to 3.3.3, and considering the observations and settings summarized in Table 8, the Temperature Driven Control Strategy proposed in this work comprises the following considerations and actions:

Three zones are defined based on temperature effect on N-Removal process given by nitrification and denitrification: Low temperatures (below 14ºC), Reference conditions (15ºC), High temperatures (Above 16ºC).

Low temperature goals:

- Minimize the S_{NHe} and N_{tote} peaks that produce violations of effluent quality limits: S_{NHe}= 4 gN/m^3, N_{tote}= 18 gN/m^3
- Improve S_{NHe} and N_{tote} levels when is possible

There are no restrictions on electricity and chemicals consumption to minimize violations of effluent quality requirements, but actions are selected considering the minimum possible consumption of electricity.

High temperature goals (Below 14ºC):

- Reduce aeration energy to minimize electricity consumption.

N-Removal performance is at least equal to Reference scenario (15ºC) performance, limits of average values of indicators at high temperatures, in the selected operation window, are: S_{NHe}= 0.22 gN/m^3, S_{NOe} = 10.3 gN/m^3, N_{tote}= 12.5 gN/m^3, *NH4-removal*= 97.1 %

The control actions considered in this work are:

1. For the Temperature Driven Control Strategy based on BSM2 default control strategy:

- Adjustment of Q_w to vary SRT as a long-term action (Timer control is kept):

a) 300 m^3/d colder period, 450 m^3/d warmer period
b) 250 m^3/d colder period, 400 m^3/d warmer period

- Influent temperature below 14ºC
  o DO_{SP}= 2 g/m^3, Q_{carb} = 3 m^3/d.
  o If $Q_{in} \geq Q_{inL}$ then: DO_{SP} is DO_{RV} to reduce violations of effluent quality limits. DO_{RV}= 2.8 g/m^3 (12ºC-14ºC), 3.2 g/m^3 (10ºC-12ºC)
- Influent temperature on 15ºC: DO_{SP}= 2.0 g/m^3, Q_{carb} = 2 m^3/d, Q_w= 300 m^3/d
- Influent temperature above16ºC
  o DO_{SP}= 1.6 g/m^3, Q_{carb} = 2 m^3/d.

2. For the Temperature Driven Control Strategy based on the BSM2 CL1 strategy:

- DO_{SP5}= 1.5 g/m^3
- Adjustment of Q_w to vary SRT as a long-term action (Timer control is kept):

c) 300 m^3/d colder period, 450 m^3/d warmer period
d) 250 m^3/d colder period, 400 m^3/d warmer period

- Influent temperature below 14ºC
  o DO_{SP}= 2 g/m^3, DO_{SP5}= 1.5 g/m^3, Q_{carb} = 3 m^3/d.
  o If $Q_{in} \geq Q_{inL}$ then: DO_{SP} is DO_{RV} to reduce violations of effluent quality limits. DO_{RV}= 3.2 g/m^3 (10ºC-14ºC)
- Influent temperature on 15ºC: DO_{SP}= 2.0 g/m^3, Q_{carb} = 2 m^3/d, Q_w= 300 m^3/d

Table 8
Summary of the effect of the evaluated strategies and control actions (↑ Positive effects, ↓ problems).

