Data analytics and pump control in a wastewater treatment plant

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Abstract

This paper evaluates data from 10, 2600 kW centrifugal pumps in a large wastewater treatment facility in order to identify efficiency opportunities. Of the three interventions explored, energy savings of more than 3 percentage-points and 800,000 kWh annually were identified. Simple efficiency metrics enable robust comparisons between pumps, of performance over time, and of intervention efficacy. Operating space analysis is introduced as a method of intersecting pump and system spaces to understand how interventions, such as pump control and maintenance, affect the performance of the system. This technique can simplify data mining for pumped systems, improve control algorithms, and chart out new opportunities for next-generation control technologies to use in addition to variable frequency drives.

Keywords: Pump system efficiency, Wastewater Treatment Plants (WWTPs), Efficiency metrics, Time-series analysis, Algebraic geometry, Operating space analysis

1. Introduction

[1]Centrifugal pumps are ubiquitous in fluid systems such as clean water distribution, wastewater treatment, pumped hydro energy storage, building HVAC systems, petroleum extraction, mining, and crop irrigation. In these energy-intensive systems pumps are often major energy consumers. Globally, pumps consume hundreds of billions of kilowatt hours of electricity each year. In the US, pumps consume an estimated 6% of U.S. electricity, equivalent to 230 billion kWh annually[2], about the output of 58 Hoover Dams [3]. This paper begins with key concepts from the literature on evaluating and

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[1]The short version of the paper was presented at Applied Energy Symposium: MIT A+ B, August 13-14, Boston. This paper is a substantial extension of the short version of the conference paper.

[2]The 1998 US Industrial Electric Motor Systems Market Opportunities Assessment [1] states that motors consume 23% of electricity and pumps represent 25% of motor consumption. Therefore, we estimate that pumps consume 6% of US electricity sold. The Department of Energy [2] records show in 2018, 3.9 trillion kWh of electricity was sold in the US. Thus, 232 billion kWh is a reasonable estimate of annual pump electricity usage.

improving pump system efficiency. Using this background, we evaluate data from 10, 2600 kW centrifugal pumps in a large New England wastewater treatment plant (WWTP) to understand the influence of pump design, selection, maintenance and operation on system efficiency. We quantitatively explore the efficiency impact of interventions and qualitatively present trade-offs to implementation. The methods and recommendations developed for this case study can be applied more broadly to other pumping systems and to motivate pump design and system operation research.

2. Background

2.1. Pump Design Life Cycle

The pump lifecycle, shown in Fig. 1, shows the strong connections between design, selection and operation. Physical dimensions, such as clearances to enhance robustness, in the design influence operational efficiency. Likewise, knowledge of the operational duty cycle influences the designed pressure and flow. Pump selection depends on knowledge of the operational system curve. Operational flexibility depends on whether controls such as variable speed drives are installed with the pumps. Furthermore, pump maintenance and monitoring can substantially reduce energy consumption. Given the wide range of operating pressures, flows, and speeds, advanced operational and pump control can further reduce energy consumption [4, 5, 6]. Pump system efficiency is maximized by a combination of improved design, pump selection, and adaptive control, which includes accounting for wear. Data collection and analysis provides a foundation to enable improvements at each stage as well as closing the loop on the pump lifecycle.

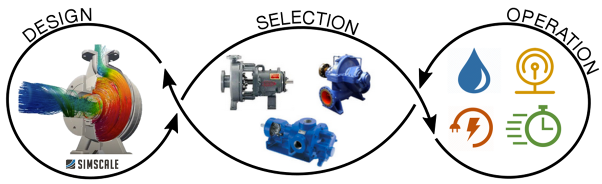

Figure 1: Available pumps influence component selection, which then influences system operation. Conversely, information about system operation influences component selection. Both, in turn, influence the design of new pumps. Pump simulation image (left) used from SimScale GmbH with permission.

Real systems operate over a range of flow and pressure conditions. In contrast, centrifugal pump manufacturers specify a single design point for most efficient operation; the best efficiency point (BEP). This is an important parameter because system fluctuation away from the BEP leads to energy losses and increased wear. Fig. 2 shows the traditional pump and system characteristics intersecting at the BEP. It also visualizes shaded ranges of variation about the characteristics. Energy losses can be reduced throughout the design life cycle:

- Design: Hydraulic geometry can create a broad efficiency curve allowing for efficient operation, typically between 85% to 110% of the BEP flow. Adaptive geometry may further expand this range.

- Selection: Best practice characterizes the system and selects a pump such that the pump characteristic intersects the system at the BEP. Selection that accounts for how the real system is operated can significantly impact lifetime efficiency and maintenance.

- Operation: Advanced control, like variable speed drives, can shift the pump characteristic to better meet changes in the system curve.

These strategies lead to more efficient operation, improved equipment lifetimes, and lower operating and maintenance costs.

