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Integrating Reliability and Energy Efficiency Assessments for Pinpointing Actionable Strategies for Enhanced Performance of Urban Wastewater Treatment Plants

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Abstract: By leveraging performance assessment systems (PASs) and incorporating targeted strategies, utilities can enhance the overall effectiveness, reliability, efficiency, and environmental performance of their wastewater treatment facilities. This work presents the results obtained from a comprehensive analysis of treatment reliability and energy performance of three wastewater treatment plants (WWTPs). The results allowed identifying, for each WWTP, improvement needs related to the aeration energy requirements, as well as to determine the effluent concentration targets required to achieve higher reliability levels while potentially reducing running costs. By analysing reliability combined with energy efficiency, this methodology allowed identifying the WWTPs' performance-limiting stages or dysfunctions that affect both effectiveness and efficiency, to estimate the investment needs and prioritize the rehabilitation or even retrofitting of facilities' assets.

Keywords: wastewater treatment; reliability; energy efficiency; performance

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Citation: Cassidy, J.; Silva, T.; Semião, N.; Ramalho, P.; Santos, A.R.; Feliciano, J.F.; Silva, C.; Rosa, M.J. Integrating Reliability and Energy Efficiency Assessments for Pinpointing Actionable Strategies for Enhanced Performance of Urban Wastewater Treatment Plants. *Sustainability* **2023**, *15*, 12965. https://doi.org/10.3390/su151712965

Academic Editor: Agostina Chiavola

Received: 31 July 2023
Revised: 11 August 2023
Accepted: 21 August 2023
Published: 28 August 2023

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1. Introduction

The intensification of wastewater quality legal requirements and users' expectations result in a growing concern for water and wastewater utilities to increase their efficiency whilst complying with local regulations.

Focused on increasing efficiency and effectiveness, AGS, a company providing operation and maintenance services in several wastewater treatment plants (WWTPs) has been using a performance assessment system (PAS) [1], under the scope of the iEQTA project [1], which has been shown to be very useful to identify and pinpoint operational optimization and rehabilitation needs [2]. Briefly, as comprehensively explained in Silva et al. [1], the PAS first evaluates the overall performance of WWTPs in terms of compliance and removal efficiency, energy efficiency [3], and sludge management, using key performance indicators. Subsequently, the WWTPs are evaluated towards the operational performance of treated effluent quality, removal efficiencies, and operating conditions [1,4]. The relevant operational performance assessment aspects of the WWTPs are expressed by state variables that are converted into dimensionless performance indices (PXs). The PXs vary between 0 and 300, 100 being the minimum acceptable performance and 300 the excellent performance [1]. The first assessment in a WWTP should target their effectiveness and reliability, and then the efficiency, integrating both [1].

Reliability is defined as the probability of adequate performance during a specified period, under specified conditions. For treatment, this translates into the time percentage the effluent concentrations meet the requirements specified in the discharge consents [4] and thus, the WWTP's stability, resilience and continuous operational performance in treating wastewater and protecting the environment [5,6]. The use of probabilistic methods to define the discharge standards is a usual approach for WWTP operation [5,6]. The simple and consolidated Niku's reliability-based method [7] was integrated with the assessment of the compliance with discharge consents and was used in the iEQTA project with 16 Portuguese activated sludge WWTPs [1]. The results showed it allows estimating the WWTPs' compliance, reliability, and stability, and the target effluent mean values needed to meet the discharge limits with a given reliability—key information to trigger operational improvements and asset management decisions [1]. This method is valid when the plant effluent concentrations fit a lognormal distribution. Otherwise, e.g., when Weibull or Gamma distributions are applicable, other probability models or fault tree analysis are used [8–10].

Energy is typically the second largest part of the running costs of a WWTP [3,11,12], after personnel. As such, improving energy efficiency is crucial to reduce costs that can be redirected to other aspects of the WWTPs such as rehabilitation or revamping of the facilities. To optimize energy efficiency, the first step is to understand where energy is being used and how efficient the use is.

The energy efficiency evaluation was developed in the iEQTA project [1], through energy performance indicators and indices [3]. The indicators assess the plant as a whole and the indices the energy consumption in each treatment step. The latter allow identifying improvement opportunities related with equipment inefficiencies, as well as in the WWTP daily operation to adjust the energy consumed to the energy required based on the plant design (pump heads, reactor volumes) and daily fluctuations in the influent wastewater flow and organic load, expressed as (5-day) biochemical oxygen demand (BOD_5) [3], which is an approximated measure of the quantity of oxygen needed to biologically treat the wastewater [4]. The main objective of the iEQTA project was to identify which operating condition(s) should be adjusted to improve energy performance and savings while achieving the desired treatment effectiveness and reliability.

Frameworks of energy-PIs of WWTPs have been developed worldwide [13–16], as well as benchmarks for influent flow pumping, aeration, and sludge processing [15]. Aspects such as the percent of facility design capacity [17,18] and plant ageing [19,20] are included in the energy cost functions and benchmarks. However, the indices applied herein for judging the performance use reference values that incorporate the aspects that may affect the energy consumption, as expressed by, e.g., the pumping head (plant layout and design), as well as concentrations, detention time, and other operating conditions regularly monitored by the water utilities [3].

