Analysis of a wastewater pumping station using an IAM-approach

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Sammendrag

En feiltreanalyse er brukt for å indentifisere kritiske forhold i pumpestasjoner for avløpsvann. Undersøkelser er utført ved en pumpestasjon i Berlin. Pumpestasjonen har 6 parallelle pumper og to av dem er i særlig grad utsatt for gjentetting. Hovedårsaken til dette er transporten av faste stoffer med avløpsvannet. Informasjon om avløpsvannet nødvendig for å kunne iverksette de riktige feilforebyggende tiltakene. Artikkelen er skrevet i forbindelse med det tyske KURAS prosjektet som omhandler funksjonsevnen til avløpsnett og er fremført for et dr kurs i regi av NTNU.

Abstract

A Fault Tree Analysis was used to identify the critical elements at a pumping station. A pumping station in Berlin was subject to the investigation. Two out of six pump units were identified as main drivers for maintenance costs due to clogging, but also as critical units for the pumping station operation. An in-depth study shows that the reasons for failures lie in external factors as solids that are brought with the wastewater. For improved performance of pumping stations, extended information of the wastewater is needed to enable failure preventive actions. The article is based on results from the cluster "Pumping System" within the German KURAS project and is prepared for a Ph. D course at NTNU.

Introduction

The access to clean water and sanitation is a human right. [1] The availability of this strategic resource is strongly connected to the physical availability of water, but also to the overall handling of the water cycle. Not only the consumption of water affects the quality of the water system, but also the approach to discarding wastewater and the handling of storm water. Water scarcity can therefore be manmade through careless discharge of wastewater into potential drinking water reservoirs due to missing treatment facilities or incapable wastewater systems that are strained by large population growth or increased stormwater loads resulting in overflows into receiving water bodies.

This is not only a problem of developing countries, but also for the industrial nations in Europe and all over the world. To prevent continuous pollution of water resources, the European Commission and the national governments set up programs for funding research projects to counter the impacts of demographic changes and Climate Change on wastewater and drainage

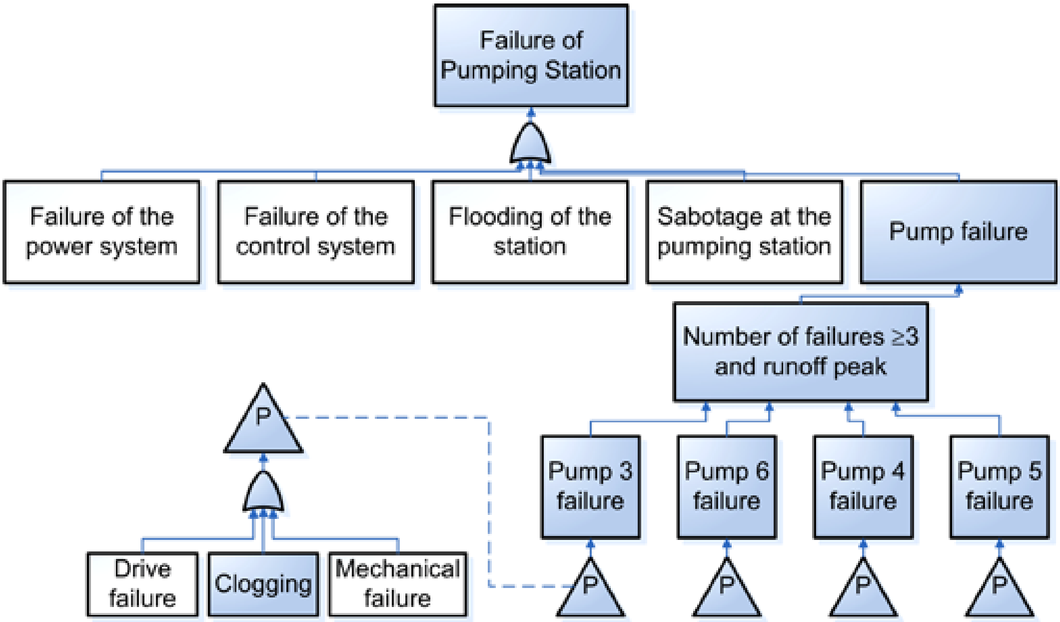

Figure 1. Fault Tree for a wastewater pumping station.

systems. An example for research projects in this area is the KURAS Project (Concepts for Urban Rainwater management and Sewer systems) as part of the German NaWaM[1] (Sustainable Water Management) programme embedded in the German "Research for Sustainability" FONA[2].

