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Design and implementation of the SRT control at the Ljubljana WWTP

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ABSTRACT

The solid retention time (SRT) is one of the most important parameters for the operation of a wastewater treatment plant (WWTP). Maintaining the SRT at the prescribed set-point is necessary to achieve an appropriate food-to-microorganism (F/M) ratio. This article describes the design and implementation of SRT control at the Ljubljana WWTP. The designed SRT control wastes a defined proportion of the mixed liquor suspended solid (MLSS) mass in the aerobic reactors. The sludge wasted from the secondary settlers is determined based on measurements of the MLSS concentration, waste sludge concentration, and waste sludge flow rate. The SRT control is simple and does not require an SRT estimation or an SRT feedback controller. It includes a constraining controller that keeps the MLSS in the aerobic reactors within the prescribed minimum and maximum values. Validation of the designed SRT control on a mathematical model of the Ljubljana WWTP shows better set-point tracking than the proportional integral (PI) SRT control, as well as reduced SRT variations and lower ammonia nitrogen concentrations compared to the initial MLSS control. The testing of the designed SRT control at the Ljubljana WWTP confirmed the set-point tracking and reduced SRT variations despite large influent variations and operational disturbances.

Key words: mixed liquor suspended solid control, solid retention time control, waste sludge control, wastewater treatment

HIGHLIGHTS

- SRT control is designed and implemented in a full-scale WWTP.
- It wastes a proportion of MLSS mass in aerobic reactors.
- It includes a constraining controller to keep MLSS within prescribed limits.
- Validation on a mathematical model shows better performance than PI SRT control and initial MLSS control.
- Real-plant testing confirms set-point tracking and reduced SRT variations despite large disturbances.

INTRODUCTION

The solid retention time (SRT), also known as sludge age, is one of the most important parameters for the operation of a wastewater treatment plant (WWTP) (Ekama 2010). Maintaining the SRT at the prescribed set-point is necessary to achieve the appropriate food-to-microorganism (F/M) ratio (Ekster *et al.* 2017). Deviations from the prescribed SRT value can cause various operational difficulties. If the SRT is too high, this can lead to a low F/M bulking, foaming, increased air demand due to endogenous respiration of the biomass, and overloading of the secondary settlers. Conversely, if the SRT is too low, this can lead to poor removal of pollutants, low dissolved oxygen (DO) bulking, and overloading of the thickening facility (Ekster *et al.* 2017).

The SRT is controlled by manipulating the waste sludge flow rate of the plant. The simplest approach to controlling SRT is hydraulic control, where a defined proportion of the reactor volume is wasted daily (Garrett 1958; Ekama 2010). This approach does not require a measurement of the suspended solids concentration. The disadvantage of this approach is that the volume of mixed liquor waste required from the reactor is up to twice as large as the volume of sludge waste from the secondary settlers. Consequently, larger pumps and pipes are required for waste sludge treatment, as well as larger sludge thickening facilities (Ekster *et al.* 2017). The implementation of such a control in plants where sludge is wasted from the secondary settlers is not feasible. The modified SRT hydraulic control can be used to waste the sludge from the secondary settlers (Stephenson *et al.* 1981). In this strategy, the waste sludge flow rate is determined from the influent and the return sludge flow rates by using the mass balances of suspended solids for both the aeration reactors and the

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secondary settlers. However, this strategy may not be optimal during storm events and seasonal variations (Schraa *et al.* 2019).

A more advanced approach to controlling the SRT is to use a feedback controller that controls the estimated SRT by manipulating the waste sludge flow rate from the secondary settlers (Vaccari *et al.* 1988; Ekster 2001; Ekster *et al.* 2017). This approach requires an accurate estimation of SRT, which can be determined using the dynamic SRT equation (Vaccari *et al.* 1985; Takacs *et al.* 2008). However, this equation requires an estimate of sludge production, which is a difficult task in practice as measurements are not available for all important influent variables. A simpler and more robust approach is to estimate the actual SRT by calculating the static SRT and filtering it with a suitable filter (Ekster *et al.* 2017; Schraa *et al.* 2019). This estimation requires measurements of the mixed liquor suspended solid (MLSS) concentration in the aerobic reactors, the waste sludge concentration, and the waste sludge flow rate, which are usually available in practice. Although a proportional integral (PI) controller can be used for feedback control, better results are obtained with a more advanced controller, such as a PI controller with gain scheduling (Ekster 2001; Ekster *et al.* 2017). In addition, the SRT control can be upgraded with a supervisory control that adjusts the set-point for the SRT control based on measurements of ammonia nitrogen and DO in the aerobic reactors (Schraa *et al.* 2019).

This article proposes a control approach similar to the hydraulic SRT control, where a defined proportion of the MLSS mass in the reactors is wasted. The difference to the hydraulic SRT control is that the sludge wasted from the secondary settlers is determined based on the measurements of the MLSS concentration, the waste sludge concentration, and the waste sludge flow rate. The control does not require an SRT estimation or an SRT feedback controller. In addition, the control is supplemented by a constraining controller that keeps the MLSS mass in the aerobic reactors within the prescribed limits.

The article is organised as follows. The next section describes the Ljubljana WWTP and the initial strategy for waste sludge removal. Then, the SRT control is presented. This is followed by the validation of the SRT control on a mathematical model of the plant. Next, the implementation and testing of the SRT control at the Ljubljana WWTP is presented. Finally, the most important conclusions and perspectives for future work are drawn.

