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An ontology-based knowledge management system for flow and water quality modeling

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Abstract

Currently, the numerical simulation of flow and/or water quality becomes more and more sophisticated. There arises a demand on the integration of recent knowledge management (KM), artificial intelligence technology with the conventional hydraulic algorithmic models in order to assist novice application users in selection and manipulation of various mathematical tools. In this paper, an ontology-based KM system (KMS) is presented, which employs a three-stage life cycle for the ontology design and a Java/XML-based scheme for automatically generating knowledge search components. The prototype KMS on flow and water quality is addressed to simulate human expertise during the problem solving by incorporating artificial intelligence and coupling various descriptive knowledge, procedural knowledge and reasoning knowledge involved in the coastal hydraulic and transport processes. The ontology is divided into information ontology and domain ontology in order to realize the objective of semantic match for knowledge search. The architecture, the development and the implementation of the prototype system are described in details. Both forward chaining and backward chaining are used collectively during the inference process. In order to demonstrate the application of the prototype KMS, a case study is presented.

Keywords: Knowledge management system; flow and water quality modeling; artificial intelligence; ontology-based

1. Introduction

The current techniques for numerical simulation of flow and/or water quality are highly specialized tasks. The numerical technique can be based on finite element method, finite difference method, boundary element method and Eulerian-Lagrangian method. The time-stepping algorithm can be implicit, explicit or characteristic-based. The shape function can be of first order, second order or higher order. The modeling can be simplified into different spatial dimensions, i.e., 1-dimensional model, 2-dimensional depth-averaged model, 2-dimensional layered model, 3-dimensional model, and so on (Blumberg et al., 1999; Chau et al., 1996; Chau and Jin, 1998; Tucciarelli and Termini, 2000).

Heuristics, empirical experience of specialists, simplifications and modeling techniques are included in the analysis of coastal hydraulics and water quality (Yu and Righetto, 2001). The accuracy of the prediction depends largely on the accuracy of the open boundary conditions, model parameters used, and the numerical scheme adopted (Martin et al., 1999). It is generally recognized that the most important assets are the expertise knowledge. The sources of knowledge are not only from books, technical manuals, and education trainings, but also the accumulation of long-term experience which is usually stored in written documents. Since the diversity and complexity of conceptual terminology in the industry and the lack of proper document management, the existing knowledge is hard to be systematically arranged and reserved, even shared, and engineers have to spend many efforts in searching the knowledge they need. As a result, it is desirable to establish the bridge between model developers and application users. The application of knowledge management (KM) is considered a feasible solution for helping engineers search for knowledge efficiently and effectively.

There arises a demand on the integration of KM, artificial intelligence (AI) with these mathematical models in order to assist selection and manipulation. During the past decade, AI techniques have been applied to the numerical simulation of flow and/or water quality (Chau and Yang, 1992; Chau and Zhang, 1995), which made use of the commercial expert system shell VP-Expert (Friederich and Gargano, 1989). Yet they are nowadays no longer the most effective in system operation and design. It is worthwhile to develop such an up-to-date integrated system for coastal water processes.

In the past decade, there has been a widespread interest in the field of KM techniques, which are able to simulate human expertise in narrowly defined domain during the problem-solving by integrating descriptive knowledge, procedural knowledge and reasoning knowledge (Hendriks, 2001; Huber, 2001; Liebowitz, 2001; Tiwana and Ramesh, 2001). It is recognized that the ontology is an appropriate methodology to accomplish a common consensus of communication, as well as to support a diversity of activities of KM, such as knowledge repository, retrieval, sharing, and dissemination (Neches et al., 1991, Gruber, 1995). In particular, it allows communication and reuse of knowledge among different entities to share the same domain area (Pundt and Bishr, 2002).

In this study, an ontology-based KMS, which can assist engineers in sharing, searching, and managing knowledge on flow and water quality modeling, is presented. The architecture, the development, the implementation and its application, as well as the knowledge representation and the visualization during the problem solving, are detailed.

2. Framework of KM system

The building of an ontology is often recognized to be the first basic step to facilitate KM activities (Guarino, 1997). Figure 1 shows the framework for the ontology KMS on flow and water quality modeling, in which a three-level architecture for intelligent decision support is adopted. It comprises the application level, the description level, and the object level, which are listed in a descending order. It should be noted that ontologies are identified in the description level, and through this arrangement, users in the application level are able to access the object-level sources in an intelligent manner. Diverse knowledge sources and information, under the format of numerical data, text streams, validated models, meta-models, movie clips, or animation sequences, and so on, collectively termed knowledge objects (KOs), are included in the object level (Nemati et al., 2002).

In this study, the ontology is divided into two groups, namely, the information ontology and the domain ontology (Abecker et al., 1998). The information ontology represents a meta-model comprising generic concepts and attributes of KOs, which are represented by the Dublin Core (Dublin Core Metadata Initiative, 2005). On the other hand, key concepts, attributes, instances, and relations of flow and water quality modeling are located in the domain ontology, whose principal role is to attain the functionality of semantic match during the search of KOs. Figure 2 shows part of the domain ontology of flow and water quality modeling. It can be observed that there exist various forms of relations, namely, the inheritance relations, functional relations, structural relations, behavior relations, and so on.

During the manipulation stage, when an end-user accesses the knowledge base, the ontology can support tasks of KM as well as searching. The knowledge base and the ontology are linked to one another via both ontology formalization and ontology implementation, which furnishes a route for the extension of the information ontology. During the maintenance stage, knowledge engineers or domain experts can add, update, revise, and delete the information ontology or the domain ontology via a knowledge acquisition module.