Action	Positive impact and problems	Settings/Effective range of temperature
Low temperatures		
Reduce Q_w to increase SRT Long-term action	– Improves N-Removal efficiency (S_{NHe}, S_{NOe}) ↑ – Reduces number and magnitude of violations of S_{NHe} and N_{tote} ↑ – Slight increase of electricity consumption ↓	Q_w: 250 m^3/d−300 m^3/d 364 d ≤t < 546 d 10ºC−14ºC
Prolonged increase DO_{SP}	– Moderate reduction of S_{NHe} levels ↑ – Deterioration of denitrification due to high DO levels oxygen, leads to violations of N_{tote} limits ↓ – Increases electricity consumption E_{ASP}/Q_{inavj} ↓	Discarded
Increase Q_{carb}	– Improves denitrification process ↑ – Significant reduction of S_{NOe} levels ↑ – Increase use of chemicals and operation costs ↓	Q_{carb} = 3 m^3/d 10ºC−14ºC
Prolonged increase DO_{SP} +Increase Q_{carb}	– Improves N-Removal efficiency, DO_{SP} increase improves S_{NHe}, Q_{carb} increase improves S_{NOe} ↑ – Increase use of chemicals, electricity consumption and operation costs ↓	Q_{carb} = 3 m^3/d DO_{SP}: 2–2.4 g/m^3, Selected: DO_{SP}= 2 g/m^3 10ºC−12ºC
CL1	– Improves of S_{NHe} due to DO_{SP5} regulation, increases S_{O5} levels ↑ – Increase electricity consumption and operation costs E_{ASP}/Q_{inavj} ↓ – Deterioration of denitrification due to high DO levels oxygen, leads to violations of N_{tote} limits ↓	DO_{SP} = 2 g/m^3 DO_{SP5}= 1.5 g/m^3 10ºC−14ºC
Strategy to reduce S_{NHe} peaks increasing DO_{SP} during disturbance	– Minimizes the number and magnitude of the violations of S_{NHe} and N_{tote} limits ↑ – Improves N-Removal efficiency, DO_{SP} increase improves S_{NHe}, Q_{carb} increase improves S_{NOe} ↑ – Increase use of chemicals and operation costs ↓	DO_{SP}= 2.0 g/m^3 Q_{inL}:28000 −32500 m^3 / d (85–92 % Q_{in} percentile) DO_{RV}: 2.8–3.2 g/m^3
Reference 15ºC (DO_{SP}= 2.0 g/m^3, Q_{carb} = 2 m^3/d, Q_w= 300 m^3/d)		
High temperatures		
Increase Q_w to reduce SRT Long-term action	– Moderate reduction of electricity consumption↑ – Deteriorates N-Removal efficiency (S_{NHe}, S_{NOe}) ↓	Q_w: 450 m^3/d-400 m^3/d t ≤ 364 d, 546 d ≤t < 608 d 16ºC−20ºC
Prolonged reduction DO_{SP}	– Reduces electricity consumption E_{ASP}/Q_{inavj} ↑ – Improves denitrification in anoxic zone due to reduced levels of oxygen ↑ – Moderate deterioration of S_{NHe} levels ↓	DO_{SP} = 1.6 g/m^3 for T ≥ 18ºC DO_{SP} = 1.8 g/m^3 for 16ºC ≤ T < 18ºC
Reduce Q_{carb}	– Increase use of chemicals and operation costs ↑ – Deteriorates denitrification process, increases S_{NOe} levels ↓	Discarded
Prolonged reduction DO_{SP} +Reduce Q_{carb}	– Reduce use of chemicals, electricity consumption and operation costs↑ – Deteriorates N-Removal efficiency (S_{NHe}, S_{NOe}) ↓ – Reduction of DO levels improves nitrates elimination while it is deteriorated by Q_{carb} decrease ↓	T ≥ 20ºC Discarded

– Influent temperature above16ºC
o DO_{SP}= 1.6 g/m^3, DO_{SP5}= 1.5 g/m^3, Q_{carb} = 3 m^3/d.

The Temperature Driven Control Strategy presented here is a basic version with primary setting of control variables, which requires a detailed analysis of the transitions between temperature scenarios and a thorough procedure to determine the settings of the control variables. Some relevant improvements to be included in future versions are the SRT adjustment with temperature instead of timer control, an appropriate adjustment of DO_{SP5} for CL1 -based strategy, an exhaustive evaluation of DO_{RV} and Q_{inL} effects. However, the Temperature Driven Control Strategy has exhibited outstanding performance compared with BSM2 default strategy considering annual influent profile.

The main characteristics of the annual influent profile are reported in Gernaey et al. (2014) and briefly described in Section 2. The BSM2 influent includes influent flow and load variations associated with human activities and meteorological events, which can be identified as periodic and unexpected disturbances. In Table 9 the annual average performance indicators for the Temperature Driven Control Strategy, considering different SRT, DO_{RV} and Q_{inL} settings are compared with indicators obtained for Temperature Driven Control Strategy. In general, the main achievement of the Temperature Driven Control Strategy is the reduction of the frequency and magnitude of the violations of N_{tote} limits first, and S_{NHe} limits in a second place. N-Removal efficiency indicators: *NO-production*, *NO-removal* and *SNH4-removal* are also improved in all cases, as well as average N_{tote}. The effect of control strategy settings on electricity consumption, Operational Costs (OCI) and average values of S_{NHe}, S_{NOe} and EQI/Q_{inavj} are determined by the resulting trade-offs between nitrification and denitrification processes, and the trade-offs between electricity consumption (E_{ASP}/Q_{inavj}) and effluent quality, in general. In all cases S_{NHe}, S_{NOe} and N_{tote} levels have been reduced compared with Default BSM2 Strategy, which indicates that the control actions applied lead to an adequate balance between nitrification and denitrification. The best global performance considering the impact of the strategy on all indicators can be assigned to the Temperature Driven Control Strategy with Q_{inL}= 32500 m^3/d and Q_w: 250–400 m^3/d, which corroborates that SRT regulation is fundamental, but not sufficient in this case study, to address temperature effects on WWTP operation.

To summarize, the proposed Temperature Driven Control Strategy is able to address satisfactorily the seasonal and unexpected changes of temperature modelled by the annual BSM2 annual influent profile, attaining an appropriated trade-off between effluent quality and electricity consumption. The violations of required N_{tote} limits are reduced up to 50 % in frequency and 33 % in length, while violations of required S_{NHe} limits are reduced up to 36 % in frequency and 40 % in length. Annual average S_{NHe} is reduced up to 19 % and annual average N_{tote} is reduced up to 11 %. All these improvements are attained together with a slight decrease on electricity consumption (E_{ASP}/Q_{inavj}).