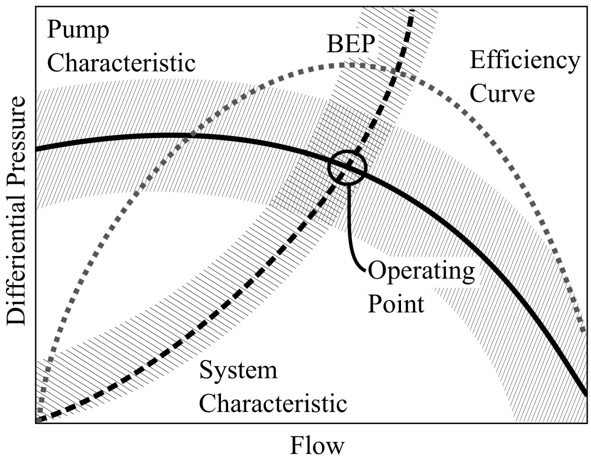

Figure 2: Traditional model of pump operation showing the pump characteristic, system characteristic, and an efficiency curve with ranges of operation shown by the shaded blue and red curves.

Although the BEP is the standard metric, it does not capture the efficiency of the system operating over a range of conditions over time. True weighted efficiency (TWE), defined in Eq. 1, is the energy-weighted average efficiency for a pump [7]. TWE directly measures energy wasted and enables engineers to compare pumps by calculating energy savings while accounting for the pump design and the system variations. The Pump Energy Index (PEI), promoted by both the Hydraulic Institute and the U.S. Department of Energy (US DOE), utilizes a similar method, but compares a pump with an aggregate baseline for a pre-determined load profile. A detailed review of pump efficiency metrics can be found in Dahl's 2018 paper [7]. TWE is a particularly helpful metric because it allows for direct and robust calculation of energy savings. Equation 2 shows how to directly calculate energy savings, E_s, from an intervention's calculated TWE, TWE_i, a baseline TWE, TWE_b, and a baseline energy consumption E_b. The results in Section 3.2 use Eq. 2 to calculate the impact of different interventions for design, selection, and operation.

$$TWE = \frac{\sum P_o t_o}{\sum \frac{P_o}{\eta} t_o} \tag{1}$$

$$E_s = \left(1 - \frac{TWE_b}{TWE_i}\right) E_b \tag{2}$$

2.2. Best Practices for Energy Efficiency

Improving the performance of centrifugal pumps has driven innovation since well before the Machine of Marly was completed in 1684. Modern books on pump performance provide great overviews of this field. Karassik in *The Pump Handbook* [8] extensively covers pump performance, design, selection, maintenance, and operation. Gülich [9] presents efficient design methodologies to address the nuances of hydraulic, volumetric and mechanical efficiency. While pump design and control are mature areas, there are still significant opportunities to improve efficiency.

Due to the large pumping requirements of wastewater treatment plants (WWTP), they are often used for case studies on energy efficiency. The National Renewable Energy Laboratory NREL published a 2012 report demonstrating the utility of intermittent process energy audits to identify systemic inefficiencies [10]. Shankar et al [4] present a comprehensive review of pump efficiency enhancement opportunities, focused on selection and operational optimization. Torregrossa [5] notes that accessible methodologies to analyze pump energy consumption are lacking. Longo et al also addresses this gap in the 2019 paper titled, *ENERWater: a standard method for assessing and improving the energy efficiency of wastewater treatment plants.* [11]

Although improving the efficiency of WWTPs is uncontroversial, limited real-time data is still lacking for better efficiency monitoring and control. Widespread implementation of Supervisory Control And Data Acquisition (SCADA) systems in conjunction with frequent digital data collection of flow, differential pressure, motor speed and power, enables real time decision making based on efficiency metrics and trends [12]. The analysis in this paper solely relies of data generally available to the plant managers thus making these methodologies accessible to widespread adoption.

2.3. Modern Methods of Increasing Efficiency

The most elementary means of flow control in a pump system is through adjusting valves or turning pumps on and off. The introduction of variable frequency drives (VFDs) in the past half century provided system control of either flow or efficiency [13]. The question of how best to control a VFD pump is still an open topic in the field of optimization. Notably, there are examples of using data and optimization to improve wastewater plant operations. For example, Zhang et al. present the use of a neural network to estimate a pump system from data and then apply aiNet to solve a bi-objective optimization in order to optimize WWTP control. They state their system can theoretically lead to as much as energy 25% savings [14]. Similarly, Torregrossa and Capitanescu share their application of heuristic optimization algorithms in one paper to reduce the energy consumption of a wastewater treatment plant, and fuzzy logic in another [5, 6]. Filipe et al [15] present model-free data predictive control using deep reinforcement learning and proximal policy optimization, which when used to control pumps in a Portuguese WWTP, led to a 16% decrease in energy consumption.

The references above show the wealth of savings that are possible through the effective adoption of optimization and control. One topic that seems to be lacking in the modern pump control optimization literature is a connection to the classical pump selection and control methods. A priori knowledge of the pump curve and its usage could simplify some of the calculations within the control scheme optimization and would likely increase the interpretability of the result for plant managers and practitioners.

