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## Modelling solution for estimating aeration energy of wastewater treatment plants

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### ABSTRACT

Energy costs in the wastewater industry are increasing due to increasing trends in electricity rates and more stringent requirements for effluent quality. Wastewater aeration process is typically the largest energy consumer of the treatment plant and the optimization of the aeration process can offer significant savings for the wastewater treatment plants (WWTPs). Utilization of dynamic models can offer optimization solutions for improving the energy efficiency and process performance. In this work a simplified modelling approach emphasizing the control valves and the blowers is tested by developing aeration system models for two Finnish WWTPs. The developed model requires calibration of only a single parameter and the results from the simulations showed that reasonable estimations of the aeration systems energy demand could be made with a limited knowledge on the details of the physical system. The promising results highlight the strong influence of the control valve positioning to the whole system and indicate that airflow distribution along the system could be estimated simply from the positioning of the valves. The presented modelling approach allows the comparison between different blower and control valve alternatives during operation and for the process upgrades and offers prospect for improving the aeration operation control strategies.

**Key words:** aeration, dynamic model, energy efficiency, wastewater

### HIGHLIGHTS

- An aeration system model based on valve positions was developed.
- The model only requires calibration of one parameter.
- Energy consumption can be estimated with only a limited information about the physical aeration system.
- Valve positions impact the system power consumption and the air distribution between and within aeration grids.
- Including valve positions opens possibilities to improve the aeration control strategies.

### INTRODUCTION

Increasing trends in electricity rates together with more stringent requirements for effluent quality are increasing the energy costs in the wastewater industry (United States Environmental Protection Agency (EPA) 2010). Typically, the aeration is the largest energy user at the wastewater treatment plants (WWTPs), accounting for 45 to 75% of the plant's total energy costs (Rosso *et al.* 2008). Because of its high energy intensity, optimization of the aeration process can offer significant cost and energy savings for the WWTPs (Rohrbacher *et al.* 2014).

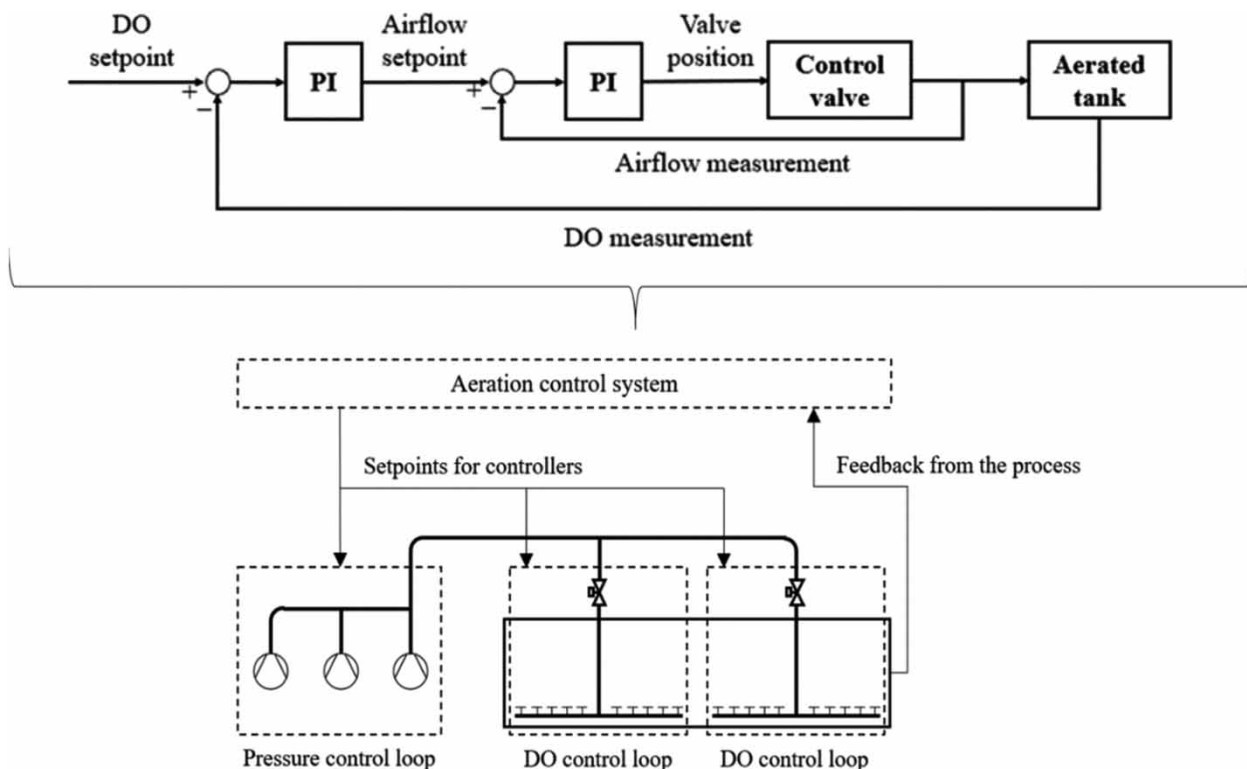
The main purpose of the aeration system is to provide the process with a sufficient amount of dissolved oxygen (DO), so that a healthy bacterial biomass can be maintained (Zuluaga-Bedoya *et al.* 2018). In the biomass, the aerobic organisms perform removal of organic matter and nitrification, processes from both of which require oxygen (Åmand *et al.* 2013). The oxygen requirement of the process will be dynamic due to varying influent loading (Gray *et al.* 2011). The presence or absence of available oxygen highly influences the biological processes, which makes the control of the DO vital for the optimal treatment process (Rieger *et al.* 2006). In biological treatment, the conditions can be aerobic (free oxygen present), anoxic (free oxygen absent but bound oxygen present) or anaerobic (no free or bound oxygen present). In addition to providing the process with sufficient amount of oxygen, the aeration should also provide adequate mixing for keeping the biomass in suspension (Larsson 2011).