One of the most difficult issues in flow and water quality modeling is how to select an appropriate model together with the associated parameters. The KM system is able to represent knowledge in a fashion that is appropriate for the modeling of application decision knowledge, to isolate the policies and decisions from application logic and to supply the intelligent support during problem solving by visual window interfaces. The KMS is tailored so that the application rules are isolated into identifiable and reusable components.

3. Domain knowledge

It is very difficult for novice application users to select an appropriate model directly. Comparatively, simple interactive questionnaires, incorporating most of questions related to users' knowledge, are easily understood and responded by users. Good questionnaires can infer the intrinsic conditions of model selection on the basis of responses from the users. The domain knowledge entailed in the development of this prototype system has been encoded mainly on the basis of literature review and interviews with experienced numerical modelers.

Project types usually impose some limitations on the application of certain models. If reservoir routing is considered as an example, the analysis can be simplified significantly since dynamic effects are neglected and only the continuity equation needs to be considered. A finite-difference approximation can be utilized to describe the change of storages, i.e., the classic continuity equation of de Saint-Venant (Chaudhry, 1993). Furthermore, when some special tasks are undertaken, such as unsteady simulation of phytoplankton growth in a coastal water system and simulation of flooding and drying of tidal waves, some complex models are necessary. Moreover, only some simplified models can be adopted in cases detailed data are lacking,.

Visual window tabular interfaces are designed here, on the basis of experience and knowledge of the domain experts. Each tab helps the user to locate different groups of questionnaire. The **Purpose** tab (as shown in Figure 3) is provided for the selection from two optional buttons, i.e., real-time or planning. Usually, the simulation of flow and water quality can be applicable to planning, evaluating, and operating stages. In this context, planning refers to planning and evaluating whilst real-time represents operating. The **Project** tab is used to choose a project amongst 11 options: river flood forecast, flood plain, tidal dynamics, estuarine hydrodynamics, temperature/density distribution, salt water intrusion, wave propagation, wind storm propagation, outfall, water pollution and eutrophication. As it was mentioned above, different projects have their constraints on the choice of appropriate numerical models. On the **Tasks** tab, multiple selection of check boxes is allowed. Common tasks, namely, water current, water level, vertical advection, horizontal dispersion, dissolved oxygen (DO), biochemical oxygen demand (BOD), phytoplankton, nutrient concentration, sediment interaction, zooplankton, other physical variables (density, temperature, salinity, air pressure, etc.) and other water quality variables, are listed in the check boxes as shown in Figure 3.

4. Model selection

The conditions for selecting models will be generated automatically immediately after the user has completed the questionnaires. Figure 4 shows the frame chart of the methodology. The first level is the problem description, which includes the primary factors having significant effects on model selection. Purpose, project and task are the three options in the first level. The second level denotes the answer sets comprising the answer for each problem description, which may be in single or compound format. The third level represents the hidden condition sets of the intrinsic constraints on numerical modeling that can be acquired through the rule sets. The fourth level is the condition sets after some repeated conditions have been filtered out. The rule sets will be triggered after the condition sets in the fourth level have been acquired. Table 1 and Table 2 show the list of models embedded in the system and the list of all inputs for model selection, respectively.

5. Knowledge base

5.1 Development tool

In this work, the layered KM system is built with The KArlsruhe ONtology and Semantic Web (KAON), which is an ontology development environment (The University of Karlsruhe, 2005). Its characteristics include the open source and the distributed component-based J2EE architecture (Sun Microsystems Inc., 2005). As such, the ontology-based KMS has the advantages of high flexibility and robustness. The ontology, comprising concepts, properties, and instances, are grouped into reusable ontology-instance models (Motik et al., 2002). Under this development environment, a property may be featured as symmetric, transitive, or inverse with other concepts which has the capability to support a lightweight inference mechanism. In this way, the ontology furnishes a search engine with the functionality of semantic match in a KM system.

5.2 Representation of domain knowledge

Condition generation and model selection constitute mostly the domain knowledge on flow and water quality modeling. The key task for a knowledge engineer is how to encode them into a KM system. Since a variety of flow and water quality models are available, it is crucial to summarize the features and conditions of these models. Table 3 is the summary of the succinct features of numerical model. Table 4 lists the summary of conditions for part of the model parameters. As shown in Table 3, there are 15 feature indexes and each model is defined by a combination of one or more indexes. The most effective model can be chosen with respect to accuracy and computational efficiency according to the types and tasks of project. It is well recognized that it is a complex task to select a model. Thus, the establishment of the knowledge rules based on the analysis of these conditions forms the major objective in this study.

5.2.1 XML/Java technology

It is acknowledged that managing and searching for KOs play a principal role in a KM system. This scheme is based on XML/Java technologies which can automatically generate the KO management components. In this way, the system can be readily re-engineered to adapt to other problem domains. KOs are managed by a Java session bean that can create, share, browse, and remove KOs through a Java entity bean component, which maintains tables about knowledge in the format of memorandum, information, and other documents in the knowledge base. The KO base represents a repository whose contents are adherent to the XML format. Regarding knowledge searching, an ontology-based search engine component furnishes the capability to search the domain and information ontology base. Whilst the information ontology model searches KOs by keyword exact-matching, the domain ontology model expands the keyword by the domain ontology.

