# APPLICATION OF EXPERT SYSTEMS IN WASTEWATER TREATMENT

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**Abstract**
Introducing more stringent effluent standards causes that more advanced treatment processes must be used and that complexity of monitoring and control system is increasing. In such situations operators' skills and professional expertise sometimes are not enough for optimal control of treatment processes, especially during abnormal operational situation. Expert systems, knowledge-based computer programs, may serve as decision support tools for operators in such situations. They are able to communicate with an operator in an understandable language, and provide him with an advice regarding optimum course of action to be undertaken. The expert system's advice is based on a database of knowledge about similar situations from the past, knowledge of human experts, on-line data collected from the plant, and sometimes from computer simulations performed by expert system's simulation modules. In this a paper a brief review of application of expert systems in designing, operation and control of modern WWTPs in presented.

**Keywords**
Wastewater treatment; artificial intelligence; expert systems; computer simulation

## INTRODUCTION

In recent years wastewater treatment is becoming increasingly more complex, as it includes more unit processes and applies more advanced monitoring and control systems. As wastewater treatment plants utilize more intense treatment processes to treat large pollution loads, the effects of potential process collapse to the natural environment might be extremely damaging. Thus, biological and chemical processes applied for wastewater treatment require careful and reliable supervision performed by well-skilled operators with operational experience, extended knowledge, and operational and emergency procedures. *Expert systems*, an emerging technology in information processing and decision support, may become very useful tools in wastewater treatment plant operation and management, as well as in technological process design and control.

The dictionary definition of an expert system is *"... a computer program that contains a knowledge base and a set of algorithms or rules that infer new facts from knowledge and from incoming data" (FOLDOC, 2001).* Expert system applies artificial intelligence (AI) to solve narrow and clearly defined problems and to provide advice in problem solving based on the knowledge of experts *(Fedra, 1991).* Based on this knowledge, a set of rules and certain questions asked the system in capable of making intelligent decisions within its domain and to support the humans in making their decisions. Combination of expert systems with other tools such as advanced simulation models may further extend their usefulness for wastewater plant operators. In this paper the basis of applications of expert systems in wastewater treatment are discussed and the examples are presented.

## OVERVIEW OF AI AND KNOWLEDGE-BASED SYSTEMS

The discussion of expert systems, as a sub-category of knowledge-based systems, should be started with definition of artificial intelligence (AI), which is a very a very broad and often incorrectly understood concept. In popular perception AI is sometime associated with human-like robots or with supercomputers, which sometimes tend to take over the world. Despite that this is also a part of AI domain let us try to formulate more precise definitions. One of many possible ones states that *"AI is the study of mental faculties through the use of computational models"* or that *"...it is the study of how to make computers do things, which at the moment people do better."* The more general definition given by *Sanchez* says that "AI is the study of the possible or existing mechanisms in human or other beings providing such behavior in them that can be considered as intelligence, and the simulation of these mechanisms in a computer through the computer programming." *(Sanchez et al., 1995)*

Similarly as there is no one definition of AI, there is no one generally accepted definition of an expert system. *Hayes-Roth* states that an expert system is knowledge–intensive program that solves problems that normally require human expertise. It performs many secondary functions as an expert does, such as asking relevant questions and explaining its reasoning. All expert systems have certain common characteristics, which may be formulated as follow *(Fedra, 1991):*

- they can solve very difficult problems as well as or even better than human experts;
- they reason heuristically, using what experts consider to be effective rules of thumb and they interact with humans in appropriate ways, including via natural language;
- they manipulate and reason about symbolic description;
- they can function with data, which contains errors, using certain judgment rules;
- they can contemplate multiple, competing hypotheses simultaneously;
- they can explain why they are asking a question;
- they can justify their conclusion.

Knowledge-base systems (KBS) and expert systems (ES) are the sub-categories of AI computer software, which go beyond the traditional procedural, algorithmic, numerical, and mathematical representations or models. They are fashioned along the lines of how an expert would go about solving a problem, and they are designed to provide expert advice. They use a knowledge base of human expertise to aid in solving problems. The degree of problem solving is based on the quality of the data and rules obtained from the human expert. Expert systems are designed to perform at a human expert level. In practice, they will perform both well below and well above that of an individual expert. The expert system derives its answers by running the knowledge base through an inference engine, a software program that interacts with the user, and processes the results from the rules and data in the knowledge base *(FOLDOC, 2001)*.

