EVALUATION OF A RULE-BASED CONTROL STRATEGY FOR AN EQUALIZATION FACILITY WITH TECHNICAL/PHYSICAL CONSTRAINTS

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Abstract

This paper demonstrates the evaluation of a rule-based control strategy for an equalization facility in front of an industrial wastewater treatment plant. The control goal is not only to dampen the flow rate but also the waste concentration and the load since its huge influence on the subsequent processes. This is complicated by the technical and financial constraints of the process. Overall, the equalization strategy consists of 32 rules in the basic configuration to which 25 rules are added to deal with the occurrence of pump failures that can be detected automatically. By means of simulation it was possible to evaluate the control performance. A 10-fold decrease of variance of flow rate, waste concentration and load was reached.

1. Introduction

Any industrial wastewater treatment facility is subject to variations in the influent flow rate as well as in the influent waste concentration. Equalization systems are thus used:

- to overcome the operational problems caused by flow rate and load (the product of flow rate and waste concentration) variations,
- to improve the performance of the downstream processes,
- to reduce the size and cost of the plant.

In fact, equalization system objectives simply consist of the attenuation of both flow rate and concentration variations so that constant, or nearly constant, flow rates and concentrations are achieved before being introduced to the treatment plant.

The wastewater treatment facilities of the studied industrial plant have to deal with a very dynamic influent: both flow rate, waste concentration and, consequently, loading rate vary. To dampen these process disturbances three equalization tanks were built at the treatment plant (Figure 1). Two of them have a working volume of 1400 m^3 each (EQ02 and EQ03) and one has a working volume of 800 m^3 (EQ01).
The plant has to cope with a mean flow rate of 70 m^3/h of process water. Next to this, there is also 21 m^3/h wastewater coming from the sludge dewatering unit and 1 m^3/h from heavily polluted truck discharges.
The installation shows a high process flexibility towards possible flow directions (Figure 1). But numerous constraints do present themselves at every plant. In that context one can refer to the presence of fixed rate screw pumps and on/off valves. Further, there is a lack of process measurements. Only liquid height measurements and pump rating curves are available.

In the near future, a new chemical production facility will be installed at the factory. This is expected to result in an increased loading rate of 34%. This increase can be due to an increase in flow rate, waste concentration or both. A rise in concentration formed the focus of this study as it was expected to be the more likely scenario in practise.
One way to cope with the increased load is an enlargement of the equalization volume. Using accepted design equations, a complete equalization of the flow rate would require a working volume of approximately 3600 m^3 (Metcalf & Eddy, 1991). Because the total volume provided by the equalization tanks cannot be used (since the law imposes that a certain reserve volume is maintained for process upsets), more basin volume would be necessary. Moreover, one should keep in mind that the aim is to equalize the waste concentration and thus the loading as well, which is not aimed at by the standard design rules.

The objective of this work is to investigate the increase of performance that can be expected from an alternative approach, namely the use of a rule-based control strategy (using the existing volumes). In the study reported here,

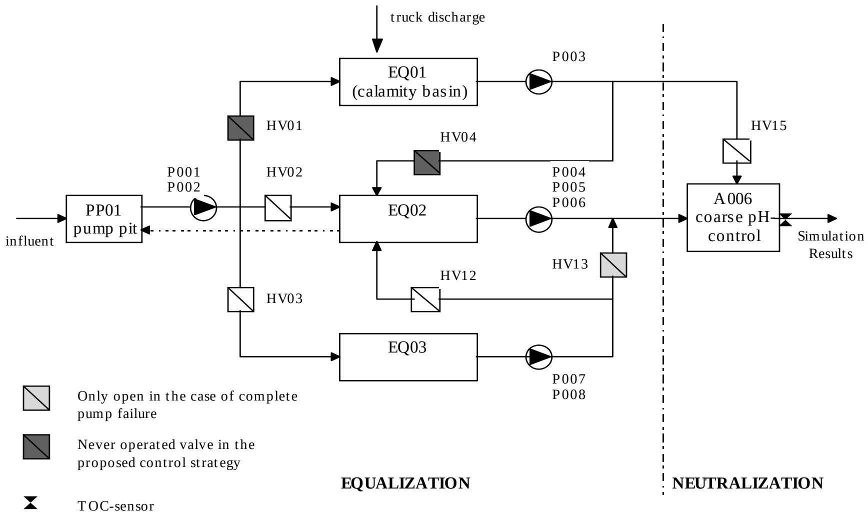


Figure 1. Detailed scheme of the present installation

several challenges are involved with the development of this strategy:

- one should be aware of the fact that in industry money is a very important factor. As a consequence, there is a rather small availability of new sensors and actuators. Hence, little control authority and little information on the plant's state and disturbances are the result.
- error-prone sensors make fault detection and a robustness study inevitable.
- a lot of practical constraints due to e.g. valves and pumps should be taken into consideration.
- the system is non-linear.

The following section will deal with the set-up of the control strategy. Its evaluation will be worked out in a separate section.

2. Proposed rule-based control approach

During the development of the control strategy it was aimed to minimize the number of modifications to the plant. Also, the technical restrictions of the installation have been taken into account as much as possible. For example, the valves currently installed at the plant cannot be controlled proportional to the flow rate but only in an open/closed status. It was aimed for not to alter these actuators to reduce costs. Fortunately, as the simulations further on show, this limitation did not influence much the performance of the control strategy.

Investment costs were also minimized by trying to upgrade only one screw pump with a frequency controller, namely the one at the outlet of EQ02. Together with the two 2-step screw pumps at that location of the equalization facility, it is possible to cover a broad range of flow rates, provided an intelligent scheduling of the pumps is worked out. All the other screws at the plant work at discrete flow rates but this does not, or not considerably, interfere the performance.

For the regulation of the equalization of waste concentration it appears at first sight necessary to have measurements available of this variable in the effluent of both EQ02 and at the preneutralization. This means that two TOC (Total Organic Carbon)-devices should be bought. However, as an alternative, it was proposed to implement a simple software sensor. Using only one TOC-sensor located after the preneutralization tank satisfies to obtain the necessary waste concentration data. Indeed, it is possible to calculate the concentration of waste in the flow pumped from EQ02 from the mass balance over the preneutralization tank and knowledge of the waste concentration in tank EQ01. The latter can be assumed quite constant over a day and, hence, a daily lab analysis suffices the data needs of the software sensor.

The proposed modifications are summarized in Table 1.

In order to devise the control strategy, tune its parameters and evaluate its performance, a mass balance model of the equalization system was derived and is reported in De Clercq *et al.* (1998) and Harmand *et al*. (1998 and 1999).

2.1 Basic Control Strategy

The principal idea behind this control strategy is to maintain the volumes in the equalization tanks constant and as big as possible. This guarantees optimal buffering of waste concentration. To achieve this the volume is kept between an upper and lower limit while the flow rate can be maintained approximately constant by filling and emptying the 'rest' of the volume.

Modified system elements	Remaining system elements
valves HV02 and HV03 with on/off controller	valves HV01, HV04, HV12, HV13 and HV15 open/closed manually
Implementation of TOC-sensor	level sensors
pump P004 with frequency controller	pumps P001-P003 and P005-P008 on/off

Table 1. Necessary system modifications for the proposed control strategy (see also Fig. 1)

Figure 2 shows an overall scheme of how the valves are set to interconnect the three tanks in the proposed control strategy. EQ01 is reserved to handle highly concentrated wastewaters only (discharged from trucks). The main wastewater flow is divided over EQ03 or EQ02 by an on/off-controller manipulating valves HV02 and HV03 (see Figure 1) as follows. If the concentration in the flow leaving EQ02 is higher than a setpoint, the water is discharged in EQ03 (HV03 open, HV02 closed). Less concentrated wastewaters are allowed to be discharged directly in EQ02.