5.2.2 Object-oriented programming

In total, three classes, namely, **Section**, **Problem** and **Question**, are defined. The following shows the structure of class **Question:**

CLASS **Question**
WITH Purposes COMPOUND Planning, Real_time
WITH Projects COMPOUND River flood forecast, Flood Plain, Tidal dynamic,
  Estuarine hydrodynamics, Temperature&density distribution,
  Salt water intrusion, Wave propagation, Wind storm propagation, Outfall, Water pollution, Eutrophication
WITH Tasks MULTICOMPOUND Water current, Water level, Vertical advection,
  Horizontal dispersion, Dissolved Oxygen, Biochemical oxygen demand,
  Phytoplankton, Nutrient concentration, Sediment interaction,
  Zooplankton, Other physical variables, Other water quality variables

The attributes of class **Section** is related to the characterization of model parameters, as detailed in Table 3. Thus, the characterization of models can be defined based on the values of attributes. The attributes of the class **Problem** is related to the initial conditions of models. Table 4 shows part of these attributes and condition sets. The attributes in the class **Question** are mainly those factors associated with the questionnaires.

5.2.3 Production rules

There are two groups of knowledge rules, namely, Rule Sets I and Rule Sets II. Whilst Rule Sets I generates automatically the conditions of model selection according to the replies, Rule Sets II recommends the most effective model for a project with special tasks. The two sets of rules are chained so that the conclusions from Rule Sets I will become the premises of Rule Sets II. When all the requisite questionnaires have been entered, the conditions on selection of models can be generated automatically based on the production rules. The following gives typical examples of these rules under this category.

```
!==================================
! Projects-Eutrophication Rules
!==================================
RULE 1 for Conditions from  Eutrophication
IF Questions.Projects IS Eutrophication
THEN Problem.Accuracy IS Not strict

RULE 2 for Conditions from  Eutrophication
IF Questions.Projects IS Eutrophication
THEN  Problem.StratificationOfWater IS Significant

RULE 3 for Conditions from  Eutrophication
IF Questions.Projects IS Eutrophication
THEN  Problem.Current IS Depth_averaged form

RULE 4 for Conditions from  Eutrophication
IF Questions.Projects IS Eutrophication
THEN  Problem.GridSize IS Uniform
……
```

The choice of models is determined by their characterizations, which can be inferred through the production rules after these questionnaires have been entered by the user.

5.2.4 Inference engine

Provided that the logical structures of the application problem have been carefully designed, all anticipative conclusions can be generated automatically by the robust inference engine built in the prototype system. The Visual Rule Studio inference engines control the strategies that determine how, from where, and in what order a knowledge base draws its conclusions. These inference strategies mimic the reasoning processes in solving a real problem employed by a domain expert. Figure 5 shows an example of the inference direction from the user's specifications through the inference engine.

At the onset, the inference engine explores **Dimensions**, which is a goal under the class **Section**. If the value of **Dimensions** is unknown, the search returns to those rules with consequent related to attribute **Dimensions**. The search explores the antecedent of the rules, for instance **ComputationTime**, which is a goal in the class **Problem**. If the value of **ComputationTime** is unknown, it then returns to those rules with conclusion related to attribute **ComputationTime**. In order to search its value, by rule chaining, the search explores the premise of the rules and evaluates **Purpose**, which is a goal under the class **Question**. Those rules related to **Purpose** will then be fired. When **Purpose** has been completed, other goals-**Project** and **Tasks** will be searched in order. The processes mentioned above will be continued automatically.

Whilst the class **Question** denotes the answer sets from questionnaires through the interactive interfaces, the class **Problem** represents condition sets obtained based on Rule Sets I. It can be observed that **Problem** is the conclusions drawn from the premise **Question**, and at the same time is also the premise about intermediate conclusions of **Section**. The logical relationship is thus **Question** → **Problem** → **Section**. In this way, the process of model selection is accomplished automatically according to the Rule Sets I and Rule Sets II after the problem description has been entered by the user.

6. Case study

In order to demonstrate the application of the prototype KMS, a case study on the eutrophication problem in Tolo Harbour of Hong Kong is presented. The study area is a nearly land-locked embayment with a narrow outlet connecting with Mirs Bay--one of the major south-facing bays in the South China Sea. The water depth varies from about 2 m in the inner part to over 20m in the outer part of Tolo Channel and about 12m on average. The averaged diurnal tidal difference is about 0.97m, mean high tide is 1.75m and mean low tide is 0.78m. For most of the year, little freshwater is discharged into the harbor, and it could be considered as an embayment. During the summer, however, the differences in surface and bottom water temperature and salinity, caused by solar radiation and rainfall, result in an obviously lighter surface layer and definite mesolimnion in the water column- a two-layered system. Density stratification weakens the vertical mixing and may remove the connection between benthic grazers and near-surface biobass by inhibiting vertical transport. In winter, higher dissolved oxygen levels in the bottom waters are generally recorded due to increased turbulent mixing within the water body, resulting from the strong northeast monsoon. However, during the summer, less bottom waters suffer from serious oxygen depletion, even approaching anoxic status, although the dissolved oxygen content in most of the surface was commonly found to be at satisfactory levels, even at super-saturation. Thus, it is necessary to simulate unsteady water quality transport in a density stratified natural water body. The readers are referred to Chau and Jin (1998) for details of the eutrophication modeling.