Additionally, framing pump control as managing the intersection between the system and pump characteristic shapes, as shown in Figs. 2 and 6, has implications for what it means to use VFDs, or any other augmentation, to control a pumped system. Section 4 uses a geometric pump and system-space framework to show that VFDs are limited to controlling for either flow or efficiency when used alone. In order to control both values independently, a second degree of control is required. The idea of framing system control as a set of degrees of freedom and degrees of constraint is well developed in chemical engineering and mechanical design [16, 17]. The operating space analysis framework in this paper uses a similar approach to better understand pump control.

3. Wastewater Treatment Plant Case study

3.1. Inflow Pump Station Data

Pump operating data were acquired from a large New England wastewater treatment plant influent pump station. The pumps consume 19.5 million kWh annually, which is approximately 2.4% of the state's annual electricity consumption. The system consists of ten vertically mounted end suction centrifugal pumps, manufactured by Fairbanks Morse with 42" 5-vane impellers.[18] Each pump is driven by a 2610 kW (3500 HP) variable speed, synchronous three phase motor with variable frequency drive. Each pump was originally rated for 110 MGD[3] at 150 ft of head at 400 rpm, 100% speed. Raw hourly data for pump status (on/off), flow (MGD), power (kWh), motor speed (RPM), and pump suction tunnel elevation (feet) were collected for each of the 10 pumps for a period of twelve months between August 2019 and July 2020. Raw 5 min data were collected for the same variables for one month, August 2019. Data were converted to metric units. Data where the pumps were off were removed from the sets, resulting in n=20,051 and n=32,440 data points respectively.

The inflow pumps move raw effluent from 2 suction tunnels up to grit chambers at 48 meters of head. Differential pressure data for each pump were intermittently measured by analog gauges and manually recorded, thus hourly pressure data were unavailable. The static pressure rise across each pump was estimated from the difference in water column height at the inlet and outlet. The pump outlet is connected to the relatively constant grit chamber elevation of 47.85 meters. The water elevation above the pump inlet was calculated by subtracting the dynamic head ($\frac{1}{2}\rho v^2$) associated with a 48" pipe diameter and the given flows from the recorded static pressure on the inlet side. The hydraulic power $P_{hydraulic}$ and wire-to-water efficiency η of the pump at each point are calculated as shown in Equations 3 and 4, where Q is the flow, Δp is the total pressure rise, and $P_{electrical}$ is the electrical power input to the motor. Friction losses in the pipes

[3] MGD: million gallons per day

and small fluctuations in the grit chamber elevation are the primary sources of error in this efficiency calculation.

$$P_{hydraulic} = Q\Delta p \tag{3}$$

$$\eta = \frac{P_{hydraulic}}{P_{electrical}} \tag{4}$$

The intensity of energy consumption was calculated as the $P_{electrical}/Q$ and measured in kWh/m^3. This is a common metric for comparing fluid systems [19].

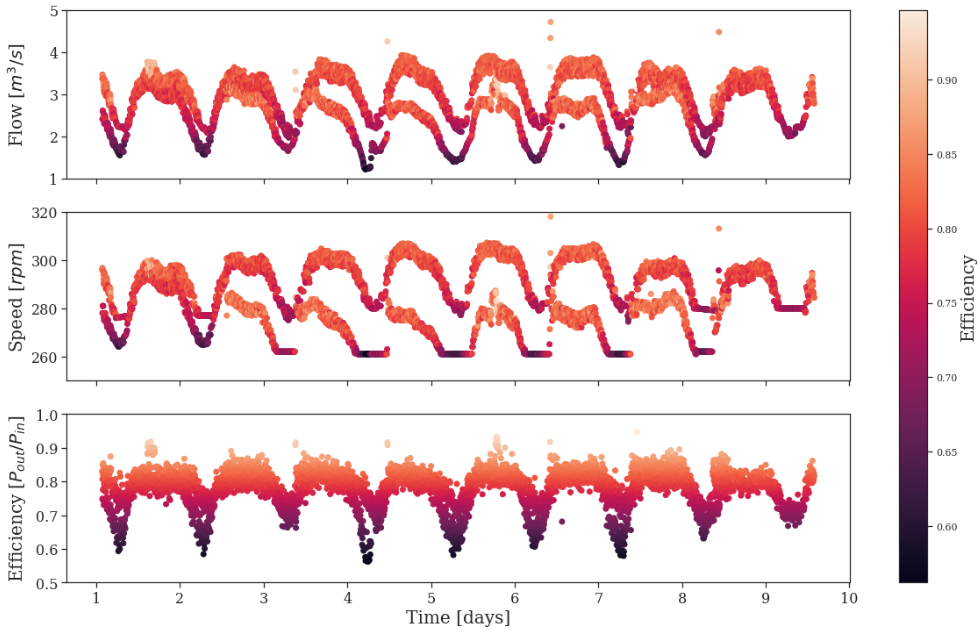

Figure 3: Time series slice of pump operational data for 9 day period taken at 5 min intervals.

3.2. Analysis

Utilizing the facility data, this section explores strategies to improve system efficiency using time series analysis, pump and system curve intersections, comparative operation between pumps, and control optimization.

