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Model-based dynamic simulation study to boost the WWTP performance in winter tourism regions

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ABSTRACT

Wastewater treatment based on activated sludge processes faces a major challenge due to an increased number of people contributing to wastewater and changes in wastewater characteristics in regions with seasonal winter tourism. The combination of significant increases in carbon (COD) and nitrogen (N) loads by a factor of four to five within a short periode of time and low wastewater temperatures (<12 °C), represents a bottleneck in meeting essential effluent requirements. According to literature research, however, little attention has been paid to these special framework conditions for wastewater treatment. Based on this fact, a model-based simulation study of the wastewater treatment plant (WWTP) in Montafon (Austria) evaluates operational optimization approaches for the above-mentioned framework conditions and is intended to provide new insights for nitrification-optimized and energy-optimized wastewater treatment. The WWTP Montafon is designed for a COD load of 6250 kg d^{-1}, a daily dry weather water discharge of 12,700 m^{3} d^{-1} and is a typical plant in a winter tourism region. The 5 studied smart operation approaches shown are a combination of two different aeration control strategies based on a time-controlled (i) or ammonia-based feedback aeration control (ABAC) (ii) for intermittent nitrification-denitrification and sludge removal control strategies based on a constant sludge concentration to 3 g L^{-1} (iii), a constant sludge retention time (SRT) to 20 days (iv) and a constant sludge retention time to 20 days combined with a higher level sludge concentration control to max. 3 g L^{-1} (v). The simulation results show that a combination of a time-controlled aeration strategy and controlling the sludge concentration to a constant 3 g L^{-1} is not recommended in order to comply with the emission limits. Under the mentioned influent conditions, ABAC control alone does not inevitably lead to a nitrification-optimized process and reduction in energy consumption. Sufficient nitrifying bacteria in the activated sludge are the key to a nitrification optimized process and reduction of energy consumption for aeration. Hence, a combination of an intermittent aeration control based on ammonium measurement and a constant sludge retention time to 20 days is preferable for nitrification capacity and is the most energy-efficient control strategy to obtain required COD and N effluent quality. An average energy consumption of 57–63 Wh PE_{120}^{-1} d^{-1} for the aeration is to be expected for combinations of (i,iv), (ii, iii) (ii,iv) and (ii,v) which is low in relation to the influent challenges and to plants with higher wastewater temperatures (>12 °C) between 27 Wh PE_{120}^{-1} d^{-1} and 121 Wh PE_{120}^{-1} d^{-1} according to literature. The approach with a time-controlled intermittent aeration and a SRT to constant 20 days was implemented at the WWTP Montafon and confirms the results of the associated simulation. According to this simulation study, a 35 % increase in nitrification capacity in existing WWTPs designed as activated sludge processes can be achieved through optimized operating conditions without additional high investments.

1. Introduction

In many mountainous regions of the world, particularly in Europe, North America and Asia, winter tourism is of crucial importance for regional economic development and the well-being of the local population. Recently published market trend analyses [1,2] show that the global winter tourism market will grow by approximately 6 % between 2023 and 2033, with growth being most pronounced in Eastern Europe and China. At the same time, however, these regions are characterized by a sensitive and fragile environment that often has a high level of biodiversity. In consequence, it is necessary to ensure environmental protection despite increasing tourist numbers. An efficient wastewater

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treatment strategy is therefore important for the stability of the water body and public health. For this reason, wastewater treatment plants (WWTPs) have been built in these regions in recent decades. Most of the existing WWTPs in these regions were designed utilizing a suspended growth activated sludge process and are now increasingly reaching their performance limits. The common small or medium-sized WWTPs must handle high fluctuations in seasonal loads caused by dynamic tourism patterns [3]. Typical days which cause short-time peaks are season-opening events, Christmas holidays, the new year celebration, and skiing championships. These fluctuations and short-time peaks lead to changes in wastewater quantity and composition, e.g., the nitrogen to COD (N/COD) ratio. In addition, WWTPs face higher loads during weekends due to day tourists. Climate change also impacts wastewater treatment due to warmer average temperatures leading to an increasing amount of meltwater in combined sewer systems, which can tremendously decrease the wastewater influent temperature even down to 4 °C, as reported by Plósz et al. (2009) [4]. Furthermore, internal measures such as massive accumulation of process water from continuous/discontinuous sludge dewatering cause load fluctuations.

In the future, stricter requirements will be imposed on WWTPs. According to the European Green Deal, WWTPs will have more stringent requirements concerning nitrogen removal and energy efficiency as was recently proposed by the European Union (2022) [5]. Intelligent approaches to optimizing WWTPs are therefore more in demand than ever. Various studies on the energy optimization of WWTPs have been published in the past [6–10]. A literature review has shown that little research has been conducted regarding how such WWTPs can be operated efficiently under these framework conditions and challenges. The increasing number of tourists will lead to higher COD and N loads and will inevitably result in higher energy consumption by the WWTPs in order to comply with the emission limits. In this context, there is certainly considerable potential for energy savings if the operating strategy is optimized.

WWTPs using the activated sludge process require most of the energy for aeration of the aeration tanks in order to provide sufficient oxygen for the nitrification process. An optimized nitrification process is therefore essential for energy-efficient wastewater treatment. Strategies exist to enhance the nitrification process in activated sludge WWTPs at low wastewater temperatures (<12 °C) [11]. These are adaption of the operational parameters [12–14], bioaugmentation [15–19], biofilm technologies such as Moving Bed Biofilm Reactors (MBBR) [20–23], integrated Fixed-Film Activated sludge systems (IFAS) [24–27], or Biological Aerated Filters [28–31]. Apart from adaption of the operational parameters, all methods imply investments and substantial changes to the existing design and cannot be implemented immediately, nor do they target an on-site optimization potential using existing infrastructure regarding the effective use of local resources. Therefore, this paper focuses on optimization strategies based on operation and control strategies in place. Different operation and control approaches were investigated by dynamic simulation based on real data of analysed parameters, and the most promising approach was subsequently evaluated in full-scale operation.

The critical parameter for successful nitrification in suspended growth biological treatment processes is the aerobic sludge retention time ($\mathrm{SRT}_{\mathrm{aerobic}}$). At steady-state, the aerobic sludge retention time is the mass of microorganisms in the aerobic zone divided by the mass of microorganisms removed from the system per day according to Eq. (1):

$$\mathrm{SRT}_{\mathrm{aerobic}} = \frac{\mathrm{SS}_{\mathrm{EAT}} \cdot \mathrm{V}_{\mathrm{AT}}}{\mathrm{SS}_{\mathrm{RS}} \cdot \mathrm{Q}_{\mathrm{ES,d}} + \mathrm{SS}_{\mathrm{EST}} \cdot \mathrm{Q}_{\mathrm{d,conc}}} \tag{1}$$

where: $\mathrm{SRT}_{\mathrm{aerobic}}$ is the aerobic sludge retention time in the aeration tank (d), $\mathrm{SS}_{\mathrm{EAT}}$ represents the suspended solids concentration in the effluent of the aeration tank (kg m^{-3}), V_{AT} specifies the volume of the aeration tank (m^{-3}), $\mathrm{SS}_{\mathrm{RS}}$ characterizes the suspended solids concentration in the return (activated) sludge (kg m^{-3}), $\mathrm{Q}_{\mathrm{ES,d}}$ represents the daily excess activated sludge flow rate ($\mathrm{m}^3\ \mathrm{d}^{-1}$), $\mathrm{SS}_{\mathrm{EST}}$ denotes the suspended solids concentration in the effluent of the secondary settling tank (kg m^{-3}), and $\mathrm{Q}_{\mathrm{d,conc}}$ indicates the daily outflow used for calculation of the concentration of loads ($\mathrm{m}^3\ \mathrm{d}^{-1}$). However, the decisive factor of nitrification is the amount of active nitrifying bacteria, representing a WWTP's maximum nitrification capacity. In this context, respiration tests by measuring oxygen uptake [32,33] were developed to monitor and quantify the current maximum nitrification capacities of the activated sludge. According to Niesen and Nielsen (2002) [34], the expected nitrifying bacteria amount is approximately 2–3 % of active sludge microorganisms in municipal WWTPs. The nitrifying bacteria (in wastewater modeling typically referred to the terminology "autotrophic bacteria") to a certain extent can adapt to load changes, as they are usually substrate-limited in their growth and upper-limited in the Monod-kinetic shown in Eq. (2):