The strategy distinguishes between low temperature and high temperature operational goals. Low temperature goals are oriented to improve performance and N-Removal balance but concentrate on the mitigation of disturbances effects that are difficult to reject at low temperatures, producing violations of effluent quality limits. Operational goals at high temperatures have also been reached since electricity consumption is reduced in all cases, despite the increased electricity consumption required to improve performance at low

Table 9
Evaluation of different settings for the temperature driven control strategy. Annual average values of selected performance indicators.

	Default	Q_{inL}= 28000 m^3/d	Q_{inL}= 32500 m^3/d	Q_{inL}= 32500 m^3/d Qw: 250–400 m^3/d	CL1-based
EQI/Q_{inavJ} (kg/m^3)	0.27	0.26	0.26	0.27	0.26
S_{NHe} (gN/m^3)	0.47	0.46	0.49	0.38	0.43
S_{NOe} (gN/m^3)	11.05	9.82	9.73	9.41	9.99
N_{tote} (gN/m^3)	13.5	12.3	12.3	12.0	12.4
E_{ASP}/Q_{inavJ} (kWh/m^3)	0.243	0.241	0.239	0.242	0.241
OCI (EUR/d)	9442	9445	9406	9416	9442
(S_{NO5}-S_{NO2})/S_{NO5}%	65.11	72.35	72.70	74.92	71.39
(S_{NORin}-S_{NO2})/S_{NORin} %	56.43	65.43	65.87	68.62	64.22
(S_{NHRin}-S_{NH5})/S_{NHRin} %	94.81	94.86	94.59	95.71	95.23
N_{tote} violation (% operation time)	1.17	0.48	0.48	0.78	0.69
N_{tote} violation (events)	32.00	16.00	16.00	16.00	19.00
N_{tote} violation (time d)	4.28	1.76	1.76	2.86	2.51
S_{NHe} violation (% operation time)	0.41	0.35	0.35	0.24	0.21
S_{NHe} violation (events)	11.00	9.00	9.00	7.00	6.00
S_{NHe} violation (time d)	1.49	1.26	1.29	0.89	0.75

temperatures. The Temperature Driven Control Strategy, with the settings considered in this work, provides a basic adjustment of control actions to current influent temperature, therefore, it can adapt operation to abnormal variations of temperature and unexpected precipitations produced by climate change.

4. Conclusions

A Temperature Driven Control Strategy designed to address seasonal variations of temperature and abnormal variations associated with climate change has been obtained in this work using the Benchmark Simulation Model (BSM2), with DO control in the 4th reactor and timer control of waste flow, as reference system.

The main problem to be addressed by control strategy at low temperatures (below 14ºC) is the deterioration of ammonium removal performance due to slowed nitrification and denitrification rates. This situation produces violations of the limits of ammonium and total Nitrogen in the effluent in the presence of strong disturbances. At high temperatures, the control objective is to reduce electricity consumption, since increased nitrification and denitrification rates lead to outstanding N-Removal performance.

The proposed Temperature Driven Control Strategy combines long-term regulation of SRT and fast actions to reject disturbances as variations of DO set-points and carbon dosage, that are incorporated to default BSM2 strategy. The Temperature Driven Control Strategy is also formulated incorporating the mentioned control actions to a variant of the default DO control scheme, that includes an additional loop to regulate DO in the 5th reactor (CL1 strategy). The trade-off between environmental impact and electricity consumption is considered to determine the appropriate control actions, but in the case of low temperatures the priority is to minimize the violations of effluent quality limits.

The relevant actions of the combined Temperature Driven Control Strategy at low temperatures are increasing carbon dosage below 14ºC and, in the case of strong disturbances in the influent flowrate, increasing DO set-point during disturbance (as carbon dosage is increased) to minimize violations of ammonium and total Nitrogen levels in the effluent. At high temperatures, reducing DO set -point to appropriated values allows to reduce electricity consumption with a minor impact on N-Removal performance, but simultaneous reduction of electricity and chemicals consumption is possible only at 20ºC with the selected control actions.

The Temperature Driven Control Strategy have exhibited outstanding performance compared with BSM2 default strategy considering annual influent profile and different settings for the control actions. SRT adjustment, that is the usual action to address temperature variation, exhibited a significant impact on control strategy performance. Then, relevant improvements to be included in future versions of the Temperature Driven Control Strategy are the SRT adjustment with temperature instead of timer control.

To further refine the strategy, the incorporation of rainfall predictions could be useful to anticipate disturbances, reducing the probability of overwhelming the system with abrupt changes on influent flow.

The proposed solution is helpful to improve the operation of WWTPs that operate in locations with severe seasonal variations of temperature where maintaining stable treatment performance throughout the year is critical. It is particularly relevant in the context of climate change, which is expected to cause more extreme and unpredictable temperature fluctuations, further impacting WWTP efficiency. By exploring temperature-driven control strategies, this study contributes to the broader effort to optimize wastewater treatment processes and supports sustainable water management practices.