Several studies have proposed methodologies to assess either reliability or energy efficiency. Rajaei and Nazif [21] proposed a WWTP reliability index as a new performance index in addition to the effluent quality and operational costs (which include energy) to evaluate the efficiency of control strategies. Longo et al. [22] applies a novel approach of Stochastic Frontier Analysis (SFA) for energy demand modelling to estimate the comparative energy efficiency of a comprehensive set of WWTPs. Hamza et al. [23] presented both energy and reliability analyses of eight WWTPs operating in small communities in Ontario, Canada. However, in terms of energy, the study focused solely on evaluating the global energy performance of WWTPs.

In contrast, the present study takes a more comprehensive approach by examining the energy performance of individual processes within the WWTPs. By assessing energy consumption in each treatment step, this study provides a detailed analysis of energy efficiency throughout the entire wastewater treatment process. This distinction highlights the novel contribution of this study in integrating reliability and energy efficiency assessments while pinpointing actionable strategies for enhancing energy performance in WWTPs.

2. Materials and Methods

2.1. Case Studies

The present work focuses on three different WWTPs with the following designed capacities (data obtained from the engineering projects):

WWTP A is located in an urban area and was designed to serve a 263,107 population equivalent, corresponding to 27,922 m^3/day and 13,984 $kgBOD_5$/day, receiving urban and industrial wastewater;

WWTP B is located in a semi-urban area and was designed to serve a 74,748 population equivalent, corresponding to 11,411 m^3/day and 4565 $kgBOD_5$/day, receiving urban/rural wastewater and rainwater given the combined sewage drainage system upstream;

WWTP C is located in an urban area and was designed to serve an 89,266 population equivalent, corresponding to 9447 m^3/day and 5356 $kgBOD_5$/day, receiving urban wastewater and rainwater given the combined sewage drainage system upstream.

In terms of wastewater treatment processes:

WWTP A includes primary clarification, secondary activated sludge process for carbon, nitrogen, and phosphorus (C, N, P) control by the anaerobic/anoxic/oxic process (A^2/O), and tertiary disinfection; the sludge line includes gravitational sludge thickening and anaerobic digestion;

WWTP B includes secondary activated sludge process (plug-flow extended aeration) for carbon removal and tertiary disinfection; the sludge line includes gravitational sludge thickening;

WWTP C includes primary clarification, secondary activated sludge process (by conventional aeration) for carbon removal and tertiary disinfection; for sludge processing, it includes mechanical sludge thickening.

The flow and plant capacity adequacy during the 5-year period can be seen in Table 1. The Adequacy of plant volume capacity (wtER13) and the Adequacy of BOD_5 mass capacity (wtER15) were calculated according to ([1] (and references therein), and were used to assess whether each WWTP was overloaded/underloaded or with adequate load according to its design. Briefly, these were calculated using the following equations:

$$wTER13\ (\%) = \left(1 - \frac{\sum_{d=1}^{n} Qt_d \times J_d + \sum_{d=1}^{n} Qt_d \times K_d}{\sum_{d=1}^{n} Qt_d}\right) \times 100$$

where

n = assessment period (day);
J_d = 1, if $Qr_d > 0.95Qt_d$ in day 'd' or = 0, if $Qr_d \leq 0.95Qt_d$ in day 'd';
$K_d = 1$, if $Qr_d > 0.70/f_s$ in day 'd'or $= 0$, if $Qr_d \leq 0.70/f_s$ in day 'd';
f_s = correction factor for seasonal variation of the flowrate during the analysed period;
Qt_d is the plant capacity (m^3/day);
Qr_d is the daily average recorded flowrate at day 'd' (m^3/day).

$$wTER15\ (\%) = \left(1 - \frac{\sum_{d=1}^{n} BODt_d \times I_d + \sum_{d=1}^{n} BODt_d \times P_d}{\sum_{d=1}^{n} BODt_d}\right) \times 100$$

where

n = assessment period (day);
I_d= 1, if $BODr_d > 0.95BODt_d$ in day 'd' or = 0, if $BODr_d \leq 0.95BODt_d$ in day 'd';
$P_d = 1$, if $BODr_d > \frac{0.70}{S_{BOD5}}$ in day 'd'or $= 0$, if $BODr_d \leq 0.70/S_{BOD5}$ in day 'd';
S_{BOD5} = correction for seasonal variation of the BOD_5 load during the analysed period;
$BODt_d$ is the plant BOD_5 load capacity (kg BOD_5/day);
$BODr_d$ is the daily average recorded BOD_5 load at day 'd' (kg BOD_5/day).

Table 1. Flow, organic load, and plant capacity adequacy for each WWTP during the 5-year period (green circles stand for good performance, yellow circles for average performance, and red circles for poor performance).

WWTP		2015	2016	2017	2018	2019
A	Flow (m^3/d)	12,358 ± 1754	12,935 ± 2209	12,264 ± 1512	13,739 ± 2023	14,387 ± 2024
	Organic load (kgBOD_5/day)	5902 ± 2172	5558 ± 1833	5050 ± 1981	7251 ± 2328	7027 ± 2311
	wtER13 (%)	0% 🔴	3% 🔴	0% 🔴	2% 🔴	2% 🔴
	wtER15 (%)	8% 🔴	0% 🔴	2% 🔴	14% 🔴	100% 🟢
B	Flow (m^3/d)	8296 ± 2037	11,076 ± 3478	8729 ± 3063	4328 ± 1209	8968 ± 2751
	Organic load (kgBOD_5/day)	2547 ± 791	1859 ± 928	8729 ± 3063	4328 ± 1209	1590 ± 762
	wtER13 (%)	88% 🟢	46% 🔴	76% 🟡	76% 🟡	41% 🔴
	wtER15 (%)	8% 🔴	13% 🔴	8% 🔴	0% 🔴	5% 🔴
C	Flow (m^3/d)	4606 ± 1346	5790 ± 2204	4328 ± 1209	5178 ± 2000	4943 ± 1550
	Organic load (kgBOD_5/day)	2260 ± 689	2542 ± 1025	2514 ± 1350	1750 ± 663	1660 ± 713
	wtER13 (%)	4% 🔴	92% 🟢	3% 🔴	11% 🔴	8% 🔴
	wtER15 (%)	4% 🔴	12% 🔴	88% 🟢	0% 🔴	0% 🔴

avg ± stdev = average ± standard deviation (flow and organic load values obtained from the operational data records at each facility).