Fig. 3 shows a slice of the 5 min interval time series distributions during a period of 9 days. The values are colored according to their calculated efficiency. Flow and speed are strongly correlated, and flow and efficiency are moderately correlated with Pearson correlations of 0.90 and 0.36 respectively. Fourier analysis confirms the visually evident daily and half day frequencies. This demonstrates a control schema which reduces the pump speed in the early morning around 4 a.m. in response to low flows. The pumps correspondingly operate in a lower efficiency regime. Sources of variation in the data include degradation and maintenance of the pumps based on usage and differences in operating parameters, such as inlet/outlet pressure, flow and motor speed.

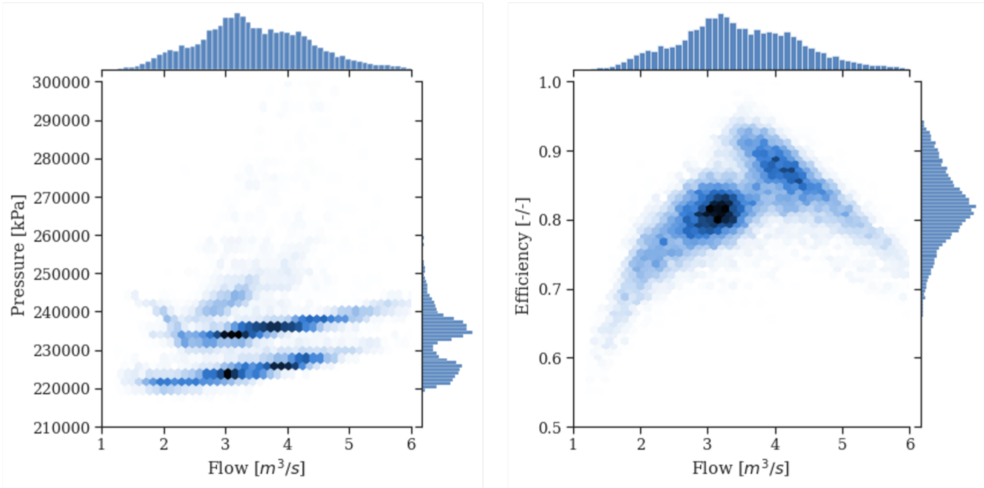

Figure 4: Aggregate data for a year of hourly interval data n=20,051. Color based on a bivariate histogram of the number of points, univariate histograms shown on the respective axes.

The two bands of data in the time series plots shows two pumps operating in parallel. For best efficiency, each pump would ideally operate consistently at its best efficiency point around 3.5 m^3/s and 310 rpm. During daytime flows without storm water spikes, running 2 out of the 10 available pumps allows for operation close to the BEP. Operational constraints may dictate that two pumps always need to be running, based on how long it would take to bring a pump online. However, during the morning low flow periods a single pump could more efficiently handle the total system flow.

Comparing Fig. 4 with Fig. 2, it is evident that the real system, with variable speed control and variable flow demands is more complex than the traditional pump curve representation. Fig. 4 shows the aggregate data for the year of hourly sampling. The left plot shows the pump operation for pressure and flow while the right plot shows the efficiency with respect to flow. The histograms of the univariate data are shown on the respective axes. The pressure-flow data show two primary pressure bands due to an approximately 0.6 meter difference in inlet elevation between the two suction tunnels. The efficiency-flow data show a broad efficiency curve, with a high density of points between 3 and 4 m^3/s. The variance in the efficiency data demonstrates deviation from the maximum efficiency potential.

Summary statistics for pump operation and performance are presented in Table 1. TWE for the August 5 min and hourly intervals are compared with each other and with mean efficiency. Yearly TWE values, recommended pump rankings, and percent operating time for the year are presented. The maximum recorded efficiency point flow, pressure and speed were determined by the point at which the maximum efficiency was recorded. The violin plots in Fig. 5 compare the flow histograms for the 10 pumps for the month of August. The two halves of the violins compare the hourly and 5 min intervals collected.

While each of the 10 pumps were originally the same installed hardware, the performance characteristics changed over time due to abrasion, cavitation, and maintenance

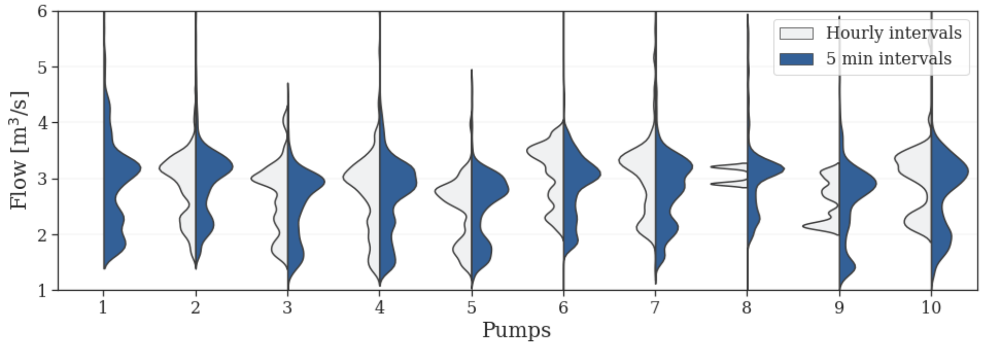

Figure 5: Violin plots compare flow profiles for each of the 10 pumps in August 2019. Labels indicate the energy weighted efficiency for each pump to compare the duty cycle to efficiency.

