Towards an integrated software environment for monitoring activated sludge plants

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This paper briefly describes an approach towards the development of a complete software environment proposed for monitoring activated sludge plants that employ minimal automatic control. The environment is essentially a toolbox where an expert system, a database tool plus a simulation-modeling program, are all integrated in one conceptual framework. During the last decade major advances were achieved in control systems employed in activated sludge plants developed in Europe, North America and Japan. However, this required a large commitment of time and budget as well as specialized expertise to handle sophisticated equipment and proved to be economically infeasible under some circumstances. The proposed environment provides an alternative that can enable plant operators take decisions with confidence in results. First the paper refers to the unique nature of activated sludge systems and presents the environment's architecture briefly describing its already developed components. Second it outlines the stages of the simulator's development procedure, where its requirements, basic modules, future enhancements and a recommended technique for implementation are discussed. Finally the paper concludes that improved treatment quality can be met by employing computer systems that provide more and rapid information about the process state and doesn't necessarily require increasing treatment complexity.

يقدم هذا البحث وصفا لعملية تطوير برنامج متكامل للمراقبة و التحكم في محطات الحمأة المنشطة التي تعتمد على الحد الأدنى من نظم التحكم الآلي. هذا البرنامج المتكامل يتكون أساسا من ثلاثة برامج تحتية هي:برنامج للنظام الخبير وبرنامج لقاعدة البيانات وبرنامج للنمذجة الرياضية والمحاكاة. هذه البرامج الثلاثة تعمل تحت إطار واحد من البرنامج المتكامل الرئيسي. السبب المباشر لتطوير هذا البرنامج انه خلال السنوات العشر الأخيرة حدث تطور كبير في نظم التحكم في محطات الحمأة المنشطة خاصة في الولايات المتحدة و أوروبا واليابان ولكن للأسف هذه النظم الحديثة للتحكم تحتاج إلى ميزانيات ضخمة وكذلك إلى خبراء متخصصين لاستخدام هذه النظم المعقدة وهذا غير متاح لعدد كبير من الدول وخاصة الدول النامية. وعليه فان البرنامج المقترح يقدم الحل البديل المناسب و الذي يمكن من خلاله مساعدة مشغلي هذه المحطات لاتخاذ الإجراءات السليمة أثناء التشغيل. هذا البحث في البداية يقدم وصفا لمكونات البرنامج ثم يقدم بعد ذلك وصفا تفصيليا لمراحل تطوير برنامج المحاكاة وهي المرحلة الأصعب وفي النهاية يستعرض البحث أهمية استخدام البرنامج وتطبيقاته.

Keywords: Wastewater treatment, Activated sludge, Simulation modeling, Expert systems, Knowledge-based systems

1. Unique characteristics of the activated sludge process

The activated sludge process is a biological unit process that is extensively used for secondary wastewater treatment for its high performance effluent. However, it has the reputation of being difficult to operate due to its unique characteristics [1]. This process is actually a complex sequence of interdependent biological, physical and chemical processes subjected to *time varying* hydraulic and organic load conditions. Its main action depends on live microorganisms especially bacteria, to degrade the organic content of raw sewage and convert it to an effluent that can be discharged to a receiving water body without being detrimental to the environment. Site-specific nature governs the process, such that for each plant, there exist specific conditions and characteristics related to its initial design and mode of operation as well as specific problems that can be mostly critical for that plant in particular [2-4]. Due to variability of influent flow rate, organic load and suspended solids concentration, wide variations in effluent quality are features of most plants [5]. The exact situation of the plant can be any one of several possibilities ranging from normal operation to bulking, foaming, rising sludge, overloading, over-aeration, surging, bad wasting etc. [4].

In addition it was found that operational practice sometimes causes serious problems to the process [6]. As a result human experience is a fundamental factor to successfully monitor a plant. Skillful operators tend to develop an understanding of how to monitor their plants and to successfully handle emergency situations by taking advantage of mere observations related to visual and physical indicators such as color, foam and odor [2]. Then as their experiences grow, they get to know when the plant is in an actual need of corrective measures and when it is best to leave what seems to be a problematic situation pass with no interference [7].