For the majority of the years, all WWTPs did not present, on an annual average, an adequate capacity for the flow and organic matter entering the plant. WWTP A and WWTP C were typically working in overload conditions in terms of volume and underload in mass capacity. On the other hand, WWTP B is mostly working in underload conditions in terms of volume and overload in terms of mass capacity.

2.2. Reliability

The reliability was computed using Niku's method [7], which is based on the lognormality of the data verified by the Kolomogorov–Smirnov test and is included in the tool to assess the WWTPs developed by the National Civil Engineering Laboratory (LNEC) [1].

Briefly, $Z_{1\text{-}\alpha}$ is the number of standard deviations away from the mean of a normal distribution and is computed by:

$$Z_{1-\alpha} = -\frac{ln\left[m_x/X_s\left(V_x^2+1\right)^{-1/2}\right]}{\left[ln\ \left(V_x^2+1\right)\right]^{1/2}} \quad (1)$$

where m_x is the mean value, X_s is the standard, and V_x is the coefficient of variation. The reliability $1-\alpha$ is determined using the standard normal table or the Excel function NORM.S.DIST("$Z_{1-\alpha}$", TRUE).

2.3. Energy Efficiency Indices

The dimensionless performance indices were computed by applying a performance function (defined by reference values) to state-variable data that express the plant's operational performance aspects [3]. These indices vary in the 0–300 range, with 100 corresponding to the minimum acceptable performance and 300 to the excellent performance. The performance function is defined by the reference values for each level, namely, by R_0, R_{100}, and R_{300}.

The reference values of energy-PXs are defined by equations incorporating the effect of key parameters, namely, pumping head, inflow quantity and characteristics, and WWTP operating conditions [3].

Table 2 shows the state variables of energy performance assessed in the three WWTPs and their reference values.

Table 2. Reference values for each state variable of energy performance (adapted from [3]).

Stage	R_{300} (Wh/m^3)		R_{100} (Wh/m^3)	R_0 (Wh/m^3)
Main pumping	4.5 ΔH		6.8 ΔH	9.0 ΔH
	ΔH = pumping head (m)			
Aeration (mechanical aerators in WWTP A)	$\frac{1.6BOD_5+1.71(Nt_{in}-NH_{4out})+2.86NO_{3out}-1.625\left(\frac{X\theta}{24\theta_c}-nbVSS\right)}{N}$ or 20θ, the highest		1.5 R_{300} or 30θ, the highest	2 R_{300} or 40θ, the highest
	BOD_5 = 5-day biochemical oxygen demand influent to the reactor (mg/L); Nt_{in} = nitrogen concentration influent to the reactor (mg N/L); NH_{4out} = ammonia concentration in the secondary effluent (mg N/L); NO_{3out} = nitrate concentration in the secondary effluent (mg N/L); X = mixed-liquor volatile suspended solids (VSS) (mg/L); θ = hydraulic detention time in the aerated tank (h); θ_c = solids retention time (d); nbVSS = nonbiodegradable VSS in influent (mg/L); N = oxygen transferred under field conditions (kg O_2/kWh).			
Aeration (air diffusers in WWTP B and in WWTP C)	$\frac{1.6BOD_5+1.71(Nt_{in}-NH_{4out})+2.86NO_{3out}-1.625\left(\frac{X\theta}{24\theta_c}-nbVSS\right)}{N}$ or $66.25\theta\left[\left(\frac{P_2}{P_1}\right)^{0.283}-1\right]$, the highest		1.5 R_{300} or $82.8\theta\left[\left(\frac{P_2}{P_1}\right)^{0.283}-1\right]$, the highest	2 R_{300} or $127.8\theta\left[\left(\frac{P_2}{P_1}\right)^{0.283}-1\right]$, the highest
	p_1, p_2 = absolute inlet and outlet pressure, respectively (kPa)			
Recirculation	WWTP A	1.1 ΔHr	9.3 ΔHr	16.8 ΔHr
	WWTP B	2.8 ΔHr	18.7 ΔHr	33.6 ΔHr
	WWTP C	1.4 ΔHr	9.3 ΔHr	16.8 ΔHr
	ΔHr = pumping head of recirculation pumps (m)			
Sludge wasting	WWTP A	0.004 θ ΔH_w	0.081 θ ΔH_w	0.168 θ ΔH_w
	WWTP B	0.002 θ ΔH_w	0.013 θ ΔH_w	0.028 θ ΔH_w
	WWTP C	0.008 θ ΔH_w	0.104 θ ΔH_w	0.194 θ ΔH_w
	ΔH_w = pumping head of sludge wasting pumps (m)			

The energy used in the aerated tank should satisfy the oxygen requirements and provide oxic conditions (i.e., the desired dissolved oxygen concentration) along the reactor, while assuring perfect mixing conditions. The reference values in Table 2 display these objectives. R_{300} is the highest value between the theoretical oxygen requirements and the typical minimum for mixing, and R_{100} and R_0 are derived considering reasonable tolerances for minimum and unacceptable performance, as comprehensively derived in [5].