CRediT authorship contribution statement

S. Revollar: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Conceptualization. **M. Meneses:** Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **R. Vilanova:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **M. Francisco:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation. **P. Vega:** Writing – review & editing, Supervision, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Complementary material

A1.1 Process parameters and relevant ASM1 information

Table A.1
Influent characteristics, operational parameters and dimensions of BSM2 plant

Influent characteristics	
Annual average influent flow rate (Q_{in})	20,648 m^3/day
Max influent flow ($Q_{in\ max}$)	85,841 m^3/day
Min influent flow ($Q_{in\ min}$)	5146 m^3/day
Annual average COD influent concentration (COD_{in})	592.2 gCOD/m^3
Max COD influent concentration ($COD_{in\ max}$)	1213 gCOD/m^3
Min COD influent concentration ($COD_{in\ min}$)	36.5 gCOD/m^3
Annual average N_{tot} influent concentration (N_{totin})	55.2 gN/m^3
Max N_{tot} influent concentration ($N_{totin\ max}$)	114.2 gN/m^3
Min N_{tot} influent concentration ($N_{totin\ min}$)	7.7 gN/m^3
Annual average NH influent concentration (S_{NHin})	23.9 gN/m^3
Max NH influent concentration ($S_{NHin\ max}$)	55.7 gN/m^3
Min NH influent concentration ($S_{NHin\ min}$)	7.7 gN/m^3
Annual average Influent Quality Index (IQI)	747,833 kg/d
Annual average Influent Quality Index per m^3 of incoming wastewater (IQI/Q_{in})	3.62 kg/m^3
Influent temperature (T)	10–20ºC
Operational parameters	
Internal recycle flow (Q_a)	61,944 m^3/day
External recycle flow (Q_r)	20,648 m^3/day
Waste flow (Q_w)	300–450 m^3/day
Hydraulic retention time (HRT)	22 h
Sludge age (SA)-Solid Retention Time (SRT)	17.3 d
Relevant dimensions	
Total ASP volume (V_T)	12,000 m^3
Anoxic reactor volume (V_1, V_2)	1500 m^3
Aerobic reactor volume (V_3, V_4, V_5)	3000 m^3

Table A.2
Activated Sludge Model No. 1 (ASM1) variables

Definition	Notation	Definition	Notation
Soluble inert organic matter	S_t	Readily biodegradable substrate	S_s
Particulate inert organic matter	X_t	Slowly biodegradable substrate	X_s
Active heterotrophic biomass	X_B,H	Active autotrophic biomass	X_B, A
Particulate products from biomass decay	X_P	Oxygen	S_o
Nitrate and nitrite nitrogen	S_{NO}	NH_{4^+}+NH_3 nitrogen (ammonium)	$S_N\ H$
Soluble biodegradable organic nitrogen	S_{ND}	Particulate biodeg. org. nitrogen	X_{ND}
Alkalinity	S_{ALK}		

Table A.3
ASM1 biological processes rates

Biological process	**Process rate**
Aerobic growth of heterotrophs	$\rho_1 = f\ (X_{B,H}, S_S, S_O)$
Anoxic growth of heterotrophs	$\rho_2 = f\ (X_{B,H}, S_S, S_O, S_{NO})$
Aerobic growth of autotrophs	$\rho_3 = f\ (X_{B,H}, S_O, S_{NH})$
Decay of heterotrophs	$\rho_4 = f\ (X_{B,H})$
Decay of autotrophs	$\rho_5 = f\ (X_{B,A})$
Ammonification of S_{ND}	$\rho_6 = f\ (X_{B,H}, S_{ND})$
Hydrolysis of entrapped organics	$\rho_7 = f\ (X_{B,H}, X_S, S_O, S_{NO})$
Hydrolysis of entrapped organic nitrogen	$\rho_8 = f\ (X_{B,H}, X_S, S_O, S_{NO}, X_{ND})$

$$\rho_1 = \mu_{HT}\cdot\left(\frac{S_S}{K_S + S_S}\right)\cdot\left(\frac{S_O}{K_{O,H} + S_O}\right)X_{B,H} \tag{A.1}$$

$$\rho_2 = \mu_{HT}\cdot\left(\frac{S_S}{K_S + S_S}\right)\cdot\left(\frac{K_{O,H}}{K_{O,H} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\eta_g X_{B,H} \tag{A.2}$$

$$\rho_3 = \mu_{AT}\cdot\left(\frac{S_{NH}}{K_{NH} + S_{NH}}\right)\cdot\left(\frac{S_O}{K_{O,A} + S_O}\right)X_{B,A} \tag{A.3}$$

- S_{NO}:

$$r_{NO} = -\frac{1-Y_H}{2.86 \cdot Y_H}\rho_2 + \frac{1}{Y_A}\rho_3 \quad \text{(A.4)}$$

- S_{NH}:

$$r_{NH} = -i_{XB} \cdot \rho_1 - i_{XB} \cdot \rho_2 - \left(i_{XB} + \frac{1}{Y_A}\right)\rho_3 + \rho_6 \quad \text{(A.5)}$$