During the last decade, as a result of major advances in computer technology and present infrastructure of wastewater treatment plants that might accommodate more complicated functions, the technical literature reflected a change of emphasis from design towards the operational control of activated sludge plants. However, despite the development of advanced control systems, still the complete control of the process is not yet solved because of the complexity and number of factors involved, the strongly nonlinear characteristics of the process, lack of reliable sensors for on-line measurement and current mathematical models that still cannot accurately describe process dynamics as should be, and that naturally cannot incorporate qualitative data [4, 8]. Also out of pure economic reasons it becomes sometimes difficult to introduce advanced control systems especially as these systems are expensive and wastewater treatment is considered to be a non-profitable project. Thus on a general basis, traditional control strategies are usually applied to achieve a prefixed level of effluent quality at the outlet and under normal conditions (conditions closest to the design) these plants usually work well [2, 3].

Similarly in conditions of tight budgets a suitable alternative to handle the complexities involved could be to condense all the knowledge and experience about the treatment of the process in an easy to use expert system that should be connected to all possible sources of readily available data whether instruments, analytical tests or visual observations [6].

In agreement with this view, this paper presents the architecture of a software environment that can be used in plants that employ minimal automatic control to satisfy the demand for rapid and adequate information about the plant's state. The idea is to put together a toolbox of computer system tools such as an expert system, a model-based simulator and a database system and provide the user with an easy access to all these tools without demanding any special computer skills. The paper explores the role of the toolbox's individual components, as well as the benefits of their integration. It starts by briefly describing the expert system, which is already developed and validated before it concentrates on the remaining stages necessary to develop the simulation program.

2. Architecture of the proposed software environment

Ref. [9] documents the stages of development and validation of the environment's expert system component, which is called the Activated Sludge Expert (ASExpert). ASExpert is mainly a rule-based expert system fully integrated to a complete database tool. It is meant to help inexperienced operators better diagnose operating conditions and as a result select appropriate control actions. Then to test the validity of the advice given by the expert system especially as it may include the execution of a specific control action, ref. [9] recommended the need to integrate a simulation-modeling tool to ASExpert. This way simulation runs can be used to predict future dynamic changes and if the expert system's advice isn't found satisfactory it can be discarded. In such a case simulations should be iterated until convenient results are reached and the means to achieve these results are defined. This extension agrees with the trend of incorporating both expert systems and mathematical models in more advanced systems [6] or software environments. Fig. 1