Activated sludge systems require sludge recirculation from the secondary clarifier to the reactor. The unit energy consumption for return sludge pumping depends on the hydraulic power, which ultimately depends on the recirculation ratio, pump efficiency, and pumping head, as detailed in [3]. The reference values for energy consumption in sludge wasting also depend on retention time.

2.4. Energy Measurements Campaigns

To determine the energy consumption of the individual process/equipment, energy campaigns were carried out. These had the duration of one week in each WWTP to guarantee all different equipment were operational during the monitoring period. The equipment's power and energy consumption were measured, every minute, using a power energy logger PEL 103. All relevant data were recorded, and lab analyses were performed to calculate the reference values (Table 2). It is important to note that the campaigns were conducted during the rainy season of 2019, and are thus representative of this season. The average flow and BOD_5 values during this campaign can be seen in Table 3.

Table 3. Operational conditions during the energy measurement campaign.

WWTP	Influent Flow (m^3/d)	Influent BOD_5 Concentration (mg/L)
A	15,926	420
B	9383	180
C	4689	220

3. Results and Discussion

3.1. Reliability of the WWTPs

The effectiveness and reliability of WWTPs play a pivotal role in ensuring the quality of effluent and compliance with regulatory requirements. To evaluate treatment performance and set practical discharge limits, designers and operators rely on the indispensable information provided by reliability analysis. By predicting outcomes based on current operating conditions, this analysis empowers policymakers and designers to make informed decisions that strike a balance between environmental standards and operational feasibility [5].

Table 4 shows that, overall, WWTPs B and C were effective in treating the wastewater, though with some annual variations, whereas WWTP A showed deficiencies, particularly for BOD_5 and TSS. Variations in the wastewater treatment's performance can be due to variations in the treatment process and/or mechanical/operational failures and to the variability of the influent wastewater flow and characteristics [4]. In fact, analysing Figure 1, it is noticeable that all three WWTPs suffered great variations in the influent wastewater quality, which were mainly due to industrial discharges and/or extreme rain events. In addition to the mentioned chemical parameters, others might be present from industrial wastewater, which can inhibit and impact the biological treatment [24].

Table 4. Reliability of wastewater treatment in terms of effluent quality for each WWTP analysed.

WWTP	Parameter (X_s Value)		2015	2016	2017	2018	2019	5 Year avg ± stdev	Effluent Concentration Goal for 90% Reliability
A	BOD_5 (25 mg/L)	Mean value (mg/L)	23.7	18.1	27.0	28.2	25.4	24.5 ± 3.5	11.2
		Reliability	68%	78%	73%	63%	66%	70 ± 5%	90%
	COD (125 mg/L)	Mean value (mg/L)	98.5	69.5	77.5	113.4	110.9	94.0 ± 17.6	69.7
		Reliability	76%	99%	97%	69%	69%	82 ± 13%	90%
	TSS (35 mg/L)	Mean value (mg/L)	30.5	16	42.3	45.5	21.4	31.1 ± 11.4	18.0
		Reliability	71%	95%	76%	55%	85%	76 ± 13%	90%
B	BOD_5 (25 mg/L)	Mean value (mg/L)	-	16.3	12.7	-	8.1	12.4 ± 4.1	12.8
		Reliability	-	83%	91%	-	100%	91 ± 7%	90%
	COD (125 mg/L)	Mean value (mg/L)	72.0	65.8	55.2	62.9	53.0	61.8 ± 7.0	76.9
		Reliability	93%	94%	100%	94%	99%	96 ± 3%	90%
	TSS (35 mg/L)	Mean value (mg/L)	22.6	24.5	15.0	18.4	13.3	18.8 ± 4.3	19.1
		Reliability	85%	82%	98%	90%	98%	91 ± 7%	90%
C	BOD_5 (25 mg/L)	Mean value (mg/L)	18.7	16.3	17.9	19.6	14.3	17.4 ± 1.9	15.9
		Reliability	85%	92%	90%	76%	93%	87 ± 6%	90%
	COD (125 mg/L)	Mean value (mg/L)	69.9	60.4	73.3	85.6	64.5	70.7 ± 8.6	84.8
		Reliability	98%	99%	98%	89%	98%	96 ± 4%	90%
	TSS (35 mg/L)	Mean value (mg/L)	33.2	25.5	33.9	25.3	24.5	28.5 ± 4.2	21.9
		Reliability	66%	85%	61%	87%	93%	78 ± 13%	90%

X_s = discharge permit limit for compliance with regulation, avg ± stdev = average ± standard deviation.