METHODS

Ljubljana WWTP and initial waste sludge removal strategy

The Ljubljana WWTP is the largest facility in Slovenia, and was originally designed for the removal of organic matter and ammonia nitrogen. The plant is currently being upgraded for the removal of nitrogen and phosphorus. At the time of the study, the plant was operating with a capacity of 435,000 population equivalents (PE) and with the average wastewater flow rate of about 82,500 m^3/days. The plant consists of mechanical treatment (screens, grit, and grease chamber), a biological stage with an activated sludge process with suspended biomass (three parallel aerobic plug-flow reactors and four parallel secondary settlers), and sludge treatment (sludge thickening, anaerobic digestion, dewatering, and sludge drying) (Hvala *et al.* 2017, 2018). The aerobic reactors have a total volume of 40,000 m^3, while the secondary settlers have a volume of 24,000 m^3. The scheme of the Ljubljana WWTP water line is shown in Figure 1.

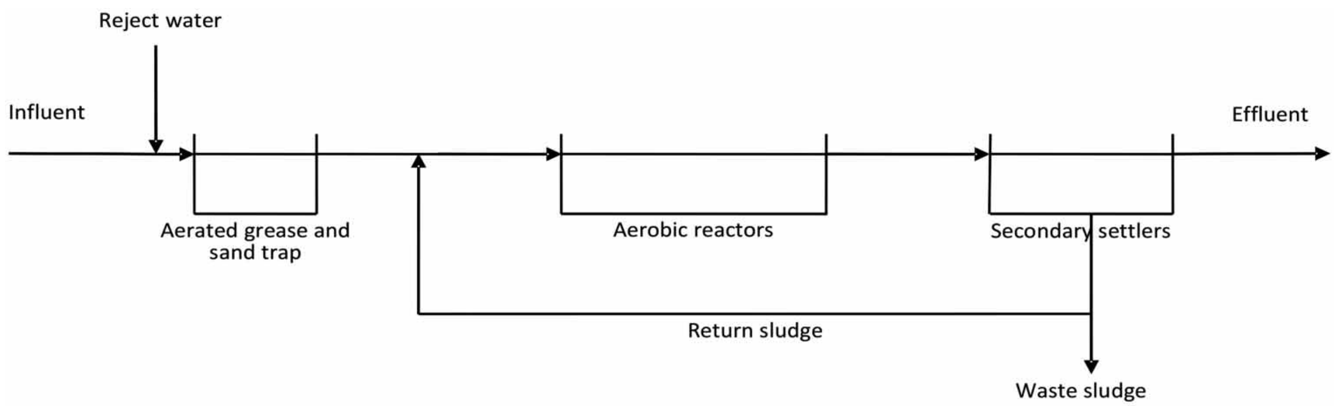

Figure 1 | The scheme of the Ljubljana WWTP water line.

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The sludge removal equipment includes sensors to measure the waste sludge concentration, the MLSS concentration at the outlet of the aerobic reactors, waste sludge flow rate, and the frequency of the waste sludge pumps.

Initially, waste sludge was removed from the secondary settlers with a constant frequency of the waste sludge pumps. The frequency of the pumps was manually adjusted daily by the plant operators to achieve the desired daily waste sludge removal. This adjustment was based on developed heuristic rules that took into account the MLSS concentration in the aerobic reactors, the daily static SRT in the biological stage of the plant, the influent load of the plant, the wastewater temperature, and other relevant factors.

The MLSS concentration in the aerobic reactors and the SRT varied during the year. Monthly variations in the average monthly MLSS concentration in the aerobic reactors and the average monthly static SRT, depending on the average monthly wastewater temperature over 14 months, are shown in Figure 2.

It can be seen that the MLSS concentration was the lowest at the highest wastewater temperature, and the highest at the lowest temperature. The average monthly static SRT in the aerobic reactors varied between 5 and 8 days. A high SRT was obtained in summer despite the high wastewater temperature. Conversely, a high SRT was not maintained in winter despite the low temperature. It can be concluded that sludge wasting was mainly based on controlling the MLSS concentration in the aerobic reactors. In winter, the MLSS concentration was set higher than in summer. However, higher MLSS concentration in the reactors does not necessarily indicate a higher biomass concentration, as this increase can be attributed to the presence of inert matter. Furthermore, maintaining a constant MLSS concentration in the reactors does not guarantee a constant SRT and F/M ratio (Smith *et al.* 2014). This is because the MLSS mass remains the same when the influent changes.

To present daily variations in the SRT with the initial waste sludge removal strategy, an excerpt of the data over 84 days is shown in Figure 3. The data shown are the average daily MLSS concentration, the filtered static daily SRT and the average daily wastewater temperature. The static daily SRT was filtered with a first-order low-pass filter with the time constant of 7.5 days (see Equation (5)). This filtered static daily SRT represents the estimate of the actual SRT.

It can be seen that the average daily MLSS concentration varied between approximately 3 and 4 g/L, except during the prolonged rainy period in December and January, when it dropped to around 2 g/L. The estimated daily SRT varied from approximately 4.5 to 9.5 days. Such large variations of the daily SRT could cause different operational difficulties, as described in the Introduction.

SRT control

To alleviate variations of the SRT at the Ljubljana WWTP, a SRT control was designed. The designed SRT control is similar to the hydraulic control (Garrett 1958; Ekama 2010), where a proportion of the MLSS mass in the aerobic reactors is wasted directly from the reactors. The difference to the hydraulic control is that the proportion of the MLSS mass in the aerobic