$$\frac{\mathrm{dX}_{\mathrm{B,A}}}{\mathrm{dt}} = -\mathrm{Q}_{\mathrm{ES,d}} \cdot \mathrm{X}_{\mathrm{A}} + \widehat{\mu}_{\mathrm{A}} \cdot \frac{\mathrm{S}_{\mathrm{NH_4}}}{\mathrm{K}_{\mathrm{H}} + \mathrm{S}_{\mathrm{NH_4}}} \cdot \frac{\mathrm{S}_{\mathrm{O}}}{\mathrm{K}_{\mathrm{O,A}} + \mathrm{S}_{\mathrm{O}}} \cdot \mathrm{X}_{\mathrm{B,A}} - \mathrm{b}_{\mathrm{A}} \cdot \mathrm{X}_{\mathrm{B,A}} \tag{2}$$

where: $\mathrm{X}_{\mathrm{B,A}}$ represents the active autotrophic (nitrifying) biomass concentration in g m^{-3}, $\mathrm{Q}_{\mathrm{ES,d}}$ denotes the daily excess activated sludge flow rate in $\mathrm{m}^3\ \mathrm{d}^{-1}$, $\widehat{\mu}_{\mathrm{A}}$ represents the maximum specific growth rate of autotrophic (nitrifying) biomass in d^{-1}, $\mathrm{S}_{\mathrm{NH_4}}$ describes the concentration of ammonia nitrogen in the filtered sample expressed as N in g m^{-3}, K_{H} is the ammonia half-saturation coefficient for autotrophic biomass in g m^{-3}, S_{O} represents the concentration of dissolved oxygen in g m^{-3}, $\mathrm{K}_{\mathrm{O,A}}$ stands for the oxygen half-saturation coefficient for autotrophic biomass in g m^{-3} and b_{A} indicates the decay coefficient for the autotrophic (nitrifying) biomass in d^{-1}. As can be seen from Eq. (2), the change in the autotrophic biomass balance is determined on the one hand by their growth and decay, which are dependent on the wastewater temperature and pH [35] as well as sufficient substrate (S_{O} and $\mathrm{S}_{\mathrm{NH_4}}$), and on the other hand by the level of excess sludge removal. Because of the challenging influent characteristics in winter tourism regions, the question arises as to which control strategy operators should select and apply for oxygen supply and excess sludge removal in order to optimize the treatment capacity. Many aeration control studies exist to provide the aerobic volume and oxygen supply needed for nitrification, which are reviewed by Åmand, L et al. (2013) [36]. At this point a recent puplished review of Yong, L et al. (2023) [37] shows possibilities for optimized aeration control strategies for WWTPs with focus on energy consumption. Ammonia-based feedback or feedforward aeration control seems to be the most effective control strategy to address atypical influent conditions, ammonia peaks, and turning on/off swing zones, whereby the feedforward control is supposed to be the more advantageous one [38–40]. The major advantage of intermittent ammonia-based nitrification-denitrification with feedback or feedforward control is that the nitrification phase is adjusted depending on the current $\mathrm{NH_4}$-N concentration in the effluent or influent and addresses the challenges posed by increased nitrogen loads. Schraa et al. (2016 and 2019) [41,42] demonstrated in a recent model-based study that ammonia-based aeration control with optimal SRT control can improve nitrification performance and lowers energy consumption by >30 %.

Another simulation-based study done by Choubert [43] showed more than six times increased nitrification capacity against winter peak loads considering variable tank volumes. However, this strategy often cannot be implemented in existing WWTPs due to a lack of space for additional aeration tanks.

In regards to the sludge removal, the common approach to increase nitrification capacity is to increase the suspended solids concentration (Suspended solids concentration in the effluent of the aeration tank - $\mathrm{SS}_{\mathrm{EAT}}$) before the winter season and adapt the oxygen supply accordingly. It should not be forgotten, however, that the secondary clarification limits this procedure by the maximum permissible $\mathrm{SS}_{\mathrm{EAT}}$ concentration. Nevertheless, this general approach may not be sufficient for energy-optimized operation of WWTPs with the wastewater charateristics described above. In this situation, the challenge is whether to increase the SS_{EAT} concentration before the peak loads or to start the winter season with low SS_{EAT} concentrations and increase it together with the increasing load. For decisions like this, dynamic simulation provides a suitable tool to model the effect and consequences of adopted operation conditions without negatively impacting the effluent quality in existing WWTPs.

In general, there is little literature on the optimization of WWTPs in winter tourism regions. Consequently, this paper presents a dynamic simulation study which investigates the effect of timer-controlled and ammonia-based feedback-controlled intermittent-aeration in combination with three different sludge removal strategies (SS_{EAT} constant 3.0 g L^{-1}, SRT constant 20 days, SRT constant 20 days + $SS_{EAT,max}$ 3.0 g L^{-1}) to the standard operation setting of the used real WWTP. The study was set up in the simulation environment SIMBA# 3.2 with the WWTP Montafon (Austria, population equivalent PE_{120} of 52,000 p.e.) which is a WWTP in a typical winter tourism region.This work investigates and assesses the performance of operation and control strategies to achieve compliance with emission limits, maximize nitrification capacity and nitrogen removal, and minimize energy consumption. These new insights provide the base for beneficial predictive plant operation within the information of expected loads and contribute the body of knowledge for wastewater treatment in winter tourism regions.

2. Materials and methods

Austria's Winter tourism sector, especially in the western federal states (Vorarlberg, Tyrol, Salzburg) exemplifies wastewater challenges in winter tourism regions. Austria's typical winter tourist season begins in November and ends in April. According to the annual report of the National Institute for Statistics (Statistik Austria 2022), the number of accommodations and bed occupancy in winter tourism regions increased by 18 % and 2.8 %, respectively, between 2012 and 2018 [44,45]. This development also poses new challenges for wastewater treatment. The WWTP Montafon (Vorarlberg) was elected as a suitable case study to evaluate the results from the simulation study. The plant treats the wastewater of the winter tourist region Silvretta Montafon in a high alpine region. The WWTP Montafon is designed according to the DWA-A 131 (1992) Guidelines [46] around 25 years ago and is now increasingly reaching its performance limits. Table 1 lists values for capacity design and treatment goals. The design is according to the German guideline A 131 (2002) [47] for a COD load of 6250 kg d^{-1} and a daily dry weather water discharge of 12,700 m^3 d^{-1}. This corresponds to a population equivalent (PE_{120}) of 52,000 p.e. and represents a typical small to medium-sized WWTP. According to national requirements (AAEV 1996) [48], the current maximum permissible day-average ammonia (NH_4 - N) concentration in the effluent is 5 mg NH_4-N L^{-1} and max. 10 mg NH_4-N L^{-1} if the day-average wastewater treatment temperature is higher than 8 °C.