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Different approaches exist for aerating the wastewater, the most common strategy being the diffused aeration, a system which consists of blowers, piping, valves and diffusers (Larsson 2011). The blowers are used for generating the airflow, while the piping, valves and diffusers form the distribution system for that airflow. In addition to the afore-mentioned components, a control system is needed for maintaining the desired DO level (Gray *et al.* 2011). A schematic of an aeration system, with an automated DO controls and pressure control is shown in Figure 1.

For large- and medium-sized WWTPs, a typical approach is to maintain a constant pressure at the common rail by modulating the output from the blowers and to control the DO of individual aerated zones by modulating the control valve positions (Alex *et al.* 2002). The most common method for the latter is to maintain a constant DO setpoint and controlling it by having two control loops in cascade, from which the outer loop calculates the setpoint for the airflow based on the measured deviation from the DO setpoint and the inner loop will adjust the control valve position based on the airflow setpoint given by the outer loop (Vrečko *et al.* 2006). The control scheme for the DO controller is shown in Figure 1. This strategy can further be extended by adjusting the DO setpoint based on the deviation from the desired effluent ammonia concentration (ammonia-feedback control) or furthermore by also using the influent ammonia as measurable disturbance for the ammonia controller (ammonia-feedforward control) (Vrečko *et al.* 2006). In addition to the actual process control, different power-minimizing strategies exist for the control of the air supply and distribution, such as direct flow control and the most-open-valve logic (MOV) (Åmand *et al.* 2013).

Blowers can be divided into positive displacement and centrifugal blowers based on their principle of producing the airflow. For both types, the output of the blower can be modulated by varying the blowers rotational speed and for the centrifugal blowers it is also possible to control the blower by throttling the airflow at the blower's inlet, or by altering the flow conditions at the blower's inlet and outlet by using inlet guide vanes together with the variable diffuser vanes. Positive displacement blowers are typically dominant technology in the smaller scale WWTPs, while different types of centrifugal blowers are utilized in mid-size and large WWTPs (Jenkins 2013). The energy consumption of these machines depends on the operating point and equipment efficiency, which varies with the operating point, blower speed and operating conditions (Spellman 2013).



**Figure 1** | Schematic of a typical aeration system with automated DO controls and a pressure controller for the blowers (below) and a control scheme for the DO controller (above). The PI blocks are proportional-integral controllers.

The valves are used in the aeration systems for modulating the airflow into different parts of the system or for isolating segments of the system completely (Jenkins 2013). The control of the airflow is necessary as the aeration requirement is not constant along the treatment lane. For the plug-flow system, the oxygen demand decreases along the aerated reactor and, for avoiding the over-aeration, the aeration intensity should be controlled separately for each zone (Åmand *et al.* 2013). The flow rate and the corresponding pressure drop over the control valve depend on the valve opening and flow characteristics, three of which are mainly used: linear, quick opening and equal percentage (Seborg *et al.* 2010). Positions of each zones control valves define the distribution of the airflow along the treatment lane and with the valve characteristics it is possible to estimate the redistribution of the airflow as a function of the valve openings (Reifsnnyder *et al.* 2020). Regardless of the control strategy used, the valves will highly influence the systems performance and energy consumption. For a typical system, when the blowers maintain a constant pressure at the common rail, the air supply will ultimately be only controlled by the valve positions (Rieger *et al.* 2006).

A common issue within the wastewater industry is the oversizing of the blowers due to too conservative design assumptions (Rauch-Williams *et al.* 2013). This oversizing of the blowers may lead into situations in which the aeration system cannot be operated efficiently with the plants actual influent loading, due to limited turndown capabilities of the blowers (Spellman 2013). The limited turndown capabilities can also contribute to the cyclic hunting of the blowers, a problem which is often observed and causes excess energy consumption and wear of the blower equipment (Henze *et al.* 2008). Another challenge for the aeration systems is tuning of the control loops, due to the non-linear relationship between the DO and the airflow rate (Spellman 2013). The afore-mentioned hunting is also an issue of different control loops responding to each other's control actions (Gray *et al.* 2011).

For the optimization of the aeration process control, dynamic models for the aeration systems are needed. In addition to optimization solutions for energy efficiency and process performance, utilization of these models can offer a possibility for troubleshooting analysis and evaluation of the systems performance under different operating scenarios (Juan-García *et al.* 2018). Accurate models would then enable comparison of different blower technologies and configurations as well as the design of different control strategies for energy efficiency improvements. Juan-García *et al.* (2018) highlight the need for more detailed energy consumption models, as the simplified approaches that do not consider the equipment limitations overestimate the energy-saving potential. Amerlinck *et al.* (2016) also notes the issues of commonly used oversimplified energy consumption models and developed a dynamic model for predicting the energy costs of a diffused aeration system, based on the physical characteristics of the system, water depth and the airflow demand imposed by the control system.

Amaral *et al.* (2017) discussed different components of the aeration system models and reasoned why more complete models are needed for realistic depictions of the process. Amaral *et al.* (2017) state that the entire piping network should be modelled for accurate predictions of the dynamic process, but also state that potential simplifications should be studied. In contrast to the modelling approaches described in Juan-García *et al.* (2018), Amerlinck *et al.* (2016) and Amaral *et al.* (2017), Harja *et al.* (2016) used a very simplified approach for modelling the aeration distribution system, which was based only on the resistance coefficients of the pipelines and valve positioning to model the pressure system.