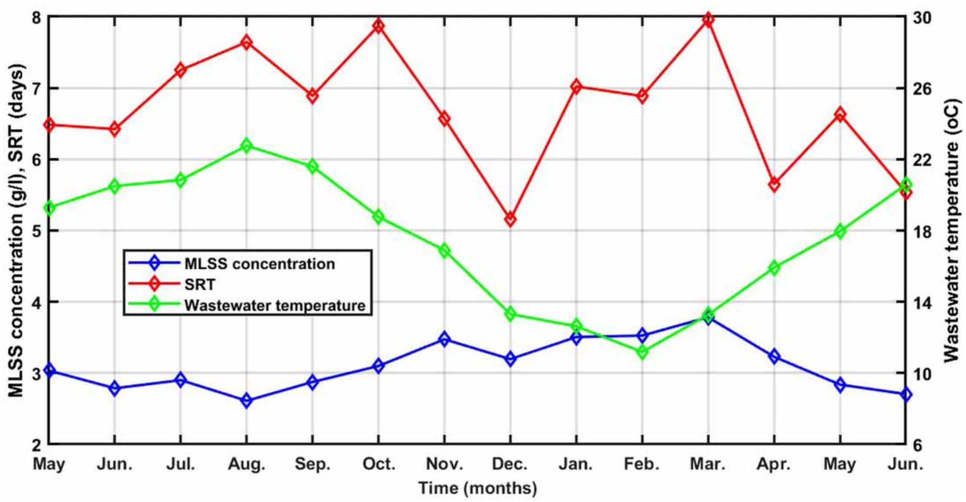

Figure 2 | Initial waste sludge removal strategy. Monthly variations of the average monthly MLSS concentration in the aerobic reactors and the average monthly static SRT, depending on the average monthly wastewater temperature over 14 months.

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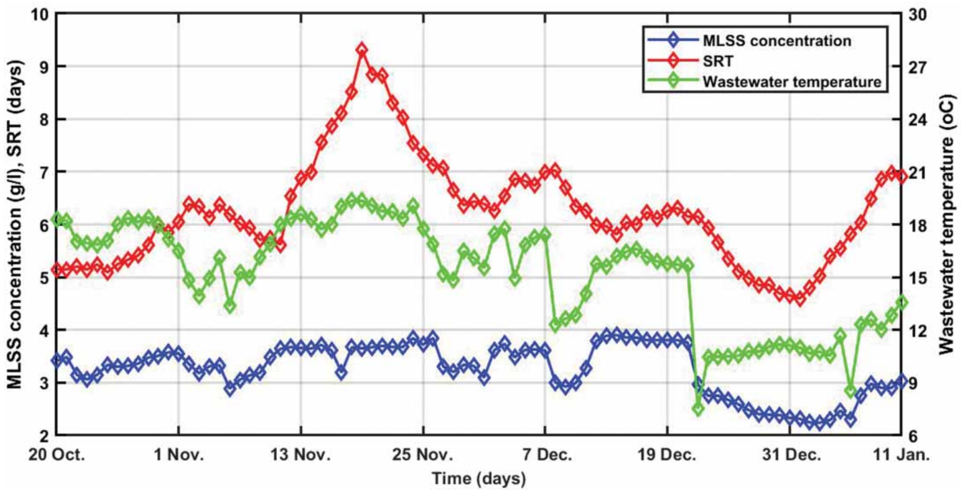

Figure 3 | Initial waste sludge removal strategy. Daily variations of the average daily MLSS concentration in the aerobic reactors, the filtered static daily SRT and the average daily wastewater temperature over 84 days.

reactors is wasted from the secondary settlers. The sludge wasted is determined based on the measurements of the MLSS concentration, the waste sludge concentration, and the waste sludge flow rate. The scheme of the designed SRT control is shown in Figure 4 and its components are described below.

SRT controller

The SRT controller calculates the set-point of the waste sludge mass flow rate to be removed from the secondary settlers on the basis of the average daily MLSS mass in the aerobic reactors and the set-point for the SRT:

$$\Phi_{w,\mathrm{set}}(k) = \frac{m_{\mathrm{aer}}\,(k-1)}{\mathrm{SRT}_{\mathrm{set}}\,(k)} \tag{1}$$

where $\Phi_{w,\mathrm{set}}(k)$ is the set-point for the waste sludge mass flow rate on the current day, $m_{\mathrm{aer}}(k\text{–}1)$ is the average daily MLSS mass in the aerobic reactors on the previous day and $\mathrm{SRT}_{\mathrm{set}}(k)$ is the set-point for the SRT on the current day.

MLSS mass constraining controller

In order to keep the MLSS concentration in the aerobic reactors within the prescribed minimum and maximum values, the SRT controller is supplemented by an MLSS mass constraining controller. The constraining controller adjusts the SRT set-point if the MLSS mass in the aerobic reactors is outside the prescribed range:

$$\mathrm{SRT}_{\mathrm{set}}(k) = \begin{cases} \mathrm{SRT}_{\mathrm{set,op}}(k); & \text{if } m_{\mathrm{aer,min}} \le m_{\mathrm{aer}}(k-1) \le m_{\mathrm{aer,max}} \\ \mathrm{SRT}_{\mathrm{set,op}}(k) + K\cdot(m_{\mathrm{aer,min}} - m_{\mathrm{aer}}(k-1)); & \text{if } m_{\mathrm{aer}}(k-1) < m_{\mathrm{aer,min}} \\ \mathrm{SRT}_{\mathrm{set,op}}(k) - K\cdot(m_{\mathrm{aer}}(k-1) - m_{\mathrm{aer,max}}); & \text{if } m_{\mathrm{aer}}(k-1) > m_{\mathrm{aer,max}} \end{cases} \tag{2}$$

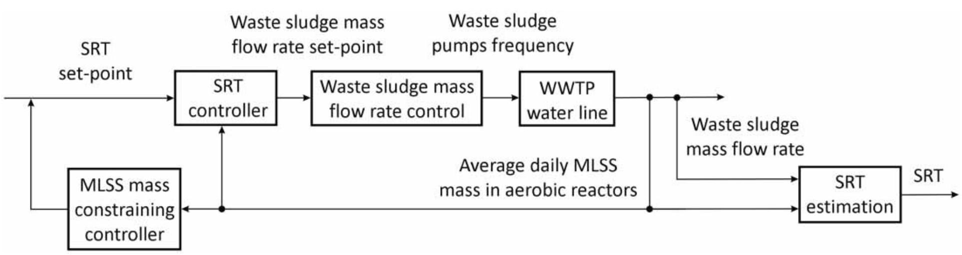

Figure 4 | The scheme of the SRT control.

