Design of a Model-based Decision Support System for Water Treatment

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Abstract

The paper presents the application of model-based systems technology within a decision support system for drinking water treatment plants. This system aims at detecting deviations from normal plant operation, identifying their possible causes, and proposing adequate remedial interventions. Its basis is a library of model fragments that represent intended processes, disturbances, and possible interventions. Based on these fragments and the available observations, possible models of the disturbed plant behavior are generated automatically as a solution to the diagnostic task. An extension of such a model by models of interventions such that the result is consistent with remedial goals represents a possible therapy proposal. We present a specification of the decision support system, the interaction between the user and the system.

1 Introduction

Knowledge-based systems provide a means for making expert knowledge available to non-experts or specialists lacking comprehensive knowledge of a certain domain. This feature is of particular interest in the domain of ecology and environmental problems because every individual, institution, or company affects the environment but cannot expected to have a proper understanding of this impact and of ways to prevent or counteract it. Environmental decision support systems have to capture domain knowledge of experts in the field of ecology and/or environmental issues and facilities for enabling the users to state information about their particular problems, for generating answers and solutions based on this information and the domain knowledge, and for presenting them in a comprehensible manner.

We chose model-based systems to approach this ambitious goal. Some fundamental assumptions our work are

- The domain knowledge can be represented by a set of generic, independent, and, hence, re-usable model fragments ("processes") that describe the relevant phenomena and are collected in a library ("domain theory").
- The user faces two distinct tasks: situation assessment (understanding "What goes on?") and therapy proposal ("What can be done?").
- A proper answer to situation assessment is given by a model that can be composed from the library and "explains" the partial information about a situation that is available to the user, and, similarly,
- an adequate therapy can be found by finding an extension of the situation model by feasible actions that satisfies a set of behavior goals.

Figure 1 shows the architecture that follows from these assumptions. The basis of our solution is a novel integration of logical theories and implementations of process-oriented modeling ([Forbus 84]) and consistency-base diagnosis ([de Kleer-Mackworth-Reiter 92], [Dressler-Struss 96]). In this paper, we will not restate the formal theories and technical details which have been described in [Heller-Struss 00], [Struss-Heller 01], and [Heller 01]), but just summarize the concepts and focus on discussing how a decision support system can be based on them.

The application context for our work is a water treatment plant. While this is not a natural system, it seems to be a good starting point: On the one hand, it comprises physical, chemical, and biological processes with only partial and qualitative knowledge and information available, like an ecological system. Furthermore, it is possible to validate and evaluate the decision support system for operators in real plants, and there is a smooth transition to real environmental and ecological systems by including phenomena that affect the natural water sources (e.g. algal bloom as in [Struss-Heller 01].

In the next section, we describe the main aspects of the water treatment process highlighting potential problems and remedies. In section 3, we summarize the modeling formalism and illustrate it with examples from the water treatment domain theory. Based on this, we present the situation assessment and the therapy proposal components.

2 The Treatment Process

The water to be treated is collected from a natural source like a river (e.g. Rio Guaíba) or a reservoir (e.g. Lomba do Sabão). After having been pumped to the water treatment plant, it passes through a sequence of process steps. Due to the lack of space, we can not detail all of the processes, illustrating with only one of them:

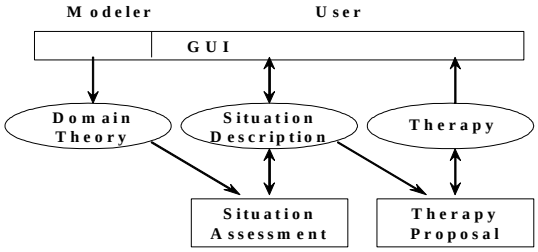

Figure 1 Architecture of the decision support system

ARRIVAL CHAMBER → ARRIVAL CANAL → CHICANERY → DECANTATION TANK → DECANTED WATER CANAL → FILTERS → FILTRED WATER CANAL

Decantation tank:

- **Purpose:** separation between solid and liquid phases, that is, flocks and water. The water flows through the tank at a low speed. During this period, the flocks sink to the bottom of the tank, forming a growing layer. At the end of this step, color and turbidity are measured.
- **Problem:** too many flocks at the end (which will cause problems in the next step) due to too much accumulation of flocks and other material at the bottom of the tank.
- **Therapy**: Removal the sludge from the bottom of the tank.