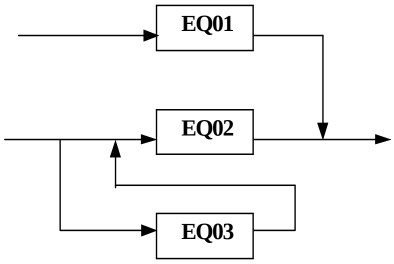


Figure 2. Configuration of the equalization tanks within the proposed control strategy

The outflow rate of EQ02 is varied around the average flow rate. The flow rate is adapted slowly in order to deal with the long term dynamics of the inflow of EQ02. The change of flow rate around this average value is subsequently determined by the volume of the tank itself. In the most extreme cases, i.e. when EQ02 reaches its minimum or maximum volume the outflow rate will be set equal to the inflow rate.
When the effluent waste concentration of EQ02 is higher than a certain setpoint (so, as a consequence, the influent is directed to EQ03), the outflow of EQ03 to EQ02 is also determined by EQ02’s volume. Consider now the opposite, i.e. when the concentration is lower than the setpoint, so that the influent goes directly to EQ02. If the volume of EQ02 is lower than the maximum one, the outflow rate of EQ03 is P-controlled with saturation based on the waste concentration of EQ02. Instead, if the volume of EQ02 is maximal the effluent flow rate from EQ03 is controlled by its momentary volume. This low gain volume-based adaptation of the outflow rate of EQ03 ensures that no sudden increase of flow out of EQ03 occurs when it becomes full.

The flow rate from EQ01 is controlled by a P-controller with saturation in such a manner that the global effluent waste concentration, just after the preneutralization, is above a setpoint concentration. This means that valve HV04 is always closed and HV15 opened (Fig. 1).

Summarizing, the variation of the flow rate to the downstream process is mainly regulated by the controller working on the flows out of EQ02 and EQ03 while the waste concentration variations are minimized by the controller manipulating the flow from EQ01. The only additional sensor is a TOC-sensor for the waste concentration and only one pump needs to be modified with a frequency controller to allow a broad range of flow rate adjustments.

2.2 Control reconfiguration in case of pump failure

Besides this main control scheme, also a control reconfiguration strategy was developed for the situation in which a pump failure occurs. In the treatment plant, an alarm signal is obtained as soon as one of the screw pumps fails. If necessary, the reconfiguration control redirects the internal flows to the other tank. In that way, inevitable tank overflow can be avoided. Besides this, the reconfigured control scheme takes the maximal pumping capacity into account as well.

Other possible system errors could not be met easily by some expansion of the control strategy and may cause problems towards robustness of the developed strategy. These implications were therefore evaluated as described next.
All these extensions make the global controller quite complex. In that way it already consists of 32 conditional rules in the basic control system, and the reconfiguration strategy adds another 25.

2.3 Sensor fault detection

Especially in wastewater treatment practice it is very important to consider the effect of malfunctioning sensors and/or actuators on a control system’s performance. Hence, quite some attention was devoted to developing ways to detect system disfunctionalities and, subsequently, deal with them. The approach taken is illustrated here with the measurement of the water level.

The effective outflow rate of an equalization tank can easily be calculated by the following equation:

$$\frac{dh}{dt} = \frac{Q_{in} - Q_{out}}{A},$$

in which h is the water level, Q_{in} the influent flow rate, Q_{out} the effluent flow rate and A the surface area of the tank.
Diagnosing the effluent screw pump can be done at those times when the controller directs the flow to the other basin (i.e. $Q_{in} = 0$). The temporal change in height can be directly related to the effluent flow rate. If this does not compare with the adjusted rate, either the screw pump or the height sensor fails and should be calibrated/checked.
With respect to the TOC-sensor, a check is difficult. Only regular calibration will prevent the operator from measurement errors and the related control malfunction.

3. Evaluation of the control strategy

To avoid any risk of putting in danger the plant's performance, the proposed control strategy is evaluated by means of simulations. In what follows a distinction will be made between two different types of performance evaluations. Firstly, the control action will be tested using different disturbances. Secondly, the robustness of the controller with respect to system disfunctionalities will be scrutinized.