For a complete model of an aeration system, the air supply system including the blowers needs to be modelled together with the oxygen transfer and demand in the bioreactors (Schraa *et al.* 2017). This study will focus on the modelling of the physical supply system. The biological model is outside the scope of this paper, although the future potential of integrating the demand side to the current model is discussed. The modelling approach presented is based around the dynamics between the control valve positions, which in our approach are simplified to one single parameter and blower power consumption. A limited knowledge on the physical system itself is required as the model can be easily calibrated against the measurement data. The airflow generation model developed in this work will take only the valve positions and the pressure setpoint as inputs for the simulations and it will calculate the corresponding airflow rates and the total power consumed by the blowers. The aim is to develop a modelling approach which, by emphasizing the influence of the control valve positioning to the systems power consumption, could offer prospects for modelling simplifications and possibilities for reducing the complexities of the existing control systems. The model is developed and validated for two Finnish WWTPs, Hermanninsaari WWTP in Porvoo and Viikinmäki WWTP in Helsinki and the performance of the model is assessed. The benefits of the modelling approach presented in this study are discussed in detail and ideas are drawn for further research and adoption of this approach.

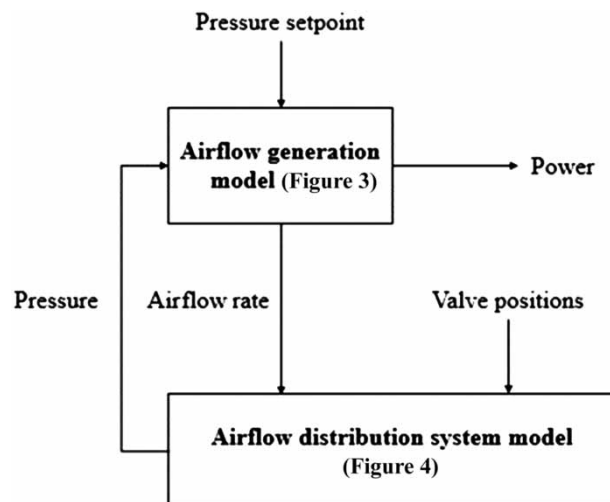
## MATERIALS AND METHODS

Two Finnish WWTPs with diffused aeration systems were modelled in this study. Both of them use automated DO controls and have blower systems which are controlled to maintain a constant pressure setpoint. Hermanninsaari WWTP's biological process consists of two parallel treatment lanes which are both divided into eight zones from which the zones 4–7 are equipped with diffuser grids and the aeration to each zone is controlled with butterfly valves. An ammonia-feedforward controller is used to determine DO-setpoints for the zones 6 and 7 which are constantly aerated and to adjust the aerated volume by opening and closing the control valves to the zones 4 and 5. Viikinmäki WWTP's process consists of nine parallel treatment lanes, each divided into six zones, from which zones 2 and 3 are either aerobic or anoxic based on the ammonia measurement at the end of the treatment lane, while zones 4–6 are constantly aerated. Each aerated zone is equipped with a DO-measurement and control valve. Initially, the modelling approach was tested on the Hermanninsaari WWTP, and later the model was verified by implementing it for the Viikinmäki WWTP. The descriptions of the key parameters related to the aeration systems of these plants are provided in Table 1.

The model constructed using MATLAB and Simulink release R2018b (9.5.0.944444) consists of two parts, the airflow generation model and the airflow distribution system model. The model acts so that the airflow generation model receives the feedback signal and the setpoint value for the pressure and then adjusts the airflow rate from the blowers based on the deviation from the pressure setpoint. The model also calculates the power requirement corresponding to the discharge pressure and airflow rate. The airflow distribution system model receives the positions of different valves and the total airflow rate from the blowers. Based on these inputs, the model calculates the corresponding pressure that is fed back to the airflow generation model. The outline of the complete model is shown in Figure 2.

**Table 1** | Key parameters of the modelled WWTPs

	Hermanninsaari WWTP	Viikinmäki WWTP
Population equivalent	46,100	1,000,000
Design airflow rate	4,600 Nm <sup>3</sup> /h	65,300 Nm <sup>3</sup> /h
Pressure setpoint	91 kPa	132 kPa
Blowers	3 high-speed turbo blowers	5 integrally-gearred centrifugal blower
Blower control method	speed control	dual-point control
Number of control valves for aeration	8	45