Within the KURAS project one research focus lies on the wastewater pumping system.

IAM approach for a wastewater pumping station in Berlin

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 a main pumping station. The main pumping station pumps 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. Naturally, this main pumping station is identified as most critical pumping station in the system.

The Fault Tree Analysis (FTA) of the wastewater system identifies the pumps in the main pumping station as critical assets to provide the service of wastewater transport to the connected wastewater treatment facilities. This section describes the structured approach of identifying the main drivers for adaption of the pumping technology used and the evaluation of possible risk reduction measures to counter pumping problems. It is focused on the adaptation of existing technology and on implementing additional measuring and Real Time Control (RTC) equipment.

This structured approach is based on the frame of Integrated Asset Management (IAM) and is oriented along the "Five Core Management Questions" of IAM. The necessary steps are addressed below:

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

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Population in catchment area: 263.0000	Total length: Separate sewers Combined sewers Stormwater sewers	756 km 278 km 237 km 241 km	Dry weather run-off 45.000 m³/d Total amount 16.576.000 m³/yr

Table 1. Catchment area for observed pumping station.

Status: What is the current state of my assets in the Pumping Station?

The observed pumping station is located in a catchment area in the south-west of Berlin. The catchment area includes separate sewer systems as well as combined sewers. The characteristic data for the catchment area and the pumping station are shown in Table 1.

The observed pumping station is one of the largest wastewater pumping stations in Berlin. It is equipped with 8 wastewater pumps that deliver flows from 100 l/s for single pump operation of the smallest pump up to 1750 l/s in parallel operation of the largest pumps to a WWTP. The power consumption ranges from 40 kW up to 455 kW for electrical power and up to 711 kW for diesel-driven peak-load pumps.

The pumps are controlled with the centralised Berliner Wasserbetriebe system LISA[3] (Control and Information System Wastewater) that was introduced to the Berlin wastewater network in 2001.

Variable speed drives are used to operate the pumps by pump sump level control, i.e. the water level in the pump sump determines the operated pump combination and pump speed. With rising water level the pumps speed is increased gradually to the maximum speed until the next larger pump is put into operation.

The pumps deliver the wastewater to three wastewater pressure lines that are connected to three different wastewater treatment plants. The main receiving WWTP is WWTP Ruhleben with about 99% of the annual wastewater load.

Performance: What is the actual performance of my assets?

Performance Indicators for pumps and wastewater pumps

The performance of pumps in pumping systems is usually based on energy considerations such as energy-efficiency η or specific energy E_S.[2]

The evaluation of the performance of wastewater pumps however is more difficult. At this moment, the European Commission is trying to implement energy-efficient regulation for wastewater pumps in the frame of the Eco-Design Directive. In a preliminary study it was shown that no standard exists to link the pump performance to anything else than energy-efficiency [3]. However, the performance of wastewater pumps should be evaluated through the following parameters:

- Efficiency
- Reliability
- Function-Efficiency-Index

The Efficiency of pumps is evaluated in accordance to DIN EN ISO 9906. 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 [6] for the most-common impeller types already shows that different impeller types result in different expected efficiencies for clear water operation. A direct comparison can only be conducted under the consideration of the real operation conditions, including equal compositions of wastewater.

Reliability is the most crucial Performance Indicator for wastewater pumps. Pump failures, especially for the large pumps, are a high risk for the failure of the pumping station as a whole. The risk reduction for mechanical failures and failures connected to the pump drive is based on condition monitoring and redundant set-ups of pumps, electrical feeds and in the case of the observed pumping station diversified drive tech-

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nologies i.e. electrical motors and diesel engines. Characteristic numbers, tools and data bases for the assessment of the remaining risks are widely available.