3.1 Equalization capability of the basic control system

Figure 3 shows the response of the installation to a two months data record of real influent data collected at the plant.
The quality of the system's response is evaluated by considering the variances of the flow rate, concentration and load. The tuning of the parameters in the control rules was done by trial and error by interpreting the histograms of flow rate, waste concentration and loading collected over the two months simulation period (Figure 4). The narrower the distribution is, the better the performance of the controller was considered. The concrete aim of the controller tuning was to minimize the variances of those variables as calculated from the histograms. The performance of the tuned controller is summarized in Table 2. For each output variable the variance decreases significantly (approximately 10-fold).

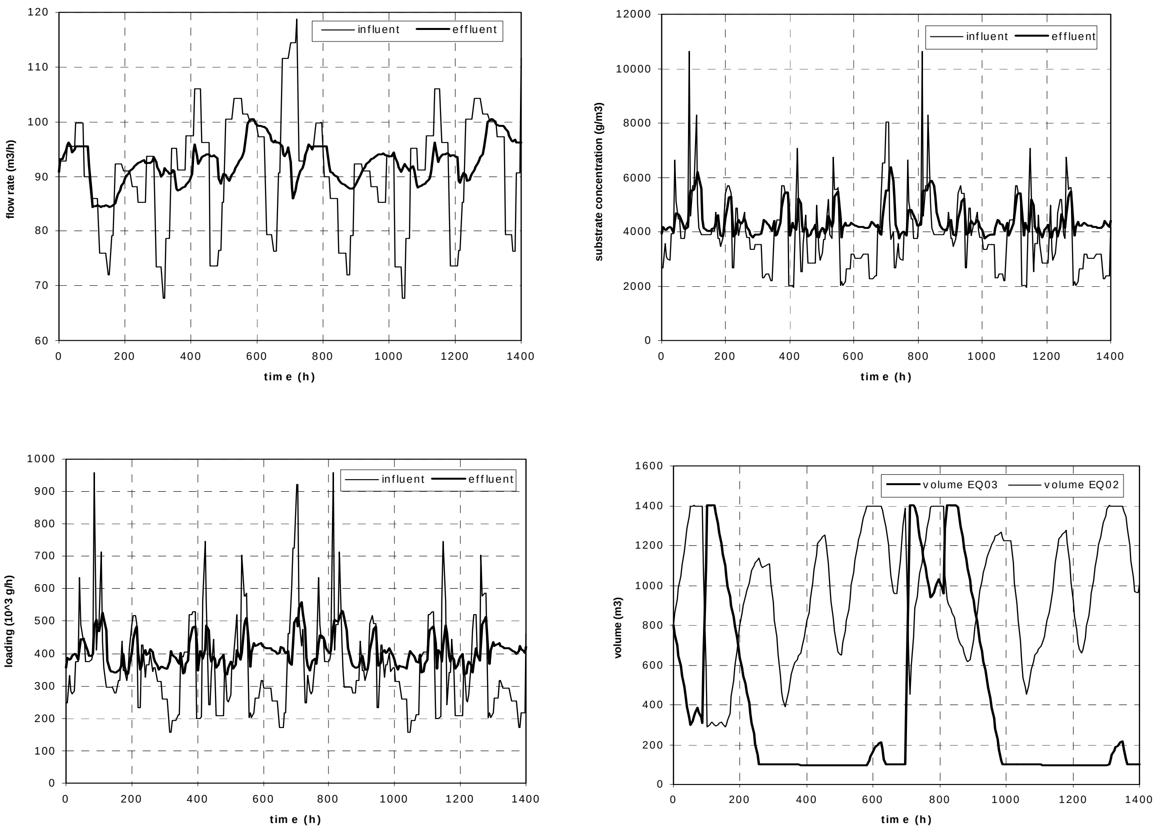
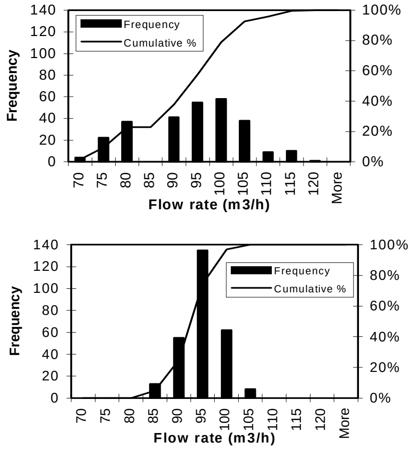
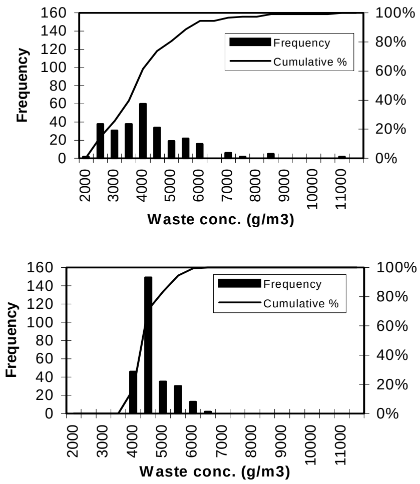


