An Expert supervisory System for a pilot WWTP

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Abstract: This paper presents the development and implementation of a real-time expert system (ES) for the supervision and control of a wastewater treatment pilot plant (WWTPP) with biological removal of organic matter and nutrients. The ES has been developed using the G2 environment, and it is implemented for real-time operation. The hardware architecture contains different supervision levels, including two autonomous process computers (plant control and analysers control) and a PLC, being the ES the top supervisory level. The ES actuates as the master in a supervisory setpoint control (SSC) scheme. It is based on a distributed architecture. The knowledge is organised in several agents, representing the available knowledge for every sub-process of the WWTPP. In addition to these independent agents, a supervisor agent acts as the master of the independent agents.

Keywords: Expert System; Knowledge-based System; Real-time; Monitoring; Activated Sludge.

1. INTRODUCTION

Actual trends in process control are determining an increase in complexity at each control level. Utilisation of automatic analysers, industrial controllers, PLC (Programmable Logic Controller) and industrial computers is continuously increasing. The application of computer technology to control and supervision of technological processes has lead to a spectacular increase in the information acquired by these systems. However, this increase in frequency, quality and diversification of process data has not lead to an equivalent system improvement. The amount of information is so vast that its depth study is impossible. The results of this technology are Data Acquisition Systems, with the purpose of giving a process situation overview. To improve this situation, utilisation of Artificial Intelligent techniques for processing this information has been proposed [Serra et al., 1993; Serra et al., 1997; Patry and Barnett, 1992].

Monitoring of the components of wastewater treatment processes is an important feature in order to assure its control, particularly when simultaneous organic matter, nitrogen and phosphorus removal are involved. The complexity of these systems, due to the number of biological processes implicated, makes necessary the development of reliable on-line instrumentation. Furthermore, a reproducible and robust sampling device is a critical fact to provide reliable data of the process. On-line and in-line measurements continuously obtained from the process, combined with a model and different control strategies implemented are capable of making wastewater treatment plants more efficient.

A Knowledge-Based Expert System (KBES) is a possible framework where measurements, rules and models can be integrated. Barnett [Barnett et al., 1992] presents an extensive literature review on application of KBES for the activated sludge process. Most of the systems here summarised are off-line KBES mainly diagnostic and advising tools to help operators [Gall and Patry, 1989; Ozgur and Stenstrom, 1994]. Some KBES have been designed with the main purpose of on-line supervision [Verheijen, 1997] though the emphasis on real-time supervisor control is usually absent.

In the present work is shown the hardware architecture and software development of an intelligent distributed control system for supervision of a wastewater treatment pilot plant with biological removal of organic matter, nitrogen and phosphorus. This development can be defined as a knowledge distributed system. This means that all the possible knowledge at every subsystem of the process is applied, as the main tendency in the actual real-time control and supervision of processes. In this supervisory control outline, every element supervises the elements situated hierarchically under its control. This fact increases system complexity, but some important advantages are obtained. Firstly, control of process failure is increased to assure system security. Secondly, the top-level control can be used to work in system supervision. With this architecture is easy to obtain a fault tolerant system. In our case, the top-level control is occupied by an Expert System elaborated with G2 [Gensym, 1995], a tool to develop real-time expert systems.