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where $SRT_{set}(k)$ is the adjusted SRT set-point for the current day, $SRT_{set,op}(k)$ is the SRT set-point set by the plant operators for the current day, $m_{aer,min}$ is the prescribed minimum average daily MLSS mass in the aerobic reactors, $m_{aer,max}$ is the prescribed maximum average daily MLSS mass in the aerobic reactors, and K is the controller constant. The set-point $SRT_{set}(k)$ equals the set-point $SRT_{set,op}(k)$ set by the plant operators if the MLSS mass in the aerobic reactors is within the prescribed range.

Waste sludge mass flow rate control

The waste sludge mass flow rate control automatically removes the defined daily waste sludge mass calculated by the SRT controller by manipulating the waste sludge pumps. The control scheme of the waste sludge mass flow rate control is shown in Figure 5.

The removal of waste sludge begins in the morning and continues until the specified daily waste sludge mass is removed. Once the specified daily waste sludge mass has been removed, sludge removal is stopped. The removal of the waste sludge is therefore not continuous, but intermittent with breaks overnight.

The set-point for waste sludge flow rate $Q_{w,set}$ is determined on the basis of two parameters specified by the plant operators: the maximum waste sludge flow rate $Q_{w,max}$ and the maximum waste sludge mass flow rate $\Phi_{w,max}$. Normally, the set-point for the waste sludge flow rate is set to the maximum value. However, if waste sludge concentration is high, the set-point for the waste sludge flow rate is reduced to ensure that the waste sludge mass flow rate does not exceed the maximum waste sludge mass flow rate. This restriction is necessary due to the limits of the sludge treatment facility. The equation for calculating the set-point for the waste sludge flow rate is as follows:

$$Q_{w,set}(k) = \min\left(Q_{w,max}, \frac{\Phi_{w,max}}{TSS_w(k)}\right) \quad (3)$$

where $Q_{w,set}(k)$ is the set-point of the waste sludge flow rate at the time of the current sampling, and $TSS_w(k)$ is the waste sludge concentration at the time of the current sampling. The set-point value for the waste sludge flow rate is calculated using the filtered waste sludge concentration. A first-order low-pass filter is used to minimise the impact of fast disturbances in the waste sludge concentration during the calculation.

The flow rate of waste sludge is controlled by a PI controller that manipulates the frequency of the pumps. The waste sludge flow rate is filtered with a first-order low-pass filter to reduce the impact of fast disturbances in the waste sludge removal on the operation of the controller.

SRT estimation

The SRT control scheme (Figure 4) includes the estimation of the SRT. The SRT estimation is only carried out for the information of the plant operators and is not used for control purposes. The SRT is estimated in two steps. In the first step, the

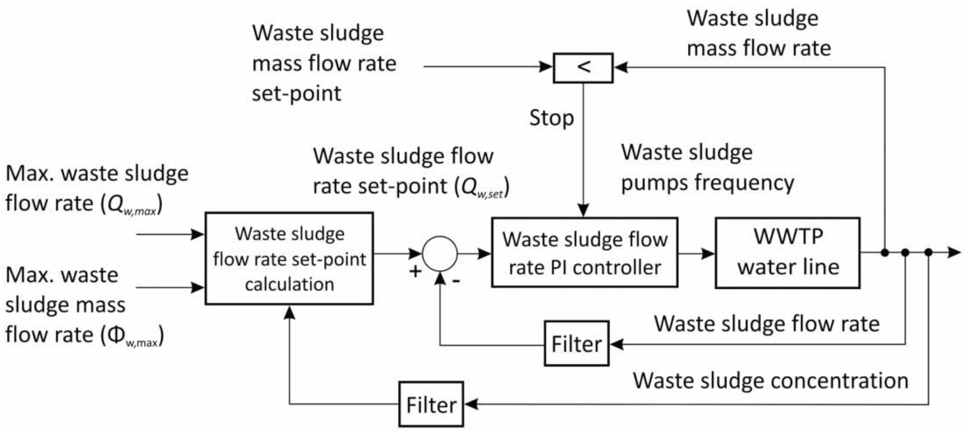

Figure 5 | The control scheme of the waste sludge mass flow rate control.

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static SRT is calculated:

$$\mathrm{SRT}_{\mathrm{static}}(k) = \frac{m_{\mathrm{aer}}(k)}{\Phi_w(k)} \tag{4}$$

where $\mathrm{SRT}_{\mathrm{static}}(k)$ is the static solid retention time on the current day, $m_{\mathrm{aer}}(k)$ is the average daily MLSS mass in the aerobic reactors on the current day and $\Phi_w(k)$ is the waste sludge mass flow rate on the current day. In the second step, the static SRT is filtered with a first-order low-pass filter:

$$\mathrm{SRT}_f(k) = \left(1 - \frac{T_s}{T_f}\right) \cdot \mathrm{SRT}_f(k-1) + \left(\frac{T_s}{T_f}\right) \cdot \mathrm{SRT}_{\mathrm{static}}(k) \tag{5}$$

where $\mathrm{SRT}_f(k)$ is the filtered solid retention time on the current day, $\mathrm{SRT}_f(k–1)$ is the filtered solid retention time on the previous day, $\mathrm{SRT}_{\mathrm{static}}(k)$ is the static solid retention time on the current day, T_s is the sampling time (1 day) and T_{f} is the time constant of the SRT filter. The SRT_f represents the estimate of the actual SRT.

The static SRT is filtered because the actual SRT changes slowly as the mass of waste sludge changes. It is important to set the appropriate filter time constant to ensure that the estimated SRT is very close to the actual SRT. Experience shows that a good approximation is achieved when the filter time constant is set to a value that roughly corresponds to the average SRT (Ekster *et al.* 2017; Schraa *et al.* 2019).