Table A.4
Control system parameters of BSM2 plant

BSM Control System	Parameters
BSM2	Controller gain: K = 25 d^{-1}/(g -COD/ m^3)
Oxygen control PI anti-windup	Integral time constant: Ti = 0.002 d
	Anti-windup time constant: Tt = 0.001 d
	Offset constant: $K_La_{4\ in}$= 120 d^{-1}
BSM2	0 ≤t < 182 d Q_w= 300 m^3/d
Sludge age control Timer control	182 d ≤t < 364 d Q_w = 450 m^3/day
	364 d ≤t < 546 d Q_w = 300 m^3/day
	546 d ≤t < 608 d Q_w = 450 m^3/day

A1.2 Performance indicators

Influent Quality Index, IQI (kg/d): it is a measure of the total pollution load of the influent for a given operation period (i.e.one year). It includes N_{totin}, S_{NHin}, S_{NOin}, COD_{in}, TSS_{in} and BOD_{5in} load in the influent.

Effluent Quality Index, EQI (kg/d): it is a measure of the total pollution load of the plant discharge for a given operation period (i.e. one year). It includes the following measurements of pollutants in the effluent: total Nitrogen (N_{tote}), ammonium (S_{NHe}), nitrates (S_{NOe}), total Chemical Oxygen Demand (COD_e), total Suspended Solids (TSS_e) and Biological Oxygen Demand (BOD_{5e}).

Electricity consumption indicator: The Electricity consumption of the ASP, *E_{ASP} (kWh/d)* is the electricity consumption of the ASP considering the aeration energy (AE), the pumping energy (PE) and the mixing energy (ME). Electricity consumption per m^3 of incoming wastewater in the evaluation period; E_{ASP}/Q_{inavJ}; is also computed:

$$E_{ASP} = PE_{ASP} + AE + ME_{ASP} \quad \text{(A.6)}$$

Pumping energy, PE_{ASP} (kWh/d): it is computed considering the pumps available on each unit: the internal recycle flow Q_a, the external recirculation flow Q_r, the wastage flow Q_w, the primary clarifier bottom flow, the thickener feed flow and the dewatering unit bottom flow.

Aeration energy, AE (kWh/d): it depends on aeration system characteristics: type of diffuser, bubble size, depth of submersion. It is computed on the basis of the oxygen transfer coefficient on each reactor and the volume of each reactor for Degrémont DP230 porous disks at an immersion depth of 4 m (Gernaey et al., 2014)

Mixing energy, ME_{ASP} (kWh/d): it is computed for activated sludge reactors if $K_La < 20\ d^{-1}$.

Economic indicator: The Operational Cost Index (OCI): it is defined in BSM2 as the weighted sum of different costs:

$$OCI = AE + PE + 3SP + 3EC - 6MET_{prod} + HE_{net} \quad \text{(A.10)}$$

Pumping energy, PE (kWh/d): it is computed considering the pumps available on each unit of the whole plant.

Mixing energy, ME (kWh/d): it is computed for activated sludge reactors if $K_La < 20\ d^{-1}$ and anaerobic digester, considering the volume of each reactor and digester volume, respectively.

External carbon, EC (kg/d): it is computed as the averaged external carbon mass flow, considering the external carbon source concentration (400,000 g/m^3) and the carbon source flow rate (Q_{carb}).

Sludge production for disposal, SP (kg/d): it is computed based on the amount of solids accumulated in the plant and from the solids removed from the plant as dewatered sludge.

Heating energy, HE (kWh/d): HE is the energy necessary to heat the sludge to the operation temperature required in the anaerobic digester.

Heating energy net (HE_{net}): HE_{net} is zero if methane produced in anaerobic digester (AD) covers its heating requirements, otherwise, $HE_{net} = HE - 7\ MET_{prod}$. It is computed considering that energy content of biogas is 13.89 kWh/kg CH_4 and biogas to heat efficiency is 50 % (Gernaey et al., 2014). *METprod (kg/d):* is the amount of biogas produced in AD.