The mechanical stage consists of two parallel longitudinal sand traps (2×180 m^3) and two primary settling tanks (2×620 m^3). Two structurally identical aeration tanks (2×3088 m^3) operated in serial mode and three secondary clarifiers (3×975 m^3) in parallel mode represent the biological treatment stage. Each aeration tank consist of 2 zones, where each first zone (2×588 m^3) is operated as a separate anoxic zone (1.1 & 2.1). The activated sludge process in the biological treatment stage achieves carbon removal, nitrification, denitrification and biological and chemical phosphor removal. Intermittent aeration in each second zone (2×2500 m^3, 1.2 & 2.2) provides an oxygen supply for the nitrification process. The intermittent aeration (nitrification and denitrification) follows an alternating aeration/mixing cycle according to a timer control with static intervals. An anaerobic digestor is in place to stabilize primary and excess sludge. The process water is returned to the influent.

Table 1
Design values and effluent emissions limits of the WWTP Montafon.

Wastewater Flow			
Maximum dry weather influent	m^3 d^{-1}	12,700	–
Maximum rainwater influent	L s^{-1}	300	–
Design Load			
COD	kg d^{-1}	6250	–
Effluent emission limits	°C	$8 < T < 12$	$T \geq 12$
COD concentration	mg L^{-1}	60	60
COD removal	%	90	90
NH_4 concentration	mg L^{-1}	5	5
Total nitrogen removal	%	–	70

2.1. Model setup and assumptions

The WWTP was set up in the simulator environment Simba#3.2 [49]. The simulation system SIMBA is a software for modeling and simulating wastewater systems. In this software, generally used activated sludge models such as ASM 1, ASMd2 or ASM3 [50], models for sedimentation tanks or selected anaerobic models according Emebu et al. [51] can be implemented using free ASM generators. These activated sludge models can then be combined with hydraulic sub-model blocks such as ideal mixed tanks for aeration tanks or sedimentation tanks. The advantages of this software environment are that real procedural and control processes, such as aeration concepts, can be modeled realistically thanks to the free model development and flexibility. Then the models for the respective blocks are solved numerically with the help of dynamic input values for each time step.

For the model structure of the WWTP Monafon, information was obtained on physical plant data such as tank volumes, depths layout and flow scheme, P&I diagram (piping and instrumentation diagram), operational settings such as operational measures and set-points which are applied to deal with the plant load and its variations (e.g. parameters for aeration control) and the associated operating data. A modified ASM3 without biological phosphorus removal was used as the basis for the biochemical wastewater treatment processes [50,52]. This numerical activated sludge model has been developed for wastewater of municipal composition, for a wastewater temperature range of 8–23 °C and a pH value range of 6.5 to 7.5. These conditions are fulfilled for the simulation of the WWTP Montafon according to the operating data.

When WWTPs are to be modeled, a certain number of simplifications and assumptions must be made in order to make the model structure traceable. These simplifications and assumptions for the WWTP Montafon modeling are the static generation of diurnal variations of the influent wastewater amount, constant fractionation of the wastewater COD and N influent loads (biodegradable or nobiodegradable and dissolved, soluble or particular) according the suggested default values of the ASM3 without the measured NH_4-N influent concentration fraction. The recommended default parameters at a temperature of 20 °C were used for the for Mono kinetics saturation constants. Growth rates for the autotrophic and heterotrophic organisms are interpolated according to the recommeded approach of Henze et al. [50] as a function of the wastewater temperature. The aeration tanks are assumed to be ideally mixed in the model and zones 1.1 and 2.1 are assumed to be purely anoxic zones. The 3 secondary clarifiers are modeled with one secondary clarifier with the total surface area and a volume of the 3 real secondary clarifiers. The applied secondary clarifier uses a 3 layer model and a tow-term exponential function for the settling velocity without biological processes according to the DWA-A 131 (1992) Guidelines [46].

Fig. 1S in the supplementary materials shows the hydraulic model configuration of the WWTP Montafon. The influent modeling according to Langergraber et al. [53] including the primary settling tank is summarized in the macro block influent. The two structurally identical aeration tanks (2×3088 m^3) operated in serial mode are shown as 2 separate ideally mixed zones, whereby each first zone (zone 1.1 and 2.1) is used as a denitrification zone. Zones 1.2 and 2.2 inlcuding control blocks which are available for the aeration strategies. A SRT calculation is implemented in the SRT control block.

2.2. *Calibration and Validation of the model setup*

The basis for the calibration and validation are measured operating data of the WWTP Montafon according to the measurement protocol ÖWAV rule sheet #13 [54] from November 2016 to April 2019. This period includes 3 winter tourism seasons and ensures successful modeling and calibration of the WWTP Montafon.This rule sheet requires monitoring and recording of both online and daily average measurements of operating parameters such as wastewater volume, influent and effluent concentrations (COD, NH_4-N, etc.), wastewater temperatures as well as energy consumption for the aeration. These operating data were previously checked for plausibility and correctness (comparison with typical rations, mass balancing, outlier detection). In the calibration, the simulated data such as inlet COD and N loads to the biological stage, the aeration volume and energy consumption of the aeration and the effluent concentrations (NH_4-N, NO_3-N, inert COD) of the secondary clarifier are compared with the operating data in the period form November 2016 to April 2018 as recommended by the IWA Task Group on Good Modeling Practice [55]. Deviations from the measurement data are minimized by adjusting the model parameters. The model was then validated according to the guidelines for acceptable error ranges according to the IWA Task Group on Good Modeling Practice using the winter season from November 2018 to April 2019. This ensures that the simulation results are reliable predictions for the real wastewater treatment process.

2.3. *Setup of cases for simulation*

The studied simulation period t_{obs} is defined from November 2019 to the end of April 2020 (181 days). All typical influent fluctuations, disturbances, peaks, sudden temperature drops, etc., describing a specific winter tourism influent pattern occur in this period.

The simulation case studies investigated are characterized as follows:

Case 0. Case 0 represents the digital twin of the WWTP Monafon with its current operating mode. This case is used as a comparison for the other cases because of the detailed calibration of the model. The intermittent nitrification-denitrification phases are static timer-controlled (20 min nitrification, 30 min denitrification). These time phases have been determined by the operating experience of the operators. The WWTP is operated with constant SS_{EAT} concentration of approximately 3 g L^{-1} as standard. For the comparison, a constant S_{SEAT} concentration setpoint at 3 g L^{-1} is therefore used as the setpoint for the sludge removal control.

Case 1. The first step is to investigate the effects that SRT control can have on the performance of the WWTP Montafon. The SRT at a wastewater temperature of 8 °C should be reasonably high to maintain sufficient nitrifying biomass in the system. Nitrification must be guaranteed down to a wastewater temperature of 8 °C according to national requirements AAEV 2021 [48]. According to Eq. (3), which is based on the German guideline A 131 E (2016) [47], the minimum SRT at 8 °C with a maximum autotrophic growth rate $\mu_{A,max}$ must be 19.55 days (Knowles et al. [56]). Therefore, the sludge removal control of the simulation model was adapted to hold the average SRT_{min} to 20 days.

$$SRT_{min} = 1.5 \cdot \frac{1}{\mu_{A,max}} \cdot 1,6 \cdot 1.103^{(15-T)} = 19.55 \sim 20 \text{ days} \tag{3}$$

Case 2. Case 2 investigates how an ammonia-based feedback control based on the NH_4-N aeration tank effluent concentration can improve the performance of the WWTP. Based on Case 0, an ammonia-based feedback intermittent aeration control for oxygen supply instead of a static time-control aeration interval is implemented. The starting point for determining the control parameters is that the NH_4-N effluent concentration must range between 0 and 5 mg L^{-1}. Therefore, the nitrification phase is initiated from an NH_4-N aeration tank (2.2) effluent concentration of 3 mg L^{-1}. Thus nitrification is initiated with a safety buffer of 2 mg L^{-1} NH_4-N in the aeration process to prevent N breakthroughs during N load peaks. In the nitrification phase, aeration is carried out with 2 mg L^{-1}, as higher concentrations of dissolved oxygen significantly increase the energy consumption of the aeration and 2 mg L^{-1} sufficiently cover the oxygen requirement of the nitrifying bacteria [36]. If the NH_4-N concentration in the effluent of the aeration tanks (effluent zone 2.2) falls below 1 mg L^{-1}, aeration is stopped. From this point on, the denitrification phase begins. The denitrification phase is also aerated with a reduced dissolved oxygen concentration (1.2 mg L^{-1}) to prevent N breakthroughs due to the longer activation time (lag phase) of the nitrifying bacteria in case of low wastewater temperatures (<12 °C). This mode of operation is permissible, as denitrification is not required at wastewater temperatures below 12 °C according to national guidelines [48]. If the NH_4-N concentration in the effluent of zone 2.2 rises above 3 mg L^1, the nitrification phase is initiated again. The SS_{EAT} concentration setpoint is set at 3 g L^{-1} for the sludge removal control.