The risk of failure due to clogging however is not yet to be evaluated by numbers or predictive tools. The reliability against clogging of wastewater pumps is influenced by [4], [5]:

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

These parameters evidently show that the performance of wastewater pumps is not so much influenced by the pumps, but merely 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.

On-going research together with the pump manufacturers associations VDMA and EUROPUMP is hinting about the different performance of different impeller technologies under real wastewater conditions. It is already known that vortex impellers operate with the lowest energy-efficiencies but also with the highest 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

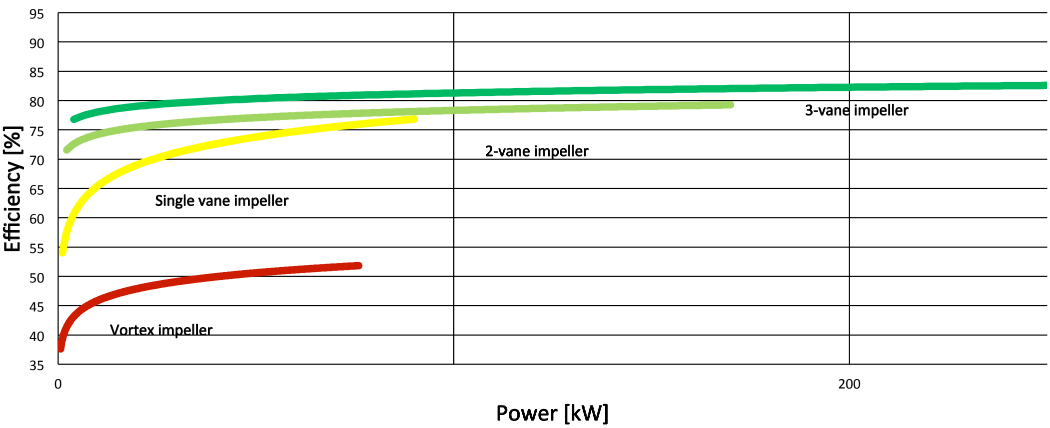

Figure 2. Mean Efficiency and power consumption for different impeller types.

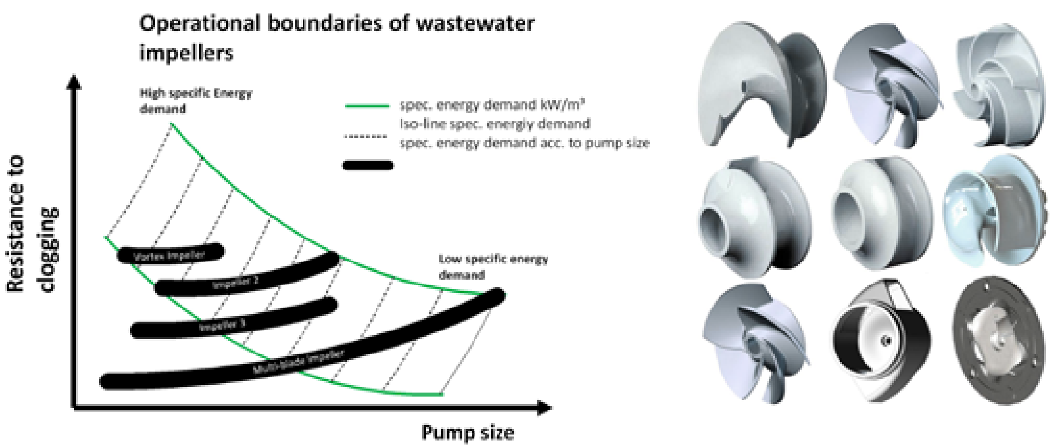

Figure 3. Performance of different pumping technologies [7].

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. [8]

$$FEI = k \cdot \frac{\rho \cdot g \cdot H \cdot Q}{P}$$

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 PQ and P is the pump efficiency for clear water operation. The factor k is used to extend the clear water pump efficiency by wastewater characteristics. It contains wastewater classes based on contamination and the pumps capability to handle the specific wastewater class. 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 efficient ratio for the pump extended by wastewater performance. As a new performance indicator it can support the decision process of pump selection for specific tasks in wastewater transport.