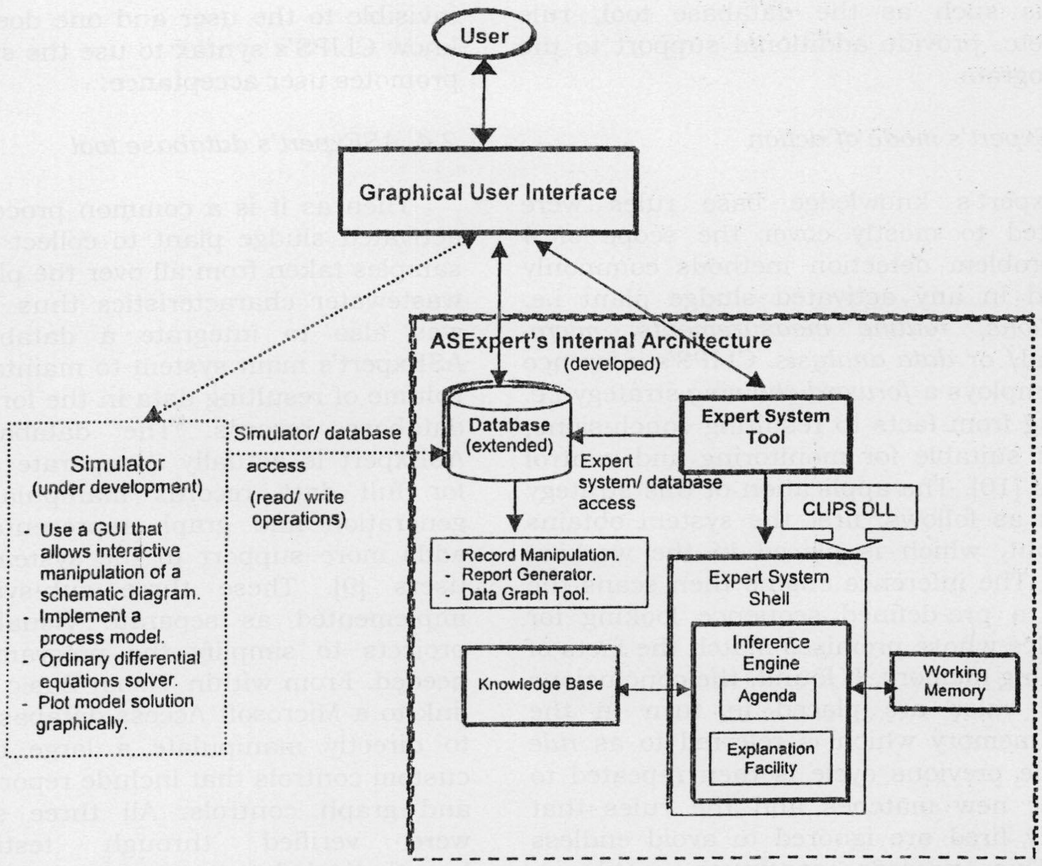

Fig. 1. The Architecture of the software environment proposed for use in activated sludge plants.

represents the complete architecture of the proposed environment where a well-designed Graphical User Interface (GUI) is the means of user interaction with essential components:

1. The readily available component or system ASExpert.
- The expert system tool.
- The database tool (record manipulation, report generation and graph representation sub-systems).

2. The proposed simulation-modeling program with additional database files specifically designed to process simulations data.

2.1. A brief description of ASExpert

ASExpert's internal architecture is made up of several elements. Typical to any other expert system the *knowledge base* and *inference engine* are the system's main building blocks. First the *knowledge base* is the system's repository of domain knowledge coded in the form of rules. *Rules* take the form of (If-Then) associations *i.e.* two-part conditional statements that represent heuristics or rules of thumb. The antecedent expresses a situation or a premise while the consequent states a particular action or conclusion that applies if the situation or premise is true. Second the *Inference engine* is the system's control mechanism that makes inferences and decides which rules are satisfied by facts, prioritizes the satisfied rules on a list called the *(Agenda)* and then executes the rule with the highest priority. The *working memory* works in harmony with the inference engine to model human short-term memory. It contains the facts of the current situation whether entered through user input or inferred as a result of rules firing. Finally the inference engine can also be programmed to provide the explanations behind the system's reasoning which is usually achieved through the *explanation facility* block. Other external programs such as the database tool, rule editors etc. provide additional support to the main program.

2.2. ASExpert's mode of action

ASExpert's knowledge base rules were formulated to mostly cover the scope of 4 major problem detection methods commonly employed in any activated sludge plant i.e. *observations*, *routine measurements*, *microscope* and/ or *data analysis*. CLIPS's inference engine employs a *forward-chaining* strategy *i.e.* reasoning from facts to resulting conclusions, which is suitable for monitoring and control problems [10]. The application of this strategy proceeds as follows; first the system obtains user input, which is placed in the working memory. The inference engine then scans the rules in a pre-defined sequence looking for those rules whose premises match the facts of the working memory. If found, the conclusions of those rules are placed in turn in the working memory which is referred to as *rule firing*. The previous cycle is then repeated to check for new matches and the rules that previously fired are ignored to avoid endless loops. This process continues until no matches are found [10]. ASExpert's mode of action is to direct the contents of the working memory or the conclusions to a separate text file for the user to view or print the system's advice in a convenient way [9].

2.3. ASExpert's implementation technique

ASExpert was implemented using the 32 bits Dynamic Link Library (DLL) of the C Language Integrated Production System (CLIPS) expert system shell version 6.05 that was integrated to a Microsoft Visual C++ 5.0 interface. CLIPS was developed in 1985 by the artificial intelligence section of NASA and has been maintained since then. It is currently used throughout all NASA sites, universities and many companies [11]. A DLL of CLIPS is also available and can be embedded within other Windows applications [11]. This technique of using CLIPS's DLL adds all the needed expert system functionality to ASExpert's customized interface and hides all manipulation details [9]. CLIPS become invisible to the user and one doesn't need to know CLIPS's syntax to use the system which promotes user acceptance.

2.4. ASExpert's database tool

Then as it is a common procedure in any activated sludge plant to collect and analyze samples taken from all over the plant to check wastewater characteristics thus the decision was also to integrate a database tool to ASExpert's main system to maintain the large volume of resulting data in the form of reliable database records. The database tool of ASExpert is actually 3 separate sub-systems for full data records manipulation, report generation and graph representation which adds more support to the system's potential users [9]. These three sub-systems were implemented as separate Visual Basic 5.0 projects to simplify the programming effort needed. From within Visual Basic it is easy to link to a Microsoft Access database as well as to directly manipulate a large collection of custom controls that include report generation and graph controls. All three sub-systems were verified through testing using hypothetical data to ensure their correctness and validity of output [9].

