An Intelligent Visualization and Decision Support System for Decentralized Wastewater Treatment Plants

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Abstract
Current sanitation concepts of decentralized wastewater treatment and reuse raise the issue of monitoring and maintenance of such systems. To guarantee a high quality of the recycled water, systems with high requirements concerning process technology are essential. With increasing numbers of decentralized treatment systems spread over far distances it will become more and more impossible and uneconomic to have expert personnel on site. Therefore new visualisation and intelligent information systems are necessary. The paper describes the structure and 3D-demonstrations as a base for information visualisation. Up-to-date visualization techniques, facilitating the cognition of context-adapted information, make it possible to maximize the amount of information presented to the user without overwhelming her or him. Concerning diagnosis and decision support systems in the domain of wastewater treatment several interesting approaches are presented, estimating their applicability for decentralized wastewater treatment systems. The intelligent decision support system presented here consists of a combined ontology- and case-based reasoning system in addition to a process monitoring system. It is responsible for plausibility checks, error diagnosis, solution proposal, and optimization suggestions.

Keywords
Decentralized sanitation and reuse; Decision support system; Reasoning; Remote monitoring; Information Visualization

INTRODUCTION

For more than a century, western industrialized nations have based their sanitation (water supply and wastewater treatment and disposal) on very costly centralized “end-of-pipe”- concepts with high water consumption. Due to the limited availability of (drinking) water, these sanitation concepts are not feasible for arid and semi-arid regions. Instead, well-adapted and sustainable systems need to be developed to solve water deficit and wastewater problems. One closed-loop approach is to separate different fractions of municipal wastewater depending on different characteristics (quality and quantity), recycle it in decentralized plants and reuse the water and nutrients at the point of origin. To reach a high quality of the recycled water (in particular cases up to drinking water quality) systems with high requirements concerning process technology are essential. These systems are based upon several biological, chemical, physical and technical functional entities which interact with each other. To give some examples for applicable process technology membrane bioreactors (MBRs) with ultrafiltration membranes, activated-carbon filters, reverse osmosis (RO) and systems for advanced oxidation could be mentioned.

Thus operators (experts supervising from afar and the staff onsite) of those complex decentralized systems are faced with a diversity of predominantly unstructured data, which has to be transformed into useable information to characterize and operate the complex treatment plant efficiently and safely.

Furthermore it is impossible to run these decentralized plants by experts onsite. Therefore, non-experts e.g. the janitor of the hotel should be able to use the system. As a result it won't be possible for the expert to take appropriate action by hand whereas a janitor probably won't have the required specialized knowledge to do so. To close this gap it is necessary to develop a tool which on the one hand enables the expert to supervise multiple systems from afar optimizing their processes and analysing critical operating conditions and on the other hand provides the staff on site with adequately processed information like maintenance guidance or basic process information to perform their duties efficiently and securely.

One approach to solve the problems mentioned above is the development of an Intelligent Information System which is context sensitive, i.e. it proactively adapts the provided information depending on user context (expert, learning employee, interested guest), task context (observation, maintenance, optimization) and device context (mobile, desktop). The idea and development of such a system is described in this paper.

In addition to the information visualisation a sophisticated diagnosis system is necessary to support the operator, optimize the process and anticipate critical operation conditions of the plant.

The intelligent decision support system presented here consists of a combined ontology- and case-based reasoning system in addition to a process monitoring system. It is responsible for plausibility checks, error diagnosis, solution proposal, and optimization suggestions.

Although developed for a specific wastewater treatment and water recycle system – namely the KOMPLETT-System - the Intelligent Visualization and Diagnosis System presented in this paper is designed to be as open and adjustable as possible so that it could be adapted to almost every other treatment process if desired or necessary.

REQUIREMENTS

In order to adequately support the staff of treatment plants, a maximum of information is needed to fulfil a task or understand a problem. This information should be transported efficiently without overwhelming the user. Such a system may include motion parallax depth clues and multiple perspective views which facilitate the insight in context-adapted information presented to the operator. The additional possibility of using mobile devices enables the operator to access all the features described in this paper even during work outside or close to the machine he actually maintains.