3 Modeling

In the following, we summarize the modeling formalism that provides the foundation of the decision support system and illustrate it with some examples from the water treatment application. According to the compositional modeling approach, this is split into two parts:

- The domain theory which represents the general knowledge in terms mathematical axioms and a library of behavior constituent types (i.e. generic processes).
- The situation description capturing the information about a specific system in a specific state stated in terms of perceivable objects, their interrelationships, and values of object variables (e.g. measurements) (see Table 1).

We follow the principles of structure-to-behavior reasoning and compositional modeling and provide a generalization of both component-based and process-based modeling paradigms. According to this view, the system model (or system description) consists of two parts: the domain theory and a situation description.

3.1 Domain Theory

The domain theory captures what we know about the domain, i. e. all systems of a certain class (e. g. hydrological ecosystems or water treatment plants). We distinguish *structural elements* (objects and relations) from *behavior constituents* (which might be processes or other model fragments). The ontology consists of:

- *object types* which occur in structural descriptions, for instance types of components in a device (resistor, broken wire), spatially distinguished entities (layers of a water body, pipes, tanks), etc. Object types can be structured hierarchically.
- *relations* for characterizing "configurations" of objects. Examples are spatial relationships (contained-in, below), connectivity of components, etc. Some important properties of relations (like uniqueness) can be specified.
- *quantities* as the basic elements for behavioral descriptions. Multiple quantity types (e. g. with different domains) can be defined and objects of a given type can be supplied with a number of associated quantities with given roles (e. g. the resistance of a resistor, the concentration of dissolved iron in a water tank etc.).

Figure 2 shows part of the object hierarchy of the water treatment domain theory. Figure 3 displays some relations and their properties.

Domain Theory
Ontology
Object Types (hierarchical)
Object Relations
Quantity Types
Behavior Constituent Types
Structural Conditions (objects and relations present)
Quantity Conditions (constraints on quantities)
Structural Effects (objects and relations created)
Quantity Effects (constraints and influences)
Basic Axioms
Situation Description
Objects
Relation Tuples
Quantity Value Assignments

Table 1 Structure of system models

The domain theory also has to provide a vocabulary for behavior descriptions and the inferences that derive behavioral constituents from a structural description. It introduces

- *behavior constituent types*. These are physical phenomena which are considered to contribute to the behavior of the overall system. They can represent basic component laws (Ohm's Law, logical-or) or processes like in the Qualitative Process Theory, QPT ([Forbus, 1984]). Examples are alcalinization, water transport or algal blooms. They occur deterministically under certain conditions, and their occurrence generates particular effects. Applying the distinction between structural and quantity aspects to both conditions and effects, we obtain
  - StructuralConditions: assertions about the existence of relations and objects (e. g. of sedimental iron)
  - QuantityConditions: statements about values of quantities (e. g. a low pH in the reservoir)
  - StructuralEffects: creation or possibly even elimination of objects and relations (e. g. the "generation" of dissolved iron from the bound sedimental one)
  - QuantityEffects: can be expressed as restrictions on variables (e g. the dissolved iron concentration rises with the sedimental iron concentration and lower pH). Here, we also allow for partially specified effects in the form of influences as used in QPT.

The abstract form of a behavior constituent type can then be written as

$$\text{StructuralConditions} \wedge \text{QuantityConditions} \Rightarrow \text{StructuralEffects} \wedge \text{QuantityEffects}$$

More precisely, we state that for each constellation of objects satisfying the structural and quantity conditions, an instance of the behavior constituent is occurring - and imposes the respective effects on the constellation.

3.2 Situation Description

A particular system under consideration is characterized by its *object structure*, i. e. instances of the object types and individual tuples of object relations (for instance the components and the connection structure of a device). In the following, we will refer to both objects and relation tuples as structural elements.