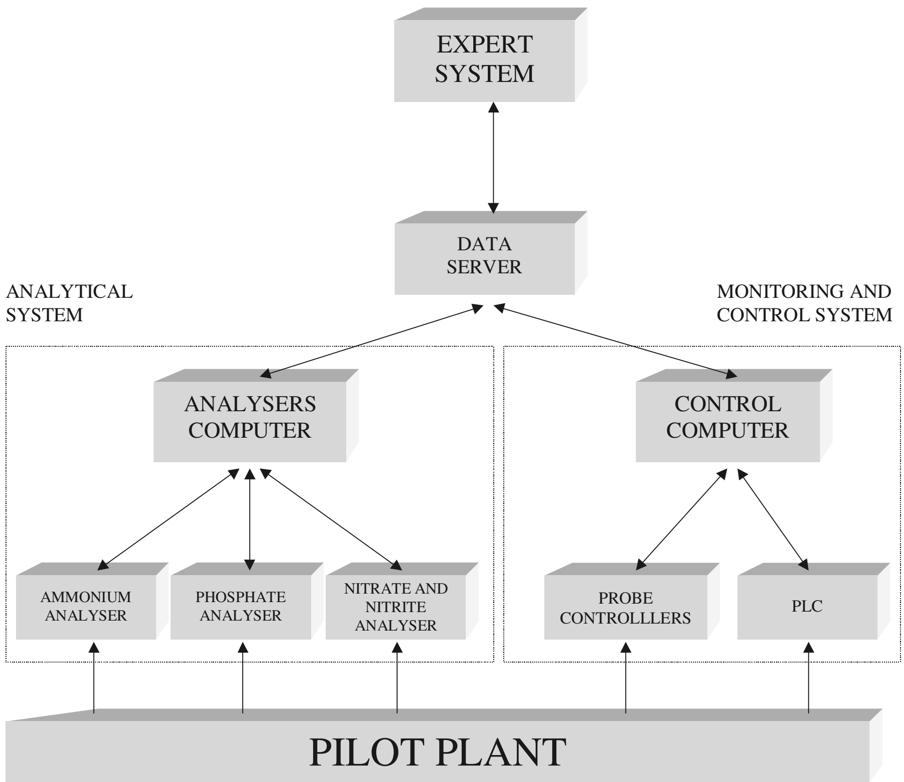

Figure 1. Outline of the architecture of the control system

2. ARCHITECTURE OF THE SYSTEM

The architecture of the intelligent distributed control system is outlined in Figure 1. The whole system can be divided in five blocks: the pilot plant, its monitoring and control system, the analytical devices, the data server and the Expert System.

In this architecture, the different control dynamics that are found in a real WWTP are reflected. The fastest dynamic is the operation of oxygen control. This parameter should be controlled in a very fast dynamic therefore the utilisation of an independent controller as for example a PID can be necessary. It depends on the aeration system used, but in our plant, the necessary frequency of actuation is about 10 seconds. Other fast parameters are the different flows of the plant, the stirring speed, etc. All these parameters should be controlled directly with local control loops. In our plant, this is done through the utilisation of an independent monitoring and control system.

In order to acquire more information about the process in the pilot plant, another subsystem has been designed and implemented. This is the automatic analytical system. This is independent from the monitoring and control system, and is controlled by other computer.

These two systems are physically independent, but are linked through the data server, which permits the data transmission between these computers and the expert system. The independence of every subsystem assures the security of the other subsystem if a problem appears in one of them.

The monitoring and control subsystem is able to maintain the plant performance in normal conditions, but this control acts with a fixed behaviour. When not normal conditions appear, this subsystem could not be able to take the plant to a good performance. Is in this moment when the need for a higher supervisory level appears. These tasks, that classical control systems are not able to manage, are the ones where expert systems are a good tool.

2.1 The pilot plant

The process under study is a biological wastewater treatment based on A^2/O multistage configuration [EPA, 1993] with nitrification - denitrification and biological excess phosphorus removal. The pilot plant is fully automated and is able to treat 500 litres per day of a synthetic influent. Figure 2 shows a schematic diagram of the pilot scale facility, which consists of an anaerobic selector (9 litres), three identical aeration tanks (28 litres) and a settler (60 litres). The oxic state of these three tanks is easily configured from the expert system. The first tank usually is used as an anoxic reactor, but an aerobic operation mode is also possible. The presence of an anaerobic selector is due to phosphorous removal. The inlet wastewater is a synthetic influent made by mixing two concentrated complex sources of carbon and phosphorus, and nitrogen diluted with tap water. Different concentrations and flows can be automatically assigned and scheduled to simulate real situations.