The following requirements for an Intelligent Visualisation and Decision Support System can be recapitulated from the conceptual formulation in the introduction:

- the system has to be able to organise large amounts of heterogeneous date, like online and offline process data, external expert knowledge or descriptions and maintenance instructions of the plant;
- it has to visually indicate trends and irregular behaviour of quantitative data, e.g. process parameters;
- semantic relations between qualitative data, e.g. data about the technical processes or the physical layout of the plant and textual data like the documentation of the plant and its components have to be visualized;
- the system has to be user-, task- and device-context sensitive, i.e. diverse users (from experts to newcomers) working on different tasks (from process optimization to plant maintenance) with various devices (e.g. the PC in a distant bureau, a PDA or even a mobile phone) have to get all the information they need in the right presentation to be able to do their jobs effectively and securely.

After describing the state of the art in industrial process visualization and information visualization details about meeting these requirements are presented.

STATE OF THE ART OF SCIENCE AND TECHNOLOGY

Process and Information Visualization

The most obvious difference between the system presented in this paper and current process information systems will be the way of presenting the information to the user. In this section conventional process and information visualization techniques will be described.

Most current industrial process visualization systems like e.g. SIMANTIC WinCC (Siemens) or FactorySuite InTouch (Wonderware) provide a fixed number of static process views containing some animated elements like colour changing symbols and value displays to indicate the state of the plant (Fig.1). Depending on the competence and the preferences of the responsible programmer the quality and consequently the information content of those views may vary from minimalist to overcrowded, unintuitive and unergonomic (in various combinations).

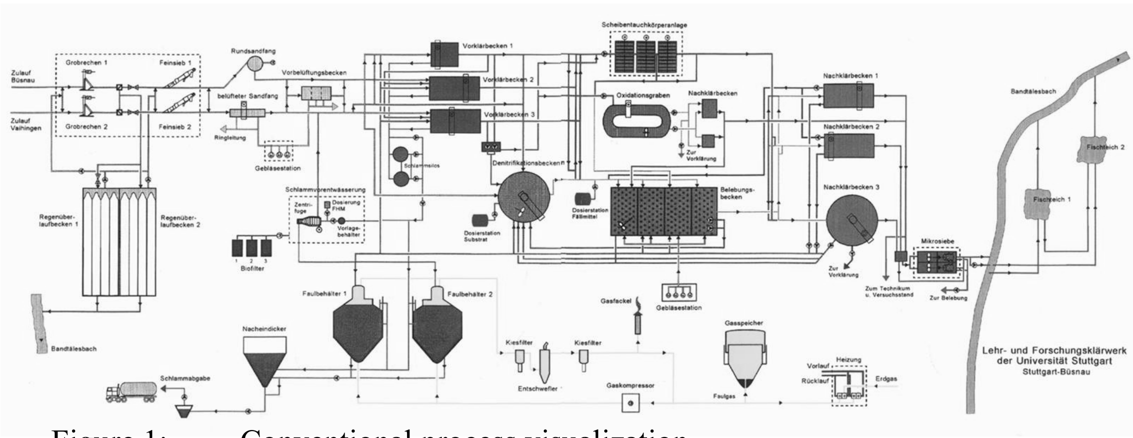

Figure 1: Conventional process visualization

Matkovic et al. (2000) presented some 2D widgets for displaying values in 2D process visualizations like bar- and gauge instruments.

Considering the requirement of non-static process visualization, semantic formalisms for modelling processes have to be used. A complex approach to this problem has been proposed by Estublier et al. (1997). Providing diverse semantic views on the data like control flow, data flow and state diagrams the process is modelled with the help of a graphical editor.

When considering the requirement of multi-perspective visualization, not only the process visualization but also the visualization of the physical layout of the plant has to be addressed. Agrawala et al. (2003) described an approach for visually explaining the construction of 3D objects with the help of explosion views. But such techniques are normally not used to visualize the system of treatment plants.

Besides the Process Visualization approaches mentioned above there is some previous research in the area of Information Visualization which is relevant to this work.

