A Fuzzy Logic Based System for Heavy Metals Loaded Wastewaters Monitoring

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Abstract: - The paper presents a fuzzy logic based system for wastewater quality monitoring with the purpose of attenuating the environmental impact of the heavy metals loaded wastewaters. The proposed method offers an improvement over the traditionally modelling techniques, when the objectives and constraints are not well defined or information is not precise. The design and implementation of a computational environment in LabVIEW for data acquisition, monitoring system operation and distributed equipment control is briefly described. Fuzzy logic techniques were used because they have good generalization capabilities. The solution efficiency relies on the integration of nine water quality variables into a single quality index of the industrial effluent (EQI) using fuzzy logic rules. The fuzzy rules for diagnosis were developed in MATLAB and were translated and integrated in a Vi LabView fuzzy rule based system, using quantitative and qualitative information, to support the decisional process in case of disturbances of the water quality status due to the effluent discharge impact.

Key-Words: - Fuzzy logic, Fuzzy rules, Wastewater quality monitoring, Environmental indices

1 Introduction

Artificial Intelligence (AI) provides several methods and techniques that can be applied with success in a variety of applications. One of the domains in which AI has a great potential of efficiency improvement is the environmental protection domain. Several systems based on AI have been reported in the literature, for air, water and soil quality monitoring, analysis, diagnosis, forecasting, planning and control (see e.g. references \cite{3}, \cite{5}, \cite{6}, \cite{7}). In particular, computational intelligence provides alternative methods to the traditional methods (i.e. non-AI based) and to the classical AI methods (i.e. those based on the symbolic paradigm). Thus, fuzzy logic, neural networks and evolutionary computing can be applied in the area of environmental sciences and environmental engineering and management. Examples of environmental systems based on computational intelligence can be found in \cite{2}, \cite{8}, \cite{10}, \cite{13}, \cite{14}.

The purpose of our research work was to develop a fuzzy logic based system for wastewater quality monitoring in order to attenuate the environmental impact of heavy metals loaded wastewaters. In this paper it is presented the current version of the system and the experimental results. The proposed fuzzy system provides information about the wastewater status through a unique effluent pollution indicator, named EQI. The water quality is characterized by fuzzy techniques applied to time series of parameters measured on-line by a complex wastewater monitoring system.

2 Computational Intelligence Applied to Environmental Problems

Environmental problems are characterized by a great degree of complexity, mainly due to the use of ecological data that can have different data structures and data formats (e.g. time series, spatial data), significant uncertainty due to incomplete data, inaccurate data, approximate estimations, incomparability of data (resulting from varying conditions of the observations and measurements). The solution to such problems is to use proper approaches, such as those provided by computational intelligence. In particular, fuzzy logic, neural networks and evolutionary computing (e.g. genetic algorithms, genetic programming) can tackle some types of environmental problems: environmental monitoring, analysis, prediction and control.
We present briefly some references to research work already done in the environmental domain, which uses computational intelligence.

Ecological modelling with fuzzy logic is tackled in [11], while in [12] it is discussed fuzzy data analysis in ecological research. In [2] it is presented an application of fuzzy mathematical methods to soil survey and land evaluation. An example of fuzzy classification use in wastewater treatment plants is shown in [10].

Several artificial neural networks were used either for environmental quality forecasting [17] or for environmental pollution analysis. Some feed-forward neural networks were applied to environmental air pollution forecasting in urban regions (see e.g. [4], [7], [8], [13], [16]). Moreover, various comparisons between different approaches were also presented (see e.g. [4] – a comparison between statistical and neural network approaches applied to urban air quality forecasting, [13] – a comparison of neural networks model and qualitative models applied to environmental engineering, and [14] – a comparison between fuzzy reasoning and neural network methods applied to runoff discharge forecast).

Few of the systems presented in the literature are applying computational intelligence to water quality forecasting and analysis. In [9] it is presented a prototype fuzzy system, FuzzyApa that we have developed for surface water pollution analysis. We have continued our research work and we have extended the functionality of the system to survey and control heavy metal loaded wastewater.

2.1 Environmental problem description

The wastewater neutralization system (fig.1) performs the water treatment by neutralization, cobarbing sedimentation and filtration of the pickling wastewaters discharged from the chemical and electrochemical etching lines of a stainless steel factory. The neutralization station is divided into three segments as follows:

- Acid wastewater neutralization system;
- Dewatering system;
- Chemical dosing system.