Actual performance of pumps at the observed pumping station

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 3 and pump 6 show an equally high number of failures. In the year of 2013, both pumps clogged about 80 times, resulting in a high demand for maintenance. This 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 observations show that slow accumulation of fibrous material in front of the impellers subsequently lead to failure of the pumps. More detailed analyses of the failure events and of the actual mechanisms leading to failure through clogging are on-going, but will need improved operational data. Therefore the observed critical pumps will be equipped with improved monitoring systems.

Performance evaluation with existing set-up

The current setup of measurement equipment does not allow the detailed observation of operating conditions for the critical pumps. Incipient clogging can be detected through changes in the operational behaviour of the pumps. This includes shifts of the operating points, increased power consumption and or increased vibrations.

At this moment the operating point is only monitored through pressure sensors that are used to calculate a theoretic discharge from the pumps characteristic curve. The theoretic discharge is compared to flow measurements at the pressure lines to the WWTP. The measuring points of the existing pressure sensors are located at cross-sections with difficult flow conditions. At the suction side of the pump for example, only one measuring point is located at the end of an asymmetric inlet nozzle. The nozzle creates an asymmetric velocity profile that reduces the quality of the acquired data. Therefore only high deviations from the calculated flow result in a failure signal to the centralised control system. It is necessary to increase the number of measuring points for pressure sensors to increase the precision of the data.

The flow delivered by the pumps is only measured at the pressure lines to the WWTPs. An observation of the hydraulic performance of single pumps is therefore only possible for single-pump operation. In parallel-operation of pumps, the flow distribution per pump cannot be determined. Since flow measuring is needed both for the determination of delivered flow Q and the total head H of the pump, this configuration results in unknown operation conditions under peak load operation. The use of additional mobile flow-metering is planned.

The consumed electrical power for the pumps is 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 difficult and cannot be used as a clogging detection.

Online monitoring of vibrations is used to predict upcoming mechanical failures. For small pumps clogging can also result in significant changes of the vibration behaviour. For the large pumps observed at the pumping station clogging results mostly in small changes of the vibration velocity. Only extreme cases will trigger vibration alarms. The vibration measuring used now can therefore not be used as a tool for clogging detection.

Risk and Costs

The risks analysis for the pumping station is done according to an adapted scheme provided by Eiswirth for the condition assessment for pipes in 2001. The scheme 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.

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 topic of this paper.

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.

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 up-stream the pumping station.