A1.3 Process Control assessment

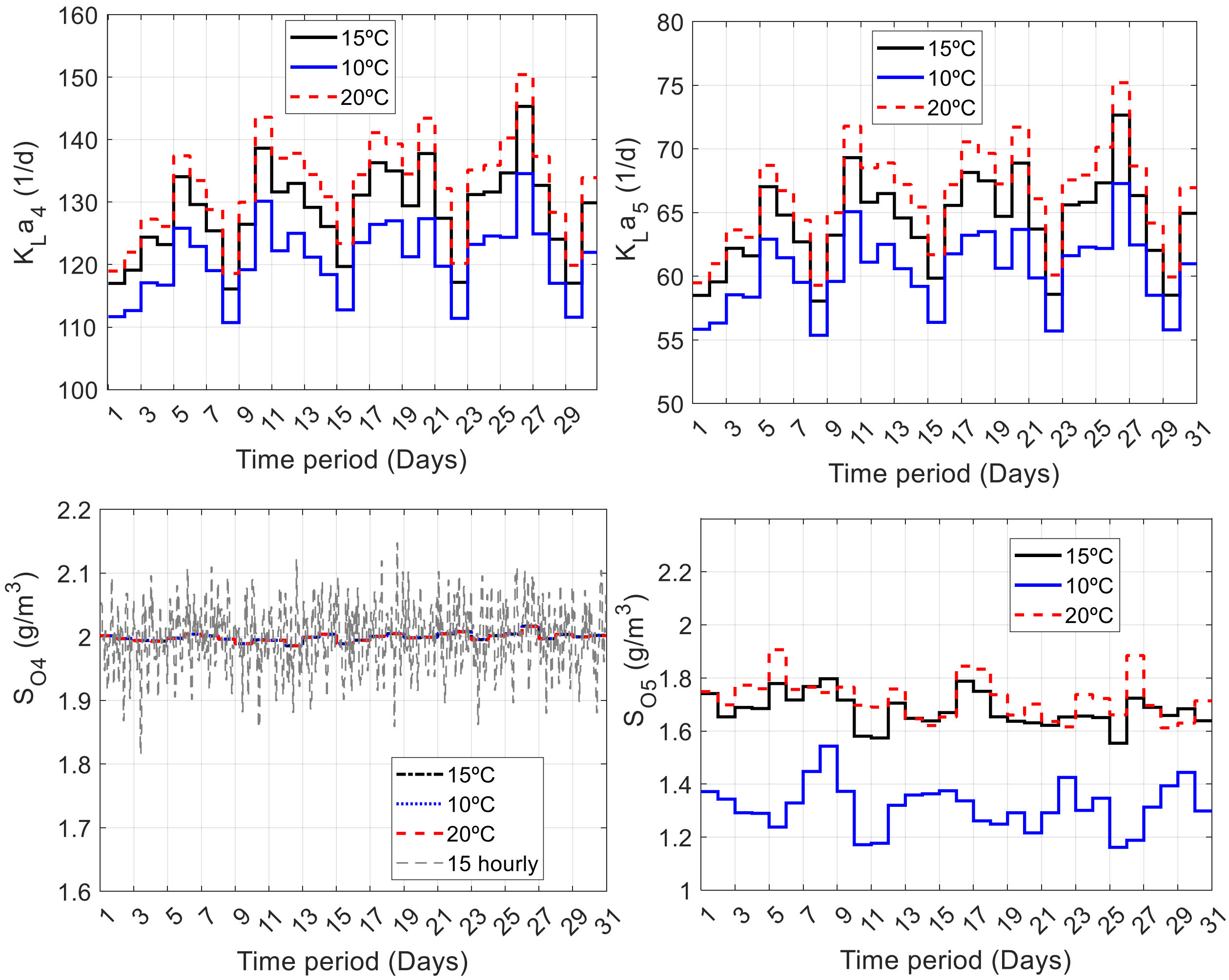

Fig. A.1. Control variables for the different temperature scenarios with default DO control BSM2 strategy

In Figure A.1, it is observed that DO reference ($DO_{SP} = 2$ g/m^3) in the 4th reactor is attained employing lower K_La_4 values in the lower temperature scenarios, which could imply lower energy consumption at low temperatures. However, in real practice and recent works (Muloiwa et al., 2023) the opposite effect is reported. This means that, aeration energy requirements increase at low temperatures. BSM2 model uses oxygen transfer coefficient (K_La) directly as manipulated variable, which is a simple representation that obviates all the variables involved in a real K_La estimation, including airflow rate, and gas and liquid properties.

References

Alex, J., Benedetti, L., Copp, J., Gernaey, K., Jeppsson, U., Nopens, I., Pons, M.N., Rosen, C., Steyer, J.P., Vanrolleghem, P., 2021. Benchmark Simulation Model no. 2 (BSM2). Wastewater Modelling. Retrieved from ⟨https://wwtmodels.pubpub.org/pub/ytwymnp3⟩.

Alisawi, H.A., 2020. Performance of wastewater treatment during variable temperature. Appl. Water Sci. 10, 89. https://doi.org/10.1007/s13201-020-1171-x.

Åmand, L., Laurell, C., Stark-Fujii, K., Thunberg, A., Carlsson, B., 2013a. Lessons learnt from evaluating full-scale ammonium feedback control in three large wastewater treatment plants. Water Sci Technol. 69 (7), 1573–1580. https://doi.org/10.2166/wst.2014.061. PMID: 24718353.

Åmand, L., Olsson, G., Carlsson, B., 2013. Aeration control - a review. Water Sci. Technol. 67 (11), 2374–2398. https://doi.org/10.2166/wst.2013.139.

Arnell, M., Ahlström, M., Wärff, C., Saagi, R., Jeppsson, U., 2021. Plant-wide modelling and analysis of WWTP temperature dynamics for sustainable heat recovery from wastewater. Water Sci. Technol. 84 (4), 1023–1036. https://doi.org/10.2166/wst.2021.277.