The questionnaires are first entered through the user interfaces based on the background of eutrophication problem for Tolo Harbour in Hong Kong. After the input data have been entered, a summary of the input requirements is shown in the left frame of questionnaires as shown in Figure 6. When the command button **INFER** is clicked, the process of model selection can be automatically attained on the basis of Rule Sets I and Rule Sets II. The right frame shows the inference result about the features of suggested model for this example, which has been verified to be consistent with the decisions reached by several domain experts.

7. Future Works

Recent advancements include the use of techniques such as geographic information systems (GIS) (Pundt and Bishr, 2002; De Donatis and Bruciatelli, 2006; Peachavanish et al., 2006) and web-based systems (Li and Zhong 2004; Mika, 2005; Eccher et al., 2006), which can be used to provide extensive capabilities including decision support and accessibility, etc. The integration of these recent technologies into this prototype ontology-based KM system would be explored in future.

8. Conclusions

This paper presents the architecture, the development and the implementation of a prototype ontology-based KM system on flow and water quality modeling. It adopts a three-stage life cycle for the ontology design and a Java/XML-based scheme for automatically generating knowledge search components. It is shown to be able to simulate human expertise during the problem solving by incorporating artificial intelligence and coupling various descriptive knowledge, procedural knowledge and reasoning knowledge involved in the coastal hydraulic and transport processes. Through the successful development of this prototype system, it has been demonstrated that the KM system can be integrated into the numerical flow and water quality modeling by incorporating AI technology so as to provide assistance on the selection of model and its pertinent parameters. The integration renders a more intelligent and user-friendly system in the problem domain, which can narrow significantly the gap between the numerical modelers and the application users. The prototype system demonstrates its capability in both the component reusability and the facilitation of knowledge acquisition and search.

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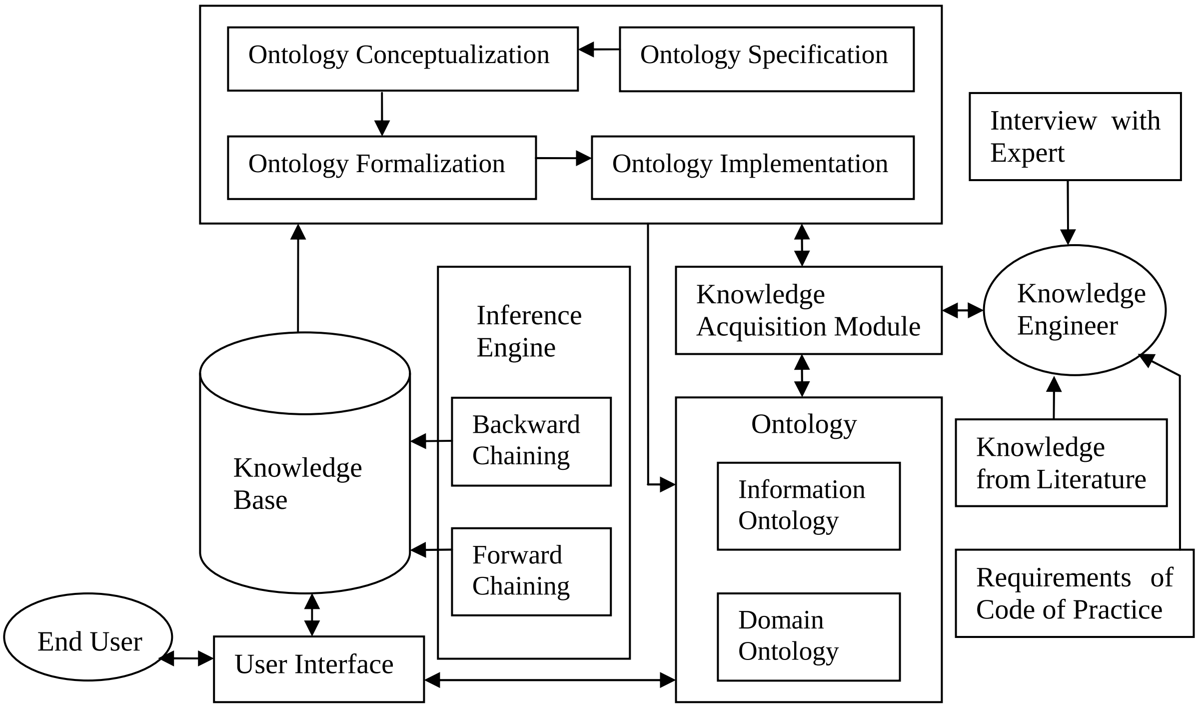