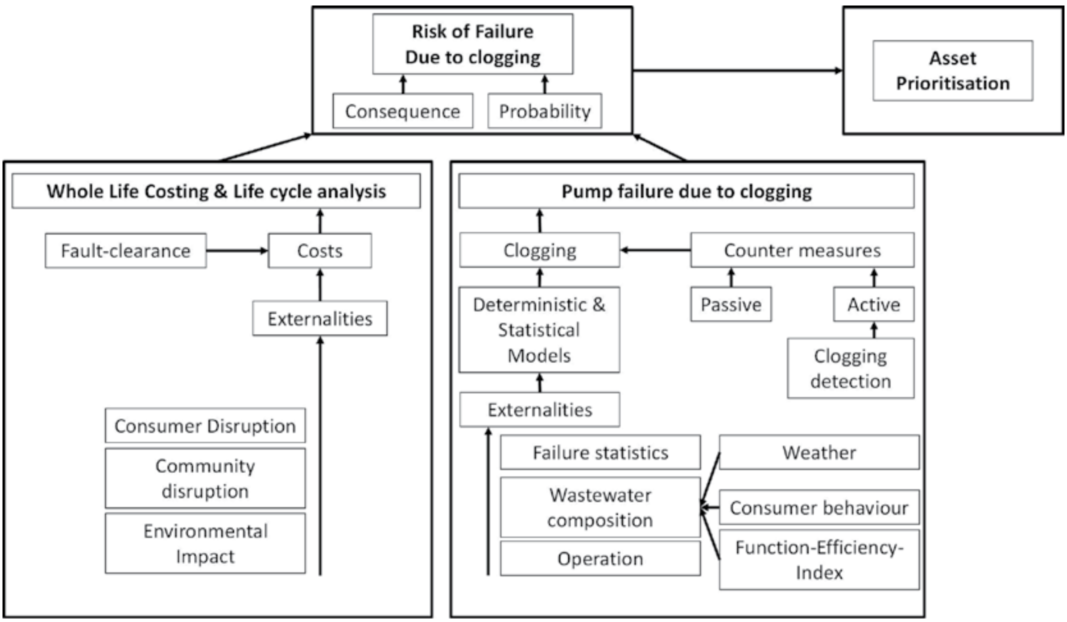

Figure 4. Adapted Eiswirth scheme for wastewater pumping stations.

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.[5] Missing operational data for the pumps at the observed pumping station do not allow the implementation of this knowledge into a risk analysis at this point.

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. Detailed information was not available to the author.

The costs that are connected to the clearance of failures at the observed pumping station however were calculated to an average 310,00 € per assignment in the year 2013.

In a simplified approach using failure data from 2013 to calculate the Failure Rate, Mean Time to Failure (MTF) and connected cost can be shown in Table 2. All pump failures are connected to changing operating conditions, weather influence, and wastewater composition. The significance of statistical methods for a detailed prediction of risk and cost for future operation is very limited. A clear calculation for a Fault Tree Analysis is not possible. The influencing factors for the clogging of wastewater pumps change to fast and do not follow any statistical distribution. At this stage only the extreme number of pump failures for pump unit 3 and pump unit 6 can be derived.

Table 2 shows that two pump units at the observed pumping station account for two thirds

	Number of failures	Failure Rate	MTF (days)	Average cost	Risk per day	Cost (year)
Pump unit 1	13	0,04	28	310,00 €	11,04 €	4 030,00 €
Pump unit 2	11	0,03	33	310,00 €	9,34 €	3 410,00 €
Pump unit 3	78	0,21	5	310,00 €	66,25 €	24 180,00 €
Pump unit 4	4	0,01	91	310,00 €	3,40 €	1 240,00 €
Pump unit 5	5	0,01	73	310,00 €	4,25 €	1 550,00 €
Pump unit 6	78	0,21	5	310,00 €	66,25 €	24 180,00 €
Pump unit 7	6	0,02	61	310,00 €	5,10 €	1 860,00 €
Pump unit 8	1	0,00	365	310,00 €	0,85 €	310,00 €
						60 760,00 €

Table 2. Risk and Cost calculation for the observed pumping station in 2013.

of the overall failure clearance costs in 2013. 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. Within the KURAS project Pump unit 3 and 6 are therefore critical elements for the overall performance of the wastewater system in the scope of the project.

Plan: Implementation of measures at observed pumping station

In the KURAS project different clusters were organised to generate catalogues of measures for the different functional units of the urban wastewater system. The cluster "Pumping system" generated a number of approaches to improve already existing and operated wastewater pumps. After evaluation through experts from research and operation, the top three measures were ranked:

- Blades
- Cleaning Sequence
- Back-flushing

Conclusion

IAM provides a strong structure to approach different parts of infrastructure research projects. The "5 Core Questions of IAM" naturally lead to an overall assessment of the observed elements, including the current status, the critical elements and the objectives for future planning.

A Fault Tree Analysis was used to identify the critical elements at the pumping station. The pump units 3 and 6 were identified as main drivers for maintenance costs due to clogging, but also as critical units for the pumping station operation. These pumps are now focus of the cluster "Pumping System" within the KURAS project.

The adapted Eiswirth-scheme for wastewater pumping stations was used to show the different influencing parameters for the operation of wastewater pumping stations and to point out missing information and topics for further research.

	Blades	Cleaning-Sequence	Back-Flushing
Precondition	Laterally reversed setup Statistical data	Clogging detection Variable Speed Drives	Installation space
Costs	Low	Installation cost: Low Implementation of clogging detection: High	Installation costs: High
Risk	Low	Low	Low
Complexity	Low	High	Medium
Exp. Performance	Under research	High	High

Performance indicator for all measures is the reduction of failures/clogging events for observed pumps at the operational level.

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