Case 3. A combination of SRT control as in Case 1 and ammonia-based feedback intermittent aeration control as in Case 2 can combine the possible advantages. How much performance gain can be expected is examined in this case. The parameter settings for the SRT control and for the ammonia-based feedback intermittent aeration control were retained from Cases 1 and 2.

Case 4. In the case of high COD loads, the SS_{EAT} concentration will increase at a constant SRT. However, the maximum SS_{EAT} concentration is limited by the performance of the secondary clarifiers. In Case 4, the same configuration is used as in Case 3, with the difference that the SS_{EAT} concentration of 3 g L^{-1} is limited to a maximum by a high-level sludge removal controller. This case should demonstrate the impact of the limited secondary clarifier capacity in case the maximum permissible SS_{EAT} concentration in the system is reached. Table 2 summarizes the different investigated cases.

2.4. *Dynamic SRT calculation*

The dynamic SRT was calculated according to the approach of Tak-

Table 2
Summary of the simulated cases at current operational and aeration control settings.

Cases	N – DN Control	O_2 control	SS_{EAT} Control	SRT Control
Case 0:	Pre-anoxic denitrification in zone 1.1 & 2.1 with supplementary intermittent denitrification in zones 1.2 and 2.2	Phase duration: 50 min	3 g L^{-1}	No
Case 1		Winter setting (< 12 °C) on: 2 mg L^{-1} (40 %), off: 0 mg L^{-1} (60 %) Summer setting (> 12 °C) on: 1.2 mg L^{-1} (40 %), off: 0 mg L^{-1} (60 %)	No	20 days
Case 2	Ammonia-based feedback control	Winter setting (< 12 °C)	3 g L^{-1}	No
Case 3	Ammonia-based feedback control	NH_4-$N < 1$ mg L^{-1} 0 mg L^{-1} O_2	No	20 days
Case 4	Ammonia-based feedback control	NH_4-$N \geq 3$ mg L^{-1} 2 mg L^{-1} O_2 Sommer setting (> 12 °C) NH_4-N < 1 mg L^{-1} 0 mg L^{-1} O_2 NH_4-N ≥ 3 mg L^{-1} 1.2 mg L^{-1} O_2	max SS_{EAT} 3 g L^{-1}	20 days

cas (2008) [57] according to Eq. (4):

$$\frac{dSRT}{dt} = 1 - \frac{SRT \cdot F_P}{M} \tag{4}$$

where SRT is the sludge retention time in the aeration tank in d, M the mass of solids in the system in kg and F_p is the mass of solids produced in the system in kg SS_{EAT} d^{-1}.

2.5. Controller setup for aeration and sludge removal control

The intermittent nitrification-denitrification phases of the WWTP Montafon are controlled by a static timer with a phase duration of 50 min. In the actual control strategy, nitrification duration is for 20 min (40 % of the phase duration), and the denitrification phase is set to 30 min (60 % of the phase duration). Control of the oxygen supply is achieved with a proportional-integral (PI) controller. The setpoint for the oxygen concentration during the nitrification phase depends on the wastewater temperature in the aeration tanks. If the wastewater temperature is below 12 °C, the setpoint is 2 mg L^{-1}; otherwise, the setpoint is 1.2 mg L^{-1}.

To determine the effects of a constant SRT control, a SRT PI controller was inserted into the simulation model with the state variable of the calculated SRT according to Eq. (5) which returns the calculated setpoint for the excess sludge flow.

$$SRT = 1.5 \cdot \frac{1}{\mu_{A,max}} \cdot 1,6 \cdot 1.103^{(15-T)} \tag{5}$$

In Cases 0 and 2, the current SS_{EAT} concentration in zone 2.2 is the state variable for the SS_{EAT} PI controller. In Case 4, SRT control is limited by a maximum SS_{EAT} concentration. If the SS_{EAT} concentration is below 3 g L^{-1}, only the SRT controller specifies the setpoint for excess sludge removal. In case the SS_{EAT} concentration of 3 g L^{-1} is exceeded, the SS_{EAT} PI controller overrides the SRT controller to achieve a constant SS_{EAT} concentration of 3 g L^{-1}.

A 2-point controller was implemented to realize the ammonium-based intermittent aeration control, which presets the setpoint for the oxygen concentration as a function of the NH_4-N effluent concentration in the effluent of zone 2.2. If the NH_4-N concentration exceeds 3 g L^{-1}, either 2 g L^{-1} ($T < 12$ °C) or 1.2 g L^{-1} ($T > 12$ °C) is specified as the oxygen concentration setpoint. Zones 1.2 and 2.2 are not aerated if the NH_4-N concentration falls below 1 g L^{-1}.

2.6. Performance assessment

For the evaluation of the aeration control and sludge removal strategies, evaluation parameters derived from the benchmark Model 1 (BSM1) [58] were used. The used evaluation parameters are defined for the investigation as follows:

a) A number of overruns of upper limits (COD, NH_4-N) according to Table 1.
b) Mean of degrees of overall removal (COD, N at T > 12 °C) in the simulation period t_{obs}.
c) The Effluent Quality Index (EQI) is based on weighted effluent loads deduced from Vanrolleghem [59] (Table 3) and defined according to Eq. (6):

$$EQI = \frac{Q_{e(t)}}{t_{obs} \cdot 1000} \int_{t=0}^{t_{obs}} B_{TSS} \cdot TSS_{e(t)} + B_{COD} \cdot COD_{e(t)} + B_{NK} \cdot S_{NK,e(t)} + B_{NO} \cdot S_{NO,e(t)} + B_{BOD5} \cdot S_{NO,e(t)} dt \tag{6}$$

Table 3
Weighting factors for the Effluent Quality Index (EQI).

Weighting factors	Unit	B_{TSS}	B_{COD}	B_{NK}	B_{NO}	B_{BOD5}
Factor	g/g	2	1	30	10	2

d) The aeration energy is calculated using Eq. (7):

$$E_{aer} = \frac{h \cdot O_P}{t_{obs} \cdot 1000} \int_{t=0}^{t_{obs}} SSOTR \cdot Q_{aer(t)} \cdot \alpha dt \tag{7}$$

where $Q_{aer(t)}$ is the air flow rate in m^3 h^{-1} as derived from the simulation, SSOTR is the specific standard oxygen transfer rate defined as 18, gO_2 m^{-3} m^{-1}, O_P defines the average oxygen yield of 1,8 kg O_2 kWh^{-1} according to the evaluation of the operational data, h represents the depth of the aerated activated sludge tanks of 5 m, α expresses the α factor for fine-bubble pressure aeration according to Krampe and Krauth [60] with $\alpha = e^{0.08688 \cdot SS_{EAT(t)}}$ as function of the SS_{EAT} concentration in the aeration volume.

e) For calculation of the total sludge production SP_{total}, Eq. (8) is used, including the excess sludge production from Eq. (9).

$$SP_{total} = SP + \frac{0,75}{t_{obs}} \int_{t=0}^{t_{obs}} SS_{EST(t)} \cdot Q_{EST(t)} dt \tag{8}$$

$$SP = \frac{1}{t_{obs}} \left(SS_{AET(t=0)} - SS_{AET(t=obs)} \right) + 0,75 \int_{t=0}^{t_{obs}} SS_{RS(t)} \cdot Q_{ES(t)} dt \tag{9}$$

where SS_{EAT} represents the Suspended solids concentration in the effluent of the aeration tank in kg m^{-3}, SS_{RS} stands for the suspended solids concentration in the return (activated) sludge in kg m^{-3}, SS_{EST} expresses the suspended solids concentration in the effluent of the secondary settling tank in kg m^{-3}, Q_{ES} indicates the excess activated sludge flow rate in m^3 d^{-1} and Q_{EST} is the effluent flow rate of the secondary settling tank in m^3 d^{-1}.