Chromium is a common surface coating and its discharge into surface water poses serious environmental hazards. Hexavalent chromium is known for its negative health and environmental impact, and its extreme toxicity. It is used for the production of stainless steel, textile dyes, wood preservation, leather tanning, and as anti-corrosion and conversion coatings as well as a variety of niche uses. It causes allergic and asthmatic reactions, is carcinogenic and is 1000 times as toxic as trivalent chromium. Chromium (VI) compounds are divided up in water hazard class 3, and are considered very toxic [15].

Hexavalent chromium is transported into cells via the sulfate transport mechanisms, taking advantage of the similarity of sulfate and chromate with respect to their structure and charge.

Trivalent chromium, which is the more common variety of chromium compounds, is not transported into cells.

Water containing hexavalent chromium is treated with a chemical reduction process. Ferrous sulfate (FeSO₄) is added to the wastewater and the pH is lowered to 3.0 or less using acid (typically sulfuric acid). A retention time is usually maintained to ensure adequate mixing and reaction with the ferrous sulfate.

This process converts chromium from the hexavalent form to the trivalent form. The trivalent form can be treated similar to other metals and the effluent from this process is treated with the other metals wastewater.

As metals enter the treatment process, they are in a stable, dissolved aqueous form and are unable to form solids. The goal of metals treatment by hydroxide
precipitation is then to adjust the pH (hydroxide ion concentration) of the water so that the metals will form insoluble precipitates. Once the metals precipitate and form solids, they can then easily be removed, and the water, now with low metal concentrations, can be discharged in the sewerage. Metal precipitation is primarily dependent upon two factors: the concentration of the metals, and the water pH.

Heavy metals are usually present in wastewaters in diluted quantities and at neutral or acidic pH values (<4.0). Both of these factors are disadvantageous for metals removal. However, when one adds Ca(OH)₂ to water, which contains dissolved metals, the metals react with hydroxide ions forming metal hydroxide solids:

- \(2\text{HF} + \text{Ca(OH)}_2 \rightarrow \text{CaF}_2 + 2\text{H}_2\text{O}\)
- \(2\text{HNO}_3 + \text{Ca(OH)}_2 \rightarrow \text{Ca(NO}_3)_2 + 2\text{H}_2\text{O}\)
- \(\text{Ni(NO}_3)_2 + \text{Ca(OH)}_2 \rightarrow \text{Ni(OH)}_2 + \text{Ca(NO}_3)_2\)
- \(\text{Fe(NO}_3)_2 + \text{Ca(OH)}_2 \rightarrow \text{Fe(OH)}_2 + \text{Ca(NO}_3)_2\)
- \(2\text{Cr(NO}_3)_2 + \text{Ca(OH)}_2 \rightarrow 2\text{Cr(OH)}_2 + \text{Ca(NO}_3)_2\)

Consequently, CaF₂, Fe(OH)₂, Ni(OH)₂, and Cr(OH)₂ are insoluble in water and are separated as solid sludge. The solids resulted in the sedimentation stage are denoted as sludge and periodically removed. This sludge is sent to the dewatering stage to remove excess water and leave only solids.

In the next sections we present our fuzzy logic based system designed to control and survey the treated water discharging process into sewerage, which afterwards discharges the effluent in WWTP, and finally into the natural surface water.

3 The Fuzzy Logic Based System

Sewage, treated to leave the industrial plant is monitored through 9 parameters (fig.2) according to the Water Management Authorization: pH, suspended solids, fixed residue, Chemical Oxygen Demand (COD- potassium dichromate), total chromium, hexavalent chromium (Cr⁶⁺), calcium (Ca²⁺), nitrates (NO₃⁻), and fluoride (F⁻). In this paper, we have selected for representation the time series recorded during one year of continuous monitoring for pH, hexavalent chromium (mg/dm³) and Total Suspended Solids (mg/dm³) – figure 2. These parameters were used together with other 6 parameters as inputs in the fuzzy logic system.

The objective of developing the fuzzy logic supervisory system was to define an input space into output space, and the primary mechanism used If-Then (facts – state or action) rules to solve this requirement. All defined rules are evaluated in parallel in a random order. These rules are useful because they make references to variables and the adjectives that describe those variables.

Fuzzy inference is the method to read input vector values and based on the set of rules, allocates the vector output values. Membership functions are curves that define how
each entry point in space belongs to a degree of membership in the range 0 and 1.

The forms of the membership function used in application were selected to meet the computational efficiency and memory savings requirements. From this point of view, the triangular and trapezoidal membership functions corresponded to the intended purpose.