2.5. Expert system/ database interface

ASExpert's expert system and database integrate to achieve some form of an intelligent database. Thus the expert system can access database files, fetch a specific data record and as a result arrive at a conclusion based on the values of this record's fields [9]. This powerful aspect of ASExpert is achieved through *CLIPS Open Database Connectivity (ODBC) support.* ODBC is a Windows Structured Query Language (SQL) standard interface for communicating with relational database systems. The CLIPS ODBC support function -included in CLIPS DLL- let us issue a SQL query against an ODBC data source or ASExpert's, database files created using Microsoft Access 7.0. As a result the rows matching the query will be fetched and asserted as facts into the calling CLIPS program fact-list (12). Depending on the facts asserted certain rules in ASExpert's knowledge base might be activated and executed. In such a case the conclusions made by ASExpert are actually triggered according to the current values fetched from the database [9].

2.6. ASExpert's GUI extensions

To enhance performance and promote user acceptance a simple built-in rule editor and an on-line help component are included. The rule editor facilitates the addition of new rules to the knowledge base as more knowledge is acquired. Whereas the on-line help provides assistance while using ASExpert and facilitates self-training [9].

2.7. ASExpert's validation

ASExpert was tested using a functional set of 47 trial cases that cover the most common trouble-shooting situations likely to take place in any activated sludge plant and initial results gave a promising indication of success [9].

2.8. The proposed simulation modeling extension

The simulation-modeling extension is essentially a program that implements a model of the process. It is a powerful tool that can provide a deep insight into the internal workings of a physical system because an appropriate model can predict how the actual system reacts under various conditions. In this context the simulator represents the activated sludge system mathematically using Ordinary Differential Equations (ODEs) and then solves this set of equations (or the present model) programmatically to provide the user with results that can also be presented in a graphical form. Generally it is useful to connect simulators of large systems with database systems to properly manipulate the data needed to run simulations and to save results as well.

ASExpert system is fully discussed in ref. [9], thus the remaining of this paper will concentrate mainly on discussing the steps necessary to develop the simulation-modeling program *(simulator)* and on exploring future directions.

2.9. An outline of a three-stage plan for the development of the simulator

The development of an activated sludge system simulator is not an easy task due to the complexity of the models used. Thus to overcome some of the difficulties involved the decision is to follow a modular approach where the task requirements are partitioned into several well-defined stages. In a similar way to what was adopted during ASExpert's development the simulator's development procedure is organized into three separate stages:

- *Stage 1 the development of the simulator.* This stage is concerned with the basic functions of the simulator: GUI development, implementing a specific model of the activated sludge process, solving the model and providing results in a graphical form.
- *Stage 2 improving the simulator.* This stage is concerned with the advanced functions of the simulator. Stage 2 would be dedicated to improving the simulator's capabilities by extending the number of implemented models and studying the possibility of accommodating more than one flow scheme within the same application.
- *Stage 3 establishing means of integration.* This stage is concerned with future enhancements and attempts to increase the overall intelligence of the environment, through the implementation of promising inter-system relationships that may be initiated between individual components. Thus a direct interface between the simulator and database will be established to automate all data manipulation processes (read from/ write to database files). However it is not apparent at the present whether an interface can be implemented to let the expert system directly trigger the simulator and whether this capability would be of any specific advantage.

Fig. 2 depicts the stepped approach adopted during the environment's development and the tasks assigned to each stage that will be further clarified later on in the paper.