3. Results and discussion

The wastewater characteristics in winter tourism regions differ from municipal wastewater from catchment areas without pronounced changes in climatic conditions and population. The differences are characterized by strong seasonal COD and N load fluctuations, COD and N peak loads and temperature drops. Simulation studies carried out to optimize WWTPs for COD and N removal and energy consumption reviewed by reviewed by Åmand, L et al. (2013) [36] and Yong, L et al. (2023), however, do not explicitly show smart approaches for WWTPs in winter toursm regions with these special wastewater characteristics. Therefore, the basic wastewater data of the Montafon WWTP will be presented, followed by an assessment and discussion of the simulation results of the cases investigated.

3.1. Influent characteristics in winter tourism regions

Basic influent data of the studied WWTP, such as daily hydraulic inflow, daily average effluent temperature, daily COD, and NH_4-N loads, including the comparison to the corresponding annual mean loads, are shown in Fig. 1 (a-c) in order to demonstrate framing conditions and the challenges of wastewater treatment in winter tourism regions.

From the beginning of the official winter season in November until early December, there hardly are any tourists in the catchment area. But daily COD and NH_4-N loads abruptly increase at the beginning of December, especially during weekends. The highest loads were found during Christmas holidays with up to 12,000 kg d^{-1} and 700 kg d^{-1} NH_4 - N and around New Year's Eve and New Year's Day. These influent loads

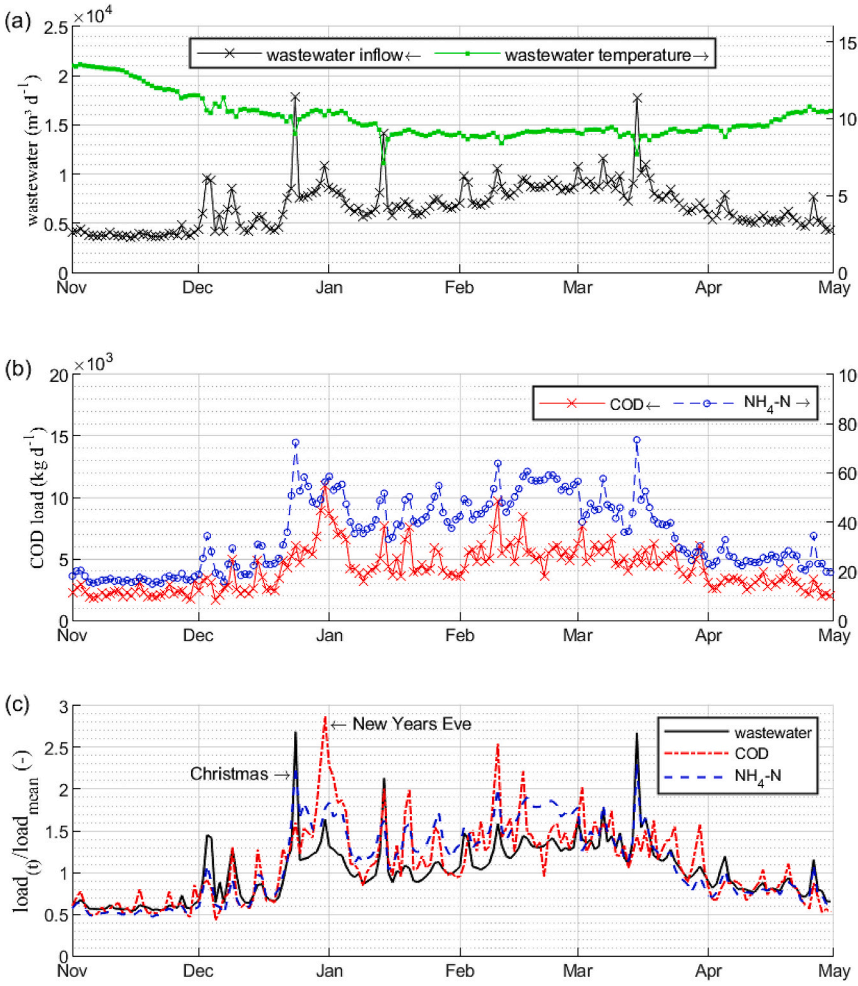


Fig. 1. (a) Daily hydraulic inflow and daily average wastewater temperature in the winter season. (b) Daily COD and NH_4-N influent load. (c) Comparison of measured daily wastewater inflow, calculated COD, and NH_4-N loads related to the corresponding annual mean load from November 2018 to the end of October 2019.

correspond to a 4–5 fold increase compared to the daily inflow observed a month earlier. Continuously decreasing wastewater temperatures from the beginning of November additionally are superimposed on this situation. Short-term drops in wastewater temperature result in melting water impact, as observed in mid-January.

It was found that not only the load, but the mean daily influent concentration for COD and NH_4-N is higher during the winter season too. This may well be due to a reduction in infiltration water into the sewer system during the frost period and less water consumption per day tourist resulting in reduced dilution. Furthermore, an increased NH_4-N/COD ratio can be observed (mid December to April), again likely caused by day tourists and representing a further challenge for nitrification and subsequent denitrification.

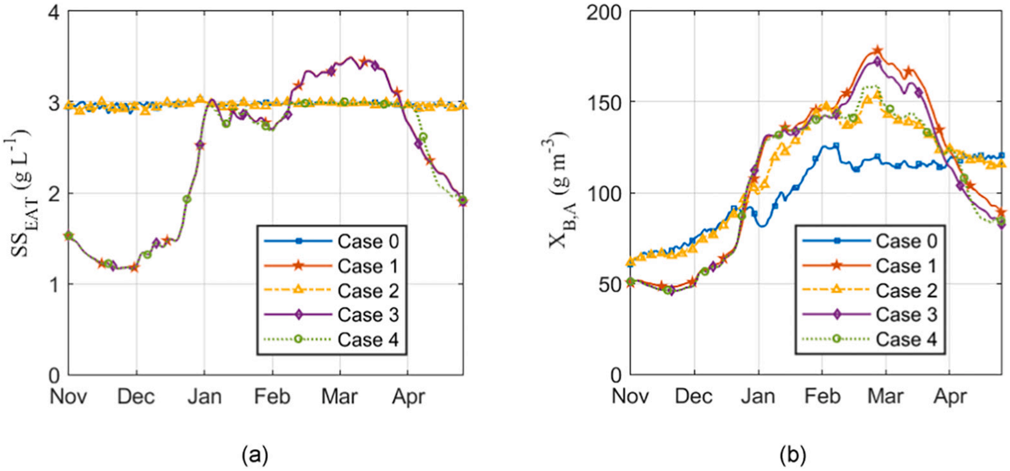


Fig. 2. (a) Comparison of the SS_{EAT} concentration (b) Concentration of the ammonia-oxidizing bacteria $X_{B,A}$ according to the simulated Cases (0–4).

