Lecture Notes in Artificial Intelligence, Vol. 3029, 2004, pp. 886-894

Knowledge Representation on Design of Storm Drainage System

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Abstract. During the design of storm drainage system, many decisions are involved on the basis of rules of thumb, heuristics, judgment, code of practice and previous experience of the designer. It is a suitable application field for application of the recent artificial intelligence technology. This paper presents the knowledge representation of the design of storm drainage system in a prototype knowledge-based system. Blackboard architecture with hybrid knowledge representation techniques including production rule system and object-oriented approach is adopted. Through custom-built interactive and user-friendly user interfaces, it furnishes designers with entailed expertise in this domain problem.

1 Introduction

In the past decade, the potential of artificial intelligence (AI) techniques for providing assistance in the solution of engineering problems has been recognized. A knowledge-based system (KBS) is considered suitable for solving problems that demand considerable expertise, judgment or rules of thumb. It has made widespread applications and is capable to accomplish a level of performance comparable to that of a human expert in different fields: vertical seawall design [1]; liquid retaining structure design [2-4]; site level facilities layout [5]; modeling in coastal processes [6]; flow and water quality modeling [7]; thrust block design [8]; fluvial hydrodynamics [9-11]; river flow routing [12].

In drainage engineering field, existing computer models may be available to perform a particular task in the whole design process [13-15]. It is difficult to code empirical rules or expert knowledge in a conventional algorithmic framework. Over-emphasis has been placed on algorithmic procedures in many computer-aided design packages, thus producing a large gap between model developers and users. This may produce inferior design and cause the under-utilization, or even total failure of these models. The application of these individual programs requires the intensive knowledge of the designer and they are prone to human errors during the data transferring processes. There is a need to develop programming environments that can incorporate engineering judgment along with algorithmic tool [16]. Yet, no attempt has been made to apply this intelligent system to this domain problem. Design of storm drainage system involves many decisions to be made by the designer based on rules of thumb, heuristics, judgment, code of practice and previous experience. Moreover, the conventional design refers to design charts [17] where pipe diameters are adjusted by trial and error, entailing laborious work. A need arises for an user-friendly computer design aid as well as training tool coupled with the automation of the design process to design the storm drainage systems speedily and precisely, and to avoid troublesome manual computations. KBS is suitable to furnish a solution to this decision making process through incorporating the symbolic knowledge processing.

This paper describes the knowledge representation of a prototype KBS for design of storm drainage system. This application domain has relations to the upcoming research area of "ecological informatics". The KBS developed is based on Civil Engineering Manual Volume IV: Sewerage and Drainage [18]. It is intended not only to emulate the reasoning process followed by drainage designers, but also to act as an intelligent tool that furnishes expert advice to its users regarding the design process and selection of design parameters. Its knowledge base comprises representations of the design entities, as well as the design knowledge of human experts. Through custom-built interactive graphical user interfaces, the user is directed throughout the design process.

2 Design of Storm Drainage System

The design of the storm drainage system is multi-disciplinary involving expert knowledge of different fields. The Colebrook-White Equation is used to describe the whole range of pipe flow and to calculate the velocity and hence the capacity. The choice of designed rainfall intensity depends upon the duration of a rainstorm and the adopted statistical frequency of recurrence. Rainfall intensity curves are acquired based on the statistical analysis of long-term rainfall records from the Royal Observatory of Hong Kong. The Rational Method is employed for estimation of design peak runoff to be conveyed in the storm drainage system of Hong Kong. The pipe size is first selected for the accumulated runoff at each manhole inlet. The minimum and maximum actual flow velocities are limited in compliance with the requirement of the Civil Engineering Manual. Besides, in the backwater checking computational procedure, adjustment of the diameter of the pipes at manholes are required to ensure the backwater levels are always lower than the finished levels and flooding will not occur. Only commercially available pipe diameters are allowed.

3 The Prototype System

A prototype KBS has been customarily designed such that the user can always overrule any design options and recommendations provided by the system. It allows for users to fine-tune the system to their preference style, yet to let them benefit from its thoroughness, speed, and overall effectiveness for designing storm drainage system. Although this system is tailored for design based on the rainfall intensity-duration-intensity curves in Hong Kong, it can be readily adapted to cater for other conditions in other countries. Most engineers can easily exploit the full potential of the system with minimum supervision and within a short time span. This system has been implemented with the aid of a microcomputer shell Visual Rule Studio, which is a hybrid application development tool under object-oriented design environment. Visual Rule Studio acts as an ActiveX Designer under the Microsoft Visual Basic 6.0 programming environment. Production rules as well as procedural methods are used to represent heuristic and standard engineering design knowledge.