Two-dimensional as well as three-dimensional environments are used to visualize information. Storey et al. (2001) developed Jambalaya, a 2D ontology viewer originally used for software visualization that is based on SHriMP (Simple Hierarchical Multi-Perspective). Animated nested (hierarchical) treemaps are used that provide details and multiple semantic perspectives on demand.

Fluit et al. (2003) and the Aduna company created AutoFocus and Spectacle, semantic desktop- and web search engines with 2D clustermaps visualizations. However this non-hierarchical approach is limited to a small number of semantic concepts.

Card et al. (1996) presented the Web Forager, which is one of the first 3D information visualization systems. It makes use of hierarchical visualization through perspective projection but there are no possibilities to visualize semantic relations between objects.

Ontosphere (Bosca et al., 2005) is a graph based hierarchical ontology visualization tool that makes good use of different visual scales like color, size, shape and distance. The abstract graph visualization with colored spheres and arrows is probably unmotivating for users not engaged in ontology engineering and the labeling of the objects is also a problem of this system.

Diagnosis and Decision Support

A literature research about diagnosis and decision support systems (DSS) in the domain of wastewater treatment showed several interesting approaches, like online-simulations (Jumar and Tschepetzki, 2002; Butler and Schütze, 2005), knowledge-based systems like ontologies (Ceccaroni, 2001), rule-based expert systems (RBES) or case-based reasoning systems (CBRS) (Wiese et al., 2005) and neuronal networks. All these approaches are rarely employed in practice yet. This might be due to the fact that the complexity of setting up and maintaining such systems for conventional wastewater treatment plants (WWTPs) exceed their benefits; however for highly automated decentralized WWTPs at least some approaches appear applicable and these shall be presented later.

CONCEPTS

After having presented the requirements for an Intelligent Visualization and Decision Support System and the state of the art in these areas, the concepts chosen for the KOMPLETT-Project will be explained in the following.

Information Management

As the core of the information management sub-system an ontology has been implemented. Simplified an ontology is an intelligent database structure which contains additional information about the data itself. For a better comprehension a few technical terms used in relation with ontologies have to be explained:

- Instance: a specific entry in an ontology is called instance. Instances can represent real objects; e.g. an instance in the KOMPLETT-ontology could be a technical component of the plant like a specific valve;
- Slot: to have more information available about an instance it is possible to create so called slots which represent specific properties of that instance like in case of the valve mentioned above the manufacturer or the ID-number;
- Concept: a concept (also called class) helps to define the nature of an instance. Our valve could be an instance of a class “hand valve” which is a sub-class of a class “valve” which is a sub-class of a class “plant component”;
- Relation: relations define the interrelationships of classes and instances. To get an overview of a process the different process steps could be related by their sequence (predecessor / successor) or to come back to the valve-example the next component following the valve in the plant layout can be defined.

Figure 2 exemplary shows just a small section of an ontology (the KOMPLETT-ontology has up to now about 130 classes, 50 slots and 1000 instances). The circles represent classes, arrows represent relations and instances are represented by rectangles. Using an ontology large amounts of heterogeneous data can be structured making use of concepts, instances and relations.
To create the ontology Protégé, a free, open source ontology editor, developed by Stanford Medical Informatics at the Stanford University School of Medicine, was used.
In a first step a basic structure with hierarchical classes was defined. Then all the available information about the plant itself and the relevant processes was transferred into this structure.