Rule-based programming is one of the most commonly used techniques for developing expert systems. In this programming paradigm, rules are used to represent heuristics or "rules of thumb," which specify a set of actions to be performed for a given situation. A rule is composed of an *if* portion and a *then* portion as shown below:

IF [*condition*]
THEN *[set of actions to be executed*]

The *if* portion of a rule is a series of patterns that specify the facts or data, which cause the rule to be applicable. The process of matching facts to patterns is called "pattern matching." The expert system tool provides a mechanism, called the "inference engine", which automatically matches facts against patterns and determines which rules are applicable. The *if* portion of a rule can actually be thought of as the *whenever* portion of a rule since pattern matching always occurs whenever changes are made to facts. The *then* portion of a rule is the set of actions to be executed when the rule is applicable. The actions of applicable rules are executed when the inference engine is instructed to begin execution. The inference engine selects a rule and then the actions of the selected rule are executed (which may affect the list of applicable rules by adding or removing facts). The inference engine then selects another rule and executes its actions. This process continues until no applicable rules remain *(Riley, 1997).*

Main components of knowledge-based expert system are, as shown in Fig. 1 *(Sanchez et al.,1995)*:
- the knowledge base or long-time memory, which collects domain-specific information;
- the inference machine, which uses the inference rules that let the system to deduce some new conclusions from a set of premise data;
- the user interface
- the knowledge engineer interface, which can acquire knowledge not only from the user, but also from other experts;
- the auto-explanation module, that can explain the system's inference procedures;
- the strategies or control module
- on-line sensors interface.

The process of development of an expert system generally follows four basic steps as listed below:
- Determining requirements, when the objective that is wished to be achieved by the expert system should be clearly outlined
- Identifying experts and attainment of knowledge
- Constructing expert system components
- Testing, reviewing and implementing results.

## APPLICATION OF EXPERT SYSTEMS IN WASTEWATER TREATMENT

In recent years the knowledge-based systems have found practical application in many fields of engineering and management. The known examples include natural resource management, data management in forestry, petrochemical plant control, dynamic processes monitoring and control, WWTP time-series analysis and control of sun-powered systems *(Ceccaroni, 2000).* In the area of environmental management and engineering most of the expert systems used are still in the R&D stage. Example areas of expert systems applications related to environmental management are listed by *Fedra (Fedra, 1991).* Despite that there are not known major applications of expert systems in wastewater treatment, there are many attempts to apply knowledge-based systems in this area. It seems that there are three fields where such systems could be effectively applied: they are designing, diagnosis and decision support, and control. The examples of such studies and applications are briefly presented below.