Percentages	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
TWE (Aug 5min)	81.0	81.1	75.1	80.3	79.5	77.5	80.0	78.6	80.9	78.1
TWE (Aug hr)	-	81.1	75.7	80.5	78.8	78.7	81.3	79.9	79.5	78.2
Mean efficiency %	80.3	80.7	74.2	79.3	78.5	77.0	79.4	78.4	79.6	77.2
std deviation %	5.5	4.6	6.8	7.3	7.2	4.7	6.3	4.2	8.3	6.8
TWE (Year hr)	83.3	82.6	79.4	81.3	84.6	79.1	82.5	83.0	84.9*	80.5
Rank	2	3	6	4	1	6	3	2	1	5
Operating time %	3.6	13.9	10.1	10.5	14.3	11.6	8.8	7.7	10.0	9.5
BEP Flow m^3/s	3.1	3.9	3.5	3.4	3.2	3.4	3.5	3.9	3.7	3.1
BEP Pressure kPa	223	235	233	234	225	234	231	236	225	248
BEP Speed rpm	283	300	300	278	281	278	291	303	289	285

Table 1: Summary statistics comparing pump operation, using the August 5 min and hourly datasets, and the year of hourly data. True weighted efficiency TWE calculated using Eq. 1. *Post maintenance TWE value used, rather than full year.

differences. Table 1 and Fig. 5 demonstrate differences in operation and efficiency, caused by more than 2 decades of intermittent operation. There is a 5.8 percentage-point spread in true weighted efficiency between pump 6 (79.1%) and pump 5 (84.9%). Pumps 5 and 2 were operated the most over the year period of data collected, while pump 1 was rarely operated.

When evaluating the TWE of a real system, is it important to consider how discretization error impacts the calculation. Equation 1 implicitly assumes uniform operation between discrete data points, ignoring fluctuation between samples. It is easy to overlook this detail when specifying a data collection system, but the impacts can be significant. For example, wastewater treatment, a pumped system that is neither exceedingly dynamic nor exceedingly static, shows a meaningful shift in TWE when data is collected on hourly and 5 minute intervals. Table 1 shows as much as a 1.4 percentage-point shift in TWE between these two sampling rates. Interestingly, the error can be both positive and negative, making it hard to simply 'offset' for expected error. For this facility, that difference can add up to 10s of thousands of kWh/year, more than enough to justify a data logging solution that can support 5 min or faster sampling. Sampling rate is even more important to consider in connected systems that use efficiency as an optimization objective. More frequent sampling can result in a more accurate metric, but needs to be balanced with increased data transmission and memory storage costs.

The violin plot histograms in Fig. 5 also highlight the differences between the hourly and 5min data. The 5min data has smoother profiles, whereas the hourly data is more discrete. The pumps show a common bulge in the peak flow range around 3 m^3/s, but vary in profile in the low flow region. Calculated from the operational data, agreement between the pumps' best operating points indicate that the system operates most efficiently around 300 rpm, 3.6 m^3/s, and 226 kPa.

Three common efficiency improvement strategies are quantitatively evaluated below: pump maintenance, utilizing the most efficient pumps, and running a single pump during low flow periods.

Pump maintenance significantly impacts efficiency. In particular, corrosion and cavitation inside of the fluid chambers of centrifugal pumps increase surface roughness, leading to boundary layer blockage and friction losses. This reduces the efficiency of the hydraulic energy conversion of rotational kinetic energy into fluid pressure rise. Wear resulting in increased clearances also promotes increased recirculation. In the plant, pump 9 was serviced in December and January, including resurfacing the impeller and flow passages. Prior to maintenance, from August through December, pump 9's TWE was 78.8%. After maintenance, the TWE improved to 84.9%, a 6 percentage-point increase. Based on how often pump 9 is operated, the 6% increase could represent yearly savings of 130-200 thousand kWh, equal to $13,000-$20,000 saved in energy costs, based on $0.10/kWh. In addition to improving efficiency, maintenance improves reliability and can reduce vibration, overheating, cavitation, and bearing and seal failures.

It is common practice to rank and utilize the most efficient equipment for the majority of operation, while keeping lower efficiency equipment as backup. After maintenance is performed the pump is often rotated into frequent use. Pump 9 operation time increased from 4 to 13% before and after maintenance. Our recommended rank in Table 1 identifies pumps 9 and 5 as top performers, closely followed by pumps 8 and 1. If the plant were to continuously operate using only the most efficient equipment our analysis shows a 3.0 percentage-point increase in true weighted efficiency. This could represent 690,000 kWh and $69,000 saved per year. Using pumps 5 and 9 most often, and pumps 1 and 8 second most is a viable energy saving strategy.