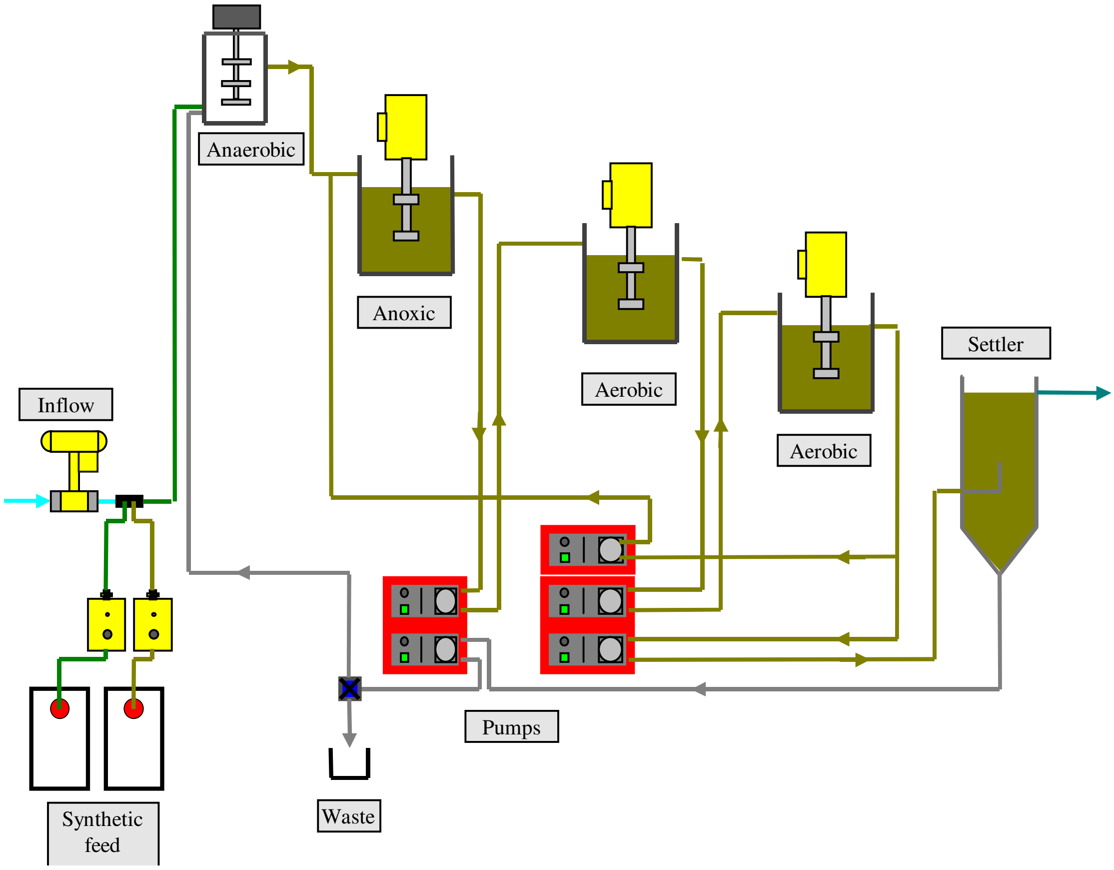

Figure 2. Scheme of the pilot plant.

2.2 Monitoring and control system

Each mechanical unit of the plant (pumps, level detectors, nipping valves, etc) is controlled by a PLC, that allows to automate all those elements. In the PLC program, the operation failure detection and corrective actions are included. This is the first control level. Every reactor of the pilot plant has in-line sensors (dissolved oxygen, pH, ORP, temperature) connected to probe controllers. A control and monitoring computer supervises the PLC (via RS-232). This computer also acquires data from the probe controllers (via RS-485) and it controls the dissolved oxygen (DO) through the manipulation of the pneumatic control valves of every reactor (via 4-20 mA loop). This control loop is based on a digital PID algorithm programmed in the computer. The software, developed in C language, includes graphic monitoring, data backup, and control of key process parameters (flow-rates, stirring rates, etc).

2.3 Analytical system

Flow Injection Analysis (FIA) and Continuous Flow Analysis (CFA) techniques have been implemented for ammonium, nitrate, nitrite and phosphate monitoring. The analytical system developed focuses on automation, reliability and long-term stability to operate the maximum time in an unattended manner. The analysers are an automation of standardised chemical procedures. They are controlled with a computer via a RS-485 bus where all the modules of the three systems are connected.

FIA for simultaneous determination of nitrate plus nitrite [Gabriel et al., 1998] is based on the Shinn method. A copper-coated cadmium reduction column for nitrate reduction to nitrite is used. Every 8 minutes, a volume of 250 µl of sample is injected. Nitrate and nitrite are detected in a range of 0.23 to 11.3 mg $N\text{-}NO^{-}_{3}$ l^{-1} and 0.015 to 1.52 mg $N\text{-}NO^{-}_{2}$ l^{-1}. The maximum sampling rate is 180 samples per day.