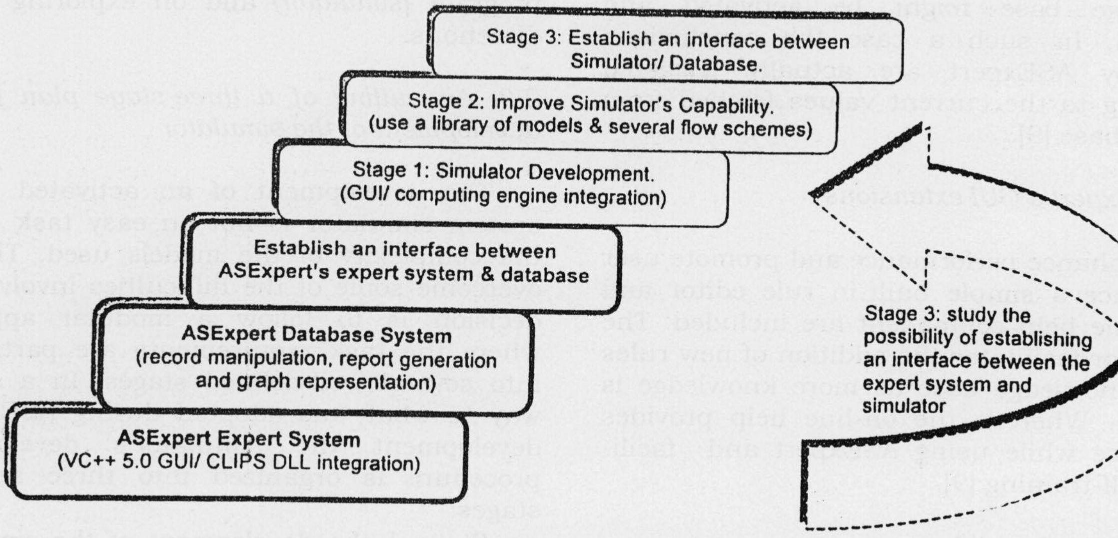

Fig. 2. A stepped procedure for the environment's development.

3. The identification of stage 1 task requirements

To take full advantage of such a simulation-modeling tool, a proper knowledge of both the system to be modeled as well as the simulation technique used is required. Thus it is necessary here to briefly review the main characteristics of current activated sludge models in order to clarify the simulator's requirements.

3.1. Characteristics of current activated sludge models

In order to adequately describe an activated sludge process a large number of phenomena have to be taken into consideration such as: characterization of the influent, hydraulics of each tank, hydrolysis of different substrates of the influent, carbonaceous, nitrogenous and phosphorous removal mechanisms, organism growth and decay and sludge clarification and thickening mechanisms [13]. Influent wastewater is characterized not only by its composition in organic carbon, nitrogen and phosphorous fractions but also in soluble, particulate, biodegradable and unbiodegradable fractions. Organisms are represented by at least one class of hetertrophs and one or two species of nitrogen consuming autotrophs. Then the main reactions are added for each class of organisms and each class of available substrate [13].

Many models have been presented; however the IAWQ model no. 1 -since it was proposed in 1986- has become the standard by which other models are assessed. It is a dynamic model that focuses on a single unit process -the aeration basin in an activated sludge system- to describe the reactions that lead to carbon and nitrogen removal. It ignores the effects of sedimentation and treats the settling tanks as perfect splitters. It uses COD as the measure of concentrations of organic material in wastewater [14, 15]. Later on, more advanced models were presented that started to include phosphorus removal or sludge bulking [15].

Most growth models also share the basic assumptions of IAWQ's model no.1 where the reaction mechanisms are modeled by non-linear Monod-type equations or by simple extensions of these equations. The bi-substrate model and death regeneration hypotheses are used to describe biological growth of biomass, hydrolysis and decay [15, 16]. Accordingly two fractions of biodegradable organic matter in influent wastewater are adopted: readily and slowly biodegradable COD. Then when microorganisms die, decayed cell material is recycled to the process as a slowly biodegradable COD that could then be used by the remaining microorganisms as substrate through hydrolysis. Whereas the non-biodegradable fraction remains as an inert residue. In a similar way the transformations of nitrogen can be described by the death regeneration hypothesis [15, 16].

Then, based on mass balance equations these models relate changes of the state of the system (concentrations of model components) to transport and transformation processes. Transport processes are characteristic for the design of a system (reactor configuration, distribution of influent, excess sludge removal, etc.) and leave the chemical structure of all materials unchanged. On the other hand transformation processes involve the change of the chemical structure of the components [17]. For each of these transformation processes the model quantifies both the kinetics and stoichiometry of model components or state variables. Typically the number of states varies between ten and fifteen for each completely mixed reactor for models described in the literature. IAWQ model no. 2 which adds the dynamics of phosphorous removal contains 19 states for each completely mixed reactor [13]. Thus for each of these states (components) the rate of accumulation within a system boundary (a completely mixed reactor) can be calculated as follows:

Rate of accumulation = Rate of Input – Rate of Output + Rate of production by reaction (ri),

where ri is the result of the conversion of component *i* due to its involvement in several processes. Traditionally the calculation of ri has been simplified through model representation in matrix format that defines fundamental reactions [17]. Matrices not only represent a convenient way to store data and complex relationships but most importantly matrices can be easily manipulated by computers [18].

