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Case Study on the Functional Performance of a large Wastewater Pumping Station

Stefan Gerlach^{1*}, Rita Ugarelli², Paul Uwe Thamsen¹



Abstract

In this paper a case study on a large wastewater pumping station is conducted. In a Fault Tree Analysis the critical assets within a wastewater pumping station are identified and the root causes for critical failures are discussed. The relevant Performance Indicators (PIs) for centrifugal pumps are presented and the significance for a PI including wastewater properties and performance under wastewater conditions is discussed. The performance of the critical wastewater pumps in the observed wastewater pumping station is analyzed. An approach for risk assessment for clogging of wastewater pumps is described and a strategy to counter clogging problems is addressed.

Keywords

Wastewater pump — Clogging — Risk — Functional Efficiency Index — Centrifugal Pump

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INTRODUCTION

Climate change, demographics and water-sensitive behaviour put a great strain on the urban wastewater system by changing amounts, composition and behaviour of wastewater. Especially, combined sewer systems face big changes of loads between dry-weather runoff as the minimum and stormwater as maximum load. Additionally operating conditions, the challenging fluid “Wastewater” and the regulatory background [1],[2],[3] create an operational frame for the main wastewater pumping station that results in a high risk of failures. Especially fibres and textile structures within the wastewater lead to frequent failures in wastewater pumps due to clogging.

In a structured approach based on the frame of Integrated Asset Management (IAM) the case study is oriented along the “Five Core Management Questions” of IAM. The necessary steps are addressed below:

- Status: What is the current state of the assets?
- Performance: What is the required Level of Service?
- Risk: Which of the assets are critical?
- Costs: What are my best minimum lifecycle cost CIP and O&M strategies?
- Plan: Given above, what are the best long-term funding strategies?

1. CURRENTS STATE THE WASTEWATER PUMPING STATION

The pumping station analysed in this paper is a large pumping station in an urban area. With a connected catchment area of more than 250,000 inhabitants and about 750km of sewer system this main pumping station delivers about 45,000m³/day of dry-weather run-off to the three connected wastewater treatment plants. The power consumption of the 8 installed pumps ranges from 40 kW up to 455 kW for electrical power and up to 711 kW for diesel-driven peak-load pumps. These machines are used to pump from 100 l/s during nights up to 1450 l/s during rain events.

The pump setup is redundant.



Figure 1. Wastewater Pumping station [8]
The most common way wastewater pumping stations are

operated in is on-off-operation. The volume of the suction chamber is used as a buffer. Once a specific water level is reached fixed speed pump operation is started. Once the level falls below a defined minimum pumping is stopped. For high levels parallel operation of multiple pumps can be implemented.

The use of Variable Speed Drives (VSD) allows adjusting the pump operation according to the inflow. In the observed pumping station a so-called level-controlled operation is used. Figure 2 shows the schematic layout of a level-controlled pump operation. Each box shows the flow rates the specific pump delivers according to the respective level in the pump sump. The left boundary of each box shows the flow rate at minimum pump speed and the right boundary the flow rate at maximum pump speed for the pump or pump combination.

Below a specific minimum level in the suction chamber pump operation is stopped. Once the level increases above this minimum the smallest pump is started with minimum speed. If the level in the suction chamber increases further the pumps speed is also increased. If maximum pump speed is reached, the small pump is stopped and the mid-sized pump starts operation with minimum speed. As long as the level still increases the pump speed is also increased accordingly. The next step is parallel operation of mid-sized pumps. For peak loads and emergencies parallel operation of mid-size and peak-load pumps is implemented.