The SRT can also be estimated using the equation for the dynamic SRT (Takacs *et al.* 2008):

$$\mathrm{SRT}_{dyn}(k) = \mathrm{SRT}_{dyn}(k-1) + \left(1 - \frac{\mathrm{SRT}_{dyn}(k-1) \cdot \Phi_p(k)}{m_{aer}(k)}\right) \cdot T_S \tag{6}$$

where $\mathrm{SRT}_{\mathrm{dyn}}(k)$ is the dynamic SRT on the current day, $\mathrm{SRT}_{\mathrm{dyn}}(k–1)$ is the dynamic SRT on the previous day, $m_{\mathrm{aer}}(k)$ is the average daily MLSS mass in the aerobic reactors on the current day, $\Phi_p(k)$ is the sludge mass flow rate produced in the aerobic reactors on the current day and T_s is the sampling time (1 day). If no sludge is produced ($\Phi_p(k) = 0$), the dynamic SRT increases by 1 day per day. Conversely, if the sludge production is equal to the wastage ($\Phi_p(k) = \Phi_w(k)$), the dynamic SRT remains unchanged and equals the static SRT. However, if the sludge production is greater than wastage ($\Phi_p(k) > \Phi_w(k)$), the dynamic SRT decreases. To calculate the dynamic SRT, the sludge produced must be estimated. This requires additional measurements of the influent such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and volatile suspended solids (VSS), which are not available online at the Ljubljana WWTP.

RESULTS AND DISSCUSION

Validation of the SRT control on a mathematical model of the Ljubljana WWTP

The designed SRT control was first validated on a mathematical model of the Ljubljana WWTP. This model was originally developed to analyse the operation of the existing plant and to verify its performance after the upgrade for the removal of total nitrogen and phosphorus (Hvala *et al.* 2017, 2018). The model is designed in the GPS-X$^{\mathrm{TM}}$ software (Hydromantis 2016) as a plant-wide model that includes all subsystems in the water and sludge lines of the plant. In the model, the influent flow rate, influent concentrations and other operational variables are dynamically varied over a period of 425 days based on actual full-scale data. The data used correspond to the period as shown in Figure 2.

The designed SRT control was simplified before it was applied to the mathematical model. The simplification was made so that the SRT control can be easily applied in the GPS-X$^{\mathrm{TM}}$ software. The simplified SRT control manipulates the waste sludge flow rate, and not the waste sludge mass flow rate. In addition, the MLSS mass constraining controller was not used.

The designed SRT control was compared with a PI SRT control that controls the filtered static SRT by manipulating the waste sludge flow rate. A first-order low-pass filter was used to filter the static SRT, with the time constant set to 8 days. The parameters of the PI SRT controller were tuned based on step response tests, in which the waste sludge flow rate was changed instantly and the filtered SRT response was observed. From the test response, the parameters of the PI controller were calculated using the amplitude optimum tuning method (Vrančić *et al.* 2010). In addition, the parameters were manually

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adjusted to achieve acceptable performance of the controller. The proportional gain and integral time constant of the PI SRT controller were set to -400 m^3/day^2 and 14 days, respectively.

The SRT set-point was adjusted based on seasonal temperature variations. A lower SRT set-point of 6.5 days was applied during the warmer periods (from day 0 to day 175 and from day 325 to day 425), while a higher set-point of 8.5 days was used during the cold period (from day 175 to day 325). The cold period was defined as the time interval in which the wastewater temperature remained below 18 °C. The increase in SRT during the cold period was intended to improve the ammonia nitrogen removal under lower temperature conditions.

The SRT control strategies were also compared with the initial waste sludge removal strategy, referred to as the initial MLSS control. To simulate this strategy, the MLSS concentration in the aerobic reactors was controlled by a PI controller, which adjusted the waste sludge flow rate to get similar MLSS concentration values as measured in the plant. The parameters of the MLSS PI controller were: sampling time 15 min, proportional gain -3 m^6/(day·g) and integral time constant 8 days (Hvala *et al.* 2018).

The comparison of the results obtained with the designed SRT control, PI SRT control and initial MLSS control on the mathematical model of the Ljubljana WWTP is shown in Figure 6. The comparison of the control strategies was made by calculating the dynamic SRT, which can be easily determined in the GPS-X^{TM} software. The wastewater treatment quality was evaluated on the basis of the effluent ammonia nitrogen concentration. The results for the effluent COD and BOD are not shown because the differences between the strategies were negligible. The performance criteria of the control strategies are calculated and presented in Table 1.

The designed SRT control maintains the dynamic SRT in the aerobic reactors closer to the set-point than the PI SRT control and achieves a lower control error (see Table 1). It adjusts the mass flow rate of the waste sludge faster than the PI SRT control because it reacts directly to changes in the MLSS mass and not to changes in the filtered MLSS mass like the PI control. The initial MLSS control resulted in greater SRT variations than the SRT control strategies.

The SRT control strategies resulted in a similar MLSS mass in the aerobic reactors during the warmer periods as that obtained with the initial MLSS control. However, during the cold period, the SRT strategies resulted in a higher MLSS mass of up to 200–240 tonnes, which corresponds to an MLSS concentration of 5–6 g/L. It is important to note, that an MLSS concentration higher than 5 g/L is in Ljubljana WWTP undesirable as it significantly increases the demand for aeration and can exceed the capacity of the aeration system. In addition, reducing high MLSS concentration requires a large amount of the waste sludge, which may exceed the processing capacity of the sludge treatment facility. Two prolonged periods of rain, observed between days 200 and 325, caused a significant decrease in MLSS mass in the aerobic reactors in all cases. During these rainy periods, some of the solids were washed out of the plant and the MLSS concentration in the aerobic reactors was reduced. The return sludge flow rate was in these periods maintained at a maximum value to return as much solids as possible back to the reactors.