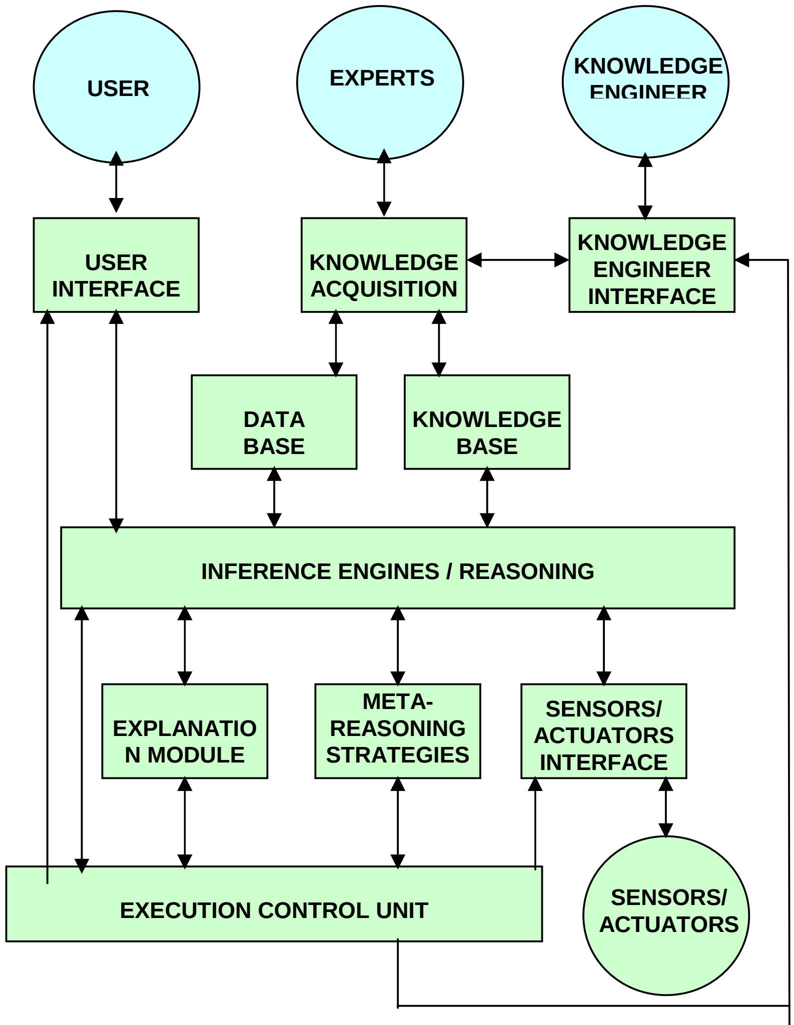


**Figure 1.** Components and interactions in knowledge-based expert system *(Sanchez et al., 1995)*

**Design systems**

Designing of WWTPs is the first place where decision support systems may find applications. Such systems may either aid the designer in making purely technological choices or to improve the organization and management of the design process.

*Sanchez et al.* in their paper *(Sanchez et al., 1995)* reviewed several applications of knowledge-based design systems in designing wastewater treatment plants. The most interesting system described there was that of *Krovvidy et al* from 1991. They proposed a two-phase approach to the design of wastewater treatment system with use of expert systems. In the first phase (analysis phase) they developed a learning system to generate knowledge rules from a treatability database and a grammar-based knowledge representation scheme to be able to generate rules for different expert systems shells. In the second phase (synthesis phase) developed two different methodologies to generate treatment train with minimum cost.

Another example of using expert system is SANEX – simple expert system software for evaluating sanitation systems in developing countries developed by *Loetscher* at the Advanced Wastewater Management Centre at the University of Queensland, Australia. This non-commercial computer program was designed to support local planners in their choices regarding the most suitable sanitation systems for their communities. Besides the technical, it also uses social, cultural and financial criteria in connection with multicriteria decision analysis techniques to assess the merits of 83 sanitation systems. The program also estimates capital and operational costs of the analyzed systems *(Loetscher, 2000).*

In the area of project management, a very interesting is the study performed by *Roda et al.* in 1999 on advantages that can be derived from the use of computer support system in designing wastewater treatment plants. In the analysis they used KBDS software, a prototype computer design support system for integrated and cooperative chemical process design, that never before was used for important application of WWTPs. The study showed how by using such a system that maintains a historical record of the design process, it is possible to: (i) rank different design proposals responding to a design problem; (ii) study the influence of changing the weight of the arguments used in the selection of the most adequate proposal; (iii) take advantage of keywords in to assist the designer in the search of specific items within the historical records; (iv) evaluate automatically the compliance of alternative design proposals with respect to the design objectives; (v) verify the validity of previous decisions after the modifications of the current constraints; (vi) re-use the design records when upgrading an existing WWTP or when designing similar facilities; (vii) generate documentation of the decision making process, and (viii) associate a variety of documents as annotations to any component in the design history *(Roda et al., 1999).*

## Decision-support systems in plant operation

The largest number of expert system application can be found in this area. A review of application of decision-support systems in WWTP´s operation was presented by *Sanchez et al*. *(Sanchez et al., 1995*). The first attempts to use the expert system rules for wastewater treatment plant operation and control were made by *Beck* and his colleagues in 1978. What they constructed was not purely an expert system, but they employed the crucial aspect of expert systems, human expertise and expert knowledge. They formulated twenty control rules and used fuzzy logic to provide qualitative interpretation of the quantitative data. In 1987 *Berthuex* and his colleagues extended *Beck*'s work and integrated the expert system to a database to provide plant operators with more powerful software package, which was supplied with wide variety of rules for unit treatment processes. The knowledge base was constructed by specifying the configuration of the plant.

A decision support system for the activated sludge process that relied on a profile of dissolved oxygen (DO) concentration along the length of the reactor as an indicator of biological activity and reactor loading was presented by *Flanagan* in 1979 and 1980 *(Sanchez et al., 1995*). The DO profile strategy was based on a mechanistic understanding of the process. Thus, in contrast to the heuristic knowledge represented in other systems previously developed, his system made use of compiled knowledge. In 1985 and 1989 *Maeda* presented a knowledge-based decision support system for WWTPs. The system gets benefit from qualitative and experienced judgment of the operator in supervisory work such as set point scheduling, plant diagnosis and maintenance *(Sanchez et al., 1995*). The architecture of the system was composed of two parts: an adaptive production system with about 100 production rules, and a multimedia user interface. He claimed that human operator will keep playing a central role in maintaining the high reliability of future biological systems and the use of the system will increase the operator's cognitive capabilities.