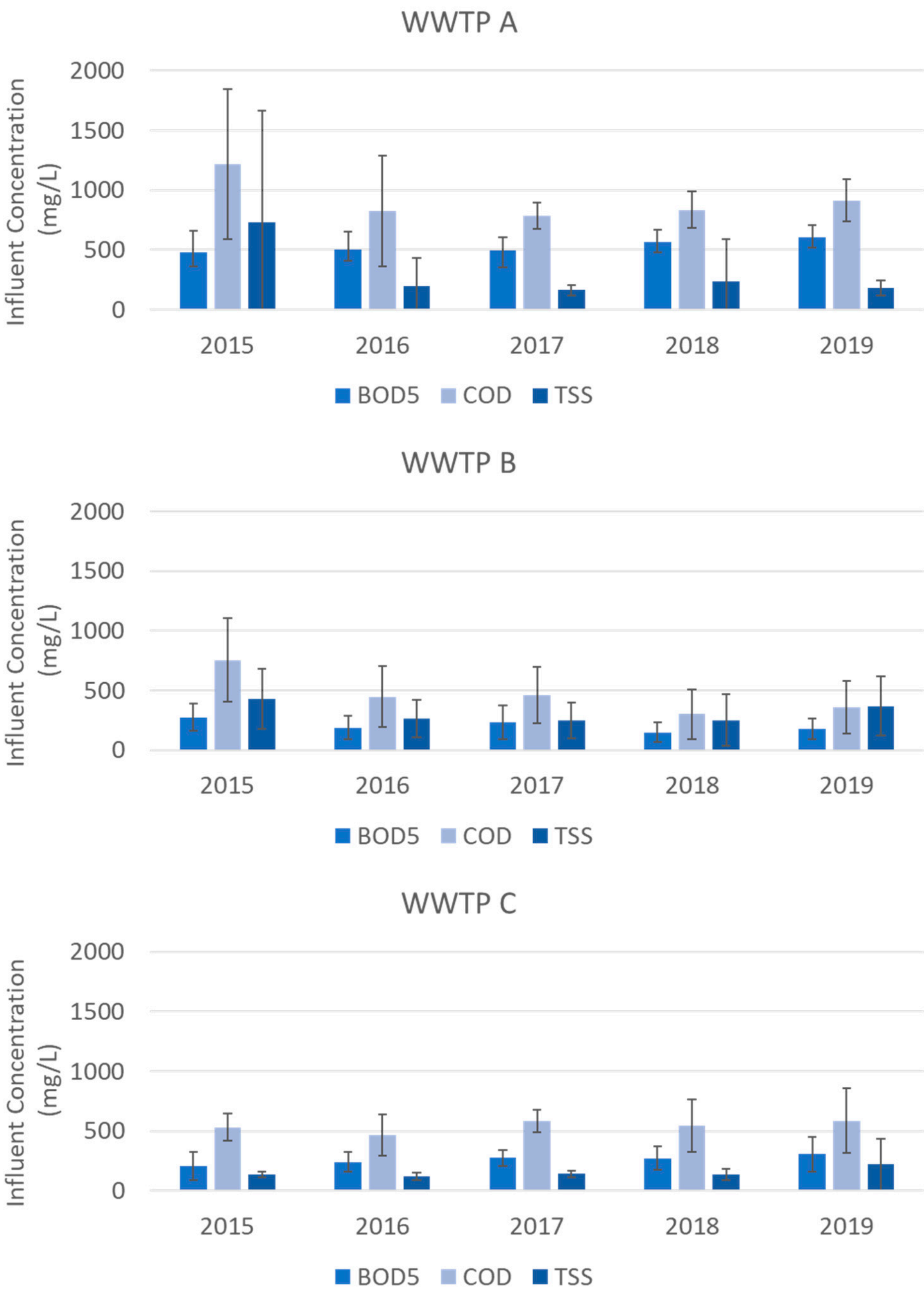

Figure 1. Influent BOD_5, COD, and TSS concentrations in each WWTP (the bars represent the 5-year average, and the error bars the standard deviations).

These variations may greatly affect the WWTPs' outcome if the plants are not managed properly. As such, one must ensure that the WWTPs are effective and reliable, i.e., capable of withstanding these variations, without compromising its efficiency. For this purpose, for each WWTP, the reliability over 5 years was determined for biological oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS), as shown in Table 4. Additionally, based on the variation throughout the 5-year period analysed, the effluent concentration goals for each parameter to comply with the standard limit with 90% reliability were determined (Table 4). A reliability goal of 90% was set as this was the value found to be necessary to guarantee a stable operation [1]. All sets of data, parameters, and WWTPs passed the lognormality test except WWTP B, which did not follow a log-normal distribution in years 2015 and 2018 for BOD_5. Thus, for these 2 years and WWTP B, the reliability was not calculated.

When comparing the reliability levels of the WWTPs, different results emerge. WWTP A does not show consistent reliability levels during the analysed period. The lower levels were due to isolated variations associated with operational failures given the WWTP's age and with fluctuations in the influent wastewater flow and quality (Figure 1) due to illegal discharges and industrial wastewater variability (industrial wastewater accounts for ca. 50% of total influent wastewater). As reported in previous studies [24], industrial wastewater composition is typically different from urban wastewater and can have a negative impact on the treatment process due to the presence of toxic substances such as heavy metals. Consequently, to consistently meet the discharge permit value with a reliability level of 90%, it is necessary for WWTP A to establish a lower effluent concentration goal for BOD_5, COD, and TSS when compared to the other two WWTPs.

In contrast, WWTP B consistently shows the highest reliability, exceeding 80%, and is able to comply with the discharge permit despite the variations that arise in the influent's quality and flows (Table 1, Figure 1). This is probably because this WWTP was built more recently than WWTP A, having fewer malfunctions, and, on the other hand, the variation of the influent wastewater characteristics is usually due to excessive precipitation, which dilutes the wastewater. These results are consistent with previous studies [1], which concluded that the studied WWTPs with extended aeration presented higher reliability results than the WWTPs with conventional aeration, such as WWTP A and WWTP C. As such, the effluent concentration goal may be set at a higher level in WWTP B than in WWTP A, which will still guarantee compliance while potentially reducing operational costs.