A particular situation of the system is characterized by *quantity value assignments*. Dependent on the task and context they may represent actual measurements (e.g. an increased amount of iron in the drinking water), specification of goals (a certain amount of iron), mere hypotheses, etc.

3.3 Representing Actions

For the task of therapy proposal we need to represent actions that affect the behavior of the system. These effects are the ones introduced above: the creations of objects and/or object relations and imposing influences and constraints on quantities. Actions may have certain physical preconditions for their applicability which can be stated in terms of structural conditions and quantity conditions. However, unlike ordinary processes, they do not become automatically active when these physical preconditions are satisfied. They have an additional precondition to become effective: some human intervention. Such an intervention can be an entire sequence of human activities which has to be taken into account when actually planning the work or estimating its costs. However, from the point of view of reasoning about adequate therapies, it suffices to regard them as atomic entities. Hence, an easy way to integrate actions in the modeling formalism is to represent the human interventions as a special kind of objects, called **action triggers**, whose existence is a structural condition of the respective actions. Since action triggers only depend on the decision and the respective activities by humans, they can never appear as structural effects of processes or other actions. Furthermore, we have to make sure that different action instances have different action trigger objects, even if they are instances of the same action type. Otherwise, several instances of an action type could be triggered by the same object.

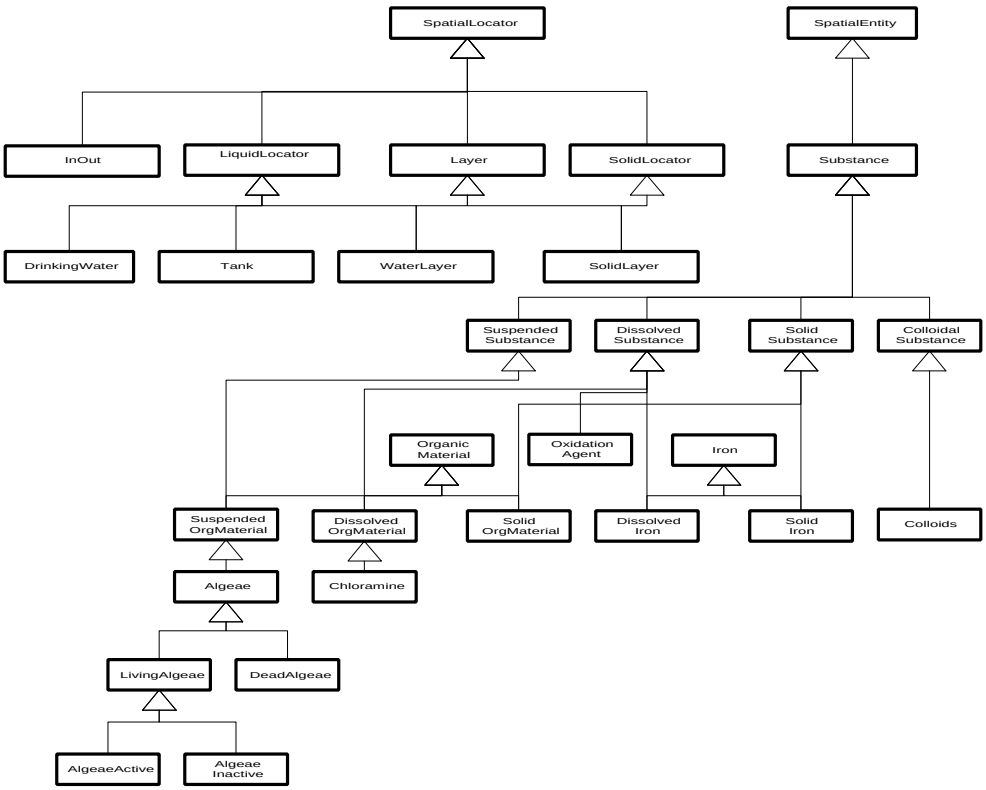

Figure 2 Part of the water treatment object hierarchy

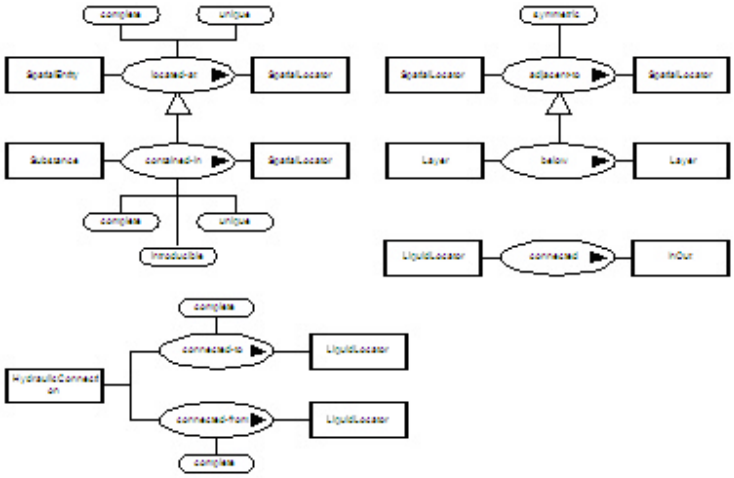

Figure 3 Object relations

3.4 Deviation models

Often, it is not even relevant to situation assessment or therapy proposal to consider the absolute values of quantities. Rather, it can be sufficient to reason in terms of (qualitative) deviations from nominal values only. For example, they can be used to express that a chlorine supply which is higher than normal tends to make the pH lower than the specified range. Descriptions of deviations can reflect the fact that it may be unnecessary or impossible to specify the normal behavior exactly and numerically. For each variable, such a deviation can be represented as

$\Delta x := x_{act} - x_{ref}$.