The structure of production rules was developed using Fuzzy Logic Toolbox module of MATLAB (fig.3). The rules were structured by level of effluent pollutants concentration (low, normal, high) taking into account the maximum limit values from the European and national standards (e.g. Directive 98/83/EC on quality of water for human consumption, Directive 91/271/EC on urban wastewater treatment, [18] etc.). Because it is a more compact and computationally efficient representation than a Mamdani system, the Sugeno system lends itself to the use of adaptive techniques for constructing fuzzy models [19]. These adaptive techniques were used to customize the membership functions so that the fuzzy system best models the effluent collected data.

Figure 3 MATLAB Rule editor showing the production rules structure used in FuzzyAPA

The set of fuzzy rules algorithm performs the following steps:
- scalar representing the system input – 9 variables (pH, hexavalent chromium, TSS, etc.) are transformed into membership functions through the fuzzyfying functions;
- this information is transferred to the inference engine;
- values of membership functions are transformed into output by defuzzification of the scalar value, representing the output indicator that evaluates the effluent quality status (0 – bad; 1 – very good).

Consequently, the main objective of the control system is to ensure the absence of hexavalent chromium, and low concentrations of nitrates, total suspended solids and COD in the plant effluent, actuating in the output variables of the fuzzy control system.

![Figure 4 Efluent Quality Index for January – output of the fuzzy logic system](image)

The FIS system provides reliable information on the quality parameters of the effluent by integrating multiple variables into a single synthetic indicator – Effluent Quality Index (EQI), which allows the user to accurately assess the pollution status (1 as "ideal" – 0 as "polluted").

Figure 4 shows the resulted output after introducing the acquisitioned data for one month as inputs in FIS. Even in the absence of chromium in the effluent, the negative effects of other parameters (eg TSS, COD) showed their influence. EQI varied mainly between 0.25 and 0.4, suggesting high level of contaminants.

![Figure 5 Evolution of the Effluent Quality Index for one year – output of the fuzzy logic system](image)

It can be observed that EQI results show that the effluent pollutants load is relatively high even if the MAC exceedances for individual pollutants concentrations did not have a higher frequency over the sampling interval. This cumulative effect of the nine variables had the same pattern when considering the yearly interval.

Figure 5 depicts EQI fluctuations of this indicator during one year of surveying, which varied mainly between 0.3
and 0.45. The construction and testing of the fuzzy logic system was performed in MATLAB Fuzzy Logic Toolbox due to its versatility in developing FIS structures.

In order to obtain a supervisory system, we have translated the optimized and tested FIS structure from MATLAB into a National Instruments LabView Vi (virtual instrument) [20] using the dedicated functions of the PID module that contains fuzzy logic capabilities (fig. 5).

The graphical user interface of the LabView virtual instrument (Vi) was associated to the technological installation providing control of the discharge of industrial treated water into the sewerage based on the synthetic effluent quality index (0-1; 0 – bad; 1 – very good).

**Figure 5** Associated LabView virtual instrument (Vi) that controls the discharge of industrial treated water into the sewerage based on the synthetic effluent quality index (0-1; 0 – bad; 1 – very good).

The main advantages of the Vi supervisory system are as follows:

- display of the synoptic schemes associated to the neutralization station;
- display of the events and alarms when exceedance of limit values occurs;
- processing the information for the optimum functioning of components and of the overall system, according to the implemented fuzzy algorithms;
- display of variables measured or modeled by the algorithm fuzzy;
- periodical recording of the measurements and their visualization in various forms (graphs, tables, file);
- reports on current status and historical events.

Figure 5 shows a screen capture of the Virtual Instrument showing the real-time installation control (flow rates, basin levels, various setpoints etc.), but most important, the evolution of each of nine parameters that characterize the effluent pollutant load.

Furthermore, depending on the EQI provided by the integrated fuzzy inference system, the effluent can be redirected to the neutralization basin. This is the case when the effluent pollutant load does not meet the established EQI, for discharging in the sewerage.

### 4 Conclusion

The application of fuzzy logic system discussed in this paper suggests that even in areas where traditional control engineering already offers versatile solutions, fuzzy logic can provide potential benefits.

The concepts underlying fuzzy technology are successfully used in water quality modeling, allowing an alternative approach in solving specific environmental problems when the objectives or constraints are not precisely defined, and necessary information is missing, is sporadic or discontinuous.

The presented method facilitates the characterization of the effluent pollutant load resulted from a stainless steel factory using fuzzy techniques for processing parameters time series.

The EQI synthetic indicator allows the user a quick interpretation of the status of analyzed water.

For policy makers, the proposed system of effluent quality monitoring is to facilitate the following goals: water quality planning, water quality monitoring, level of compliance verification of the collected data with the environmental standards, and application of prevention, remediation and control measures to meet the planned objectives of water quality.

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