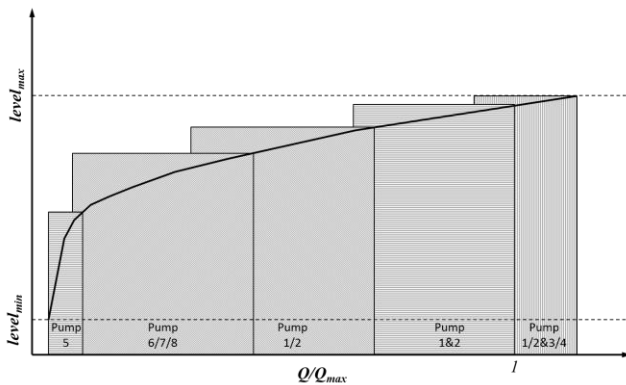


Figure 2. Scheme for level-controlled operation based on actual operating schemes provided by Berliner Wasserbetriebe

In many cases urban wastewater systems are set up hierarchically with a number of wastewater pumping stations spread over the catchment area that transport the wastewater to one or more main pumping stations. These main pumping stations pump the wastewater through pressure lines to the wastewater treatment facilities. The first step to identify the crucial pumping station is a criticality analysis of the wastewater network. The observed catchment area includes only one main pumping station that is fed by a gravity sewer system. Naturally this main pumping station is identified as most critical pumping station

in the system.

The Fault Tree Analysis (FTA) for the wastewater pumping station results in the main events leading to a critical failure of the whole pumping station. Figure 3 shows that out of 8 pumps only 4 pumps contribute to a failure of the whole pumping station under certain conditions.

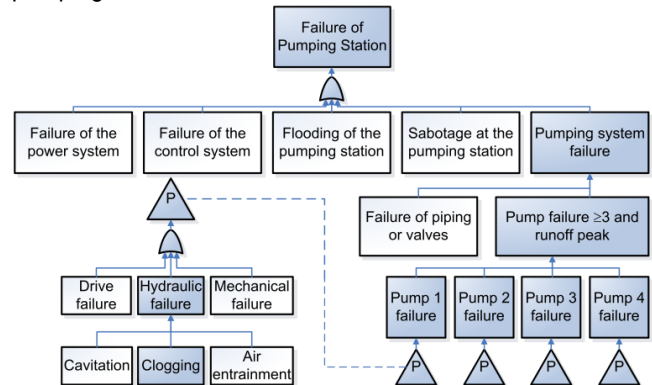


Figure 3. Fault Tree Analysis for the observed Wastewater Pumping Station showing clogging as a root cause for critical failure

Pump 1 to Pump 4 are the large and peak-load pumps of the pumping station. Two out of these four pumps are needed to deliver the required quantities of wastewater during peak-load or rain operation.

While Pump 1 and Pump 2 are driven electrically, Pump 3 and 4 have diesel engines. The allowed operating hours for the diesel engine are limited by clean-air regulations.

In this context the FTA identifies Pump 1 and Pump 2 as the most critical pumps in the pumping station.

2. PERFORMANCE OF THE WASTEWATER PUMPING STATION

2.1 PERFORMANCE INDICATORS

The evaluation of performance of pumps in pumping systems is generally based on hydraulic characteristics and energy considerations such as energy-efficiency η or specific energy E_s . [1]

The evaluation of the performance of wastewater pumps however is more difficult. At this moment, the European Commission is implementing energy-efficiency regulation for wastewater pumps in the frame of the European Ecodesign Directive [11]. In a preliminary study it was shown that no standard exists to link the pump performance to anything other than energy-efficiency [1]. However, the performance of wastewater pumps is evaluated through the following parameters:

- Hydraulic performance
- Efficiency
- Reliability

Pumps are designed for a specific hydraulic task, i.e. a

specific flow rate at a specific head. Any deviation between this design point and the actual operating point results in loss of energy-efficiency.

The operating point itself is predefined by system conditions and characteristic pump curve. Any change of system conditions, i.e. system pressure, or flow conditions within the pump, i.e. clogging, result in a shift of the operating point.