FIA for phosphate determination is based on the colorimetric determination of the vanadomolybdophosphoric acid previously formed by addition of vanadate-molybdate reagent. This analyser is based on the reverse-FIA technique where reagent is injected to a sample flow. The volume injected is 50 µl. Phosphate is determined every 3 minutes in the range of 0 to 30 mg $P\text{-}PO^{3-}_{4}$ l^{-1}, and the detection limit is 0.35 mg $P\text{-}PO^{3-}_{4}$ l^{-1}. The maximum sampling rate is 480 samples per day.

The CFA for ammonium is based on potentiometric determination of ammonia. The sample is continuously feed to the analyser and mixed with a flow of sodium hydroxide to obtain quantitative ammonia. This flow passes through a gas diffusion unit where ammonia is transferred to a crosscurrent flow of ammonium chloride buffer solution. This flow passes through a cell with a flat pH electrode where the potential is read. The system is able to determinate ammonium in the range of 0 to 40 mg $N\text{-}NH^{+}_{4}$ l^{-1}. Detection limit is 0.4 mg $N\text{-}NH^{+}_{4}$ l^{-1}. The maximum sampling rate is 90 samples per day.

An automated sampling system was mounted to obtain a continuous biomass-free sample flow. It is constituted by aspiration and feedback circuits for each reactor, coupled with a peristaltic pump and a Minitan® (Millipore) tangential filter. A set of computer controlled nipping valves is used to select the sampling circuit.

The software for the analysers computer has been developed in C language and it includes data acquisition, graphic monitoring, data backup, and control of the sampling system. In addition, it actuates each module of the analysers (three-way valves, injection valves and pumps).

2.4 The data server

The process computers (Pentium processors) are linked via Ethernet to a data server executed in a Sun Sparcstation running Solaris operating system. This gateway, developed in C language, allows the maintenance of a real time database with the information generated in the system.

Any on-line real-time ES should receive data when it is produced. In addition, if the ES has to control the plant, a way to send information from the ES is required. A bi-directional communication system, pilot plant ⇔ ES, has been developed for this purpose. This system also accomplishes G2 communications requirements. The data server is able to receive a petition from G2 at any moment, and it sends the required information immediately. The data server is capable of maintaining several communications with different clients simultaneously to avoid any delay in the connections of the clients.

TCP/IP protocol, which is based on a client/server architecture, has been used to solve communication requirements. With the implemented system, communication between any client computer connected to Internet and the data server is possible. In our case, the computers that monitor and control the pilot plant and the analysers are the clients of the services offered by the SUN workstation. This bridge has been developed in C standard (GCC 2.2.7).

2.5 Expert System

The expert system developed in G2 (version 4.0), running in the Sun workstation, is on the top of system's architecture. It actuates as the master in a supervisory setpoint control (SSC) scheme. The ES systematises the knowledge about the process being based on the existing scientific knowledge and the practice acquired in our particular system. All this knowledge is structured trough a whole of rules and procedures for each subsystem of the pilot plant, co-ordinated with a supervisory agent.