**Figure 2** | The outline of the model.

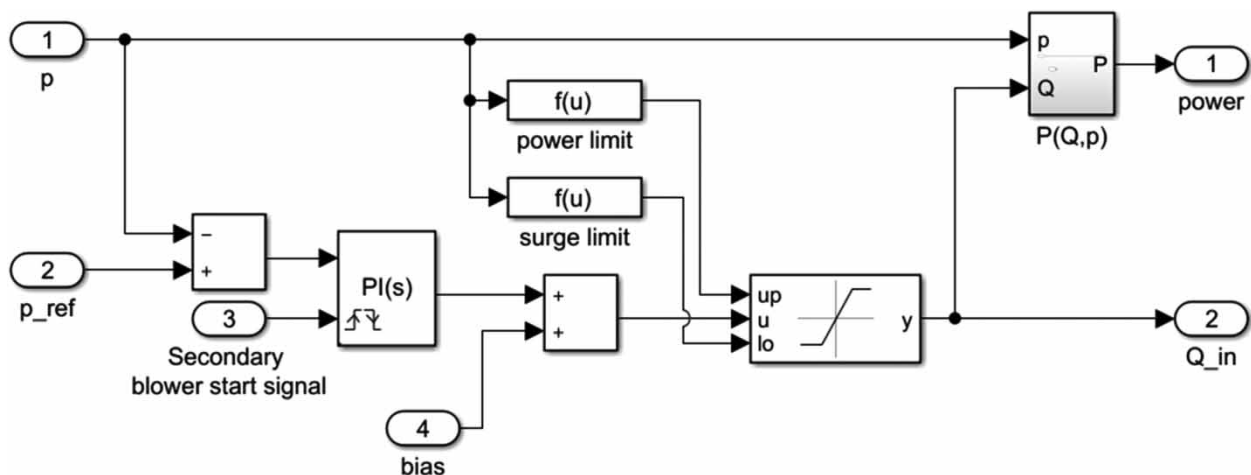
### Airflow generation model

The airflow generation model consists of the blowers and their control system. The blower system of Hermanninsaari WWTP was modelled based on the manufacturer's data and by using polynomial approximation and affinity laws for generating the blower curves. For reducing the complexity of the model, only the relationship between the pressure ( $p$  [bar]), airflow rate ( $Q$  [ $\text{Nm}^3/\text{h}$ ]) and power ( $P$  [kW]) was defined. The blower power is first defined as a function of the airflow rate under a constant discharge pressure ( $P(Q,p)$  in Figure 3). This curve is then shifted by using affinity laws according to the changing discharge pressure. Description for more detailed model including the blowers rotational speed can be found in the first author's Master thesis (Pöyry 2020). For increasing the accuracy of the blower model, the model was defined for 20 kPa pressure range, as the actual pressure can be assumed to fluctuate within a narrow range around the setpoint value ( $p_{\text{ref}}$  in Figure 3). This range is also adequate for assessing the effects of reasonable changes in the pressure setpoint. If the model would be defined for the full pressure range of the blower, the accuracy of the model would deteriorate when using the affinity laws for generating the additional blower curves. The control system for the blowers was defined based on the actual control parameters, which determine when the additional blower is started and when it is stopped (power limit and surge limit in Figure 3). The airflow rate of a single blower is controlled with a PI controller (PI(s) in Figure 3), which adjusts the blower's output to maintain the pressure at its setpoint. The physical limitations of the centrifugal blowers were accounted for by defining the surge line and maximum power limit based on the manufacturer's data. These limits are implemented so that, for a specific pressure condition, there is a limit for the maximum and minimum airflow rate, which are given as inputs for a dynamic saturation block. The layout of the blower model is shown in Figure 3.

For the blower system in Viikinmäki, the model was developed based on the measured power and airflow rate, as the manufacturer's data were not available. Also, the capacity of the blowers in Viikinmäki is controlled by using a dual-point control, which defines quite different behavior than with blowers that are speed controlled. As the data were available for each individual blower, a relation between the power and airflow rate could be defined. Because each blower showed similar characteristics, the blower system model could be simplified by generating a single curve for the whole system. The drawback of this approach is that it does not allow assessing the effects of reduced backpressure on the power requirement.

### Airflow distribution model

For the airflow distribution system, a model for the system curve needs to be defined. The system curve describes the relation between the airflow rate and pressure which is developed due to the dynamic losses across the system and the static pressure due to the diffuser submergence. The static portion of the pressure depends on the water level in the tanks and it can be assumed to remain constant. The dynamic pressure is caused by the resistance to the airflow in the pipes, control valves and diffusers, and it will be proportional to the square of the airflow rate (Jenkins 2013). Many factors affect the resistance causing the pressure losses along the distribution system, such as properties of the air and characteristics of the pipeline, the



**Figure 3** | The blower model for the Hermanninsaari WWTP. The start signal for the secondary blower is determined by the blower power and while the secondary blower is running, the outputs from this subsystem (airflow rate and power) are doubled, as it can be assumed that the loading is distributed equally between the blowers.

control valves and the diffusers (Amerlinck *et al.* 2016). Most of these characteristics will not remain constant and, for example, the changes in the control valve positions will alter the system curve. There are multiple different ways of approaching the modelling of the system pressure and for this study a simple pressure model by Harja *et al.* (2016) is used as a reference. The model uses the following equation for calculating the pressure:

$$\frac{dp(t)}{dt} = \frac{p(t)}{V} (Q_{in}(t) - Q_{out}(t))$$

where  $p$  [bar] is the total system pressure,  $V$  [m<sup>3</sup>] is the volume of the pipeline  $Q_{in}$  [Nm<sup>3</sup>/h] is the airflow into the system from the blowers and the  $Q_{out}$  [Nm<sup>3</sup>/h] is the airflow rate at the pipelines discharge. The  $Q_{out}$  [Nm<sup>3</sup>/h] will be defined as:

$$Q_{out}(t) = k \sqrt{p(t) * (p(t) - p_{stat})} \sum_{i=1}^j Kv_i(t)$$

where  $p_{stat}$  [bar] is the static pressure,  $Kv_i$  [Nm<sup>3</sup>/h/bar] is the flow coefficient and the  $k$  is a dimensionless factor defining the resistance of a specific piping segment. In the model by Harja *et al.* (2016) a single control valve was modelled as a multiplier for the factor  $k$ , but in this study a group of essentially parallel control valves (V1.4 to V\_pre\_aer in Figure 4) is modelled as a single valve yielding a total flow factor which will be scaled by adjusting the factor  $k$  during the calibration of the model. For individual control valves, the flow characteristics based on the manufacturer’s data are used and they are modelled as lookup tables, which yield the flow factors based on the valve position. It should be noted that the valve characteristics provided by the manufacturer are the inherent valve characteristics and the installed characteristics may differ from the manufacturer’s values (Seborg *et al.* 2010). The model will only take the valve positions as an input to the model and adjusts the blower output, so that the system pressure will remain constant. The model of the air distribution system is shown in Figure 4.

In the Hermanninsaari WWTP, the aeration system consists of eight control valves, which all are butterfly valves. Four of the eight zones are constantly aerated while the rest are only aerated during higher influent loadings. The airflow from the blowers is also used for the pre-aeration, which also uses a control valve to modulate the airflow. The data on the pre-aeration control valve were not available, so a constant setpoint for valve position during high and low influent loadings was used.