The efficiency of pumps is evaluated in accordance to ISO 9906 [12]. This standard defines the testing setup, the testing conditions and the measurement setup to obtain data on hydraulic performance and energy demand. It describes solely the hydraulic performance for clear water operation. A market-study [4] for the most-common impeller types already shows that different impeller types for wastewater pumps result in different expected energy-efficiencies for clear water operation. A direct comparison of existing wastewater pumps can only be conducted under the consideration of the real operating conditions, including equal compositions of wastewater.

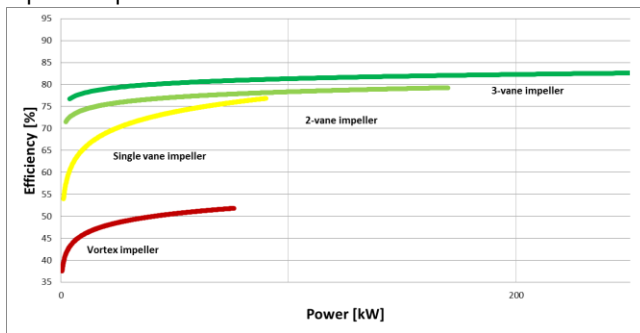


Figure 4. Mean efficiencies of wastewater pumps for different impeller types according to power consumption [4]

On-going research in cooperation with the pump manufacturers associations EUROPUMP is showing the different performance of different impeller technologies under real wastewater conditions. It is already known that vortex impellers operate with the low energy-efficiencies but also with high reliability for difficult wastewater compositions especially for high textile or fibre load. Other impeller designs however show higher efficiencies but operate with lower reliability. To define a scientific foundation for the comparison of reliability for different impeller types is focus of present research at the TU Berlin.

To increase the significance of wastewater pump testing a new Performance Indicator has to be defined. Within a research project with the pump manufacturers associations the Function-Efficiency-Index FEI is proposed[5]:

$$FEI = (\alpha \cdot D_C + \beta \cdot D_F + \gamma \cdot D_{LTF}) \cdot \frac{\rho \cdot g \cdot H \cdot Q}{P} \quad (1)$$

where ρ is the water density, g is gravitational constant, H is lifting height (pressure increase) and Q is the flow delivered by the pump, altogether representing the pump output P_Q . The required power is P . The ration of P_Q and P is the pump efficiency for clear water operation. The energy-efficiency is

extended by wastewater characteristics. It contains wastewater classes based on the degree of contamination D_C and the pumps degree of functional performance D_F for the specific wastewater class and the degree of long-term functional performance D_{LTF} . Pump testing is done using artificial wastewater represented by clear water with added dusters. The artificial wastewater simulates textiles and fibers that are found in real wastewater and result in pump clogging.

The degree of contamination D_C describes the actual contamination of the artificial wastewater used for the specific pump test compared to a defined maximal contamination. Clear water results in $D_C=0$ and testing with highest contamination results in $D_C=1$. The mechanical properties of the artificial wastewater used for testing are not only defined by amount of textiles used for simulating the behavior of rags and fibers in real wastewater (D_C), but also their size and their material.

The pumps actual capability of handling the specific degree of contamination is evaluated during the actual experimental pump test and results in D_F and D_{LTF} . Where D_F is the dry-weight of material that passed the pump during the test compared to the total dry-weight of textiles in the artificial wastewater and D_{LTF} assesses the resistance against accumulative clogging by observing changes of the pumps efficiency.

α , β and γ are scaling factors. The tasks of on-going research are the clear definition of different wastewater classes that allow pump testing using artificial wastewater with the same mechanical properties and actual pump testing to describe pump performance for contaminated fluids.

The FEI therefore represents the total efficiency ratio for the pump extended by wastewater performance. This new Performance Indicator can support the decision process of pump selection for specific tasks in wastewater transport.

The most crucial Performance Indicator for wastewater pumps is Reliability. Pump failures, especially for the large pumps, are a high risk for the failure of the pumping station as a whole. As shown in the Fault Tree Analysis [Figure 3] different failure types contribute to pump failures.