In 1989 a knowledge-based system for diagnosis of an activated sludge system was developed by *Gall and Patry*, which used two sources of information: literature review of wastewater treatment plant operation, and site visits and interviews with experienced plant operators. The knowledge base consisted of 169 rules and the system was tested under actual plant operating conditions. It was concluded that feedback obtained from the operators confirmed the potential benefits of expert-assisted operation of WWTPs. They also stated that the operational benefits of a knowledge-based system for the activated sludge diagnosis depend largely on the continuing contributions from plant operators. Thus the knowledge base should not be viewed as a static piece of software but should be updated on a regular basis to reflect the cumulative experience of the operators as well as the changes made to the different unit processes *(Sanchez et al., 1995*).

In 1994 *Sanchez et al*. presented the development of integrated supervisory distributed system expert system DAI-DEPUR useful for the diagnosis and management of wastewater treatment plants. The system assumes that there is a set of fixed abnormal situations such as storm, bulking, toxic load, etc. that may be treated with predefined plan or strategy. The system recognizes predefined situation that has occurred and uses the right strategy, together with knowledge about specific similar situations, which occurred at that plant in the past. If normal situation is detected then the automatic numerical control is maintained or activated. Thus there is a cooperation among classical control methods, expert control (predefined strategies), and experimental control (solved situations).

In 2000 *Ceccaroni* presented an extension of the above system called DAI-DEPUR+. It was a decision support system integrating a rule-based expert system, a case-based reasoner and an ontological knowledge base. The system was able to model the information about a wastewater treatment plant, including the micro-biological components *(Ceccaroni, 2000).*

One of the known practical applications of expert systems is Activated Sludge Advisor Prototype (ASAP), an expert system that was developed by the Dallas Central Wastewater Treatment Plant in The USA. It was designed to help its beginning operators keep the activated sludge process running smoothly. It was developed by CDM FPC's Expert Systems team, through a contract held by Camp Dresser & McKee-Dallas with the Dallas Water Utilities. The team prepared themselves for interviewing the domain expert by reading Water Pollution Control Federation Publications and wastewater operator instruction manuals to gain an understanding of the wastewater treatment. This was necessary for when interviewing the domain expert. Following this acquiring of information the team then interviewed their domain experts. After that the team assembled their notes and constructed a knowledge tree that was developed during the first session was then used when questioning the expert at the second session. Thus the final diagram ended up with six possible paths with even more branches on each path with possibility of 50 diagnoses. ASAP was set up in KnowledgeGarden's PC-based expert system shell called KnowledgePro *(Weaver,1990).*

**Control systems**

Control and supervision of WWTP operation is another area where expert systems may find practical application in near future. An example of that could be a real-time expert system designed to control wastewater treatment plants presented by *Serra et al.* in 1993. The software, developed in the G2 shell, is composed of an interface for on-line acquisition of process data using, a predictive control algorithm for dissolved oxygen concentration, graphic interface for the operator and the expert knowledge database. The dissolved oxygen control is performed using a nonlinear predictive control algorithm that has been developed to satisfy quality constraints while reducing energy demands. The algorithm uses data obtained from the plant by hardware sensors, and software, which recursively estimates the oxygen uptake rate (OUR). All these elements are integrated in a knowledge database that includes a set of diagnosis, detection, prediction and operation rules, making the system capable of handling a wide number of usual (with predictive control) and unusual (without predictive control) situations, where quantitative and qualitative information must be considered *(Sanchez et al., 1995*).

In 1999 Paraskevas et al. *(Paraskevas, 1999)* presented the integrated expert system, which supervises the control system of the whole plant. The described expert system was an extension of DAI-DEPUR system proposed by *Sanchez*. The system consists of several interacting subsystems that can be executing in parallel processing. The modules are organized in three levels: data, distributed knowledge and supervisory as shown in Fig. 2. Data level receives the information from the plant and is organized in three modules: numerical knowledge module, which contain IAWPRC No.1 activated sludge model, wastewater line module which supervises wastewater treatment processes, and sludge line module, which supervises sludge treatment processes. Distributed knowledge level contains general process knowledge obtained from literature and from interviews with experienced process engineers. Supervisory level manages the whole control system and communicates with the operator through the user interface. The system has the capability to learn from the correct or wrong solutions applied in the past. The history of such cases is stored in the case library. In all cases the supervisory module reaches to its own conclusion about the action to be taken, but it is the human operator, who decides what course of action will be taken.