Figure 3. Performance of the equalization towards 4 system variables: flow rate (top, left); waste concentration (top, right); loading (bottom, left); reactor volume (bottom, right)



Flow rate



Waste concentration

Figure 4. Comparison of histograms of influent (top) versus effluent (bottom)

	Variance		
	Flow rate	Waste concentration	Loading
Influent	112	$2\ 10^{6}$	$2.2\ 10^{10}$
Effluent	14	$3\ 10^{5}$	$2.3\ 10^{9}$

Table 2. Statistical evaluation of the equalization performance

3.2 Equalization capability of the control system reconfigured in case of pump failure

As already mentioned above control problems may arise as soon as pump failure appears. To avoid overflow or complete emptying of the equalization tanks an appropriate reconfiguration strategy was implemented.
Simulations have been used to evaluate the system performance under the different pump disfunctions summarized in Table 3. It has been assumed that 50 hours (approximately 2 days) should be enough to repair the failing pump. Since a maximal increase of flow rate (as a result of 34% load increase) stresses the control system the most, simulations were run for the scenario with a 34% increase of flow rate (initial values are those of Fig. 3).

Time (h)	Equal. tank	Number of disabled pumps
250 - 300	EQ03	1
400 - 450	EQ02	1
700 - 750	EQ02	2
900 - 950	EQ02	2
	EQ03	1
1100 - 1150	EQ01	1

Table 3. Simulation of pump failure

In Figure 5 one notices that the system does not really suffer from such different system disfunctionalities imposed in the simulations. The variance only increases a bit, with the concentration being influenced most negatively, especially when the one and only pump of EQ01 fails.

3.3 Analysis of control system robustness

The robustness of a controller to factors unknown or not considered at the time of its development, is a very important factor.

In a first test the effect of different initial system states has been considered. Apparently, the controller is sufficiently robust to evolve to the same time trajectory and was therefore found to be very insensitive to the initial state. This is a good characteristic of any controller.
Secondly, regarding the control of the equalization, three possible errors/failures should be mentioned that were not considered during control system development.

Pump flow rate error: In addition to the pump failure disfunctionality that was taken into account in the reconfiguration of the control strategy, a deviation of the effective flow rate from the control flow rate may also occur. The effect of a fixed and a 25%-deviation was evaluated below.

Waste measurement error: Two kinds of errors have been considered: an assumed 50%-deviation and a complete sensor failure (which typically results in a hold of the last measurement value). Evaluation of this measurement error is a priority since it will not be detected immediately.

Error of level measurements: Again, two errors can occur, i.e. complete failure of the sensor and a proportional error. The simulation of this kind of error is not a priority since the sensor error will always give control failure. The negative effect on the system is known a priori and that is why one is not much interested in its simulation. Besides this, the operator will detect it quite soon. Hence, no further attention was given to this type of error.