Mechanical and electrical failures are assessed using MTBF (Mean Time between Failures), failures per 1000 operating hours or similar markers. Additionally condition monitoring is commonly used to monitor critical assets to predict failures and plan predictive maintenance.

The reliability against clogging of wastewater pumps is influenced by [2], [3]:

- Wastewater composition
- Operational conditions
- Impeller geometry
- (Maintenance)

In opposition to pumps in clear water operation, where

failure occurs mainly because of ageing or wear of components, wastewater pumps fail due to clogging. Obviously the wastewater composition contributes greatly to this type of failure. Large solids result in clogging if the pumps ball passage is exceeded. More commonly pumps are clogged by accumulations of fibres. Here geometric dimensions, material and surface conditions, but also existence of other substances, such as fat, contribute to clogging.

It was also shown that operating conditions, i.e. operating point, pumps speed, influence the clogging behavior of wastewater pumps. [3]

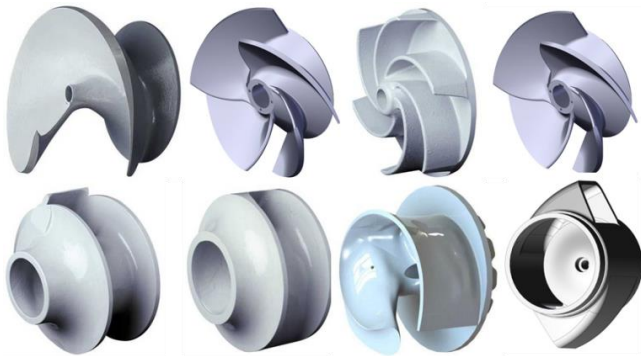


Figure 5. Different impeller types for wastewater application [9,10]

Finally, manufactures have developed many different impeller types and shapes with different behaviors in wastewater operation (Figure 5).

These parameters evidently show that the performance of wastewater pumps is not only defined by the pump type, but additionally by the conditions they are operated in. To this date, there are no existing standards or testing procedures that consider their impact on the actual pump performance.

2.2 Actual performance of critical pumps at the observed pumping station

2.2.1 Reliability

The task of the observed pumping station is the safe transport of wastewater from the sewer system to the connected wastewater treatment plants. Apart from energy-considerations, the hydraulic performance and the reliability of the pumping station are of main concern.

The observed pumping station shows a clear distribution of failure events for the last years. While most of the pumps show a low number of clogging events, Pump 1 and Pump 2 show equally high numbers of failures. In the observed period of 12 month, both pumps clogged 78 times, resulting in a high demand for manual cleaning(Figure 6).

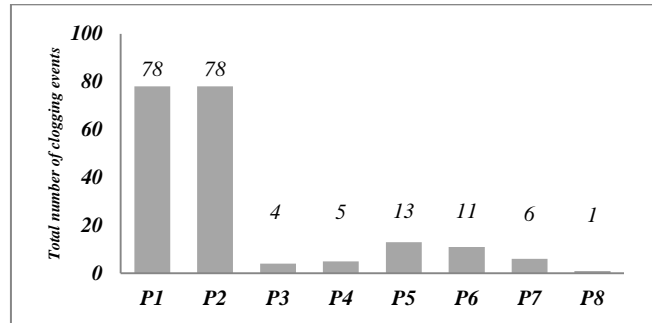


Figure 6. Distribution of clogging events for the installed pumps in a period of 12 month

These number exceeded mechanical or other failures by far. In most cases, the clogging material could be removed through a service opening at the pump. In some cases the pumps had to be disassembled resulting in costs exceeding 1000€ per assignment. The common clogging mechanism is ragging in front of the impeller. Actual observation shows slow accumulations of fibrous material in front of the impellers that subsequently lead to failure of the pumps. It shows that the most critical pumps in the pumping station are also the pumps with the highest rate of failures due to clogging.