The Viikinmäki aeration system consists in total of 45 control valves of varying types, most of which are either butterfly or ball segment valves; 27 of the zones are constantly aerated, while the rest 18 are aerated only during higher loadings. The

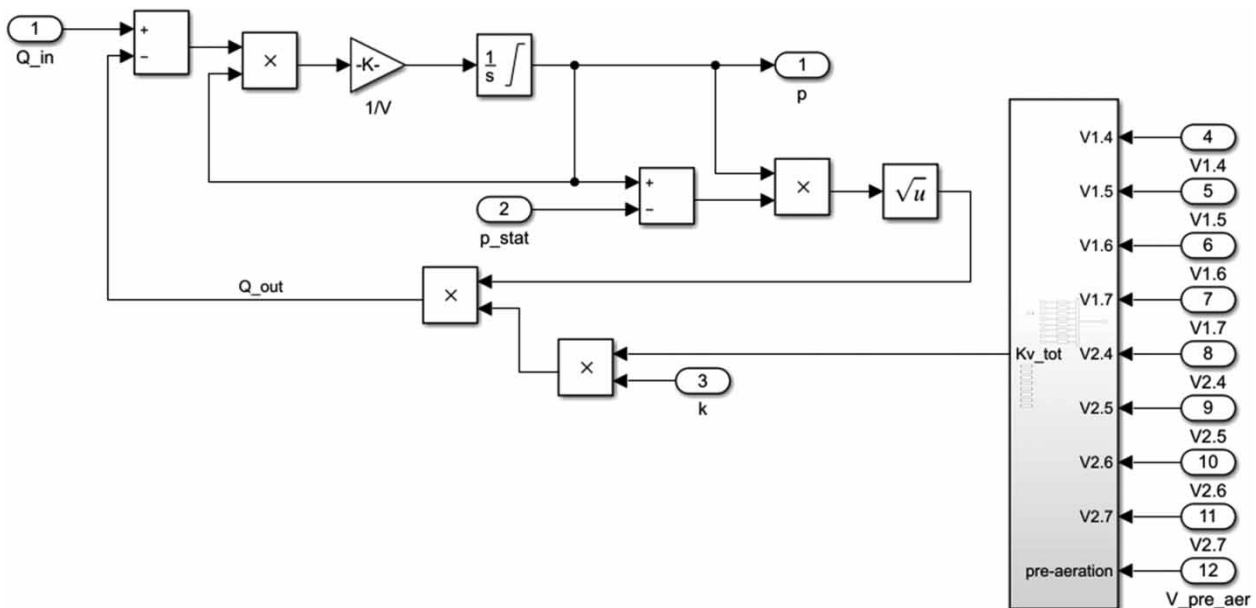


Figure 4 | Model of the aeration distribution system of the Hermanninsaari WWTP.

airflow from the blowers is also used for backwashing of tertiary denitrifying filters, for which the airflow is also measured, but the portion of this airflow from the total is only on average 0.15% for both calibration and validation periods.

### Calibration and validation of the model

For both the modelled WWTPs, five-day periods were used for both calibrating and validating the models. For Hermanninsaari WWTP, the calibration period was from 6 April to 10 April 2019 and the validation was from 13 April to 17 April 2019. Both of these periods were quite close to each other as the amount of available blower operating data was limited. Nevertheless, the calibration and validation periods showed a different operating pattern of the blowers, as during the validation period the airflow requirement was higher than during the calibration. This higher airflow requirement led to continuous parallel operation of the blowers, rather than cyclic starting and stopping of the secondary blower. For Viikinmäki WWTP the calibration period was from 2 November to 6 November 2019 and the validation from 4 August to 8 August 2019. These periods were selected so that they would be representative of the normal operation of the plant.

The assessment of the performance of the models was made based on the modelled and measured power of the blowers. During the model calibration, the factor  $k$  was adjusted so that the system pressure would remain constant and the blower output would match the measured values. The match between the modelled and measured power was assessed based on the relative error. For assessing the performance of the models more comprehensively, other metrics such root mean square error (RMSE) and the comparison of the mean values of the measured and modelled values is used. The reason for using both relative error and RMSE is to enable the comparison between the models of systems with varying sizes. By giving the RMSE and relative error as they are, also allows other studies to easily draw comparisons with this modelling approach. The mean values are compared so that performance of the models could be estimated for a longer time frame, which is important for evaluating the possibility of using the model for estimating the feasibility of different energy conservation methods.

## RESULTS

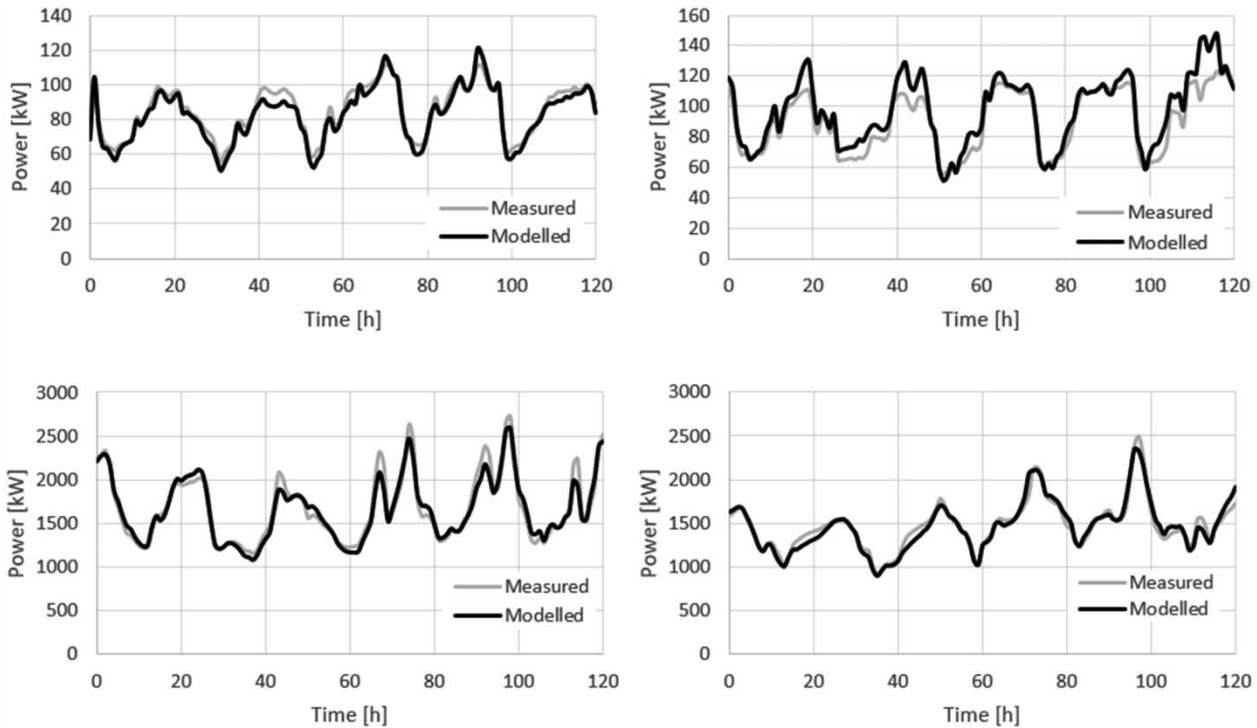
For the calibration period of the Hermanninsaari model, the RMSE and the relative error are 4.2 kW and 4.2% and for the validation period 9.4 kW and 7.8%. For the Viikinmäki model, the errors for the calibration are 92.1 kW and 4.1% and for the validation 66.2 kW and 3.4%. It should be noted, that for the Hermanninsaari model, the starting and stopping of the blowers highly influence the systems power consumption and modelling the dynamics between the blowers is a major source of error. Furthermore, the model of the blower system of the Viikinmäki WWTP was based on the measured airflow and power, rather than being an estimation from the manufacturer's data, which may contribute to the better accuracy. The measured and modelled power for both calibration and validation periods are shown for Hermanninsaari model and for the Viikinmäki model in [Figure 5](#).