Figure 1. Framework of ontology-based KMS on flow and water quality modeling

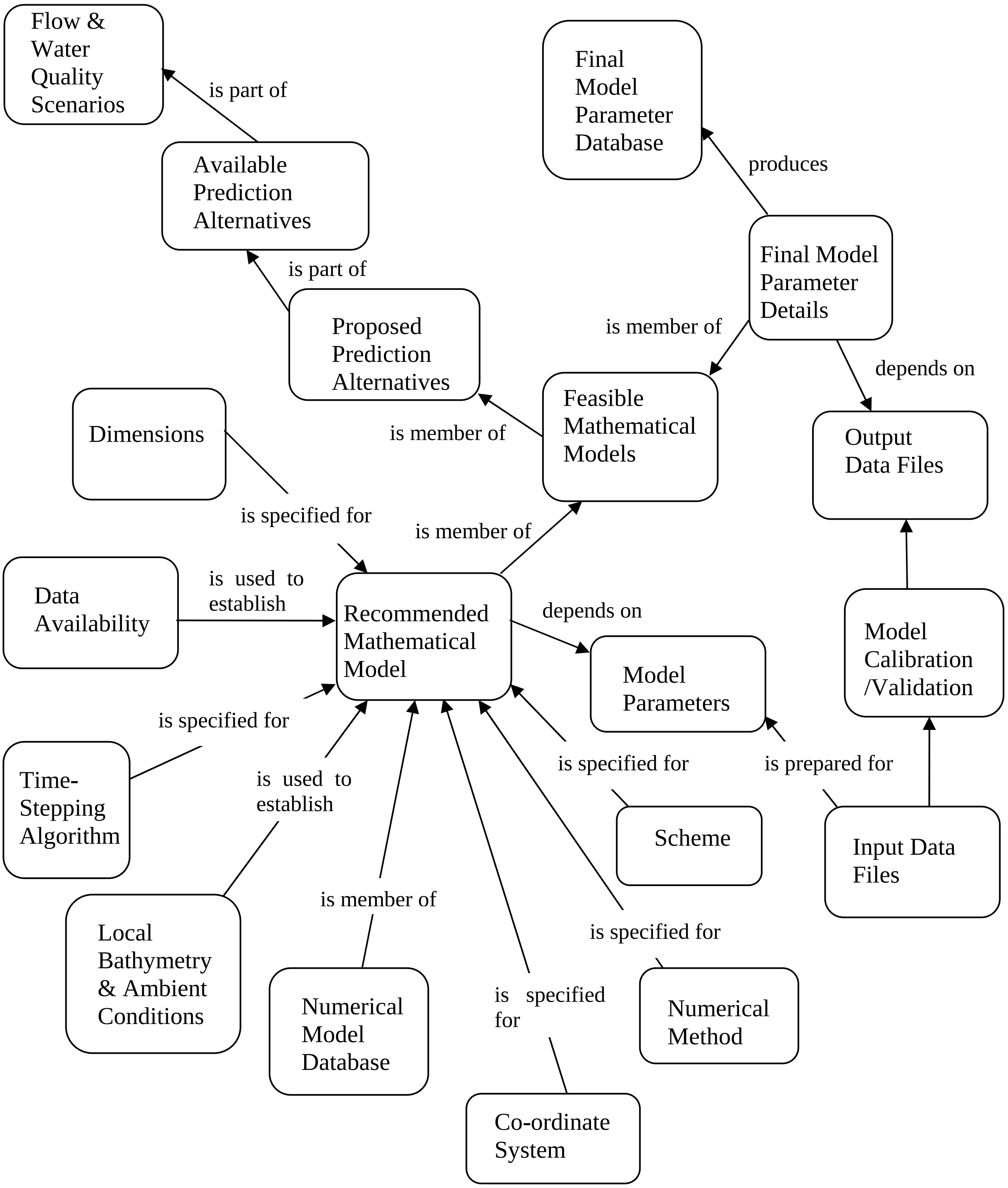
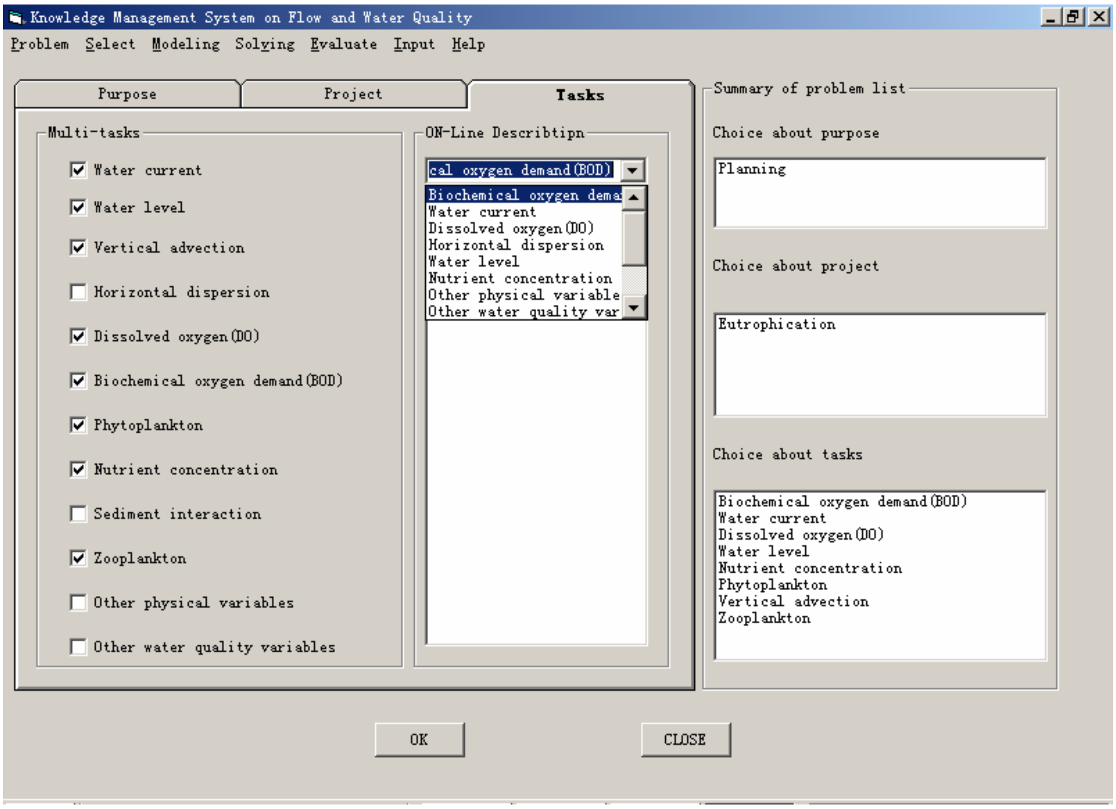