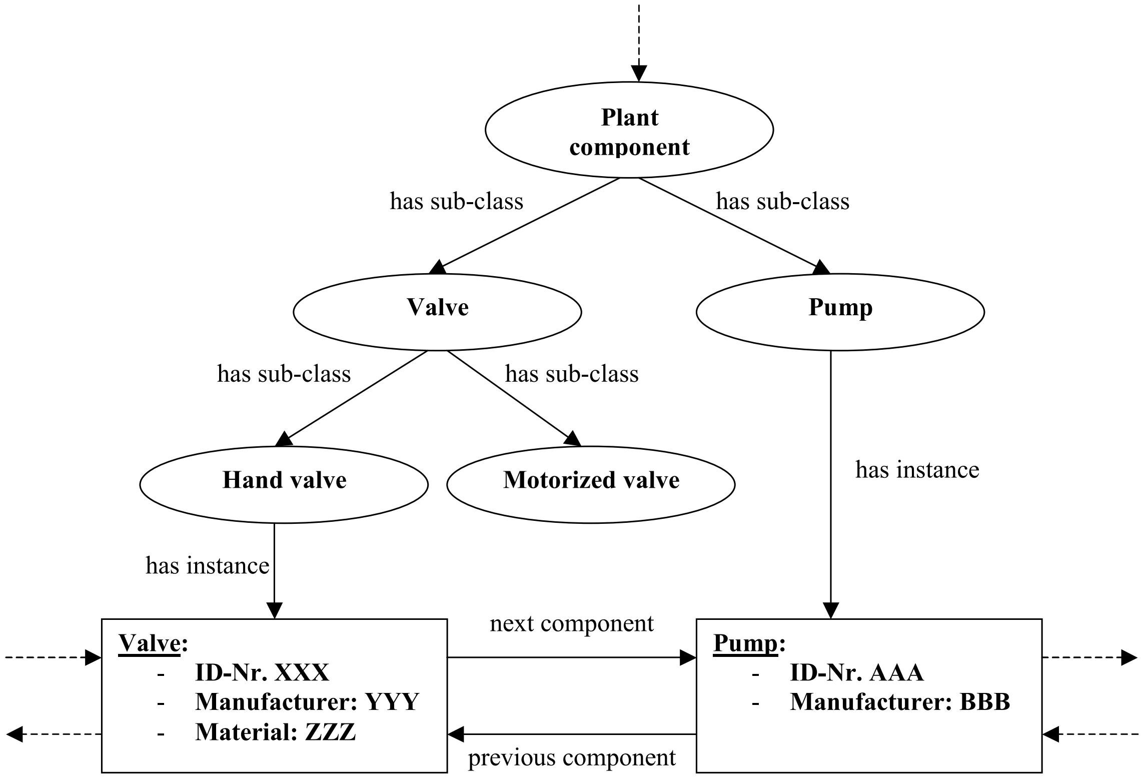

Figure 2: Structure of an Ontology (part of the KOMPLETT-System)

Relations between the different instances were added modelling the whole process and the plant layout this way.
Figure 3 shows two states of an animated ontology visualization based on the modelling mentioned above. Classes and instances are presented as colour- and shape-coded 3D-objects which are visible or not by choice of the user; the object of interest is always placed in the centre and in the foreground, the related objects are arranged in concentric circles placed more and more in the background with increasing distance of the relationship. Thus, one can explore detailed information