3.2. Evaluation of nitrification performance based on operational process parameters

In this subchapter, the operational process parameters SS_{EAT}, $X_{B,A}$, NH_4-N effluent concentration and the COD and N removal of the investigated Cases 1–4 were compared to the reference Case 0. The different excess sludge removal strategies influence the SS_{EAT} concentration and the concentration of active autotrophic, nitrifying bacteria ($X_{B,A}$) in opposite ways. Fig. 2 (a) shows the effects of the different control strategies on the daily mean SS_{EAT} concentration. Fig. 2 (b) shows the daily mean concentration of active autotrophic bacteria ($X_{B,A}$) for the examined 5 different control strategies studied.

In contrast to Cases 0 and 2, the SS_{AET} concentration is lower in the cases with an SRT for 20 days (Case 1, Cases 3 and 4), which is caused by the low daily COD inflow loads in November and December. Consequently, the concentration growth and subsequent abundance of autotrophic bacteria is low. For Case 0, the concentration of active autotrophic bacteria only increases with higher NH_4-N loads from the beginning of December until a local maximum at about December 24th–25th. From there on, their concentration is higher for the cases where the SRT is controlled to 20 days (Cases 1, 3–4) compared to the cases with constant SS_{EAT} control (Cases 0 and 2).

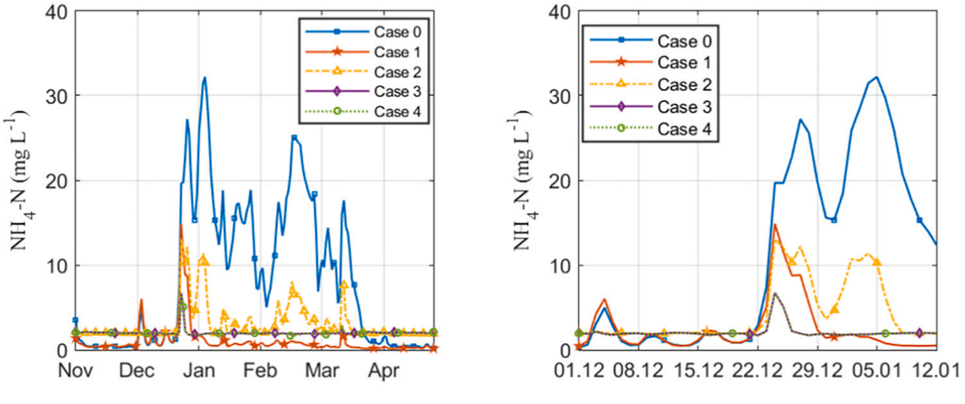
The comparison of Cases 0 and 1 shows that setting the SRT to 20 days (Case 1) would substantially increase the concentration of autotrophic bacteria compared to the status quo (Case 0). This additional nitrification capacity can be maintained until the high loads decrease in January. On average, with this strategy, the nitrification capacity can be increased by approx. 20 % related to Case 0 in the observed period from January to April. The ammonium-based intermittent-aeration control strategy (Case 2) increases the nitrification capacity concerning the mass of autotrophic bacteria by a factor of 1.12. This demonstrates that ammonium-based intermittent aeration favors the growth of autotrophic bacteria in periods of high NH_4-N inflow loads and low wastewater temperatures (Fig. 2 (b)) compared to an intermittent aeration controlled by a static timer.

The daily mean NH_4-N effluent concentrations for the modeling results are presented in Fig. 3 (a). Case 0 represents the worst nitrification performance in periods of high NH_4-N inflow loads. The crucial loads are around December 24th (Christmas) and New Year's day. However, biomass growth is very high during this period due to the high COD and NH_4-N influent loads. This situation leads to high rates of excess sludge removal in case of constant SS_{EAT} control and decreasing SRT. This implies that the high excess sludge removal also removes newly grown autotroph biomass from the system, that subsequently is unavailable for the necessary nitrification.

NH_4-N breakthroughs are particularly noticeable during inflow peaks around Christmas and New Year, which are shown in detail in Fig. 3 (b). Case 1 leads to a substantial decrease in NH_4-N effluent concentrations compared to Case 2, as evidenced by an increased nitrification capacity by approx. 20 % compared to 12 % in Case 2. This circumstance indicates that an SRT control to 20 days prevents more NH_4-N breakthroughs than only an ammonium-based feedback intermitted-aeration control strategy. This confirms that ammonium-based oxygen control contributes to compliance with the NH_4-N emission limits in comparison to the simulation case study according Rieger et al. [38–40]. However, sufficient active nitrifying bacteria must also be present in the activated sludge for nitrification, which is explicitly shown in this work. Without sufficient nitrifying bacteria, the ammonium-based aeration control would otherwise constantly aerate, increase energy consumption enormously and would not contribute the compliance to the NH_4-N emissions.The combination of both strategies, SRT control to 20 days and ammonium-based feedback intermitted-aeration control, is applied in Case 3. It can be noted that this combination integrates these two favorable properties for further enhancement of nitrification. Furthermore, a complete NH_4-N load treatment is impossible at the first load peak, as a kinetic limitation occurs. These results confirm the efficient performance of this control strategy which was first investigated by Schraa et al. [41] Schraa describes a 10 % reduction in of energy consumptions compared to ammonia based aeration control on its own and 25 to 30 % compared to traditional DO control at storm events. In this work it is shown that this control strategy of coupling SRT control and ammonia based oxygen control is not only suitable for storm events but also for the previously shown influent conditions in Fig. 1.

The comparison between Case 4 to Case 3 in Fig. 3 a) and b) shows that the daily average NH_4-N effluent concentrations are similar. The results obtained for NH_4-N removal in Case 4, with a limitation to a maximum SS_{EAT} of $3\ g\ L^{-1}$, are already sufficient to comply with the required daily average NH_4-N effluent limits. However, the nitrification capacity is only increased by 14 % compared to Case 0.

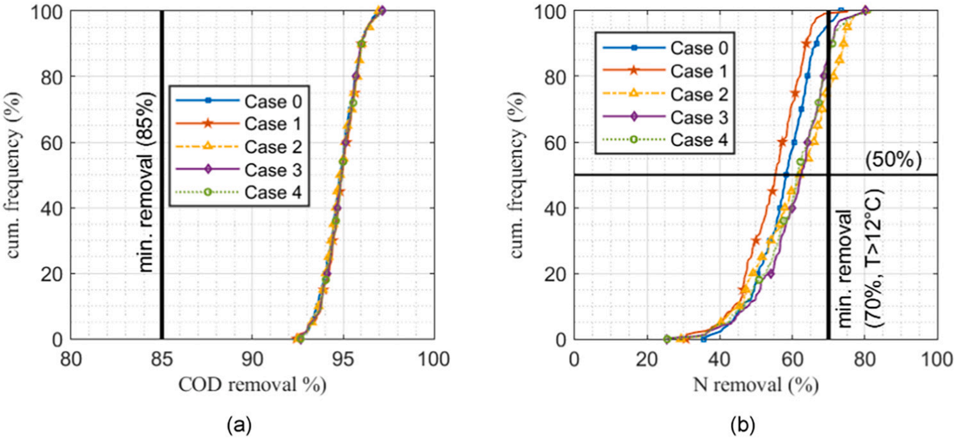
Fig. 4 shows the cumulative frequency of the COD and N removal in percent. The minimum COD removal must be at least 85 % according to the permitted level and the N removal must be above 70 % as an annual average at a daily average wastewater temperature of >12 °C. The COD removal is not limited in all simulation scenarios as well as the reference scenario in Case 0 and removal consequently does not change due to the different aeration and sludge removal strategies. In contrast to COD removal, the examined control strategies differently influence N removal (denitrification). Both Case 0 and Case 1 represent the lowest percentage of nitrogen removal. A higher denitrification performance was observed in Cases 2, 3, and 4 with no significant difference between Cases 3 and 4. This was also found for the NH_4-N nitrification in these cases. In contrast, higher N removal can be achieved in Case 2. However, the average N removal (50 % cumulative frequency) of Case 2 equals the



(a)

(b)

Fig. 3. (a) Comparison of the daily mean NH_4-N effluent concentration for the five examined cases and (b) detail results from 1. December to 12. January.