WWTP C, despite being older than the other two WWTPs, underwent a major rehabilitation in 2013, before the analysed period, which improved all infrastructure and treatment processes. The results indicate compliance with the discharge permit throughout the 5-year period analysed and a better discharge quality and higher reliability in 2019, which coincides with the installation of an automatic aeration control. Yet, there is potential for improvement, particularly, regarding TSS, the parameter with the lowest 5-year average reliability ($78 \pm 13\%$), to ensure a more stable and reliable operation.

An important factor that may affect the reliability and efficiency (as discussed in Section 3.2) is the adequacy of the plant's capacity and, as seen in Table 1, the three plants are typically operating out of the designed capacity. This is usually the case for most WWTPs, which are traditionally designed based on 25–40 years forecast, grounded on assumptions of stable and predictable wastewater characteristics (quality and quantity/intensity), which is not the case for most WWTPs experiencing drastic changes over time [25]. This must be taken into consideration when planning future rehabilitation where different scenarios must be reflected upon.

In addition, all WWTPs must seek an optimal operation towards both effectiveness and reliability, but also environmental and economic efficiency, energy being the critical resource, as addressed in the following section.

3.2. Energy Efficiency

Energy is typically the second largest part of the running costs of a WWTP [3] after personnel. As such, improving energy efficiency is crucial to reduce costs that can be redirected to other aspects of the WWTPs, such as rehabilitation or revamping of the facilities. To optimize energy efficiency, the first step is to understand where energy is being used and how efficient the use is. As such, energy measurement campaigns were conducted tackling the main treatment stages where energy is consumed. During these energy campaigns, all necessary wastewater quality parameters were measured to calculate the reference values (Table 2).

The results are presented in Figure 2 and show that all WWTPs presented a similar energy consumption distribution, with aeration being the main contributor for energy consumption, accounting for over 50% of total energy consumption, as found in other studies [26,27]. Aeration (54–64%) was followed by main pumping (8–10%), sludge recirculation (7–11%), and sludge dehydration (1.4–13%).

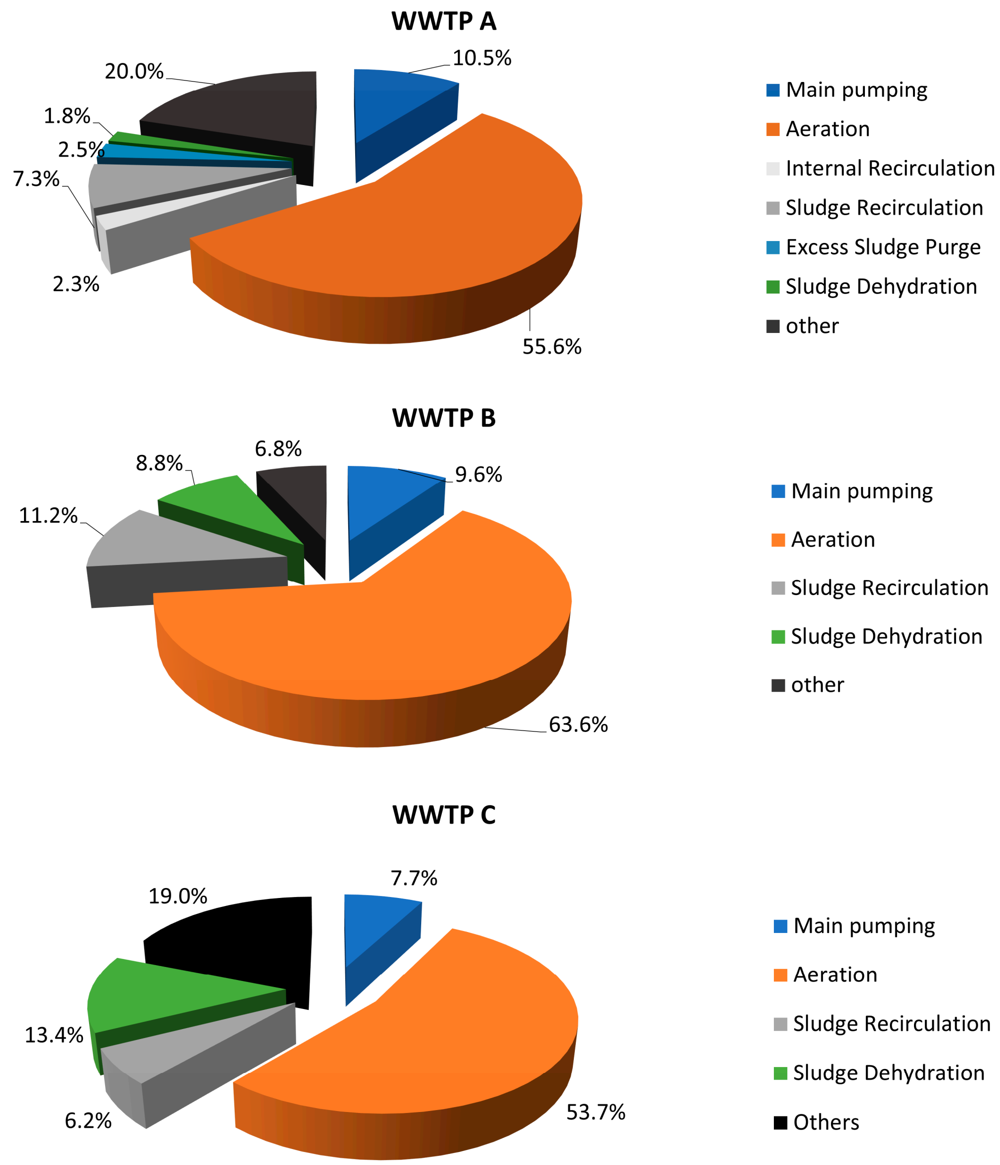

Figure 2. Energy consumption distribution within each WWTP analysed.