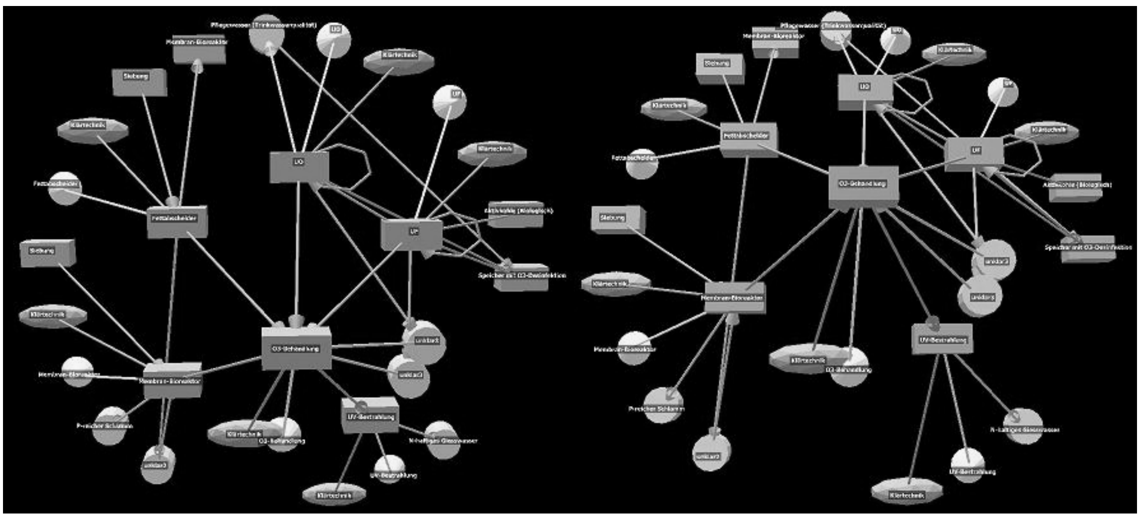

Figure 3: Visualization of an Ontology for the KOMPLETT-System

without losing sight of the surroundings. The transition between different views is smoothly animated to reveal relations and to track und understand changes between different states.
On the other hand this visualisation type is very complex and may be difficult to understand for the staff onsite. Therefore another type of 3D-visualization is under way for the KOMPLETT- system. Figure 4 shows an explosion view. The Figure is animated, so that the user can determine, if he wants to have the overview (shown on the left side of the figure) or more details and subunits, as shown in the middle and on the right side of the figure. The advantage of this visualisation type is that the viewer is able to see both, the overview and the subunits with the relations at the same time. Furthermore the most important unit can be moved into the foreground.

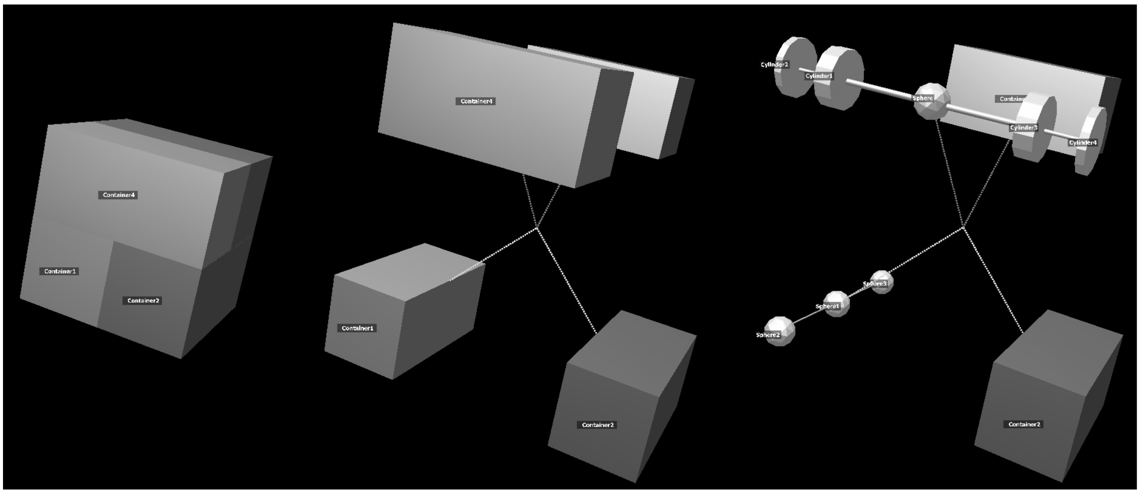

Figure 4: Three states in Animated Explosion View

Within the KOMPLETT- project different types of visualization will be tested.

Diagnosis and Decision Support

For such high-tech facilities with a wide range of process steps like the KOMPLETT-plant it is not only important to identify a malfunction but also to isolate its cause and to propose a problem solving strategy. By combination of monitoring and reasoning tools the KOMPLETT-System aims for predicting critical operation conditions of the plant thus making it possible to countersteer in advance.

The basis of the diagnosis sub-system is a series of plausibility checks of the incoming data. For example flow measurements could be verified by checking the setting of the relevant valves or the state of a pump and vice versa. Again making use of the ontology structure it will be possible to infer the cause of a malfunction from the actual plant conditions. But not only technical problems can be diagnosed; by expanding the ontology e.g. with a microbiological or a chemical knowledge base the system will also be able to provide problem solving solutions in these fields of interest (Ceccaroni, 2001).