Figure 2 Part of the domain ontology on flow and water quality modeling



Multi-tasks

☑ Water current
☑ Water level
☑ Vertical advection
☐ Horizontal dispersion
☑ Dissolved oxygen (DO)
☑ Biochemical oxygen demand (BOD)
☑ Phytoplankton
☑ Nutrient concentration
☐ Sediment interaction
☑ Zooplankton
☐ Other physical variables
☐ Other water quality variables

ON-Line Describtipn

cal oxygen demand (BOD)

Biochemical oxygen dema
Water current
Dissolved oxygen (DO)
Horizontal dispersion
Water level
Nutrient concentration
Other physical variable
Other water quality var

Summary of problem list

Choice about purpose

Planning

Choice about project

Eutrophication

Choice about tasks

Biochemical oxygen demand (BOD)
Water current
Dissolved oxygen (DO)
Water level
Nutrient concentration
Phytoplankton
Vertical advection
Zooplankton

Figure 3 The user interface of **Tasks** tab

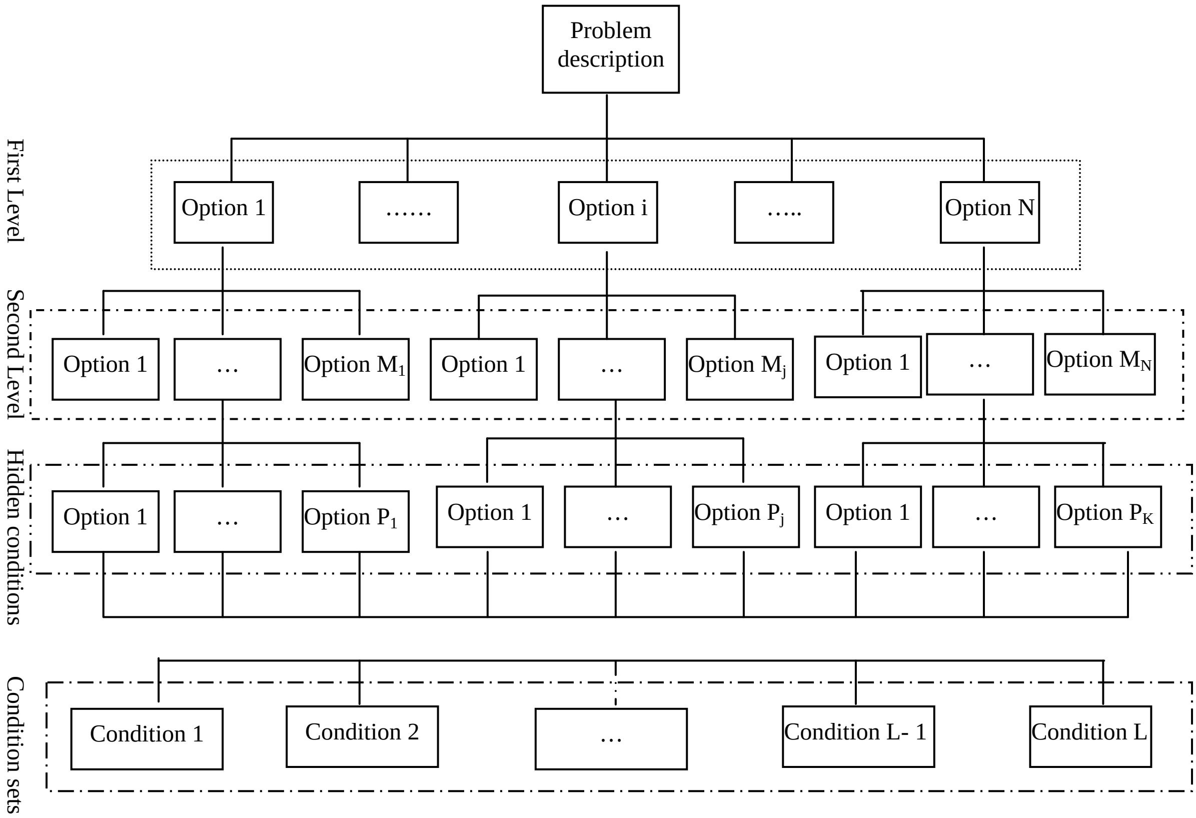


Figure 4 Frame chart of automatically generating conditions of model selection

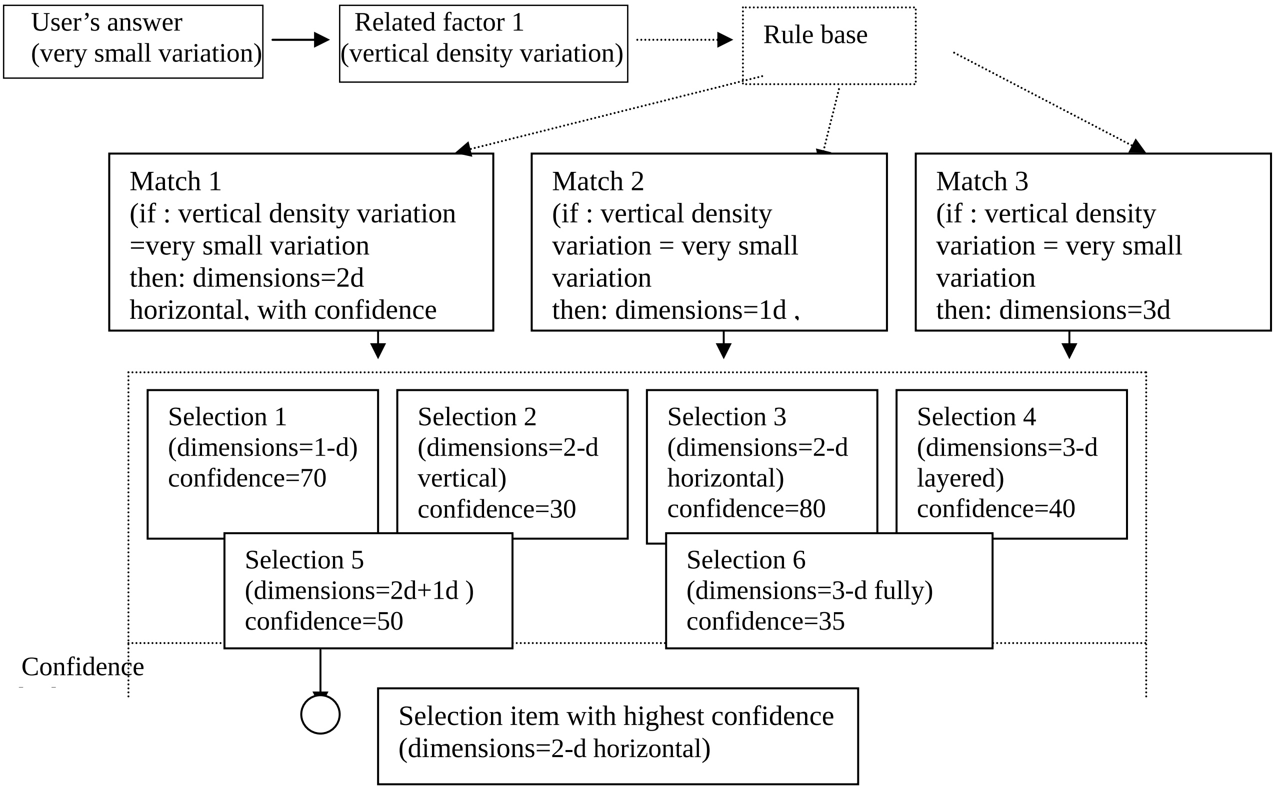
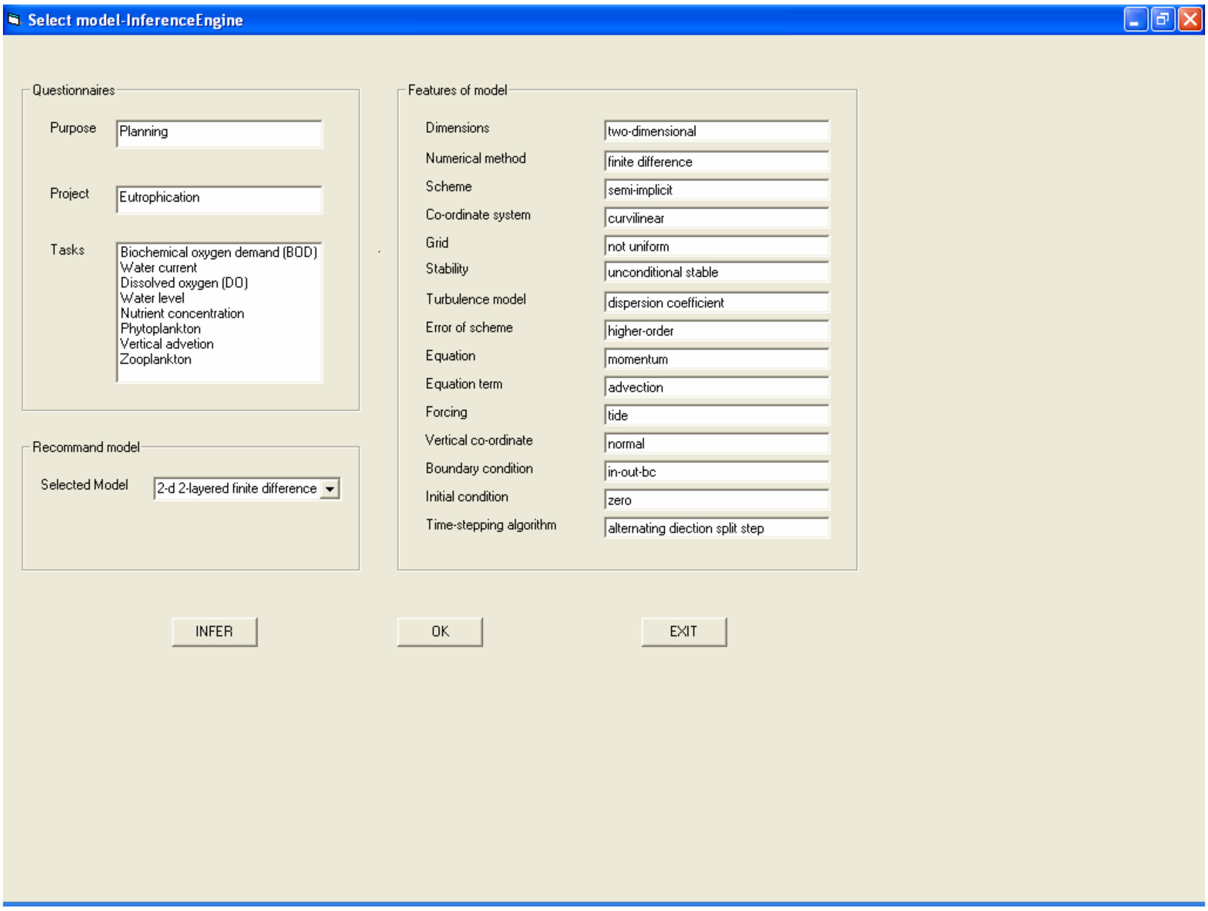