Baquero-Rodríguez, G.A., Lara-Borrero, J.A., Nolasco, D.A., Rosso, D., 2018. A critical review of the factors affecting modeling oxygen transfer by fine-pore diffusers in activated sludge. Water Environ. Res. 90.

Batstone, D., Keller, J., Angelidaki, R., Kalyuzhnyi, S., Pavlostathis, S., Rozzi, A., Sanders, W., Siegrist, H., Vavilin, V., 2002. Anaerobic Digestion Model No.1, STR No.13; IWA Publishing: London, UK.

Ganora, D., Hospido, A., Husemann, J., Krampe, J., Loderer, C., Longo, S., Moragas Bouyat, L., Obermaier, N., Piraccini, E., Stanev, S., Vaci, L., Pistocchi, A., 2019. Opportunities to improve energy use in urban wastewater treatment: a European-scale analysis. Environ. Res. Lett. 14 (4), 044028. JRC115605.

Gerardi, M., 2002. Nitrification and denitrification in the activated sludge process. John Wiley & Sons, Inc.

Gernaey, K., Jeppsson, U., Vanrolleghem, P., Copp, J., 2014. Benchmarking of control strategies for wastewater treatment plants. Scientific and technical report No. 23. IWA publishing.

Gernaey, K., Rosen, C., Benedetti, L., Jeppsson, U., 2009. BSM2: A model for influent data generation. ⟨https://wwtmodels.pubpub.org/pub/web0fxkd⟩.

Guerra-Rodríguez, S., Oulego, P., Rodríguez, E., Singh, D.N., Rodríguez-Chueca, J., 2020. Towards the implementation of circular economy in the wastewater sector: challenges and opportunities. Water 12 (5), 1431. https://doi.org/10.3390/w12051431.

Hegerl, G.C., Zwiers, F.W., Braconnot, P., Gillett, N.P., Luo, Y., Marengo Orsini, J.A., Nicholls, N., Penner, J.E., Stott, P.A., 2007. Understanding and Attributing Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Henze, M., Gujer, W., Mino, T., Van Loosedrecht, M., 2006. Activated sludge models ASM1, ASM2, ASM2d and ASM3. IWA publishing.

Henze, M., Leslie Grady, C.P., Gujer, W., Marais, G.V.R., Matsuo, T., 1987. A general model for single-sludge wastewater treatment systems. Water Research 21 (5), 505–515. https://doi.org/10.1016/0043-1354(87)90058-3.

Hreiz, R., Latifi, M., Roche, N., 2015. Optimal design and operation of activated sludge processes: State-of-the-art. Chem. Eng. J. 281, 900–920. https://doi.org/10.1016/j.cej.2015.06.125.

Jeppsson, U., Pons, M.N., Nopens, I., Alex, J., Copp, J.B., Gernaey, K.V., Rosen, C., Steyer, J.P., Vanrolleghem, P., 2007. Benchmark simulation model no 2: general protocol and exploratory case studies. Water Sci. Technol. 56, 67–78.

Lawrence, J., Giurea, R., Bettinetti, R., 2024. The impact of seasonal variations in rainfall and temperature on the performance of wastewater treatment plant in the context of environmental protection of lake como, a tourist region in Italy. Appl. Sci. 14, 11721. https://doi.org/10.3390/app142411721.

Maktabifard, M., Zaborowska, E., Makinia, J., 2018. Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. Rev. Environ. Sci. Biotechnol. 17, 655–689. https://doi.org/10.1007/s11157-018-9478-x.

Metcalf and Eddy Inc, 2013. Wastewater Engineering: Treatment and Resource Recovery. McGraw-Hill Medical Pub.: Burr, Ridge, IL.

Muloiwa, Dinka, M.O., Nyende-Byakika, Stephen, 2023. Modelling and optimization of energy consumption in the activated sludge biological aeration unit. Water Pract. Technol. 1 Jan. 18 (1), 140–158. https://doi.org/10.2166/wpt.2022.154.

Otterpohl, R., Freund, M., 1992. Dynamic Models for Clarifiers of Activated Sludge Plants with Dry and Wet Weather Flows. Water Sci Technol 26 (5-6), 1391–1400. https://doi.org/10.2166/wst.1992.0582.

Palatsi, J., Ripoll, F., Benzal, A., Pijuan, M., Romero-Güiza, M.S., 2021. Enhancement of biological nutrient removal process with advanced process control tools in full-scale wastewater treatment plant. Jul 15 Water Res 200, 117212. https://doi.org/10.1016/j.watres.2021.117212.

Ranieri, E., D'Onghia, G., Lopopolo, L., Gikas, P., Ranieri, F., Gika, E., Spagnolo, V., Herrera, J.A., Ranieri, A.C., 2024. Influence of climate change on wastewater treatment plants performances and energy costs in Apulia, south Italy (Feb). Chemosphere 350, 141087. https://doi.org/10.1016/j.chemosphere.2023.141087.