Figure 7. Fibre accumulation in front of the impeller and pump cleaning at the observed pumping station [8]

2.2.2 Hydraulic performance and Energy-efficiency

Figure 8 shows the theoretical Characteristic Pump Curve for Pump 2 at 780 rpm and the specific System Curve for the connected wastewater pressure line to the connected Wastewater Treatment. Also included are actual operating points for pump speeds between 580rpm and 630rpm in comparison to the scaled pump curves for these speeds. All data was gathered from the operators' data-management system over the course of one year. The flow

rate Q is measured at the pressure main exit of the wastewater pumping station using a Magnetic Flow Meter. This setup allows direct flow measurement only for single pump operation, since multiple pumps are feeding the pressure main. The pump head H is calculated from pressure sensors at suction side and discharge directly at the pump and the flow rate at the pressure main. Only single operation is considered for the data analysis. All sensors are installed according to their specification and are routinely calibrated.

Theoretically all operating points should fall between the scaled pump curves close to the theoretical System Curve. Operating points that fall below the scaled pump curve for 580rpm are affected by clogging.

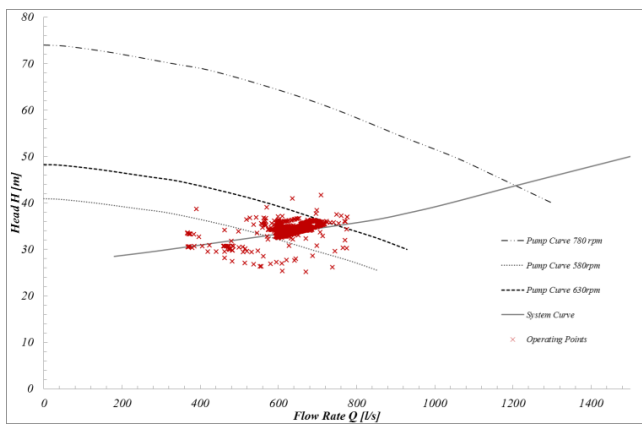


Figure 8. Pump 2: Theoretical Characteristic Pump Curve for Pump 2 and actual operating points for pump speeds 580rpm – 630rpm

While for low pump speeds most operating points are not affected by clogging the picture changes for higher pumps speeds. Especially for the highest speeds it is shown that the actual pump performance is affected by clogging to high extend and the observed pump never actually works under design conditions when operated with full pump speed. [Figure 9]

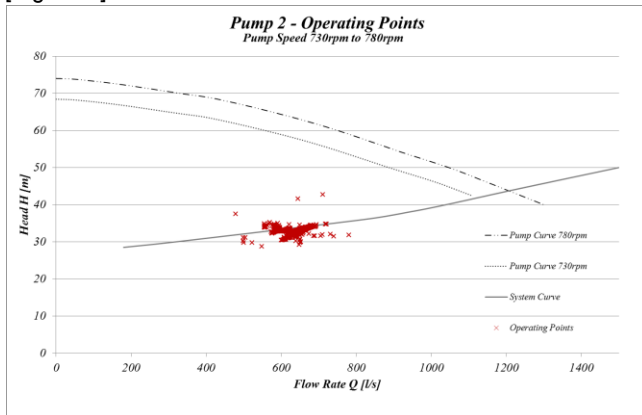


Figure 9. Pump 2: Theoretical Characteristic Pump Curve for Pump 2 and actual operating points for pump speeds 730rpm – 780rpm

This behaviour is supported by level-controlled operation of the pumping station. Once the level in the suction chamber reaches the starting level for Pump 1 or Pump 2, one of the pumps is started at the lowest pump speed of 580rpm. As long as the level in the suction chamber is increasing, the pump speed is gradually increased. In case of beginning accumulation of fibres in the impeller, the actual delivered flow rate decreases resulting in increasing water levels in the suction chamber thus increasing the pump speed. While the accumulation of fibres grows pump speed increases while the actual operating point shift further away from the theoretical Performance Curve.