3.2. *Modeling of a reactor and model solution via numerical integration*

Performing a *separate* mass balance over each reactor for each model component and adding the input/ output terms, results in a set of non-linear ODEs of the form:

$$dZ/dt = Q/V\,(Zin - Z) + rz.$$

Z represents the concentration of a specific component inside the reactor. Zin is the concentration of the same component in the water incoming to the reactor. Q, V and ***rz*** represent the flow rate, the reactor's volume and the rate of production by reaction of component Z [19] respectively. These ODEs define the system state and when solved characterize its behavior.

In a similar way if the reactor is divided to separate anoxic and aerobic zones, each zone will be treated as a separate unit with its own characteristics such as volume, flows and process constants [19].

The set of non-linear ODEs comprising the model are usually very complex and can't be solved analytically. Therefore numerical integration techniques based on Euler and the classical 4th order Runge-Kutta methods [18] are adopted for model solution.

3.3. *Modules of the basic activated sludge simulator*

After the determination of a specific model to be simulated, the steps necessary to accomplish the simulation process can be summarized in the following main modules [17]:

1. Definition of influent concentrations specific for the model to be simulated and the present flow scheme with relevant flow rates (number of reactors, re-circulations, solids separation etc.).
2. Setting up mass balance equations for each component in each reactor.
3. Determination of the initial conditions as well as the desired integration period required to integrate the ODEs forward in time.
4. Calling the program's embedded numerical integration solver to perform the required simulations.
5. Using a convenient GUI to facilitate graphical presentation of predicted results and interactive application of the program.

These modules determine the essential features of any basic activated sludge simulator and act as the broad guidelines that will apply during the development of the proposed simulator.

4. Main features of the proposed simulator

4.1. The simulator's intended role

Similarly the proposed simulator is required to be capable of simulating a complex ODEs system as well as representing results graphically in a convenient way. In addition, the simulator's unique characteristics as a *standalone* application demand further requirements that are expressed in the following points:

1. GUI requirements. The simulator should employ a customized GUI that allows representing a hypothetical real activated sludge plant graphically on the monitor's screen as well as interactive manipulation of this schematic diagram. This provides the user -through simple mouse clicks- with the versatility to customize the plant's modes of operation and control *-to some permissible extent-* according to his desire and to set the simulation start-up conditions and conduct "what if" investigations to inspect the effect of different operating conditions or throughputs etc. Fig. 3 represents a typical activated sludge scheme where the reactor is divided to several zones that can be switched between aerobic and anoxic modes to represent a plant capable of performing oxidation of organic matter, nitrification and denitrification. The user can switch process modes of operation between (post-denitrification/ pre-denitrifaction) and modes of control (e.g. from a fixed excess sludge flow to a fixed sludge age mode). In such cases the plant's schematic diagram should be redrawn on the screen immediately to reflect these modifications (highlight active pumps, dim inactive pumps, show air bubbles in aerobic zones and remove air bubbles from anoxic ones etc.). Similarly upon user request dialog boxes should appear to enable the user view and modify -if need be- influent concentrations, flow rates, zone volumes, default values of the initial conditions (state variables) and model parameters etc.
2. Secondly to extend the present database files with new files capable of providing data necessary to start simulations and save results for any future use.
3. Future major enhancements: to make the simulator more general purpose i.e. not limited to a specific model or flow scheme. This capability requires the implementation of Several IAWQ models as well as several flow schemes of the process in the same application. Thus creating a library of models where IAWQ models no. 1,2,3 and reduced order models as well as settler models of different complexities for the clarification and thickening zones can be simulated and results compared which broadens the chance of using the simulator for educational and research purposes. Similarly if several flow schemes