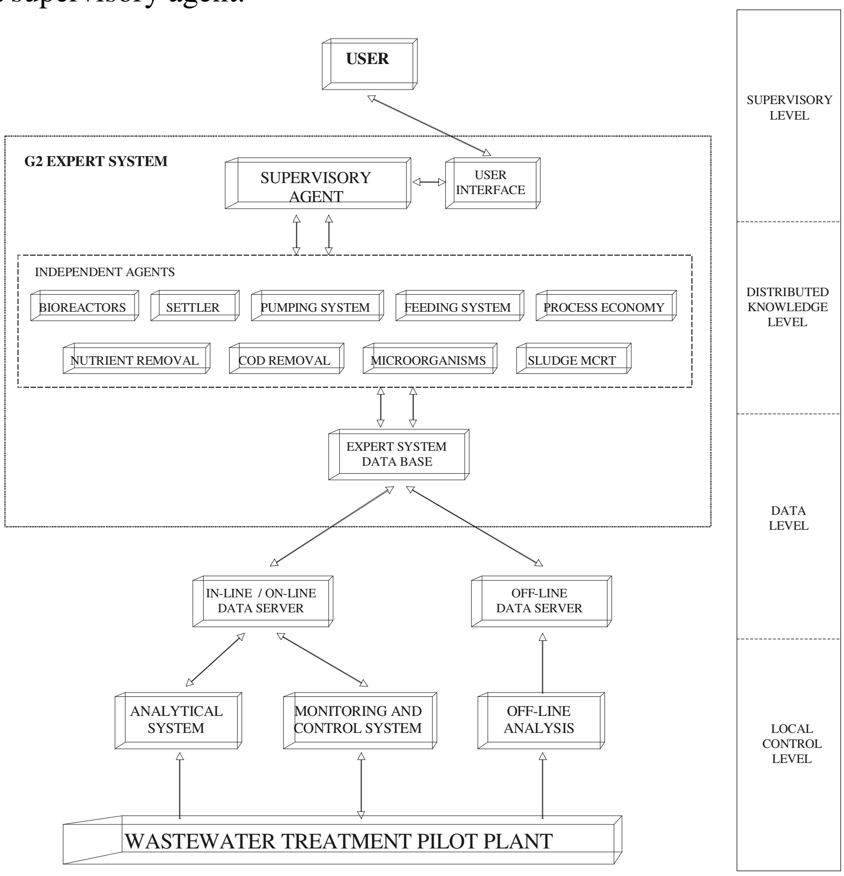

Figure 3. Scheme of the Expert System architecture.

3. ARCHITECTURE OF THE EXPERT SYSTEM

The expert system is based on a distributed architecture integrated by a supervisor, as was defined in previous works [Serra et al., 1994; Sànchez et al., 1994; Sànchez et al., 1996]. The knowledge is organised in several agents, representing the available knowledge for every sub-process of the WWTPP. In figure 3, a scheme of the ES architecture is shown. The system is divided in four different levels: Local control level, Data level, Distributed knowledge level, and the Supervisory level.

3.1 Local control level

The WWTPP is built with a distributed control system. This hardware architecture permits the independence of the monitoring and control system and the ES. This level of control allows direct control of the pilot plant, with a set of pre-defined setpoints. These setpoints can be a fixed one, or they can be an ES defined set. This control could work without the presence of the ES, although it would be with a fixed behaviour. The local level control is the level of the architecture where more numerical control is applied.

3.2 Data level

The data level includes the bi-directional data transmission between the local control level and the expert system. It also includes the real-time database maintained by the ES. This data level profits of the real-time interfaces and assures a real-time environment for the ES. This level not only takes into account the data transmission from the pilot plant to the ES, but also is in charge of the transmission of setpoints from the ES to the distributed control system.

3.3 Distributed knowledge level

In this level, several independent agents take charge of a part of the WWTPP. The actual number of agents is nine, although some additional integration is possible. The specific agents are:

- Bioreactors agent. It supervises the operation in the bioreactors, specially the aeration and stirring subsystems behaviour.

- Settler agent. This agent takes in charge the supervision of the settler operation. This is an important element to assure the correct performance of the activated sludge process, because the water - microorganisms separation is a general source of problems in WWTP.

- Pumping system agent. It supervises the operation and maintenance schedule of the pumps used in the pilot plant. A problem with any pump produces a disturbance of the biological process because the plant has to stop. In these conditions, an early diagnostic of any possible problem is a great help for the whole process.

- Feeding system agent. This agent supervises the automatic feeding system. It integrates the total volume and concentration of compounds fed to the pilot plant. This agent makes estimations of the volume of concentrates used, and advises to the operator when the vessel of concentrate should be filled. It also estimates the ratio food / microorganisms, and advises when this relation can produce problems in the plant.

- Process economy agent. In all the WWTP processes, economy must be taken into consideration. In some situations, the main restrictions come from the economic point of view, therefore, it should be taken into account when necessary.

- COD removal agent. The organic matter removal is the most important task in a WWTP. This removal must accomplish some legal requirements and it should be supervised to assure those requirements.

- Nutrient removal agent. Nutrient removal is a new requirement for WWTP. The processes involved are more complicated than the COD removal. The combination of COD, phosphorous and nitrogen removal produces new problems in a more complex framework. The COD removal and the nutrient removal are two very interrelated agents, so the co-operation through the supervisor agent is very important in this case.

- Microorganisms agent. This agent uses the information obtained off-line with the microscopic observation to supervise the microorganisms present in the sludge. These observations are very useful to infer future problems. Taking into account these possible problems, preventive actions can be executed in order to avoid them.

- Sludge MCRT agent. MCRT is an important parameter of the process that determines the species of microorganisms present in the system. For its calculation, in-line and off-line data are required, therefore is a complex key parameter. The MCRT setpoint is calculated by the supervisor agent taking into account information provided by this and other agents as the Process economy, the Nutrient removal or the Microorganisms.