To understand to what extent the efficiency can be improved, the reference values for energy performance (shown in Table 2) were computed. R_{300} values (excellent performance) correspond to the theoretical energy requirements for each stage in each WWTP, taking into account the technology and the influent and effluent wastewater characteristics (quantity and quality) [1,4]. R_{100} and R_0 reflect the deviations from the excellent performance corresponding to acceptable and unacceptable performance. Subsequently, these requirements were compared with the measured values obtained during the energy measurement campaigns (Table 5). Additionally, pump energy efficiency was calculated [3] to understand whether the inefficiencies were due to the equipment or to the operation mode and conditions. The energy measurement campaigns were conducted over one week, representing a normal operational period of each WWTP, so it is reasonable to conduct an integrated analysis of the energy and the reliability (5-year) results. This integrated analysis indicates potential for improvement in all WWTPs, which should be taken into consideration for future WWTP diagnosis.

Table 5. Energy campaign results for each WWTP analysed.

Equipment	Measured Value (Wh/m^3)	R_{300} ●	R_{100} ●	R_0 ●	PX	Pump Efficiency
WWTP A						
Main pumping	45	22	34	45	45 ●	30% ●
Aeration	236	361	542	723	300 ●	-
Sludge recirculation	31	5	35	56	168 ●	53% ●
Excess sludge wasting	11	1	17	31	207 ●	7% ●
WWTP B						
Main pumping	65	53	80	105	233 ●	50% ●
Aeration	89	27	113	175	194 ●	-
Sludge recirculation	36	16	98	157	250 ●	45% ●
WWTP C						
Main pumping	37	27	41	54	189 ●	45% ●
Aeration	192	260	390	520	300 ●	-
Sludge recirculation	22	5	30	48	172 ●	40% ●

R_{300}, R_{100}, and R_0 are the operational performance values (i.e., the reference values) to meet PX 300 (good performance; green), PX 100 (minimum acceptable performance; yellow), and PX 0 (poor performance; red), respectively. Pump efficiency was calculated according to [5] (and references therein).

When evaluating energy efficiency results, it is crucial to analyse them in parallel with the respective effectiveness and reliability outcomes (Figure 3). The ANOVA analysis has shown that the reliability results obtained for each WWTP are significantly different (ANOVA p-value < 0.05).

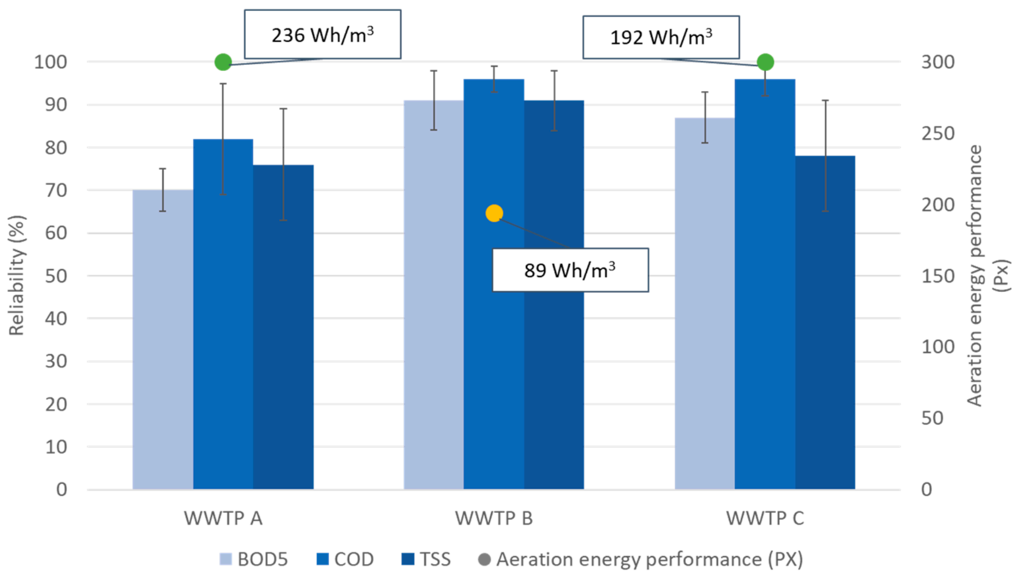

Figure 3. Reliability vs. aeration energy performance for each WWTP analysed (bars correspond to 5-year average reliability, error bars to standard deviations, green circles correspond to good performance, and yellow circles to acceptable performance) and corresponding measured values (Wh/m^3).

Although WWTP A demonstrates high energy efficiency in the aeration stage, it exhibits lower reliability compared to WWTP B, which maintains consistently high reliability despite having slightly lower energy efficiency. This suggests that WWTP A might not be fulfilling its theoretical aeration requirements, leading to an inconsistency between its positive energy efficiency and its reliability. It is worth noting that WWTP C achieves both high energy efficiency and acceptable reliability levels, which is aligned with the overall goal.