The time-series data shows that during the nightly low flow periods a single pump could handle the total system flow. Operating a single pump close to the best efficiency point can consume less power than operating two pumps at the less efficient low flow points when pipe losses are small. Low flows, defined here as less than 2.5 m^3/s, make up 14% of operation. In order to quantify potential energy savings, we segmented the 5 min dataset and summed simultaneous low flows to compute a combined flow, less than 5.0 m^3/s. Using pump surfaces parameterized by fitting a quadratic response surface to the full dataset, we recalculated the pressure, speed, power consumption, and efficiency for these combined flows. Those response surfaces were used to calculate the original and improved True Weighted Efficiencies. These results show a 3.6 percentage-point improvement from 83.0 to 86.6%. This improvement could lead to 809,000 kWh and $80,900 saved per year.

Operationally, it may be necessary to run two pumps to mitigate the operational risk of one pump clogging or going offline. However, alternatives could include installing lower flow 'pony' pumps; using a water tank/inflow tunnel as a buffer while a replacement pump is brought online; and a smart controller to turn on a new pump when an issue is detected on the first pump. Implementing pony pumps and combinations of pump sizes is a widely recognized strategy by practitioners, but adoption is often limited by the available footprint in wastewater facilities. Simply running one already installed pump, rather than two, during low flow periods is a simple energy saving strategy without requiring additional capital investment. The risks, alternatives, and potential energy and cost savings should all be considered when evaluating these trade-offs.

Considering the three interventions presented here, it is clear that significant energy savings can be found by collecting data and evaluating possible interventions.

4. Operating Space Analysis

VFDs are effective tools for improving pump operation. Typical practitioners strive to control speed and maximize efficiency at the same time. The question considered here is: 'to what degree can VFDs, or other designs, enable control over both of those objectives?'. This can be directly addressed with the same algebra that lets us find an operating point, p_o, by intersecting a pump curve, $C_p \subseteq \mathbb{R}^2$, in pressure and flow space, with a system curve $C_s \subseteq \mathbb{R}^2$, in pressure and flow space. This is method of intersecting the pump and system curves is shown in Fig. 2. Equation 5 formally expresses this classic case.

$$p_o = C_p \cap C_s \tag{5}$$

VFDs expand the operating envelope of the pump from a line for a surface $S_p \subseteq \mathbb{R}^3$ in pressure, flow, and speed space. S_p can be approximated with response surface fitted to existing operating data. Because the system curve is independent of the pump speed, the system curve can be linearly extended to occupy pressure, flow, and speed space, $\mathbb{R}^3$, as S_s. The intersection of two lines is a point[4] and the intersection of two surfaces is a curve in space[5]. VFD operation is often depicted as multiple pump curves of different speeds, intersecting the system curve at different points. Astute practitioners already recognize that these curves are discrete slices of the continuous spectrum that composes the pump surface: S_p. Thus, the operation of a fixed system and VFD pump can be represented as the operating curve, C_o, a 1-dimensional object in $\mathbb{R}^3$, pressure, flow, and speed space. Figure 6 shows what this intersection and resulting operating curve can look like.

$$C_o = S_p \cap S_s \tag{6}$$

The interesting conclusion of Eq. 6 is that the operating curve is a 1-dimensional object with 1 degree of freedom. Since each point on C_o has one corresponding efficiency, the operator can only control for one of flow, pressure, or efficiency. This is a significant improvement over being constrained to one operating point and having no on-line control.

[4] in the non-degenerate case
[5] also in the non-degenerate case

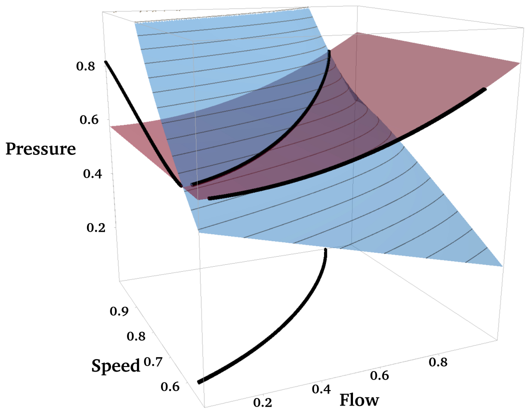

Figure 6: An intersecting pump surface (S_p - blue) and system surface (S_s - red). The resulting operating curve (C_o) is show in in black, and is projected into the three coordinate planes.

Control valves can add one degree of freedom to the system space, enabling control of one additional variable, but this comes at the cost of energy economy because control valves are energy destroying devices.

The nuances of this insight can be seen in Fig. 4, where the operation of wastewater plant pumps is plotted in time-series over 9 days. In the early morning, the pump speed is lowered to match the reduced flow requirements. This is intended to reduce power consumption, but also reduces the pump's efficiency. This control scheme leaves room for improvement in two ways. The reduced efficiency indicates that there is room for energy conservation. Additionally, operation off of the best-efficiency point increases wear on the pump, impacting operating and maintenance costs. The addition of one non-energy destroying degree of freedom to on-line pump control would eliminate that wasted energy and increase pump life.