The deviation models can be generated from the absolute models and propagate deviations from some nominal or reference behavior (which is possibly left unspecified). In the situation assessment phase, one may start from a deviation from the goal state which is indicated by measurements and try to find deviations of other quantities that cause the former.

4 Situation Assessment Component

As stated earlier, the first task to be solved is to determine hypotheses about the current situation based on available information about the system, i.e. observations. If the observations are true statements about all relevant objects involved in the system, situation assessment would just have to determine the active processes entailed by them. In general, observations are incomplete and may contain uncertain information. For instance, if the iron concentration of the incoming water is not measured, then a statement about iron is either missing or only a guess. In this case, situation assessment has to complete the description provided by the user and/or revise uncertain information. Therefore, we allow for user-defined assumptions to qualify quantity assignments.

The completion of the situation description cannot be arbitrary. Some objects may simply be “introduced” without any further explanation, such as iron in the incoming water, whereas others are only accepted if they follow from the rest of the model, e.g. iron in the treated water. To this end, certain object types can be named as being *introducible* to allow the addition of objects of the respective type to the system model. This provides the most important means for controlling the problem solving task, since a more restrictive set of introducibles requires to "deepen" the search for causes. Introducibles specify what cannot be expected to be explained and, hence, represent the model boundary.

On the basis of defeasible assumptions as well as introducible elements, one can now define the set of acceptable solutions of situation assessment as *the minimal consistent allowable structures in which a maximal set of user-defined assumptions holds*. A structure is defined to be *allowable*, if it contains at least the structural elements specified by the user as facts (without assumption) and all other structural elements are either introducible or a necessary consequence of an occurring behavior constituent (by ways of structural effects).

Minimality is understood w. r. t. set inclusion. Note that we do not use the absolute cardinality of structural elements present in a solution as a criterion for preferring one solution over another, we just exclude "unnecessary" or "superfluous" objects from being included in a solution.

Based on the four categories fact, assumption, introducible, and consequence, Figure 4 illustrates input and output of this step in the decision support system in an abstract way.