During the warmer periods, all strategies achieved low effluent ammonia nitrogen concentrations. However, in the cold period, the ammonia nitrogen concentration in the effluent increased in all cases. During this period, the SRT control strategies resulted in lower effluent ammonia nitrogen concentrations compared to the initial MLSS control, as they maintained higher SRT values. The designed SRT control achieved slightly lower effluent ammonia nitrogen peaks than the PI SRT control (see Table 1), due to better set-point tracking performance. With the designed SRT control, nearly all effluent ammonia nitrogen peaks were reduced to below the required limit of 5 mg/L. The designed SRT control enables the SRT set-point to be adjusted based on seasonal temperature variations. Increasing the SRT set-point during the cold and prolonged rainy periods could further reduce effluent ammonia nitrogen peaks.

Implementation and testing of the SRT control at the Ljubljana WWTP

The designed SRT control was implemented in the programmable logic controller (PLC) and supervisory control and data acquisition (SCADA) system. It was tested for several months at the Ljubljana WWTP. The aim of testing was to tune the control parameters.

The SRT control parameters, including the minimum and maximum mass flow rates of the waste sludge, and the minimum and maximum average daily MLSS masses in the aerobic reactors ($m_{aer,min}$, $m_{aer,max}$) were set based on the experience of the plant operators. The limit values for the waste sludge mass flow rate were set according to the processing capacity of the sludge treatment facility. The $m_{aer,min}$ and $m_{aer,max}$ were derived from the minimum and maximum average daily MLSS

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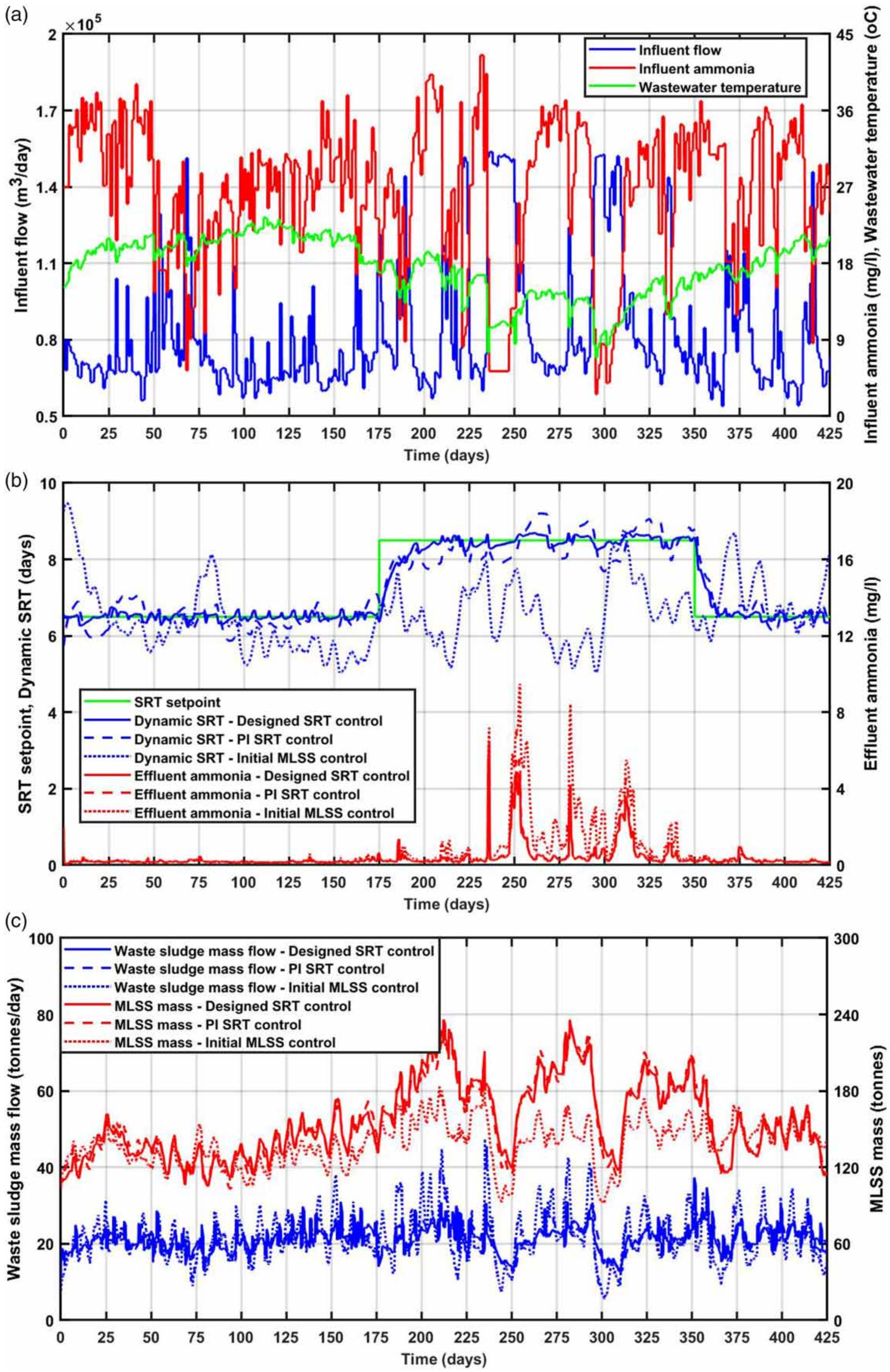

Figure 6 | Comparison of the results obtained with the designed SRT control, PI SRT control, and initial MLSS control on the mathematical model of the Ljubljana WWTP over 425 days: (a) variations of the influent flow rate, the influent ammonia nitrogen concentration and the wastewater temperature, (b) comparison of the dynamic SRT values and the effluent ammonia nitrogen concentrations and (c) comparison of the waste sludge mass flow rates and the MLSS masses in the aerobic reactors.