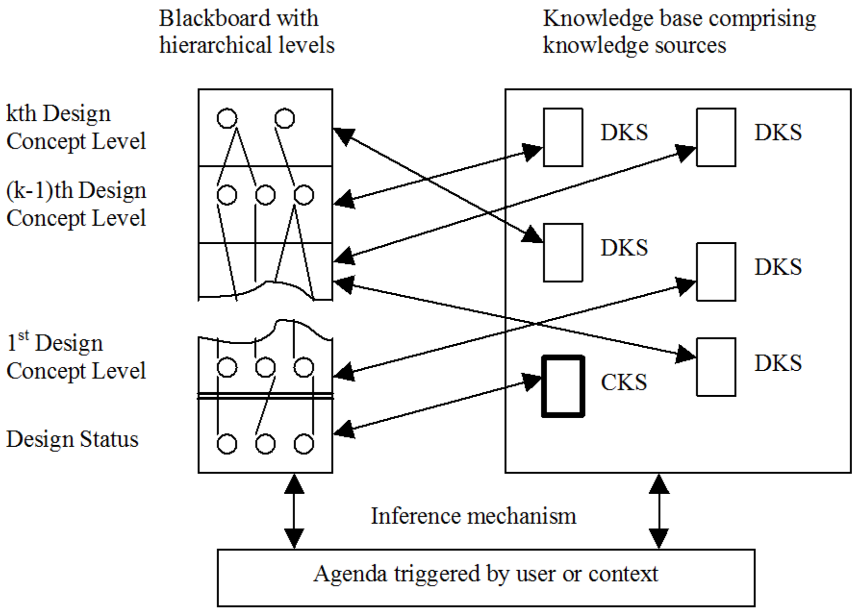

Fig. 1. Blackboard architecture of the prototype expert system (DKS and CKS denote Domain Knowledge Source and Control Knowledge Source respectively)

3.1 Blackboard Architecture

Blackboard architecture has been developed to furnish a problem-solving model with contribution from a multitude of knowledge sources at different levels by integration into a single system. A variety of specialized expertise or knowledge sources are grouped into separate modules by employing both rules and frames and, sometimes under object-oriented programming environment. Blackboard system encapsulates information sharing through the common data structure called a blackboard, which compiles the data entries as well as acts as the communication link among various knowledge sources. The blackboard acts as the global system context, which stores the current state of the solution, including problem data, intermediate parameters and final outputs of the design.

Previously, the blackboard architecture has been applied in solving a diversity of problems in other areas: control [19], speech recognition [20], dynamic rescheduling [21], crankshaft design [22], damage assessment of steel bridge [23], control of a cryogenic cooling plant [24], large space structures [25], liquid retaining structure [26], etc. Figure 1 shows the blackboard architecture of the system, which consists of diverse knowledge sources, a blackboard and an inference mechanism. It is adopted since the reasoning with multiple knowledge sources is essential to solve the problem on design of storm drainage system, which usually entails interaction between diversified knowledge sources. Moreover, the design follows from opportunistic decisions, which are often made incrementally.

Under the declarative knowledge representation environment, objects are used to encapsulate knowledge structure, procedures, and values. The prototype system combines expert systems technologies, object-oriented programming, relational database models and graphics in Microsoft Windows environment. By defining various types of windows as different classes, such as Check Box, Option Button, List Box, Command Button, Text Box, etc., they can inherit common characteristics and possess their own special properties.

3.2 Knowledge Representation

The knowledge is represented in multi-formalism approach comprising object-oriented programming, rules, procedural methods, extensive numerical algorithm and databases in this system. Its knowledge base comprises representations of design knowledge of the drainage expert.

Design context and the processes in the design, both represented as objects, are organized separately. The objects define the static knowledge that represents design entities and their attributes, which can be either descriptive or procedural in form. The blackboard is partitioned into a number of hierarchical levels, corresponding to different stages of the design process. This kind of declarative knowledge is unable to effect program execution merely by itself, but the attribute values of different objects can be stored and retrieved whenever they are required during the problem solving process. This organization emulates closely the reasoning mechanism of a human expert designer. Either one of the following attribute types, namely, compound, multi-compound, instance reference, numeric, simple, string, interval, and time, is defined for each class. A facet designs the inference strategy for processing an attribute. A search order list is set optionally for each attribute, whose value is obtained from rules, session context, default value, method or end-user query.