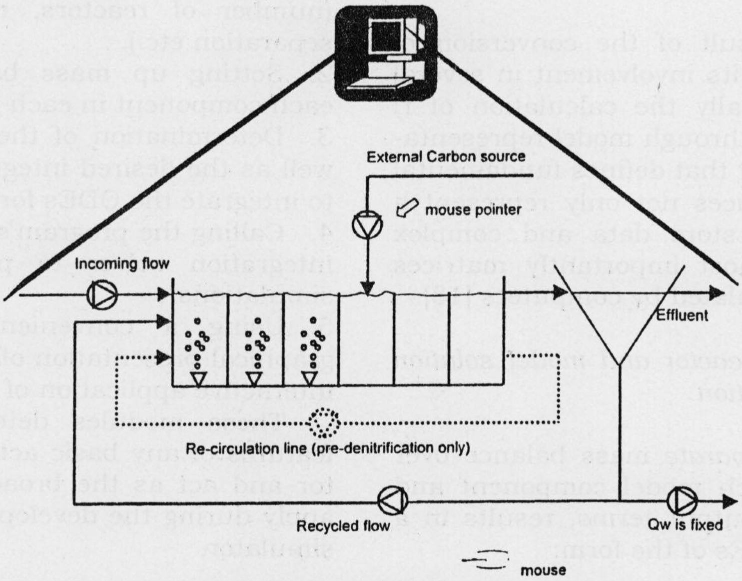

Fig. 3. A typical activated sludge flow scheme.

can be investigated in one application, this gives the user a chance to evaluate a set of different case studies, which can be very useful for design purposes.

4.2. Main flow of the proposed simulator

The block diagram of fig. 4 describes the main flow of the proposed simulator. The simulation process is of an iterative nature till satisfactory results are achieved. Interactive application of the simulator is emphasized to flexibly start new simulations with new data upon user request. As an option the user can use data fetched from database records to start the simulation process. In such a case this data will be presented to the user at startup instead of the already built-in startup values. It is important here to note that the simulated model as well as the ODEs solver are both handled as separate programming modules separated from the rest of the program. This facilitates to a great extent the implementation of more models within the same application as well as the capability to call different numerical integration routines to simulate the same model upon user request.

4.3. The proposed implementation technique.

To satisfy the needs of a customized GUI as well as the computational capabilities of an ODEs solver, a recommended implementation technique is to use two separate implementation tools such that the tool most suitable to handle the respective requirement can be used. Thus similar to the successful technique used within ASExpert, where VC++/ CLIPS integration is employed [9], the simulator's GUI can be developed using a powerful general purpose programming language, then the GUI can be linked to the computational engine of Matlab which is a recognized world wide powerful environment dedicated for scientific computations and graphical representations.

4.4. Suitable programming languages for the implementation of the interface

Thus the decision is not to use a dedicated simulation language e.g. Simnon, instead programming languages like VC++ or Java are more suited for the implementation of a real world interface. However the initial decision is to prefer using Java for the following reasons:

- Although Java may be considered as the number 1 language of choice for Internet applications, still the power of Java is not limited to web applications only. It is has full programming features and can be used to develop standalone applications. Java is inherently object oriented and has now replaced C++ as the dominant software development language [20]. Although it is modeled after C++, Java is much simpler to use while pertaining even better capabilities than C++ [20].
- Java contains a broad set of predefined classes and methods including a rich set of GUI components that handle most of the fundamental requirements of programs, which makes it easier and faster to use [20, 21].
- Multithreading -the capability to run multiple tasks simultaneously in one program- is smoothly integrated to Java [20]. Java programs can be created with multiple threads of execution to handle several tasks at the same time. This provides more productivity to the end user and satisfies the needs of a responsive user interface.
- Despite being an interpreted language Java has a relatively high performance. The speed of Java is completely sufficient to handle most real time interactive applications [19, 20].
- There is currently an enormous worldwide interest in Java and a near universal agreement that Java is the next generation programming language *i.e.* Java is a hot topic.
- In addition there is a lot of powerful Java Integrated Development Environments (IDEs) on the market that speed up coding, debugging and facilitate the development process to a great extent by freeing the developer from time-consuming tasks thus enabling him to focus on providing the real solutions.

4.5. Reasons for choosing Matlab

Ref. [19] pointed out the possibility to write computationally demanding differential equa-