5 Therapy Proposal Component

After having identified the current situation, the question arises whether this situation is compliant with the goal performance or actions have to be taken to make it compliant. The input to therapy proposal is a result of the situation assessment and a description of the goals to be achieved by remedial actions. In general, a therapy would be a sequence of actions that ultimately lead to a system state that is consistent with the specified goals and requires planning. In this paper, we address only a more specific problem:

- We assume that the goals can be described by a set of quantity assignments (as opposed to complex constraints on several system variables), e.g. limiting iron concentration by a certain threshold.
- A therapy is defined as a set of feasible actions that move variables that deviate from their goal values in the right direction (without disturbing the proper ones) when applied in the current situation. For instance, if the iron concentration is too high, then the intermediate goal of a therapy is to reduce it and leave other goal variables unchanged.

Under these assumptions, we can be more specific about the input to therapy proposal:

- The intermediate goals: they can simply be expressed by the derivatives of goal variables taking a sign opposite to the deviation of the respective variable.
- The current situation: this has to include everything as a fact that resulted from the situation assessment step (because we committed to it) with one exception: the derivatives of non-goal variables have to be turned to assumptions. The reason for this lies in the fact that we assume the actions and their effects are introduced instantaneously. Therefore, we have to allow that derivatives change their values (discontinuously) if influenced by the actions.

This is indicated in Figure 4. Since it may be impossible to satisfy all intermediate goals, we also provide a means for dropping some of them. Then a therapy is identified as a set of action triggers that, together with the current situation, yields a model that *the minimal consistent allowable structures in which a maximal set of intermediate goals holds.*

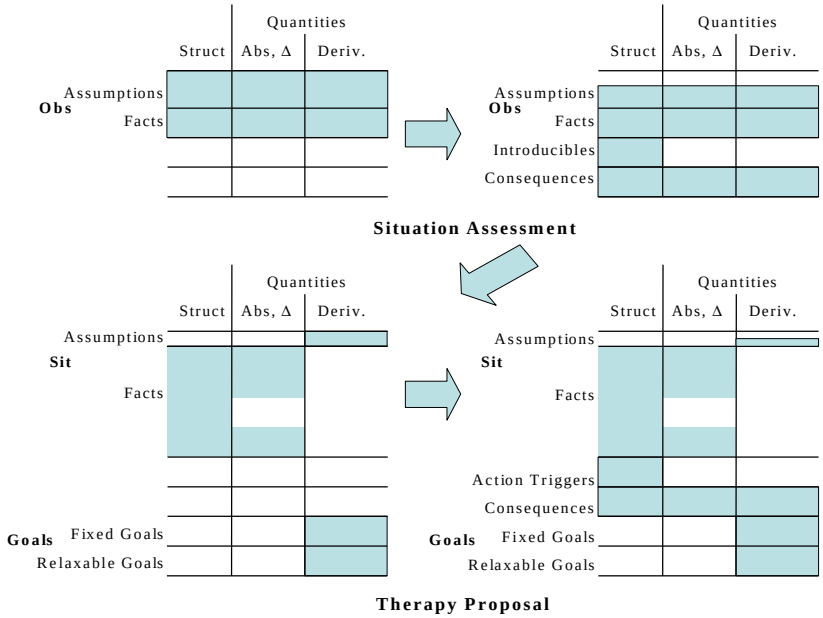

Figure 4 Input and output of the two steps and their connection

6 Discussion

The decision support system presented here applies process-oriented modeling and consistency-based diagnosis to perform situation assessment and therapy proposal. It is based on a number of assumptions. The most important restrictions are due to the static perspective taken: in both steps, a solution is sought only by analyzing a snapshot of the system. The first step determines only the current state rather than providing information about the development of a disturbance over time. While this seems appropriate as an input to therapy proposal which, indeed, has to be applied to the current state, one-step therapy may be unrealistic for many other applications which may require a sequence of interactions.

At the current state of the project, graphical editors for the domain theory and the situation description, the consistency-based problem solver, and a domain theory are available, and a first version of the decision support system is being implemented. This will be a highly interactive version which presents inconsistencies to the user and lets him guide the search for a consistent model. Based on this experiment, a version with automated generation of consistent solutions will be developed.

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