There are many design variables that could provide that extra degree of freedom. Some options include: impeller outlet height/width, impeller outlet diameter, impeller eye diameter, impeller blade angle, fluid pre-swirl, volute geometry, and diffuser blade angle are some notable examples. It is beyond the scope of this paper to discuss these options in detail, and considerable work has been done on a variety of these design strategies [20, 21]. Building a robust understanding of how these concepts affect the pump space is a rich field of research.

One illustrative toy problem that can be computed from existing operating data is the independent operation of two wastewater treatment plant pumps. The two extra degrees of freedom are provided by Ω_a and Ω_b, the impeller speeds of the two active pumps, in Eq. 7. The pump space, now a sub-volume in $\mathbb{R}^4$, intersected with the system curve provides two degrees of control. In this configuration, both efficiency and flow can be controlled to some degree of independence. The resulting operating surfaces are shown in Fig. 7.

$$Q_t(\Delta p, \Omega_a, \Omega_b) = Q_a(\Delta p, \Omega_a) + Q_b(\Delta p, \Omega_b) \tag{7}$$

Ω_a and Ω_b are the x and y axes in Fig. 7a because they are the independent variables.

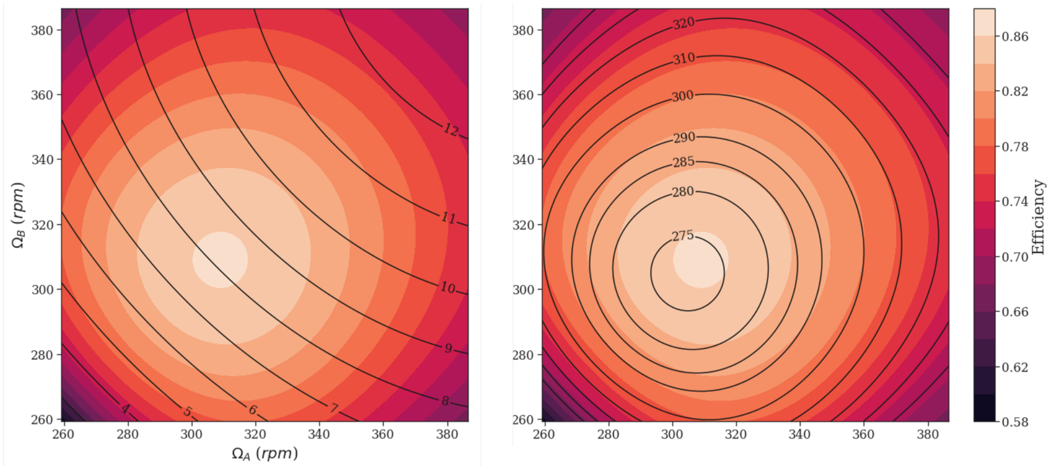

Figure 7: Pump efficiency[W/W], with respect to Ω_a and Ω_b, overlaid with flow [m^3/s] (a) and energy intensity [kWh/m^3] (b) contour lines. The x and y axes represent degrees of operational control. Each point on the operating surface represents a unique operating point between the pumps and system.

The pressure rise is set by the system's flow resistance. The contour lines show that it is possible to maintain a certain total flow, Q_t, over a range of efficiencies. In this example the two pump models are identical response surfaces. Because of that symmetry, the chart shows that it is most efficient to run the two pumps at the same speed. While this toy problem has a simple finding, it illustrates how an operating space is defined and visualized. Other methods of pump control will likely yield more interesting results, and are worth investigating in future studies.

There is still one interesting findings from this operating space analysis toy problem shown in Fig. 7b. The minimum energy intensity (kWh/m^3) does not occur at the lowest speed or the BEP. Reduced pressure losses at lower speeds and increased efficiency at higher speeds compete. This creates a minimum that has the best energy economy, which can be rigorously found with this operating space analysis.

5. Conclusion

Even though pump design, selection, and operation are all mature fields, there are still good opportunities to improve performance with new short-term interventions and ambitious research programs. The case study in this paper examines one of the largest wastewater plants in the United States. The existing plant data show that at least a 3% improvement in efficiency is possible with short-term interventions. It is also shown that more opportunities for improving pump efficiency can be found by increasing the sampling rate of operating data.

This paper also introduces operating space analysis and uses it to prove the need for new pump control methods to empower pump operators to achieve desired flow and efficiency at the same time. This method draws heavily on existing system design and control best practices. This new perspective on pump control shows that there is a considerable amount of future work to be done. There are still substantial savings to be had by developing a pump control method that is effective and robust enough for use alongside VFDs.