In terms of the mean values of the observed periods, the Hermanninsaari model underestimated the power during the calibration period by 2.7 kW and overestimated during the validation by 6.2 kW. These values correspond to the 3.2% and 6.9% errors relative to the measured mean values. For the Viikinmäki model, the mean values for both calibration and validation were below the measured mean, the error being 16.3 kW for calibration and 3.7 kW for validation. Considering the scale of the Viikinmäki system, the predicted mean values for both periods are exceptionally good, only 1% and 0.3% relative to the measured mean values.

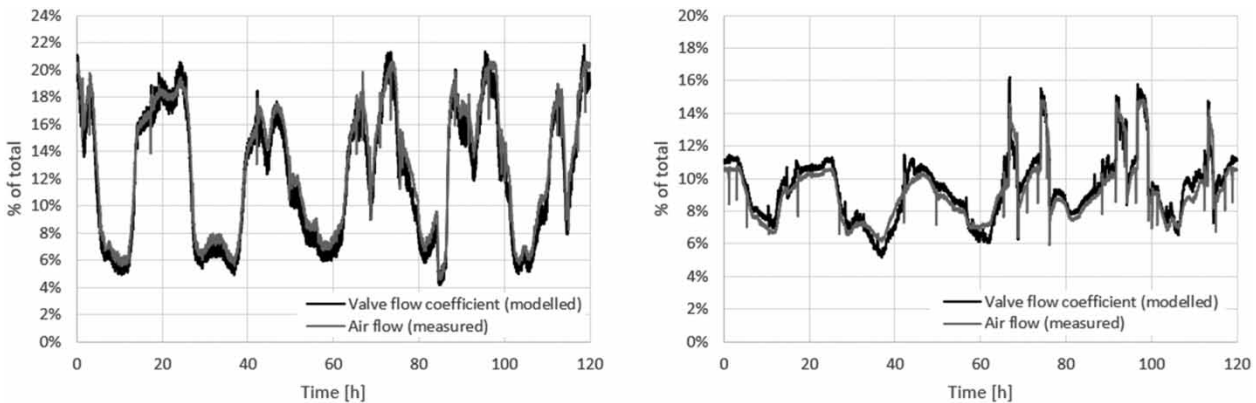
By the visual inspection of the model's output, it can be seen from [Figure 5](#) that the Hermanninsaari model struggles during the daily peak airflow demands, periods which may lead to cyclic starting and stopping of the secondary blower. This cyclic starting and stopping of an additional blower makes the model prone to error during these periods, as the wrongly timed starting or stopping of the additional blower increases the total error of the model. For the Viikinmäki model, it can be seen from [Figure 5](#) that the model underpredicts the sharper peak values, especially during the calibration period. Overall for the both of the modelled plants, the results are quite promising, considering the increased complexity of the Viikinmäki aeration distribution system and the modelled dynamics between the blowers in the Hermanninsaari WWTP.

As the data on the airflow measurements of individual aeration zones were available for the Viikinmäki plant, the distribution of the airflow rate and the valve flow factors could be assessed. Comparison of the distributions is shown in [Figure 6](#). For the calibration period, the difference between the distribution of the airflow and the valve flow coefficient in the individual zones is on average 3.4%. When the distributions are compared between the lanes, the difference was on average 0.98%. The values for the validation period are respectively 2.7% and 0.91%. These results show that the distribution of the airflow





**Figure 5** | Hourly average values for the calibration (left) and validation (right) periods for the Hermannsaari WWTP model (above) and of the Viikinmäki WWTP model (below).



**Figure 6** | Distribution of the modelled airflow based on the valve flow coefficient  $K_v$  and the measured airflow at the Viikinmäki WWTP. Comparison of a single zone to the lanes total (left) and a lane to the systems total (right).

can be estimated quite well directly from the valve positions. This also supports the idea that the control valves of each lane can essentially be modelled as a single valve, because the piping network does not seem to have that large effect on the distribution of the airflow between the aeration lanes and individual zones.

## DISCUSSION

For the model presented in this study, it is possible to estimate the effects of changing the aeration systems equipment such as control valves and the blowers. For example, the model could be used as it is for the comparison of different blower technologies, as this would not cause any changes to the demand side of the process. The major driving force for the consumption

side is the biological process. This model could be extended with a biological model of the aeration process and different control strategies for the whole aeration system, valves and the group of blowers could be assessed. With the biological portion of the model, the effects of the changes in the plants influent loading could be estimated, enabling the improved planning of the aeration system upgrades.