The ontology is suitable for giving more general, knowledge-based statements. To get a decision support system which is more specialized and better adapted to the operation conditions of a single plant location a case-based reasoning system (CBR) will be added .
Case-based reasoning is based on the assumption that similar initial conditions will result in similar effects and that similar problems can be solved with similar solutions (Fig. 5). This principle resembles the human problem solving process and therefore is easy to understand.

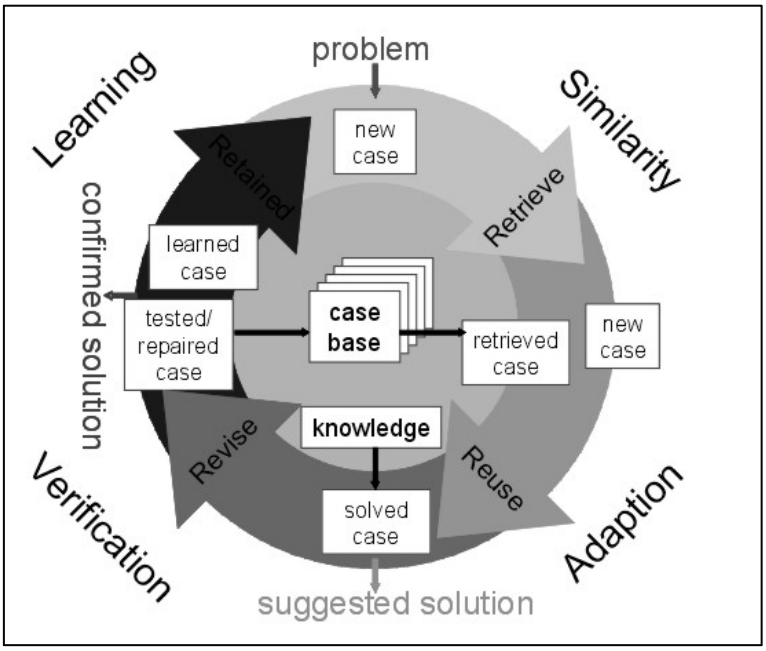

Figure 5: Process of problem solving with CBR

To get reasonable results from a CBR-system it is necessary to have a database with cases for a specific problem. With increasing time of operation (and increasing number of operational plants) more data about the different processes is produced. This leads to a better operating experience (knowledge base) and so the statements given by the system will become more and more precise and dependable.

First offline tests of such a system on a SBR (sequencing batch reactor) plant show, that the use of CBR could be very promising (Wiese et al., 2006).

System Interface and Compatibility

As the proposed solution presented here is an add-on system to a process control system running in the background (in the case of KOMPLETT SIMANTIC WinCC from Siemens is used) at least some of the features could be realized directly with this system. However the main advantage of an platform independent system is – as the term already suggests – the possibility to use the system on various platforms with the help of a standardized and commonly used gateway/interface like OPC to connect the two systems and to make data exchange possible.

SUMMARY AND FUTURE PROSPECTS

The Intelligent Visualization and Decision Support System developed for the KOMPLETT-Project can be divided into two main sub-systems.

The implemented visualization system will help to make work with large amounts of data like the data collected on wastewater treatment plants (WWTP) easier and more effective. In addition the comprehension of the mostly very complex processes and interrelationships will be facilitated by the use of new visualization techniques and intelligent data processing. An integrated maintenance guidance system makes it possible even for unskilled staff to accomplish at least the most basic duty without the help of expert personnel.

The diagnose and decision support sub-system provides the distant expert supervisor with all the information about actual and predicted operational states of the different plants he is responsible for, enabling him to optimize the process and to transmit the most important information and instructions in an easy understandable way to the staff onsite.

As the KOMPLETT-plant is just undergoing assembly at the site (an apartment building with about 20 inhabitants in the city of Kaiserslautern) there is no practical experience with the system yet. But for the near future it is planed to undertake specific user tests to optimize sub-systems like the intelligent visualization and the maintenance guidance.

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