(a) (b)

Fig. 4. (a) Cumulative frequency of COD removal efficiency. (b) Cumulative frequency of N removal.

N removal of Cases 3 and 4.

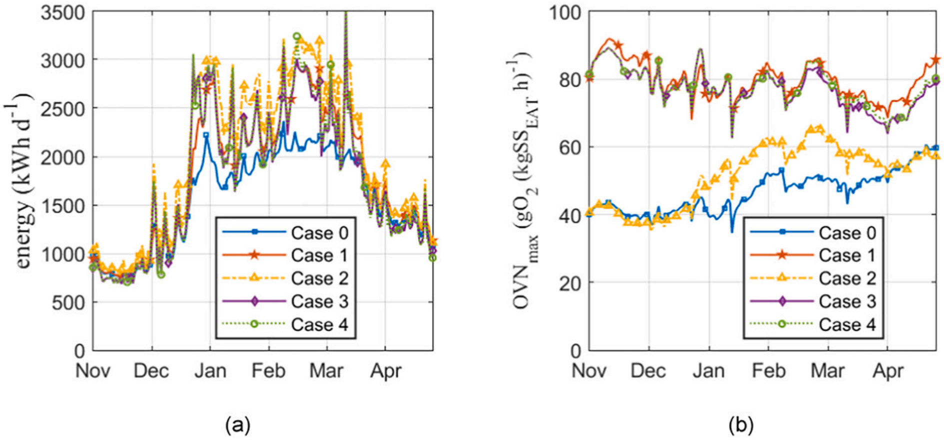
3.3. Evaluation of energy consumption for aeration based on operational process parameters

How much energy is needed to treat the wastewater is a key performance indicator for WWTPs. However, the energy consumption depends on many local boundary conditions, with the size of the system having the greatest influence on the specific energy consumption [6]. Typical values for the specific energy consumption are between 0.18 kWh m^3 and 0.8 kWh m^3 (Longo et al., 2016), representing on average 40 % and 75 % of the total energy consumed in large and small plants, respectively (Mamais et al., 2015). In relation to the population equivalent (PE$_{120}$) - with a daily wastewater consumption of a resident of approximately 0.15 m^3 d^{-1} - the energy consumption of the aeration is approximately between 27 Wh PE$_{120}^{-1}$ d^{-1} and 121 Wh PE$_{120}$ d^{-1}. Fig. 5 (a) shows how much daily average electrical energy consumption per day can be expected for aeration for the different cases. The results show that the electrical energy consumption is higher in all cases compared to Case 0. This is understandable as in Case 0 the fewest autotrophic active microorganisms are present in the activated sludge and less oxygen is required. However, this means that the NH$_4$-N discharge limits cannot be complied with. It is therefore important to know the concentration of active nitrifying bacteria. The concentration of nitrifying bacteria can be simulated indirectly via the maximum specific oxygen respiration OVN. The courses of the average daily theoretical maximum oxygen respiration for nitrification (OVN$_{max}$) per hour and kg SS$_{EAT}$ are shown for that reason in Fig. 5 (b). The following insights can be drawn from this: 1) Cases with constant SRT control to 20 days (Cases 1, 3 & 4) allow a much higher nitrification performance. On average, the nitrification capacity can be increased by approximately 35 % in comparison to Case 0. 2) The ammonium-based feedback intermitted-aeration control in Case 2 also increases the nitrification capacity compared to Case 0 over a longer time. Still, it does not provide the minimum amount of nitrifying bacteria in the activated sludge for sufficient nitrification performance and therefore can not be considered as a suitable strategy in contrast to the Cases 1, 3 & 4. A comparison of energy consumption therefore only appears to make sense for Cases 1–4, in which the emission limits are also largely complied with. The simulated specific energy consumptions for aeration per day in relation to the population equivalent PE$_{120}$ are listed in Table 4. The average COD load is 31.760 PE$_{120}$ during the investigated time period from November to April.

The results of Cases 1, 3 and 4 show that a clear recommendation can be made to minimize the energy consumption for the aeration. SRT control to a constant 20 days is very energy efficient for the influent characteristics presented in this article compared to typical values

Table 4
Comparison of the energy consumption for the aeration of the investigated cases.

	Unit	Case 1	Case 2	Case 3	Case 4
Specific aeration energy consumption	Wh PE$_{120}^{-1}$ d^{-1}	57	63	57	57



(a) (b)

Fig. 5. (a) Maximum oxygen respiration of active nitrifying bacteria in relation to the SS$_{EAT}$ concentration in the system. (b) Average daily electrical energy consumption for the aeration in the biological state.

between 27 Wh PE_{120}^{-1} d^{-1} and 121 Wh PE_{120}^{-1} d^{-1}. From these results it can be deduced that only an additional ammonia based oxygen control does not reduce energy consumption under the influent conditions described, which is in contrast to the selected simulation studies [39,40,61], where it is shown that ABAC generally leads to energy savings. Cases 3 and 4 are recommended in any case, as these configurations provide higher treatment capacities at N peak loads due to the higher concentrations of autotrophic bacteria with regard to increasing nitrification capacity and energy-efficient wastewater treatment. However, there is further potential for increasing the energy efficiency of existing WWTPs through a wide range of measures, such as replacing old, low-efficiency units with high-efficiency units (pumps, compressors) or replacing aerator panels with more efficient models. General approaches for increasing the energy efficiency of WWTPs were recently published by Cardoso et al. [6] and by Gu et. Al [37] recently published on this topic.

3.4. Performance assessment

Table 5 summarizes the comparison of all simulated cases based on the defined assessment parameters. Section (a) presents the absolute and section (b) the relative changes to Case 0. Fig. 6 shows a comparison of the investigated cases in a spider diagram with the used assessment parameters effluent quality index (EQI, range 6–9 t d^{-1}), energy consumption for aeration (Energy, range 1200–2200 kWh d^{-1}), total sludge production (SP_{total}, range 30–50 t d^{-1}) and nitrogen removal (N_{rem}, range 40–70 %) and effluent NH_4-N concentration (NH_4-$N_{effl,}$ > 5 mg L^{-1}). Case 0 is the worst operating variant in regard to NH_4-N effluent exceedances (NH_4-$N > 5$ & > 10 mg L^{-1}). Remarkably this is not represented by the effluent quality index. The EQI comparison shows that Case 1 scores the worst due to decreased N removal. The results show no significant change in sludge production, but substantial differences exist in the electrical energy consumption for aeration. This is because the electrical energy consumption for aeration depends on the choice of oxygen control, nitrification, and the SS_{EAT} concentration. Energy consumption is lowest for Case 0 since there is no sufficient nitrification. In general, ammonium-based feedback intermittent-aeration control is reported to reduce aeration energy [38]. This could not be detected in this study. Sufficient autotrophic bacteria must be present in the system to result in adequate nitrification. If there are not sufficient nitrifying bacteria in the system, the ammonium-based intermittent aeration control will continuously turn on aeration to comply with the NH_4-N effluent limits. Case 2 shows a significant increase in energy consumption up to 28 % to meet the NH_4-N effluent limits compared to Case 0. Nevertheless, the NH_4-N effluent limits are not permanently met due to the low concentration of autotrophic bacteria. Compared to Case 2, the strategies in Cases 3 and 4 represent a simultaneous reduction in energy consumption and improved compliance with the NH_4 - N emission requirements. This is based on the fact that in both cases more autotrophic bacteria are present in the system.

Table 5
Summary and comparison of the performance assessment regarding Case 0.