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Table 1 | Performance criteria of the control strategies

Control strategy	Dynamic SRT (days)	Effluent ammonia nitrogen concentration (mg/l)		
	Average absolute control error	Average	Standard deviation	Maximum
Designed SRT control	0.15	0.39	0.62	6.30
PI SRT control	0.35	0.42	0.73	6.42
Initial MLSS control	/	0.74	1.28	9.49

concentrations in the aerobic reactors, which were set at 2.25 and 3.5 g/L, respectively. The $m_{aer,max}$ was set to a relatively low value to ensure that the capacities of both the aeration system and the sludge treatment facility were not exceeded.

The time constants of the first-order low-pass filters and the constant of the MLSS mass constraining controller were set manually to achieve satisfactory control performance. The parameters of the waste sludge flow rate PI controller were tuned using the amplitude optimum tuning method (Vrančić *et al.* 2010). The sampling time of the PI controller was equal to the sampling time of the SCADA system. The values of the SRT control parameters are given in Table 2.

An example of the operation of the waste sludge flow rate control over a period of 2 days is shown in Figure 7. The set-point for the waste sludge flow rate varies throughout the day. In the morning at around 8 h, when the control is activated, the set-point for the waste sludge flow rate is initially set to the maximum value. Later in the day, it decreases due to the increased concentration of the waste sludge, which ensures that the mass flow rate of the waste sludge does not exceed the maximum limit. The waste sludge flow rate follows the set-point well. As soon as the specified daily waste sludge mass is removed, the sludge removal is stopped and the pumps are switched off. In addition, pumping the grease out of the secondary settlers causes considerable oscillations in the waste sludge flow rate. However, these oscillations have no significant influence on the control operation due to the signal filtering.

The results of the SRT control operation over 2.5 months (July, August, September) are shown in Figure 8. At the beginning of the testing period, the set-point for SRT was increased from 6.5 to 7.5 days, while the other control parameters remained as

Table 2 | The values of the SRT control parameters

Parameters of the SRT controller	Value
Min. waste sludge mass flow rate	12 tonnes/day
Max. waste sludge mass flow rate	24 tonnes/day
Time constant of the SRT filter	7.5 day
Sampling time of the SRT controller	1 day
Parameters of the MLSS mass constraining controller	**Value**
Min. average daily MLSS mass in the aerobic reactors	90 tonnes
Max. average daily MLSS mass in the aerobic reactors	140 tonnes
Constant of the controller	0.02 day/tonnes
Parameters of the waste sludge flow rate control	**Value**
Max. waste sludge flow rate	160 m^3/h
Max. waste sludge mass flow rate	1,200 kg/h
Time constant of the waste sludge concentration filter	15 min
Proportional gain of the PI controller	0.25%/(m^3/h)
Integral time constant of the PI controller	20 s
Min. waste sludge pumps frequency	0%
Max. waste sludge pumps frequency	200%
Time constant of the waste sludge flow rate filter	10 s
Sampling time of the PI controller	0.2 s

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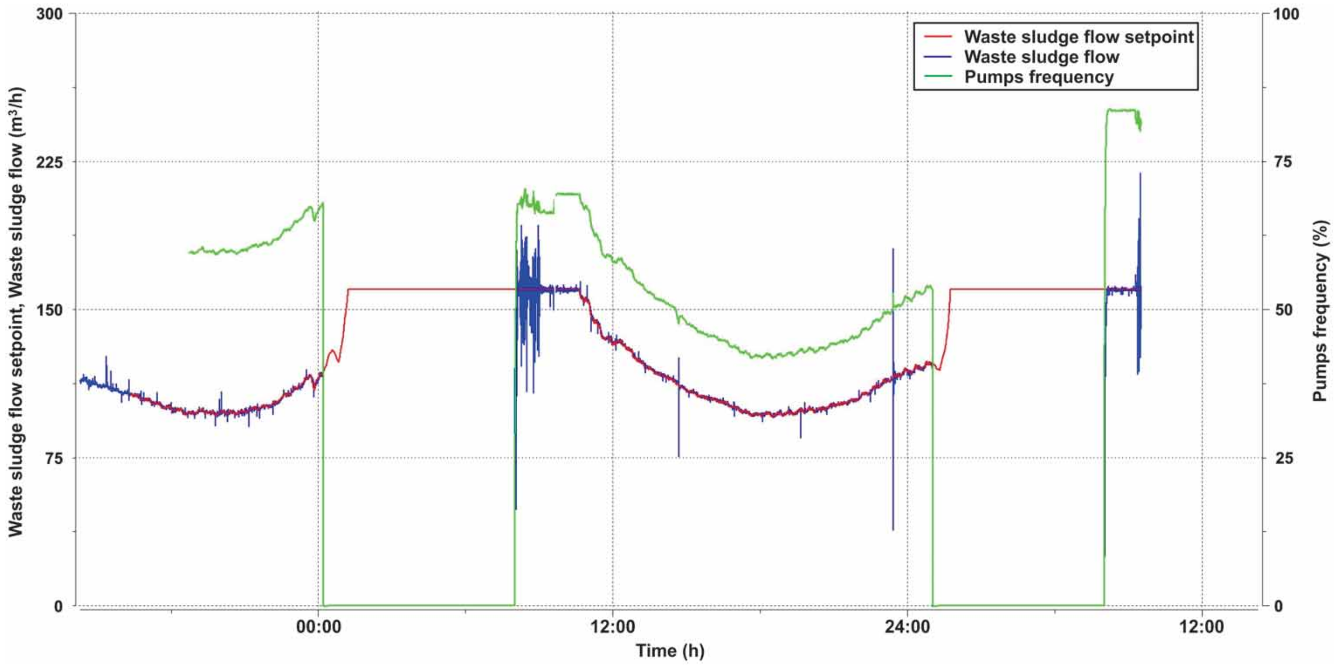

Figure 7 | Results of the waste sludge flow rate control over a period of 2 days.