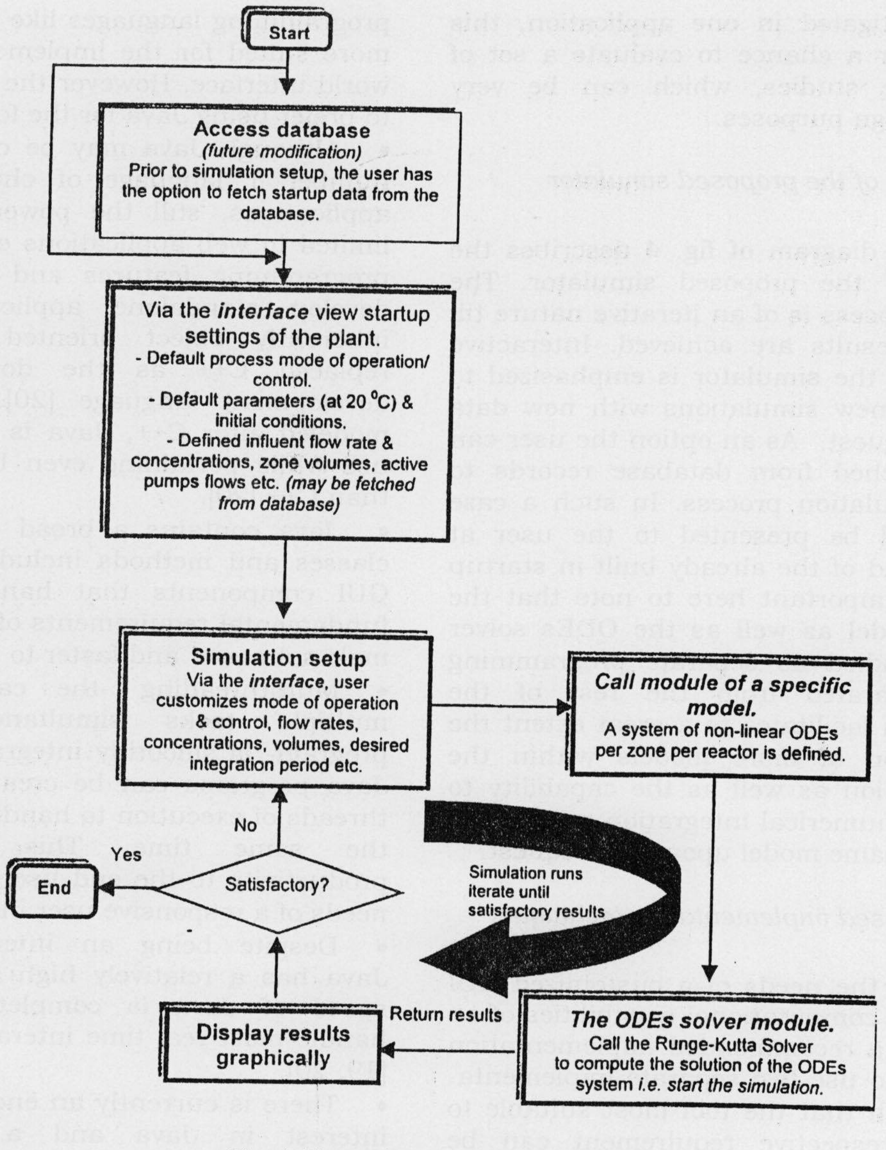

Fig. 4. The main flow of the simulator.

tion solvers completely in Java. However to cut development time the decision is to use Matlab's built-in ODEs solvers. Matlab provides easy access to a whole suite of programs for solving ODEs and some of these are based on explicit Runge-Kutta methods that can efficiently and conveniently solve initial value problems [22] typical to the present activated sludge system. Also using Matlab provides a chance to explore some of the capabilities of *Simulink* -Matlab's integrated simulation toolbox- for real time graphical representation of simulation results. Finally it has to be noted here that although Matlab can be used for GUI implementation the decision was against using it, because the real-time update of a complex interface would be too time-consuming in such a case.

5. Conclusions

When dealing with a biological system the key to success, is not necessarily to adopt the highest level of technology but just an adequate level linked to an effective system capable of providing rapid access to information about the system's state in a visual, easy to grasp graphical form.

Appropriate information sources that should be integrated to such a system are primarily expert systems and mathematical models. A simple expert system can store all the experience in the operation of the treatment plant and can thus provide guidance and advice to plant operators whenever qualitative data is involved. On the other hand model simulations allow the operator to be aware of problems on the plant before becoming too serious to deal with. Also simulations let the operator visualize the results of his actions beforehand, which makes him take decisions with more confidence in the outcome. Further the presence of such easy to use information sources will encourage operators to use both the expert system and the simulation program on a regular basis. This puts operators on a sort of a continuing training program that will essentially leverage their skills. Finally the integration of several powerful tools in one environment would yield the ultimate software tool that could be a feasible alternative for not employing expensive levels of sophisticated technology to monitor plants.

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