6. Acknowledgements

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Nomenclature

Δp Total pressure rise [Pa]

η Efficiency [W/W]

Ω_a Rotational speed of pump 'a' [rpm]

Ω_b Rotational speed of pump 'b' [rpm]

ρ Density [kg/m^3]

C_o Operating curve

C_p Pump curve

C_s System curve

E_b Energy consumption of the baseline case [kWh]

E_s Energy saved [kWh]

P_o Operating power [W]

p_o Operating point

$P_{electrical}$ Electrical power [W]

$P_{hydraulic}$ Hydraulic power [W]

Q Flow [m^3/s]

Q_a Flow through pump 'a' [m^3/s]

Q_b Flow through pump 'b' [m^3/s]

Q_t Total system flow [m^3/s]

S_p Pump Surface

S_s System Surface

t_o Operating time [s]

TWE True Weighted Efficiency

TWE_b True Weighted Efficiency of the baseline case [W/W]

TWE_i True Weighted Efficiency of the intervention [W/W]

v Fluid velocity [m/s]

References

[1] United States Industrial Electric Motor Systems Market Opportunities Assessment (1998).

[2] Table 1.1 Total Electric Power Industry Summary Statistics, 2018 and 2017 (2018). URL `https://www.eia.gov/electricity/annual/html/epa_01_01.html`

[3] Hoover Dam — Bureau of Reclamation (2020). URL `https://www.usbr.gov/lc/hooverdam/faqs/powerfaq.html`

[4] V. K. Arun Shankar, S. Umashankar, S. Paramasivam, N. Hanigovszki, A comprehensive review on energy efficiency enhancement initiatives in centrifugal pumping system, Applied Energy 181 (2016) 495–513. `doi:10.1016/j.apenergy.2016.08.070`.

[5] D. Torregrossa, J. Hansen, F. Hernández-Sancho, A. Cornelissen, G. Schutz, U. Leopold, A data-driven methodology to support pump performance analysis and energy efficiency optimization in Waste Water Treatment Plants, Applied Energy 208 (2017) 1430–1440. `doi:10.1016/j.apenergy.2017.09.012`.

[6] D. Torregrossa, F. Capitanescu, Optimization models to save energy and enlarge the operational life of water pumping systems, Journal of Cleaner Production 213 (2019) 89–98. `doi:10.1016/j.jclepro.2018.12.124`.

[7] T. Dahl, Theory and application of true weighted efficiency – a new metric to evaluate pump energy efficiency considering multiple operating conditions, in: Turbomachinery Laboratory, 2018, p. 25.

[8] I. J. Karassik (Ed.), Pump Handbook, 3rd Edition, McGraw-Hill, 2001.

[9] J. F. Gülich, Centrifugal Pumps, 3rd Edition, Springer-Verlag, 2014.

[10] J. Daw, K. Hallett, J. DeWolfe, I. Venner, Energy Efficiency Strategies for Municipal Wastewater Treatment Facilities (2012). `doi:10.2172/1036045`.

[11] S. Longo, M. Mauricio-Iglesias, A. Soares, P. Campo, F. Fatone, A. Eusebi, E. Akkersdijk, L. Stefani, A. Hospido, ENERWATER – A standard method for assessing and improving the energy efficiency of wastewater treatment plants, Applied Energy 242 (2019) 897–910. `doi:10.1016/j.apenergy.2019.03.130`.

[12] D. Torregrossa, G. Schutz, A. Cornelissen, F. Hernández-Sancho, J. Hansen, Energy saving in WWTP: Daily benchmarking under uncertainty and data availability limitations, Environmental Research 148 (2016) 330–337. `doi:10.1016/j.envres.2016.04.010`.

[13] R. D. Zimmerly, Variable speed motor driven pumping system (1970).

[14] Z. Zhang, A. Kusiak, Y. Zeng, X. Wei, Modeling and optimization of a wastewater pumping system with data-mining methods, Applied Energy 164 (2016) 303–311. `doi:10.1016/j.apenergy.2015.11.061`.

[15] J. Filipe, R. J. Bessa, M. Reis, R. Alves, P. Póvoa, Data-driven Predictive Energy Optimization in a Wastewater Pumping Station (2019). `arXiv:1902.03417`. URL `http://arxiv.org/abs/1902.03417`

[16] J. B. Jensen, S. Skogestad, Steady-State Operational Degrees of Freedom with Application to Refrigeration Cycles, Industrial & Engineering Chemistry Research 48 (2009) 6652–6659. `doi:10.1021/ie800565z`.

[17] T. Pham, Degrees of freedom of equipment and processes, Chemical Engineering Science - CHEM ENG SCI 49 (1994) 2507–2512. `doi:10.1016/0009-2509(94)E0056-V`.

[18] Fairbanks Morse Pump Technical Data - 2410 Series Solids Handling Pumps (2011).

[19] A. Plappally, J. Lienhard V, Energy requirements for water production, treatment, end use, reclamation, and disposal, Renewable and Sustainable Energy Reviews 16 (2012) 4818–4848. `doi:10.1016/j.rser.2012.05.022`.

[20] G. H. Caine, Adjustable Centrifugal Pump (1987).

[21] A. Posa, A. Lippolis, A LES investigation of off-design performance of a centrifugal pump with variable-geometry diffuser, International Journal of Heat and Fluid Flow 70 (2018) 299–314. `doi:10.1016/j.ijheatfluidflow.2018.02.011`.