Reasoning knowledge, both heuristic and judgmental, including the constraints between the objects, is represented as rules. Knowledge represented in the IF/THEN production rules with confidence factors can be assigned either automatically, or in response to the user's request. These rules are a formal way of specifying how an expert drainage designer reviews a condition, considers various possibilities, and recommends an action. If the antecedent of a rule is determined to be true, the inference engine may fire the rule, inferring the conclusion statements to be true, which is then added to the working memory. Such rules are invoked mainly through change in pattern of other subprograms, instead of through a call from other subprograms in a specified algorithmic fashion. During each cycle, the conditions of each rule are matched against the current state of domain contexts. Rules are grouped into a rule set representing a collection of production rules with the same attribute as the conclusion. The rule sets include the knowledge necessary for the determination of different material properties, various geometrical ratios, interpolation of head loss coefficients, and selection of design parameters such as runoff coefficients in determination of peak runoff.

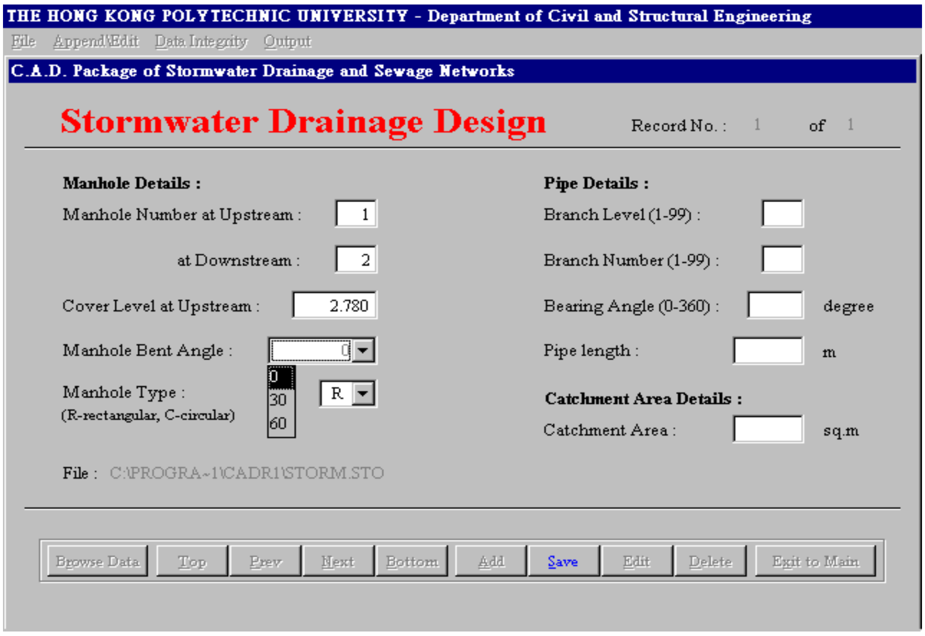

Fig. 2. Screen displaying interactive user interface of the system

Procedural knowledge, such as numerical processing, is represented in the form of object-oriented programming. Generic design entities are structured in a hierarchical knowledge base with inheritance properties. Besides, it comprises a blackboard together with two sets of knowledge sources, namely, Domain Knowledge Sources and Control Knowledge Sources, which represent the design processes. Diverse Domain Knowledge Sources, functioning independently and cooperatively through the blackboard, encode the actions to take for incremental build-up of the entire design process. Control Knowledge Sources involve meta-level knowledge, which establishes the problem solving strategy and controls the execution of the Domain Knowledge Sources. Since design steps in this system are explicitly seen on the main screen display, the sequence of design processes is primarily selected by the user. However, the validity of the sequencing is checked by Control Knowledge Sources.

Design Status only comprises a single object whereas there are several objects in the Design Concept level. Data inside Design Status are employed by the Control Knowledge Sources to determine the next possible action. After a specific design stage has been satisfied, the pertinent Design Status indicator will be assigned one of the values from the preset value list.

Most KBS development tools are not tailored for numerical processing but, instead, are designed for symbolic processing. However, this system can handle both symbolic and algorithmic programs simultaneously. Algorithmic models include capacity checking, velocity checking and backwater calculation. Custom-built codes as well as available existing codes are employed to perform these number-crunching tasks. Upon completion of execution of the external program, the previous session in the KBS is resumed. Of course, the Process Control knowledge modules continue to control the actions to be taken, depending on the outputs.

A database system is typically a record-keeping system employed to maintain relatively large amount of data. Some types of engineering knowledge are represented more conveniently in a database format. Here, database tables are used to represent engineering knowledge, such as head loss coefficients for various manhole configurations, fitting coefficients of the Intensity-Duration-Curves in Hong Kong, properties of pipe sections and properties of proposed alternative. Some heuristics are used to limit the choice of some design parameters to only practical values, acquired from practice engineers and code requirements. These databases contribute as a part of the entire design knowledge. Some of them such as the head loss coefficients are static and are not changed by any design activity whilst the others such as the database on properties of proposed alternative are dynamic and are generated during the execution of the system.