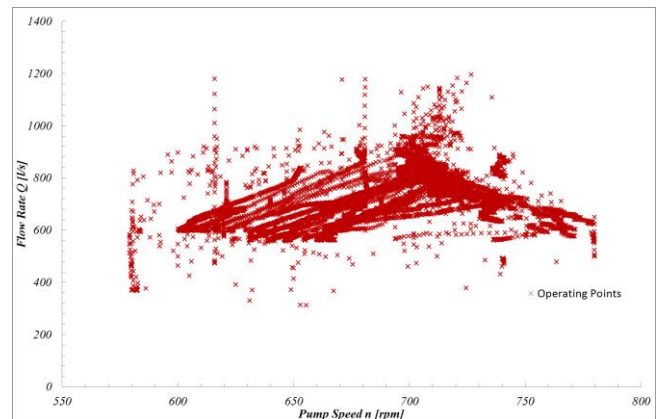


Figure 10. Pump 2: Actual attained flow rates for all pump speeds

Figure 10 shows that the actual hydraulic capacity of the pumping station is limited. Increased accumulation of fibres affect flow rates to an extent where increasing pump speeds cannot deliver higher flow rates, but flow rates actually decrease.

This behaviour is shown for all pump speeds using dimensionless coefficients in Figure 11.

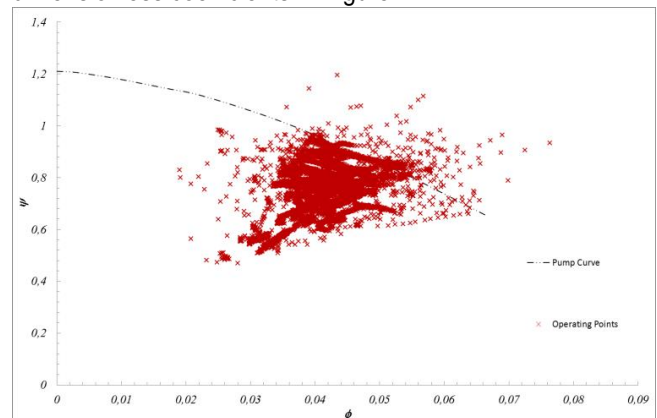


Figure 11: Pump 2: Pressure coefficient over flow coefficient Pump 2 actual operating points in comparison to the theoretical pump performance curve for all pump speeds

Head and flow rate are presented through pressure coefficient and flow coefficient. These are dimensionless

values of the head and the flow rate. The pressure coefficient ψ is defined by:

$$\psi = \frac{2 \cdot g \cdot H}{\pi^2 \cdot n^2 \cdot D^2} \quad (2)$$

where g the gravitational acceleration in m/s^2 , H the head in m, n the rotational speed in 1/s and D the impeller diameter in m.

The flow coefficient φ is described by:

$$\varphi = \frac{4 \cdot Q}{\pi^2 \cdot n \cdot D^3} \quad (3)$$

where Q the flow rate in m^3/s , n the rotational speed in 1/s and D the impeller diameter in m.

It is shown that the actual pump operation is strongly influenced by clogging for all pump speeds.

The consumed electrical power for the pumps is only measured at the electric feed of the Variable Speed Drives. Since the efficiency of the motors and the variable speed drives are not constant but functions of different operational parameters such as speed, current and torque, a precise determination of the pumps power consumption is not performed at the pumping station. A calculation of energy-efficiency for the pumps is not done. The decreased hydraulic power transferred by the pumps due to clogging results in an overall drop of energy-efficiency.

3. Risks and costs

The risks analysis for the pumping station is done according to an adapted scheme provided by Eiswirth et al. [6] for the condition assessment for pipes in 2001. Figure 12 was adapted to fit the conditions of the observed pumping station.

The risk of failure is a combination of the probability of failures and the consequences connected to the occurring failures.