Reifsnyder, S., Garrido-Baserba, M., Cecconi, F., Wong, L., Ackman, P., Melitas, N., Rosso, D., 2020. Relationship between manual air valve positioning, water quality and energy usage in activated sludge processes. Water Res. 173, 115537. https://doi.org/10.1016/j.watres.2020.115537.

Revollar, S., Meneses, M., Vega, P., Francisco, M., Vilanova, R., 2023a. Eco efficiency dependencies for Wastewater Treatment Plant operation. Proceedings of the 36th ECOS. Las Palmas de Gran Canaria. June, 2023.

Revollar, S., Meneses, M., Vega, P., Francisco, M., Vilanova, R., 2023b. Effect of climatological variations on Eco-efficiency of Wastewater Treatment Plants operation, Proceedings of the IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA). Sinaia. September, 2023.

Revollar, S., Meneses, M., Vilanova, R., Vega, P., Francisco, M., 2020a. Quantifying the benefit of a dynamic performance assessment of WWTP. Processes 8, 206.

Revollar, S., Meneses, M., Vilanova, R., Vega, P., Francisco, M., 2021. Eco-efficiency assessment of control actions in wastewater treatment plants. Wate 13, 612.

Revollar, S., Vilanova, R., Vega, P., Francisco, M., Meneses, M., 2020b. Wastewater treatment plant operation: simple control schemes with a holistic perspective. Sustainability 12, 768.

Ruano, M., Ribes, J., Ruiz-Martinez, A., Seco, A., Robles, A., 2024. An advanced control system for nitrogen removal and energy consumption optimization in full-scale wastewater treatment plants. J. Water Process Eng. 57, 104705. https://doi.org/10.1016/j.jwpe.2023.104705.

Sanjrani, M., Nafees, A., Sakina, R., Xue, G., 2022. A review on application of external carbon sources for denitrification for wastewater treatment. Glob. NEST J. 24 (1). https://doi.org/10.30955/gnj.004248.

Santín, I., Pedret, C., Vilanova, R., 2016. Control and decision strategies in wastewater treatment plants for operation improvement. Intelligent Systems, Control and Automation: Science and Engineering. Springer.

Santín, I., Pedret, C., Vilanova, R., Barbu, M., 2022. New approach for regulation of the internal recirculation flow rate by fuzzy logic in biological wastewater treatments. ISA Trans. 120, 167–189. https://doi.org/10.1016/j.isatra.2021.03.028.

Smith, R., Elger, S., Mleziva, S., 2013. Implementation of Solids Retention Time (SRT) Control in Wastewater Treatment. ISA Water/Wastewater and Automatic Controls Symposium. Orlando, Florida, USA. 2013. ⟨www.isawwsymposium.com⟩.

Smith, R., Elger, S., Mleziva, S., 2014. Wastewater: solids retention time control in wastewater treatment. Filtr. + Sep. 51 (3), 12–17. https://doi.org/10.1016/S0015-1882(14)70102-8.

Takács, I., Patry, G., Nolasco, D., 1991. A dynamic model of the clarification-thickening process. Water Res. 25, 1263–1271. https://doi.org/10.1016/0043-1354(91)90066-Y.

Toreti, A., Bavera, D., Acosta Navarro, J., Acquafresca, L., Arias-Muñoz, C., Avanzi, F., Barbosa, P., Cremonese, E., De Jager, A., Ferraris, L., Fioravanti, G., Gabellani, S., Grimaldi, S., Hrast Essenfelder, A., Isabellon, M., Maetens, W., Magni, D., Masante, D., Mazzeschi, M., Mccormick, N., Rossi, L., Salamon, P., 2024. Drought in the Mediterranean Region - January 2024, Publications Office of the European Union, Luxembourg, 2024, doi:10.2760/384093, JRC137036.

2030 Agenda United Nations 2030 Agenda. https://sdgs.un.org/2030agenda.

Vanrolleghem, P.A., Batstone, D., Pons, M.N., 2009. Temperature effects in BSM1_LT and BSM2. ⟨https://assets.pubpub.org/n81cwqx8/01603225029377.pdf⟩.

Vega, P., Revollar, S., Francisco, M., 2014. Integration of set point optimization techniques into nonlinear MPC for improving the operation of WWTPs. Computers & Chemical Engineering 68, 78–95. https://doi.org/10.1016/j.compchemeng.2014.03.027.

Zaborowska, E., Krzysztof, C., Mąkinia, J., 2021. Integrated plant-wide modelling for evaluation of the energy balance and greenhouse gas footprint in large wastewater treatment plants. Appl. Energy 282, 116–126.

Zhou, H., Li, Xin, Xu, Guoren, Yu, Huarong, 2018. Overview of strategies for enhanced treatment of municipal/domestic wastewater at low temperature. Sci. Total Environ. 643, 225–237. https://doi.org/10.1016/j.scitotenv.2018.06.100.