## SUMMARY

Knowledge-based decision support systems are certainly a new and intriguing development in computer science and there are many hopes for their better applications in many fields, including environmental engineering and management. Wastewater treatment is certainly a field where such applications could bring significant improvement in process efficiency, decrease the risk of process failure, and lower capital and operational costs. Obviously, expert systems could support selection and decision-making process already at the stage of plant designing and process selection, and such attempts have been already undertaken as it was described in this paper. Most applications of expert system in wastewater treatment are usually associated with supporting every-day decisions made by WWTPs' operators. The expert system maintains a database of knowledge about the processes and a specific plant, and usually keeps record of various abnormal situations, which occurred at the plant in the past. Using this knowledge and certain inference rules, it is able to suggest the operator proper solution to a problem, which has emerged. The most advanced application of expert systems is continuous control of the plant, with data gathered through the on-line sensors. However, this type of expert system application is still in the research phase.

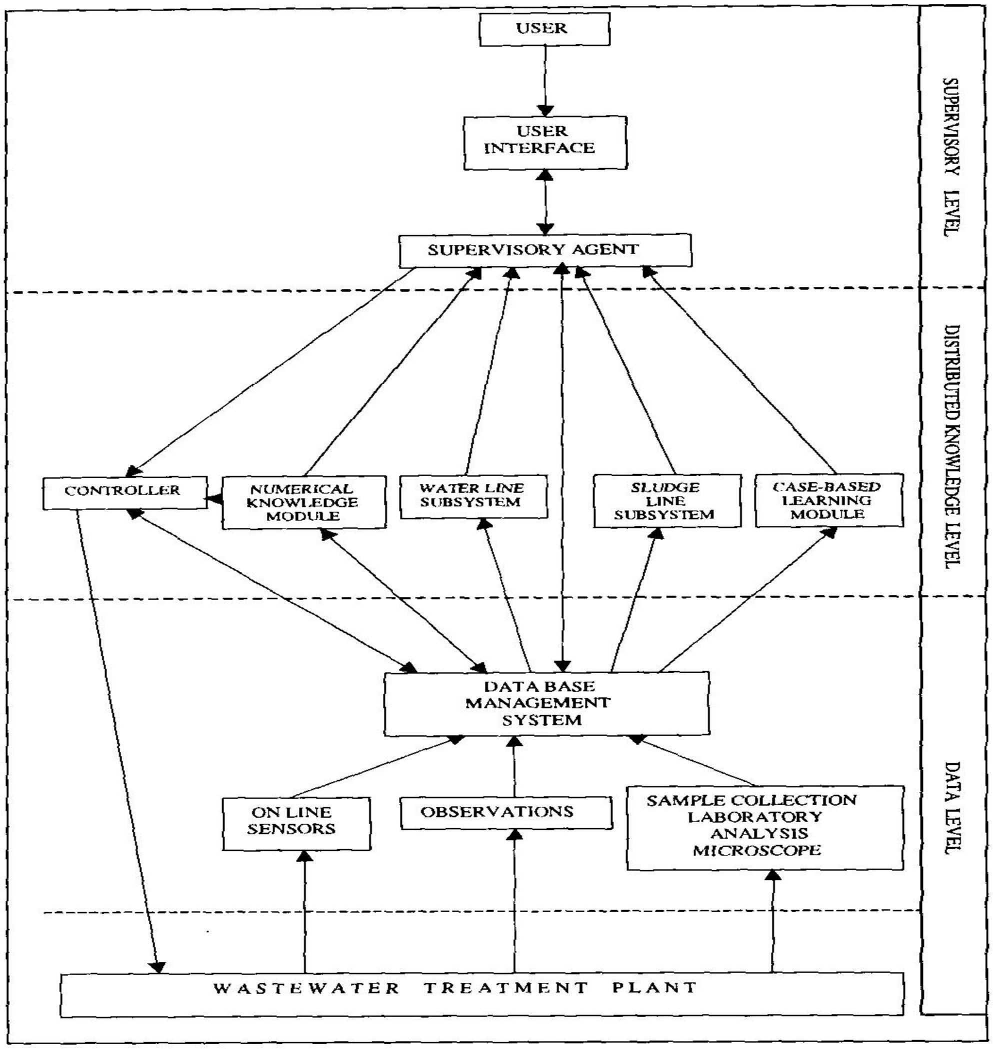


**Figure 2.** Structure of the integrated distributed expert system *(Paraskevas et al., 1999)*

Expert systems, like any other method, do not offer universal solutions and require a thorough understanding of their requirements and limitations. They are not and they certainly will not be a substitution for humans designers and operators with their knowledge and experience. They will not substitute existing models, simulation programs and time-tested methods either. Expert systems should be seen as complementary techniques, which can improve plant designing, operation and control. While pure knowledge-based expert systems will find many applications in classification and diagnosis tasks, most of their application will require that they were coupled with simulation programs and embedded within hybrid systems, which can collect and process data, perform simulations, and undertake proper action or present reliable advice to a human.

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