They act as independent agents applying numerical algorithms and rules when the situation is normal and are controlling a simple process parameter. When the situation is not normal or when a complex parameter (as MCRT) has to be calculated, the supervisor requires information to the agents and deduces the correct control action to be made. These agents can be deactivated or partially deactivated by the Supervisor agent when some problems are detected, so the supervision and control over the agents is guaranteed although they are independent.

3.4 Supervisory level

The Supervisor agent is the manager and master of the distributed system. It receives the information required to the independent agents and concludes if a supervisory control action is necessary. If no action is required, the agents maintain active its algorithms and rules. In addition, it controls complex operational parameters that involve information generated from several agents.

The Supervisor agent permits the data interchange between the user and the ES, by means of the user interface. This interface includes graphical monitoring of the data acquired and an explanation module which allows the debug of the way used to arrive to a determined conclusion of the ES. This module is very useful for the ES validation, usually a long and difficult task.

4. EXPERT SYSTEM IMPLEMENTATION

G2 permits the organisation of an ES in knowledge bases (a container in which a set of knowledge about real or virtual entities is collected and organised). A knowledge base can contain one or many workspaces (the blank pages upon which we create and maintain objects). The objects upon workspaces are capable of having their own subsidiary workspaces. Thus, logical hierarchy of objects and workspaces to group and organise data can be created. In our prototype definitions, plant diagrams, graphical monitoring, and agents are considered as main workspaces. The agents are subdivided in several workspaces, maintaining an organised structure.

Knowledge representation in G2 is maintained and extended through classes. Classes have attributes; these define the inherited and locally defined properties of the class. G2 maintains class attributes within attribute tables. Main classes considered include process units (14 object definitions), instrumentation (38 object definitions), connections (27 object definitions), sludge and microorganisms (84 object definitions), and computers (4 object definitions). Every object is an instance of a class, which is defined through an object definition. Figure 4 presents the ES shell with several workspaces, objects with their icons, and connection stubs.

The ES is fed with in-line data (pH, T, DO, ORP, aeration and flows) and on-line data (NO_3^-, NO_2^-, NH_4^+ and PO_4^{3-}) generated by the plant using the data server. Qualitative data (odours, colours, microbiological observations data) and discrete data from off-line analyses (COD, TSS, VSS, TKN, and SVI) are sent to the ES. Both last tasks are accomplished using the Internet as a vehicle. Each specialised operator can send specific data from any computer using a form page in WWW. HTML code generates an e-mail formatted message using the PERL script language. The ES is able to read these messages, and to use this symbolic and numeric knowledge to update the attributes of the object. Using rules based on the available data and the operator confirmation in problematic situations, the expert system continuously decides the optimum operation. Finally, control actions are transmitted to the process computers that act on the required plant elements.