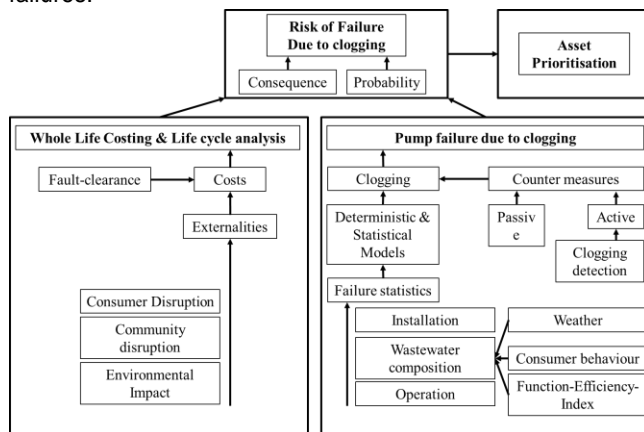


Figure 12. Risk Assessment for wastewater pumping stations

The probability of pump failure is determined by failures connected to the service life of the pump and external

failures due to the difficult fluid to be pumped. Failures that are connected to the service life are countered by detailed maintenance of the pump units. Condition Monitoring is used for predictive maintenance. These procedures are defined by the operator and are not connected to clogging. Failures through externalities for wastewater pumps are hard to predict. The main parameter leading to failures is the wastewater itself in connection to the used pump. At this moment, there are no known deterministic or statistic models that link wastewater composition and pump type to failure probabilities. On the one hand, it is impossible to predict the wastewater composition for any given time; on the other hand, there are no existing performance indicators for wastewater pumps that describe the ability of handling textiles or solids during operation. The proposed FEI will support the decision process for choosing the right wastewater pump for a specific task. In-depth knowledge of wastewater compositions for the planned application are to be provided by the operator. At this time research on mechanical properties of wastewater components is only starting.

Anyhow, it is already seen that certain parameters have a negative effect on wastewater pump performance:

- **Single events:** Wastewater transports all sizes of solids that can enter the system at any place upstream the pumping station. This ranges from small debris, to dead animals and bricks from canals, up to car tires or truck tarpaulins. Failure events connected to large fibre accumulations or solids are impossible to predict.
- **Ragging:** Ragging is a gradual accumulation of textiles, tissues and fibres in the wastewater pump. This process can be supported by starts and stops of the pump. Gradual ragging of impellers can be the objective of clogging detection and counter-measures at the pump.
- **Wastewater composition and impeller type:** At the moment, pump manufacturers describe the capabilities of their pumps for handling different wastewater “classes” very vaguely. Wastewater classes are only described by their origin, e.g. municipal, industrial, and not by their actual load with fibres or textiles. The capability of handling those classes is described by good, neutral or bad.
- **Weather influence:** Rain events lead to first-flush effects the lead to increased loads of solids and fibres in the wastewater. The missing link between wastewater composition and actual pump performance does not allow any calculation.
- **Critical operating points and VSD operation:** Certain operating conditions aggravate the occurrence of clogging in wastewater pumps. It was observed that low pump speeds and part-load operation increase the risk of clogging [3]. Low

pump speeds with low flow rates result in sedimentation of material in the suction chamber. Sediments are remobilised when flow rates increase and can result in higher failure rates.

The consequences of failure at the observed pumping station are divided into external cost driven by service disruption, community disruption and environmental costs and cost directly connected to the clearance of failures. The redundant setup-up of the observed pumping station reduces the risk for external disruption and damage to a minimum. Residents of adjacent buildings however file complaints about vibrations that are connected to operation of clogged pumps. More detailed information was not available to the author.