Being the second largest energy consumer (Figure 2) as found by others [28], the main pumping stage is underperforming in all WWTPs, particularly in WWTP A, and thus, to improve its performance, it should be included in the asset management plan. This entails evaluating the pump's curve fitting concerning the existing operational conditions and implementing various measures, including repair, rehabilitation, or replacement with more efficient technologies and appropriate sizing. This should also be extended to the recirculation pumps.

For WWTP A, the sludge recirculation could be improved and, although the energy consumption for aeration is low (Table 5), it does not meet the minimum requirements, which could affect the reliability, as verified in the previous section. Thus, it is advised to include asset management measures that allow the aeration to be increased/decreased according to the influent wastewater's characteristics and the treatment needs. For the sludge recirculation, the pump efficiency is above 50%, which translates into excellent performance [3]. Therefore, the improvement should be mainly focused on the operational parameters. The improvement measures were identified in a previous study [2] and briefly translate into reducing the recirculation rate, reducing the number of primary and secondary clarifiers, and increasing the Food/Microorganism ratio in the aeration reactor. These measures should not negatively affect the effectiveness, as seen in the operational performance evaluation completed for this WWTP [2].

The sludge recirculation system could also be analysed for WWTP B, given the low pump efficiency (45%), as it could lower energy costs. In terms of aeration, this WWTP is over-aerating the mixed liquor, which results in higher energy costs. Since the reliability is high and the effluent concentrations are considerably below the legal requirements, the air supply could be lowered without compromising compliance. Even though always compliant, the efficiency of this WWTP is highly affected by the variations of influent wastewater flow dictated mainly by the precipitation events during rainy seasons. Thus, there is potential for improvement in terms of efficiency. Currently, WWTP B is under a digitalization process, where several parameters are to be monitored online and connected to an online control system developed in-house. Additionally, the aeration diffusion system and blowers are being replaced. The new air diffusion system will potentially reduce the air flow requirements by 40% and the new blowers will reduce the energy consumption by up to 42% (data provided by the supplier).

WWTP C is efficient in terms of energy consumed in the aeration stage, likely due to the recent rehabilitation (see Section 3.1) and update of the aeration system to a more efficient technology and to the implementation, in 2019, of online oxygen measurement for automatic control of the operational parameters in the aeration tanks. Like the other WWTPs, this WWTP does not perform efficiently in terms of sludge recirculation, which could be due to the low-efficiency performance of the pump (40%). Thus, similarly to WWTP B, the pumping system should be audited as it could increase the energy operational performance and subsequently lower the energy costs. Additionally, like WWTP A, both WWTP B and WWTP C were evaluated in terms of operational performance and the results showed some operational parameters could be optimized, which would further increase the energy efficiency performance.

Since the influent wastewater has characteristics with high variability over time (Figure 1), all WWTPs could benefit from an online automated control, which could optimize all operational parameters in real-time, reducing costs and increasing reliability. Additionally, by automating the treatment process and thus, improving digitalization, an increased knowledge of the facility would be achieved by the staff, contributing to achieving a better performance.

4. Conclusions

In summary, the performance assessment system allowed us to identify improvement measures highlighting distinctive characteristics of individual WWTPs. For instance, WWTP A exhibited commendable aeration energy efficiency but demonstrated lower reliability, with an average of 82% ± 13% for COD over a 5-year period (below the 90% set goal). In contrast, WWTP B presented low energy efficiency in comparison, yet displayed high reliability with an average of 91% ± 7% for COD over the same 5-year span. The results for WWTP C indicate both high energy efficiency and acceptable reliability levels, effectively aligning with the overall goal.

The insights gained allowed also to determine optimal aeration energy requirements specific to each WWTP, and the effluent concentration targets for the parameters in the discharge consents to achieve the desired reliability levels whilst potentially reducing running costs. The savings obtained could potentially be redirected to implement asset management strategies and tactics. These can be defined with the support of the PAS by identifying the limiting stages or dysfunctions of the WWTPs and, thus, determining the investment needs and prioritizing assets for rehabilitation or retrofitting.

Furthermore, the integration of reliability and energy efficiency assessments presented in this study provides a comprehensive framework for enhancing WWTPs' performance. By considering both aspects simultaneously, decision-makers can prioritize actions that not only improve energy efficiency but also ensure the reliable and effective treatment of wastewater. This holistic approach to performance assessment and optimization enables utilities to align their operational goals with regulatory requirements and customer expectations. The findings of this study emphasize the importance of continuous monitoring, evaluation, and implementation of improvement measures in WWTPs to achieve sustainable and cost-effective wastewater treatment processes. By leveraging performance assessment systems and incorporating targeted strategies, utilities can enhance the overall efficiency, reliability, and environmental performance of their wastewater treatment facilities.

Author Contributions: Conceptualization, J.C., T.S., N.S., P.R., C.S., M.J.R., A.R.S. and J.F.F.; methodology, J.C., C.S. and M.J.R.; data curation, J.C. and C.S.; writing—original draft preparation, J.C., C.S. and M.J.R.; writing—review and editing, J.C., T.S., N.S., P.R., C.S., M.J.R., A.R.S. and J.F.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study is confidential.

Acknowledgments: The authors would like to thank the staff from all WWTPs for their assistance in data acquisition and during the energy measurement campaigns.

Conflicts of Interest: The authors declare no conflict of interest.

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