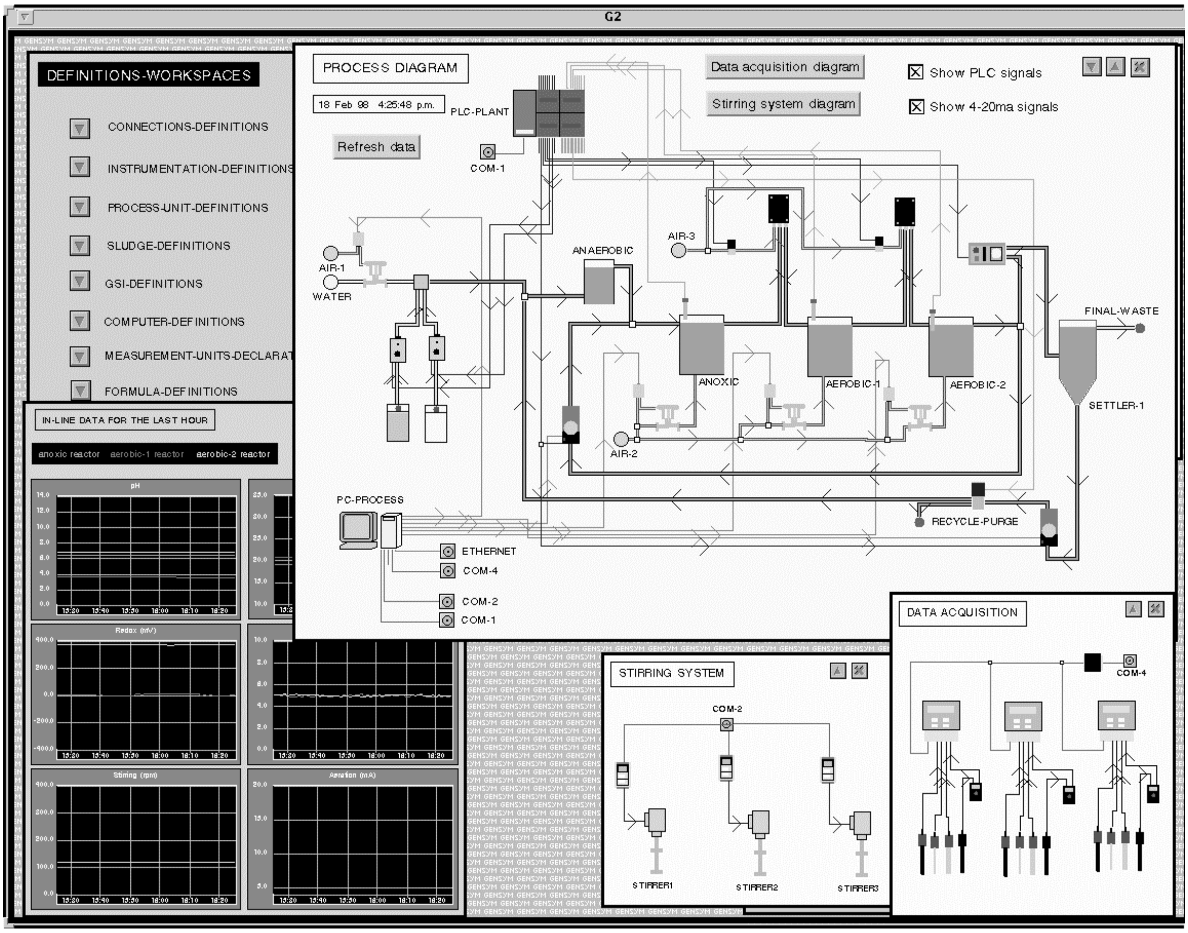

Figure 4. The Expert System shell.

5 . APPLICATION

A detailed practical example of how the overall supervisory system works is shown, focusing on the control of the Mean Cellular Residence Time (MCRT):

The operator realises a routine analysis and introduces the analytical results in the Web Page using a standard browser. This produces an e-mail, with the data codified, which is sent to the workstation.

The expert system checks periodically if a new e-mail message has arrived. When detected a new e-mail, the data included is read. This data is used to update the corresponding attributes of the defined objects.

The changes of the value of the attribute 'suspended volatile solids' in the reactors produce a new value of the MCRT. If this value is different to the previous value, the agent 'Sludge MCRT' is automatically activated.

This agent checks if the new value was into the predefined band. This band is determined by the Supervisor agent, taking into account the information provided by several agents, as the 'Nutrient Removal', the 'Microorganisms' or the 'Economical Restrictions' agents.

If a difference between the required MCRT and its actual value is detected, a procedure is activated. This procedure calculates the purge parameters to obtain the required MCRT.

These parameters are sent to the data server, who is in charge of transmit them to the monitoring and control computer through the TCP/IP connection.

The control computer, with the new setpoints obtained from the data server, sends to the PLC new setpoints, corresponding to the opening time of the purge electrovalve.

The PLC uses the new setpoints to open and close the purge electrovalve in the prefixed intervals. The position of this electrovalve determines if the sludge recycling flow is directed to the anaerobic reactor or to the vessel where the purge of the system is accumulated. The change in the recycling flow derived to the vessel determines a new value of MCRT.

A change in the plant conditions, for example if the external recycling flow is modified by another rule, can produce new values for the parameters of the system involved in the MCRT calculation. These news values are detected by the ES, which will activate the necessary agents to conclude new control parameters if necessary, as has been shown before.

6. CONCLUSIONS

The main achievement of this prototype is a versatile framework able to deal with different plant configurations, based on the object-oriented paradigm and on rule-based reasoning. The on-line feature is an important innovation of this system, particularly for data monitoring and supervisor control. Recently, some papers with good results have appeared showing the promising potential for implementing on-line monitoring and control [Balslev et al., 1996; Nielsen and Önnetrh, 1996], though their knowledge integration is not as formal and versatile as KBES would require. In our system, different control strategies can be implemented for activated sludge control of carbon, nitrogen, and phosphorus removal with different plant configurations. In addition, the developed KBES can be adapted to a new plant in a short time because of object-oriented design.