The costs that are connected to the clearance of failures at the observed pumping station were calculated to an average 310,00€ per assignment in the observed 12 month. Number of failures and connected clearance cost allow a brief calculation of Failure Rates, MTBF, Risk per day and actual Costs per year.

$$\text{Failure Rate} = \frac{\text{Failures}}{365d} \quad (4)$$

$$\text{MTBF} = \frac{1}{\text{Failure Rate}} \quad (5)$$

$$\text{Risk per day} = \text{Average Cost} \cdot \text{Failure Rate} \quad (6)$$

$$\text{Costs per year} = \text{Risk per day} \cdot 365d \quad (7)$$

Table 1. Cost calculation for the observed pumping station

	Number of failures	Failure Rate	MTF [days]	Average cost	Risk per day	Cost [year]
Pump 1	78	0,21	5	310,00 €	66,25 €	24.180,00 €
Pump 2	78	0,21	5	310,00 €	66,25 €	24.180,00 €
Pump 3	4	0,01	91	310,00 €	3,40 €	1.240,00 €
Pump 4	5	0,01	73	310,00 €	4,25 €	1.550,00 €
Pump 5	13	0,04	28	310,00 €	11,04 €	4.030,00 €
Pump 6	11	0,03	33	310,00 €	9,34 €	3.410,00 €
Pump 7	6	0,02	61	310,00 €	5,10 €	1.860,00 €
Pump 8	1	0,00	365	310,00 €	0,85 €	310,00 €
						60.760,00 €

Table 1 shows that two pump units at the observed pumping station account for two thirds of the overall failure clearance costs during the observed 12 month. In this case, this simplified approach already allows identifying the main objectives for the implementation of risk reduction measures to increase the reliability of the pumping station. The overall significance of the calculated MTBFs is missing. Due to the high influence on the clogging behaviour of the

described parameters, additional knowledge to use for future planning cannot be derived. For mechanical failures, low MTBF values create a high pressure of action, resulting in exchange of equipment, change of suppliers or improved maintenance strategies. For wastewater pumping stations the pressure is equally high, while above strategies will most likely not improve the situation.

4. Plan

High failure risk for the critical pumps at the observed pumping station and a high number of complaints call for action. An exchange of equipment is no option. On the one hand different pumping technology for this specific task is not available on the market and on the other hand a prediction of the actual performance of other impeller technologies for example is at this time not possible.

A strategy to reduce the impact of clogging on the actual pump performance should be based on counter-measures. Especially detection of beginning fibre accumulations in front of the impeller connected to automated cleaning procedures show a high potential of reducing complaints due to vibration and reducing cost by decreasing the amount of manual work for cleaning clogged pumps.

In the IMEBA Project several active and passive counter-measures were proposed [7].

At this point it is planned to implement the Measure *Cleaning Sequence* at the pumping station. In a two stage approach data is collected to support the set-up of a clogging detection tool, while simultaneously the technical preconditions for implementing VSD-driven “Cleaning Sequence” based on variations of pump speeds are worked out.

5. Conclusion

A Fault Tree Analysis was used to identify critical pumps for the safe operation of the observed pumping station. The root causes for failures were identified and it was shown that the most critical pumps show the highest rate of failures. An analysis of the hydraulic performance of the wastewater pumping station discovered that clogging not only leads to pump failures but also reduces the attainable flow rates greatly. Additionally clogging results in a loss of energy-efficiency.

A risk assessment scheme is proposed that shows the different influential parameters on pump clogging and the lack of deterministic or statistical models was discussed.

A possible approach to counter pump clogging by implementation of early-detection and an automated cleaning sequence was presented.

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NOMENCLATURE

H	Head in m
Q	Volume flow rate in m ³ /s
P	Electric power in W
P _Q	Hydraulic Power in W
D _F	Degree of functional performance
D _C	Degree of contamination
D _{LTF}	Degree of long-term functional performance
D	impeller outlet diameter in m
g	gravitational acceleration in m/s ²
n	rotational speed in 1/s
α	scaling factor for D _C
β	scaling factor for D _F
γ	scaling factor for D _{LTF}
ψ	pressure coefficient
φ	flow coefficient