The model shows promising results for possible simplifications in the aeration system modelling. Although the previous studies by [Juan-García \*et al.\* \(2018\)](#), [Amerlinck \*et al.\* \(2016\)](#) and [Amaral \*et al.\* \(2017\)](#) emphasize that the aeration systems should be modelled more comprehensively, the results from the modelling approach presented in this study show that there might be potential in giving more weight directly for the valve positions and characteristics than focusing on the detailed modelling of the piping network itself. [Juan-García \*et al.\* \(2018\)](#) noted that the simplified models overestimate the energy-saving potential because the equipment constraints are not incorporated in these models. For the model developed in this study, the equipment constraints can easily be accounted for by including the limitations in the operating range on the blowers within the blower system model and by using the valve characteristic curves. The opportunity to assess the plants status and to optimize the process by using more detailed distribution system models is noted by [Amaral \*et al.\* \(2017\)](#), as the data on the DO profile are usually limited and as over- or under aeration is a typical issue of the treatment plants. The data on the Viikinmäki WWTP showed that there is a close relation between the valve positioning and the distribution of the airflow between the individual zones and aeration lanes, which would further validate the strength of using the valve positions and characteristics in the modelling. When compared to the model by [Amerlinck \*et al.\* \(2016\)](#), the simplified modelling approach assumes that the air temperature does not significantly vary with the airflow rate and neglects the fouling of the diffusers over the simulated period. Basically, apart from the valves flow factors, the variables for the distribution system model are reduced to a single constant which is defined by calibrating the model against the measurement data. It should be noted that the calibration of this type of model that does not take the diffuser fouling into account, has an expiration date, and the model should be re-calibrated if the conditions of the diffusers significantly change over time.

The model developed in this study relied heavily on the assumption that the valve characteristics and positions dominate the dynamics of the distribution systems airflow rate and pressure. The promising results from the model's performance also indicate that there might be prospects for incorporating the feedback from the valve positions more directly in the control system. As there are inconsistencies associated with the airflow measurements, the valve position together with the characteristic curve or even an estimation of the valve characteristics could provide a possibility to omit the zone-specific airflow measurements that are used in DO-control loops of individual aerated zones. This approach could also make it possible to test the automated DO controls in WWTPs which do not currently have the airflow measurement for the automated DO control.

If it is assumed that the valve positions give us reasonable accuracy on the airflow distribution throughout the system, the airflow could be measured at a single point in the beginning of the distribution system and from there on be estimated by the valve positions. This, in combination of the biological model, could offer the possibility for model predictive control of the DO profile that, instead of using multiple individual control loops, could establish optimal set of valve positions which minimize the aeration, while maintaining the treatment performance. This approach could also be valid for WWTPs that use manually controlled valves and the model could be used for multi-objective optimization as was done in the study by [Reifsnnyder \*et al.\* \(2020\)](#).

The direct flow control is often mentioned as an example of an energy-minimizing method for the aeration systems, but its implementation depends on the quality of the airflow feedback. Valve flow coefficients could be used for the verification of the airflow measurement and work as a sanity check for the feedback. For a direct flow control system, the implementation of the MOV logic is a bit more straightforward than for the pressure-controlled systems and from the energy efficiency perspective, the maximum benefit could be gained through combining these two power-minimizing strategies.

Typically, with the automated control of the aeration process, it is attempted to minimize the aeration by optimizing the DO setpoint to the influent loading. From the energy efficiency perspective, the pressure setpoint should also be included in the optimization for gaining the maximum benefits. A simulation with our model using the Hermanninsaari WWTP data revealed that a feasible 2.2% drop in the backpressure setpoint resulted in a 15% decrease in energy consumption. With the pressure-controlled aeration systems, the blower's discharge pressure will remain within a narrow range, apart from possible transient increases and decreases during starting and stopping of the additional blowers. While assessing the system's energy efficiency, these transients should not play a large role in the big picture and a constant pressure can be assumed for rough estimations of the blower systems energy consumption under different pressure setpoints. The blower system model presented in this study can therefore be used for estimating the effects of reduced discharge pressure on the energy consumption, by giving the

airflow demand and the desired pressure setpoint as model inputs. For more accurate testing, the aeration system model presented here should be extended with controllers for the individual valves and a model for calculating each zones oxygen demand. This would give a more realistic idea of what kind of pressure reduction may be feasible without altering the equipment itself.

Apart from using the model as a basis for testing different control strategies and finding solutions for process optimization, the model could offer interesting insights on a system level. As the valve flow factors would be checked against the measured airflow rate, it could be possible to detect abnormalities in operation of an aeration system. For example, as it can be assumed that the airflow is divided between the zones proportionally to the flow coefficients of the control valves, if the measured airflow to a zone with a relatively high flow coefficient is significantly less than would be estimated, there might be something wrong with the zones diffuser (excess fouling etc.). Based on the previous assumptions of the proportionality of the flow between the zones, the flow coefficients of different zones can be directly used to estimate the distribution of the airflow within a single aeration lane and between the lanes. This would then enable further analysis of the aeration process as a whole, if there are significant differences between the lanes estimated and measured airflows or if the aeration demand is actually higher within some of the lanes.

The modelling approach suggested in this study is fairly simple and does not require detailed knowledge of the aeration system at hand. The resulting models are also light and would allow running longer simulations, given that the input data are available. For truly comparing this approach to the more detailed models, the assessment should be done by modelling the same plant with alternative methods and simulating for the same time period with the same input data. Comparing just the RMSE of the models of different plants with varying sizes and configurations does not give a clear indication which modelling approach is better than the other. The time and data required for building the model should also be considered together with the required accuracy from the model. A clear weakness of the modelling approach used in this study, is that it can only be used for modelling existing systems, as the calibration relies on the measurement data. It also does not allow evaluation of the changes in the piping network or the diffusers, which would be the case when extending the aeration system with additional lanes.