Finally, this system was running continuously during 400 days. In this period the operational objectives of the pilot plant was changing periodically (nitrogen removal, phosphorus removal, etc.). The supervisory expert system shows an excellent performance to manage the pilot WWTP. The system developed detects and controls all the wrong and special operations, as for example: pump failure, feeding problems, probes malfunction, equipment maintenance, analysers control and maintenance, etc.

7. REFERENCES

[Balslev et al., 1996] P. Balslev, A. Lynggaard-Jensen, C. Nickelsen. Nutrient sensor based real-time on-line process control of a wastewater treatment plant using recirculation. In *Wat. Sci. Tech.* **33**(1), 183-192. 1996.

[Barnett et al., 1992] M.W. Barnett, G.G. Patry, M. Hiraoka. Knowledge-based (expert) systems for the activated sludge process. *Dynamics and Control of the Activated Sludge Process*, Technomic Publ. Co., Lancaster, pp. 231-243. 1992.

[EPA, 1993] *Manual Nitrogen Control.* EPA, Washington, DC, USA. 1993.

[Gabriel et al., 1998] D. Gabriel, J. Baeza, F. Valero, J. Lafuente. A novel FIA configuration for the simultaneous determination of nitrate and nitrite and its use for monitoring an urban waste water treatment plant based on N/D criteria. In *Analytica Chimica Acta,* **359**, 173-183. 1998.

[Gall and Patry, 1989] R.A.B. Gall, G.G. Patry. Knowledge-based system for the diagnosis of an activated sludge plant. *Dynamic Modeling and Expert Systems in Wastewater Engineering*, Lewis Publ., Chelsea, pp. 193-240. 1989.

[Gensym, 1995] Gensym Corporation. *Gensym G2 Reference Manual Version 4.0.* Gensym Corporation. Cambridge, Massachusetts. 1995.

[Nielsen and Önnetrh, 1996] M.K. Nielsen, T.B. Önnerth. Strategies for handling of on-line information for optimising nutrient removal. In *Wat. Sci. Tech.* **33**(1), 211-222. 1996.

[Ozgur and Stenstrom, 1994] N.H. Ozgur, M.K. Stenstrom. KBES for process control of nitrification in activated sludge process. In *J. of Environ. Eng*. **120**(1), 87-107. 1994.

[Patry and Barnett, 1992] G.G. Patry, M.W. Barnett. Innovative computing techniques for development of an integrated computer control system. In *Wat. Sci. Tech.* Vol. 26, No. 5-6, pp. 1365-1374. 1992.

[Sànchez et al., 1994] M. Sànchez, I. R-Roda, M. Poch, U. Cortés, J. Lafuente. DAI-DEPUR architecture: Distributed agents for real-time WWTP supervision and control. *Proc. Of IFAC/IFIP/IMACS Symp. on Artificial Intelligence in Real Time Control (AIRTC'94), València (Spain),* 147-152. 1994.

[Sànchez et al., 1996] M. Sànchez, U. Cortés, J. Lafuente, I. R-Roda, M. Poch. DAI-DEPUR: an integrated and distributed architecture for wastewater treatment plants supervision. In *Artificial Intelligence in Engineering* **1**, 275-285. 1996.

[Serra et al., 1993] P. Serra, J. Lafuente, R. Moreno, C. De Prada, M. Poch. Development of a real time expert system for wastewater treatment plants control. In *Control Eng. Practice.* Vol. 1, No. 2, pp. 329-335. 1993.

[Serra et al., 1994] P. Serra, M. Sànchez, J. Lafuente, U. Cortés, M. Poch. DEPUR: a knowledge-based tool for wastewater treatment plants. In *Engng. Applic. Artif Intell.* **7**(1), 23-30. 1994.

[Serra et al., 1997] P. Serra , M. Sanchez , J. Lafuente, U. Cortes, M. Poch. ISCWAP: A knowledge-based system for supervising activated sludge processes. In *Computers Chem. Engng.* Vol. 21, No. 2, pp. 211-221. 1997.

[Verheijen, 1997] L. Verheijen, I. Uchiakawa, T. Kobayashi, I. Endo. IMCS (Intelligent Monitoring and Control System) for wastewater-treatment. *Book of Abstracts of 8th European Congress on Biotechnology*, Budapest, pp. 299. 1997.