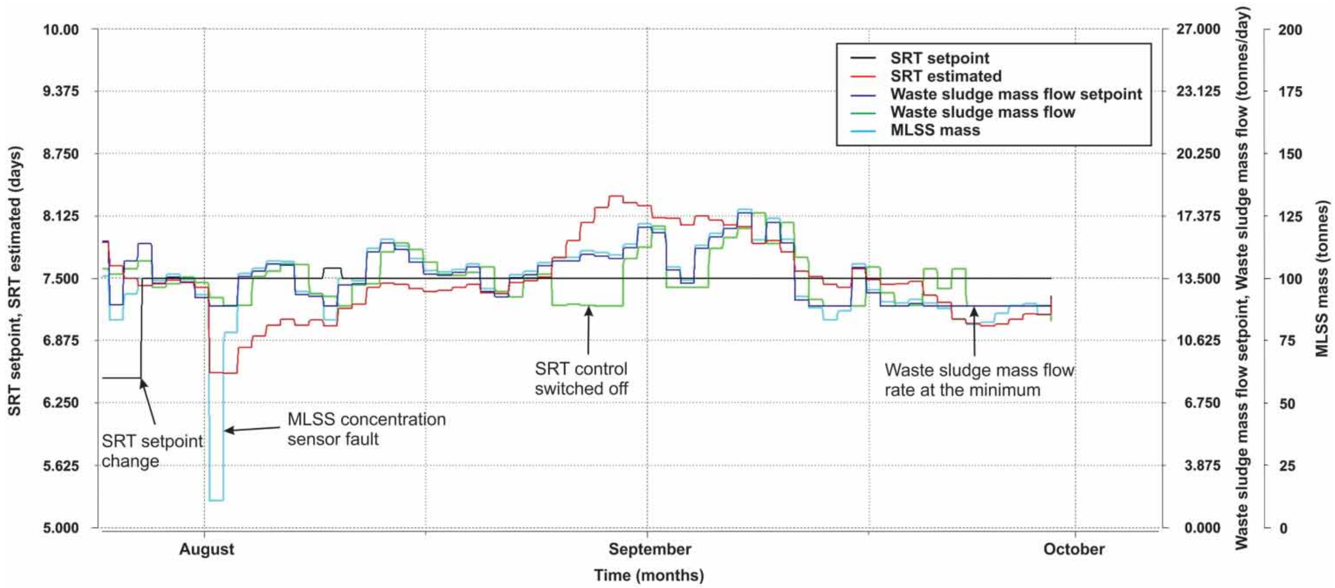

Figure 8 | Results of testing the SRT control at the Ljubljana WWTP over a period of 2.5 months.

shown in Table 2. The testing showed that in the real plant, the set-point value for the SRT should be between 7 and 8 days. An SRT below 7 days is not recommended as it significantly reduces the MLSS concentration in the aerobic reactors and thus reduces nitrification (Smith *et al.* 2014). Conversely, an SRT of over 8 days is not recommended as it can increase the MLSS concentration in the aerobic reactors above specified limits.

The estimated SRT approximately follows the prescribed set-point value. The average daily MLSS mass in the aerobic reactors varied around 100 tonnes, which corresponds to an MLSS concentration of 2.5 g/L. The waste sludge mass flow rate varied around 13.5 tonnes per day. A significant short-term decrease in the estimated SRT from the set-point value at the

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beginning of August was due to a fault in the MLSS concentration sensor. Due to this fault, the sensor value was significantly lower than the actual value for 1 day. Deviations from the set-point value were also observed at the end of August when the SRT control was switched off and the plant operators adjusted the waste sludge mass flow rate manually. During this period, the set-point for the waste sludge mass flow rate was much higher than the actual waste sludge mass flow, so that the estimated SRT increased significantly above the set-point. In the second half of September, the average daily sludge mass flow rate in the aerobic reactors decreased due to a prolonged rainy period. During this time, the SRT control reduced the waste sludge mass flow rate to its minimum, which was not sufficient to maintain the set-point. Due to the disturbances and limitations in the waste sludge mass flow rate, the estimated SRT varied approximately from 6.5 to 8.5 days. However, before control implementation, the SRT varied over a wider range, approximately from 4.5 to 9.5 days (see Figure 3).

It can be concluded that the control reduces the SRT variations and maintains the SRT in the aerobic reactors approximately at the prescribed set-point. It also allows plant operators to adjust the SRT set-point according to seasonal variations. However, a longer evaluation period is required to fully assess the benefits of the designed control due to various disturbances in the plant, such as variations in influent and wastewater temperature, changes in operational variables such as DO set-points in the aerobic reactors, etc.

CONCLUSIONS

The SRT control, which wastes the defined proportion of the MLSS mass in the aerobic reactors, was designed and implemented at the Ljubljana WWTP. The control determines the sludge to be wasted from the secondary settlers based on the measurements of the MLSS concentration, the waste sludge concentration, and the waste sludge flow rate. An advantage of the designed control is that it does not require an SRT calculation or an SRT feedback controller. The control includes a constraining controller that keeps the MLSS mass in the aerobic reactors within specified limits. The control enables the SRT set-point to be adjusted based on seasonal temperature variations.

Validation of the SRT control on a mathematical model of the Ljubljana WWTP has shown better SRT set-point tracking than the SRT PI control. It has also shown that SRT control results in reduced SRT variations and lower effluent ammonia nitrogen concentrations compared to the initial MLSS control. Testing of the SRT control at the Ljubljana WWTP has confirmed that the SRT set-point is maintained despite large influent variations and operational disturbances, and that the SRT variations are reduced. The SRT control is of great benefit to the operators of the WWTP, who initially adjusted the waste sludge flow rate on the basis of manual calculations.

Further improvement to the SRT control could be achieved by upgrading it with a supervisory control that optimises the SRT set-point according to the ammonia nitrogen and DO measurements in the aerobic reactors.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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