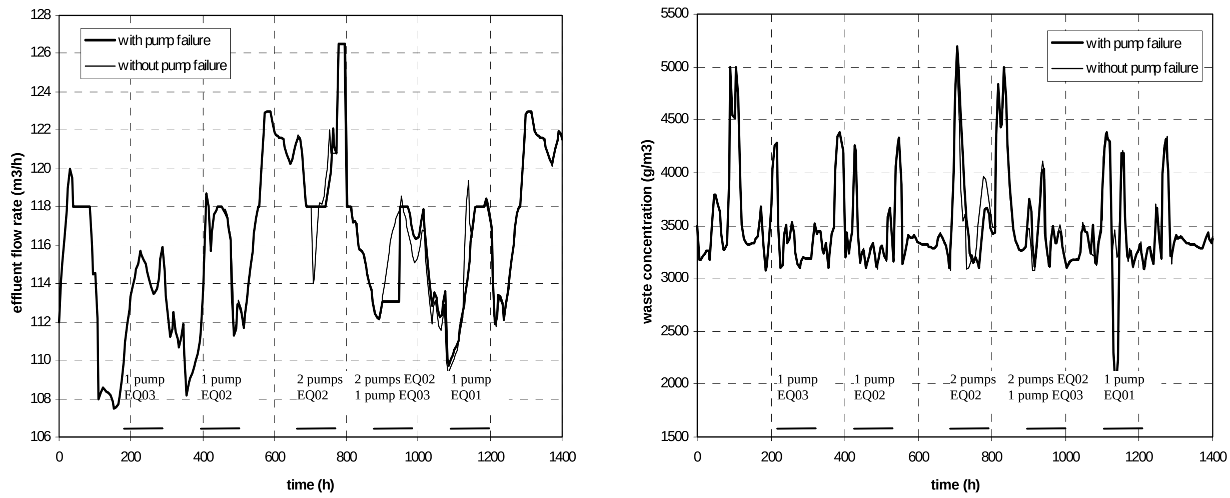


Figure 5. Comparison of equalization performance on flow rate (left) and waste concentration (right) between the cases without and with a pump failure

In the simulations the sensor failures and systematic errors were considered to last for two days (50 hours) at the most, as for the pump failure evaluated in the previous section. The proportional errors could last longer since it is possible that they are not detected immediately. In the simulations an error period of 150 hours or approximately 6.5 days was considered.

Simulations of the effect of proportional and systematic errors on the pump action lead to identical conclusions: the tank will flow over or will be emptied completely. With respect to the TOC-sensor a hold of the last measured value after complete sensor failure appears not to deteriorate the performance of the control system dramatically: the evolution of the flow rate remains approximately the same compared to the no-failure case; the evolution of the waste concentration, however, shows some substantial differences. On the contrary, a proportional error on the TOC-measurement make the equalization performance to deteriorate considerably.

4. Conclusion

A rule-based control strategy for an equalization facility, on an industrial wastewater treatment plant, has been proposed. It consists of 32 rules in the basic configuration to which 25 more rules are added to deal with the occurrence of pump failures that can be detected automatically. Technical and economic limitations have led to the inclusion of a considerable number of constraints in the control strategy. Basically only two hardware modifications are necessary to the plant: a TOC waste concentration sensor at the outlet of the preneutralization (that also provides the necessary data for a software sensor) and an upgrade of one of the fixed speed pumps with a frequency controller allowing a broad range of flow rate adjustments.

Simulations have shown that the variances of the time evolutions of flow rate, waste concentration and loading rate could be decreased 10-fold by the controlled equalization system. The reconfiguration of the control strategy appeared able to deal with pump failures. The robustness of control performance against other errors was investigated as well. The effect of systematic and proportional errors on flow rates, level and waste concentration measurements was evaluated in long term simulations. Sensor failure detection appears of paramount importance and an error detection system for level measurement and flow rate was presented. Especially for the detection of the TOC measurement errors further research appears necessary.

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