## CONCLUSION

In this study, an aeration system model was developed for two Finnish WWTPs with a promising result for possible modelling simplifications. The model developed only takes the valve positions as inputs for the simulations and requires the calibration of only one parameter. Results showed that reasonable estimations of the blower's power requirement can be obtained, with only a limited knowledge on the details of the physical system, apart from the characteristics of the blowers and the control valves. The modelling approach emphasized the influence of the control valve positions to the system's power consumption and a relation between the valve positioning and the airflow distribution between the treatment lanes and within the lanes was observed. This could offer prospects for utilizing the valve positions more directly in the control systems or for the predictive control of the DO profile.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## REFERENCES

- Alex, J., Binh To, T. & Hartwig, P. 2002 Improved design and optimization of aeration control for WWTPs by dynamic simulation. *Water Science and Technology* **45** (4–5), 365–372.
- Åmand, L., Olsson, G. & Carlsson, B. 2013 Aeration control – a review. *Water Science and Technology* **67** (11), 2374–2398.
- Amaral, A., Schraa, O., Rieger, L., Gillot, S., Fayolle, Y., Bellandi, G., Amerlinck, Y., Mortier, S., Gori, R., Neves, R. & Nopens, I. 2017 Towards advanced aeration modelling: from blower to bubbles to bulk. *Water Science & Technology* **75** (3), 507–517.

- Amerlinck, Y., De Keyser, W., Urchegui, G. & Nopens, I. 2016 A realistic dynamic blower energy consumption model for wastewater applications. *Water Science and Technology* **74** (7), 1561–1576.
- Gray, M., Kestel, S. & Stahl, T. 2011 Aeration system design for energy savings. *Proceedings of the Water Environment Federation* **2011** (6), 312–324.
- Harja, G., Nascu, I., Muresan, C. & Nascu, I. 2016 Improvements in dissolved oxygen control of an activated sludge wastewater treatment process. *Circuits, Systems and Signal Processing* **35** (6), 2259–2281.
- Henze, M., Loosdrecht, M. C. M. v., Ekama, G. A. & Brdjanovic, D. 2008 *Biological Wastewater Treatment – Principles, Modelling and Design*. IWA Publishing, London, UK.
- Jenkins, T. E. 2013 *Aeration Control System Design*. John Wiley & Sons, Hoboken, New Jersey.
- Juan-García, P., Kiser, M. A., Schraa, O. & Rieger, L. 2018 Dynamic air supply models add realism to the evaluation of control strategies in water resource recovery facilities. *Water Science & Technology* **78** (5), 1104–1114.
- Larsson, V. 2011 *Energy Savings with A new Aeration and Control System in A mid-Size Swedish Wastewater Treatment Plant*. Uppsala Universitet, Uppsala, Sweden.
- Pöyry, L. 2020 *Modelling Wastewater Aeration System and High-Speed Turbo Blower for Energy Efficiency Improvements*. Aalto University, Espoo, Finland.
- Rauch-Williams, T., Pretorius, C. & Reardon, R. 2013 How oversized blower designs became an industry standard. *Proceedings of the Water Environment Federation*. Federation Technical Exhibition and Conference (WEFTEC), Chicago, 5–9 October 2013 **2013** (16), 2189–2210. Presented at the Federation Technical Exhibition and Conference (WEFTEC), Chicago, 5–9 October 2013.
- Reifsnnyder, S., Garrido-Baserba, M., Cecconi, F., Wong, L., Ackman, P., Melitas, N. & Rosso, D. 2020 Relationship between manual air valve positioning, water quality and energy usage in activated sludge processes. *Water Research* **173** (2020), 115537.
- Rieger, L., Alex, J., Gujer, W. & Siegrist, H. 2006 Modelling of aeration systems at treatment plants. *Water Science and Technology* **53** (4–5), 439–447.
- Rohrbacher, J., Stanley, E. & Phipps, S. 2014 Sustainable aeration design - 'Right-Sizing' blowers and aeration systems to facilitate energy efficient operation of WWTFs. *Proceedings of the Water Environment Federation* **2014**, 5607–5614. Presented at the 87th Annual Water Environment Federation Technical Exhibition and Conference (WEFTEC), New Orleans, 28 September to 1 October 2014.
- Rosso, D., Stenstrom, M. K. & Larson, L. E. 2008 Aeration of large-scale municipal wastewater treatment plants: state of the art. *Water Science and Technology: A Journal of the International Association on Water Pollution Research* **57** (7), 973–978.
- Schraa, O., Rieger, L. & Alex, J. 2017 Development of a model for activated sludge aeration systems: linking air supply, distribution, and demand. *Water Science & Technology* **75** (3), 552–560.
- Seborg, D. E., Mellichamp, D. A., Edgar, T. F. & Francis III, J. D. 2010 *Process Dynamics and Control*. Wiley, New York.
- Spellman, F. R. 2013 *Water & Wastewater Infrastructure: Energy Efficiency and Sustainability*. CRC Press, Boca Raton, Florida.
- United States Environmental Protection Agency (USEPA). 2010 *Evaluation of Energy Conservation Measures for Wastewater Treatment Facilities*. USEPA, Washington DC.
- Vrečko, D., Zupančič, U. & Babič, R. 2006 Improvement of ammonia removal in activated sludge process with feedforward-feedback aeration controllers. *Water Science & Technology* **53** (4–5), 125–132.
- Zuluaga-Bedoya, C., Ruiz-Botero, M., Ospina-Alarcón, M. & Garcia-Tirado, J. 2018 A dynamical model of an aeration plant for wastewater treatment using a phenomenological based semi-physical modeling methodology. *Computers and Chemical Engineering* **117** (2018), 420–432.

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