Figure 5. An example of the inference direction from the user’s specifications through the inference engine



Purpose: Planning

Project: Eutrophication

Tasks:
- Biochemical oxygen demand (BOD)
- Water current
- Dissolved oxygen (DO)
- Water level
- Nutrient concentration
- Phytoplankton
- Vertical advetion
- Zooplankton

Selected Model: 2-d 2-layered finite difference

Dimensions	two-dimensional
Numerical method	finite difference
Scheme	semi-implicit
Co-ordinate system	curvilinear
Grid	not uniform
Stability	unconditional stable
Turbulence model	dispersion coefficient
Error of scheme	higher-order
Equation	momentum
Equation term	advection
Forcing	tide
Vertical co-ordinate	normal
Boundary condition	in-out-bc
Initial condition	zero
Time-stepping algorithm	alternating diection split step

Figure 6. Display screen of model selection for the application example

Table 1 List of models embedded in the system

	Horizontal discretization	Vertical discretization	Turbulence closures	Drying/ Flooding routine
COHERENS	Cartesian	Sigma	Yes	No
ECOM	Curvilinear	General	Yes	Yes
GETM	Curvilinear	General	Yes	Yes
GHER-M	Cartesian	Sigma	Yes	No
MARS3D	Cartesian/ Curvilinear	Sigma	Yes	Yes
MIKE-3	Cartesian	Z-coordinate	Yes	No
MOHID	Cartesian	General	Yes	Yes
MOM-4	Curvilinear	Z-coordinate	No	No
POL3DB	Cartesian	General	Yes	No
POM	Curvilinear	General	Yes	No
ROMS	Curvilinear	General	Yes	No
SHOC	Cartesian/ Orthogonal curvilinear	General	Yes	Yes
TELEMAC-3D	Finite element	Sigma	Yes	Yes
TRIM-3D	Cartesian	Z-coordinate	No	Yes

Table 2 List of all inputs for model selection

Tabs	Choices of input
Purpose	Planning, Real time
Projects	River flood forecast, Flood Plain, Tidal dynamic, Estuarine hydrodynamics, Temperature & density distribution, Salt water intrusion, Wave propagation, Wind storm propagation, Outfall, Water pollution, Eutrophication
Tasks	Water current, Water level, Vertical advection, Horizontal dispersion, Dissolved Oxygen, Biochemical oxygen demand, Phytoplankton, Nutrient concentration, Sediment interaction, Zooplankton, Other physical variables, Other water quality variables

Table 3 Characterization of model parameters

	Choice 1	**Choice 2**	**Choice 3**	**Choice 4**	**Choice 5**
Numerical method	Eulerian-Lagrangian method	finite element	finite difference	boundary element	
Scheme	implicit	semi-implicit	explicit		
Dimensions	1-d	2-d vertical	2-d horizontal	3-d layered	3-d fully
Time-stepping algorithm	single step	alternating velocity and elevation split step	alternating direction split step		
Grid	uniform	not uniform			
co-ordinate system	rectangular	curvilinear	polar		
Vertical co-ordinate	normal	sigma	refined near surface	refined near bottom	refined near specific area
Stability	conditionally stable	unconditionally stable			
Error of scheme	first-order	second-order	higher-order		
Equation	momentum	continuity	state	density	pressure
Equation term	advection	Coriolis force	horizontal diffusion	decay	sediment interaction
Forcing	tide	river discharge	wind	density difference	
Initial condition	zero	non zero			
Boundary condition	zero value	first order zero	second order zero	in-out-bc	
Turbulence model	mixing length	k-ε model	dispersion coefficient		

Table 4 Conditions for various model parameters

Parameter	**Condition 1**	**Condition 2**	**Condition 3**	**Condition 4**	**Condition 5**	**Condition 6**
Finite difference method	1-d, 2-d or 3-d modeling	Often used in flow and water quality problems	Some of these methods only allow for uniform grid size			
Finite element method	1-d or 2-d modeling	More easily adapted to irregular grid size				
Boundary element method	Water depth very deep					
Eulerian-Lagrangian method	Advection-dominated transport problem	Unstructured grid				
1-d	Desire minimum computational time	Parameter variation substantially along one direction only				
2-d	Variation of flow or water quality parameters along the 3rd direction is small	Avoid excessive computation time in 3-d modeling				
3-d	Complex geometry	Stratification of water is significant	Large vertical current or vertical variation of current	Difference of salinity & temperature are important	Interested to vertical current or vertical structure of current	Tidal elevation not too large relative to water depth
Explicit	Accept both smaller spatial grid size and time step	Problem with small space scale and/or time scale	No problem on excessive computational time	High accuracy is more important than efficiency		
Semi-implicit	Feasible splitting of terms into implicit and explicit groups	Balance between implicit and explicit schemes				
Implicit	Accept smaller spatial grid size but not smaller time step	Problem with large space scale and/or time scale	Avoid excessive computational time	Efficiency is more important than accuracy		