(a)	NH_4-N >5 mg L^{-1}	NH_4-N >10 mg L^{-1}	EQI	SP_{total}	Energy	N removal
Unit	[−]	[−]	t/d	t/d	*10^3 kWh/d	%
Case 0_{abs}	91	68	7,45	41	1,56	58
Case 1_{abs}	7	2	8,53	42	1,81	54
Case 2_{abs}	23	8	7,62	41	2	60
Case 3_{abs}	2	0	7,45	42	1,77	61
Case 4_{abs}	2	0	7,45	42	1,68	60

(b)	Unit	NH_4-N >5 mg L^{-1}	NH_4-N >10 mg L^{-1}	EQI	SP_{total}	Energy	N removal
Case 0_{rel}	%	100	100	100	100	100	100
Case 1_{rel}	%	7	3	114	101	117	93
Case 2_{rel}	%	25	12	102	101	128	103
Case 3_{rel}	%	2	0	100	101	113	105
Case 4_{rel}	%	2	0	100	102	108	103

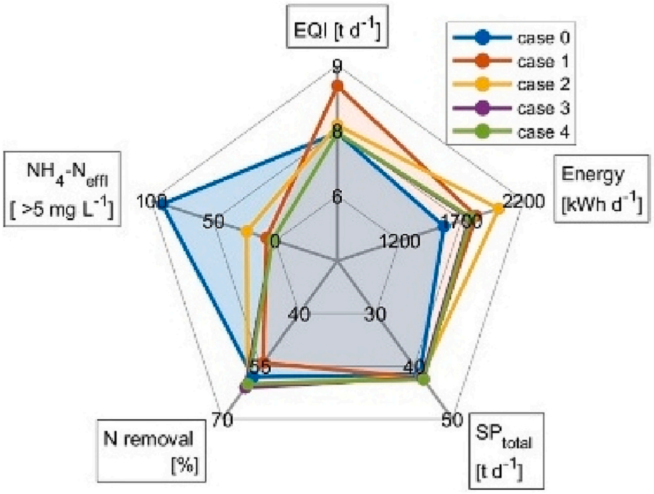


Fig. 6. Changes of the assessment parameters to the reference Case 0.

The SS_{EAT} concentration in Case 4, in contrast to Case 3, is limited to a maximum of 3 g L^{-1}, which has a beneficial effect on energy consumption. Overall, it can be concluded that an ammonium-based oxygen control combined with an SRT control to 20 days and a limitation of the SS_{EAT} concentration to approx. 3 g L^{-1} as in simulation Case 4 results in the best treatment performance and energy efficiency.

3.5. On-site validation of the most promising strategy

For validation of the simulation results, the strategy defined in Case 1 was implemented on site at the WWTP Montafon during the winter season of 2019/20. For this purpose, the excess sludge removal was continuously adjusted manually by the operators so that a sludge age of approx. 20–25 days was maintained. For Cases 2, 3 and 4, an ammonium-based feedback control for aeration would have to be implemented, which was not implemented at the time of validation. This case is the most “promising” case due to low implemention effort and high increase in nitrification capacity compared to the other Cases (2,3 and 4). The results from the large-scale implementation confirm the simulation results from Case 1. In Case 1 the emission limit value for the NH_4-N effluent concentration of 5 mg L^{-1} is compliant in contrast to Case 0. Fig. 2S shows the comparison of the real measurements with optimized process control for the winter season 2019/20 to the baseline (Case 0) from prior winter season 2018/19 as a summary of operating data according daily COD and NH_4-N load, daily average wastewater temperature, SS_{EAT}, daily average NH_4-N effluent concentration and daily average energy consumption for aeration. The comparison of the two seasons is permissible insofar as the COD and NH_4-N load and the wastewater temperatures are almost identical. The restrictions in tourism due to the coronavirus pandemic explain the divergence in NH_4-N load from mid-March 2020, but this has no influence on the general review of the most “promising” case. The SRT was controlled to approx. 20–25 days from the beginning of December 2019. As a result, the SS_{EAT} will fall continuously from December 2019 until a load peak at the end of December and mid-January. The previous increased removal of excess sludge in December allowed new nitrifiers to grow and be used for nitrification during periods of high N loads and low wastewater temperatures. This means that the nitrification capacity of the WWTP is optimally utilized during these periods, as already shown in the simulation results of Case 1. Consequently, the NH_4-N emission limits will be met in the 2019/20 winter season with almost the same energy consumption for aeration in contrast to the 2018/19 winter season. Based on the large-scale validation of Case 1, an SRT controlled excess sludge removal can therefore be recommended for WWTPs with similar plant configuration and wastewater characteristics for optimum utilization of the nitrification capacity and maximum nitrification performance.

4. Conclusions

Wastewater treatment in winter tourism regions can be very challenging due to fluctuating influent characteristics such as COD or N peak loads and wastewater temperature drops. Existing WWTPs therefore frequently are structurally expanded to comply with emission limits required. However, it is recommended to first exploit the maximum performance of the existing WWTPs through optimized and appropriate process control. According to literature research, however, little attention has been paid to the special framework conditions of wastewater treatment in winter tourism and smart optimization approaches have yet to be identified. This study therefore examines 5 combinations of three excess sludge removal strategies (constant SS_{EAT} concentration to 3 g L^{-1}, SRT-controlled sludge removal to constant 20 days, and SRT-controlled sludge removal to 20 days combined to a maximum SS_{EAT} concentration of 3 g L^{-1}) and two aeration control strategies (static time-controlled and ammonia-based feedback intermittent aeration). The combinations were investigated for the real WWTP Montafon (52,000 PE_{120}) in a winter tourism period by dynamic simulation. It could be shown that an SRT control to a constant value of 20 days can significantly increase the nitrification capacity up to 35 % in contrast to a constant SS_{EAT} concentration approach to 3 g L^{-1}. A postmortem On-site implementation of a constant SRT control for 20–25 days confirms the improvements for the WWTP Montafon. Intermittent aeration using ammonium-based feedback control also improves nitrification compared to a static time-controlled intermittent aeration control. An average daily energy consumption for the aeration of 57–63 Wh PE_{120}^{-1} d^{-1} is to be expected for aeration, which is very low in relation to the wastewater characteristics and in comparison with other plants according to the literature. It must be emphasized that the SRT control to 20 days significantly reduces the energy consumption for aeration in contrast to an ammonia-based aeration control. However, if only a low concentration of active nitrifying bacteria is present in the system, the energy consumption for nitrification increases significantly, especially with an ammonium-based feedback aeration control. Therefore, a combination of ammonium-based intermittent aeration control and SRT-based sludge removal control is recommended for existing WWTPs in winter tourism regions that are designed as suspended growth activated sludge processes and similar wastewater characteristics as the examined WWTP Montafon. This combination boosts the potential nitrification capacity and reduces the energy consumption for aeration while complying with emission limits. Further process optimizations are promising for future simulation research. For example, NH_4-N peak loads from anaerobic digesters should be homogenized or temporarily stored at times of high NH_4-N influent loads. However, feeding the activated sludge with NH_4-N-rich process water in low-load phases can help to selectively increase the concentration of nitrifying bacteria before the seasonal influent peak loads occur. Other process-engineering possibilities, e.g., a step-feed operation, can also improve treatment performance where additional nitrifying bacteria can grow in the system without extra SS_{EAT} potentially overcharging the secondary clarification. These approaches can be further optimization concepts for WWTPs in winter tourism regions designed as suspended growth activated sludge processes.

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CRediT authorship contribution statement

Felix Pilz: Conceptualization, Data curation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Karl Svardal:** Conceptualization, Methodology, Project administration, Supervision. **Norbert Kreuzinger:** Conceptualization, Project administration, Software, Supervision. **Jörg Krampe:** Conceptualization, Funding acquisition, Software, Supervision.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The data presented in this study are available on request from the corresponding author. The real operating data are not publicly available due to the request of the example WWTP Montafon.

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