The knowledge used has been acquired mostly from written documents such as code of practice, textbooks and design manuals and complemented by experienced engineers involved with the design of storm drainage system. The user is guided through the process with step-by-step instructions. The system is capable of modeling and analyzing a network of up to 1,000 manholes. During execution, the screen shows the key parameters in one of the following forms: (i) flow number, pipe diameter, flow capacity, peak runoff; (ii) flow number, pipe diameter, actual flow velocity; (iii) flow number, pipe diameter, backwater level, and finished level, corresponding with the current calculation: i.e., capacity checking, velocity checking or backwater calculation.

3.3 Inference Methods

The inference engine controls the strategies on the selection of procedure methods and production rules and determines how, from where, and in what order a knowledge base draws its conclusions or design context. The Control Knowledge Sources evaluate the Design Status and decide the action in a data-driven forward chaining mechanism. The Domain Knowledge Sources need both forward and backward chaining inference mechanism to arrive at the solution. Based on the rated heuristic scores, Control Knowledge Sources then select the best action and proposes to the user before execution. All the design steps can be seen explicitly on the main screen display. This cycle is repeated until some feasible solutions satisfying all constraints are found.

The validity of the user's choice on the preferred sequence of design processes is checked by Control Knowledge Sources, which act opportunistically upon being triggered by user or situation during the design process. An event-driven inference processing mechanism is adopted so that the ensuing action of the system will depend on the input made by the user. For example, the applicable time of concentration is considered in accordance with the type of catchment. If developed area has been selected, the user is prompted to enter the time of entry and the pipe length. If natural area has been chosen, the user is prompted to enter the average fall from summit of catchment and the longest distance on the line of flow.

The input data entries by the user are kept at minimum, mostly through selection of appropriate values of parameters from the menus and answers to the queries made by the system. The input value will be rejected if it is not within the specified range. The system provides multi-window graphic images combined with valuable textual information, which is extremely valuable to novice designers. Figure 2 shows a typical screen displaying interactive user interface of the prototype system.

3.4 Application Examples

A typical storm drainage network in developed area with 39 manholes and a number of secondary and tertiary branches demonstrates the use of the prototype KBS. Each manhole should be numbered in a prescribed numbering order. Only the commercially available pipe diameters are given, i.e., multiple increments of 75 mm from 150 mm to 1,200 mm, and multiple increments of 150 mm from 1,200 mm to 2,100 mm. The design storm frequency, in accordance with the Hong Kong Civil Engineering Manual [18], is 1 in 50 year. The roughness value of all concrete pipes is assumed to be 0.6mm. For demonstration purpose of the capability of the KBS, arbitrary initial pipe diameters of 300 mm are input for all the pipes. The results have been verified rigorously with the conventional manual calculations, from which good agreements have been recorded. When performed manually, designing this system and producing design drawings required at least three iterations and 40 man-hours. Using the KBS, the same design did not require manual iteration and the design, including design drawings, was completed in only 1 man-hour. For larger storm drainage networks, the time savings become even greater.

3.5 Evaluation of System

In order to gauge the effectiveness of the system, 30 designers of varied technical backgrounds and experiences are required to complete a questionnaire with 8 questions that evaluate the presented system after their use. The feedback and written evaluations of the users on the scope and effectiveness of the system comprise several useful points. Table 1 shows the results of the user feedback questionnaire survey on using the system. Owing to the inherent variability in user rankings, only extreme rankings, such as exceeding a rank of '4-Agree', are considered significant. From the results, it is delighted to notice that no aspect of the system receives an unfavourable ranking. The tool is considered to be easy to comprehend, interesting, interactive, and relevant to designers. More importantly, the users find that it is extremely helpful and that the tool substantially increases their productivity in this application domain.

Table 1. Results of the user feedback questionnaire survey on using the system

Questionnaire item	Average rating#
Users basically possess good basic skill in using computer.	3.5
Users can actively control the design process through the system.	4.1
The system is easy to comprehend and follow.	4.2
The material with multiple formats of presentation is interesting.	4.0
The tool is interactive and user-friendly.	4.1
The presented material is relevant to the application domain.	4.2
The package is very helpful in assisting the design.	4.2
The tool substantially increases the productivity of users.	4.1

#1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree

4 Conclusions

It is demonstrated that the hybrid knowledge representation approach combining production rule system and object-oriented programming technique is viable with the implementation of blackboard system architecture for this domain problem. The knowledge base is transparent and is readily updated, which renders the KBS an ideal tool for incremental programming. By using custom-built interactive and user-friendly user interfaces, the prototype system is able to assist designers by furnishing with much needed expertise and cognitive support in the design activity. Some advantages of the KBS include improvement in efficiency and consistency of advice.

5 Acknowledgement

This research was supported by the Central Research Grant of Hong Kong Polytechnic University (G-T592) and the Internal Competitive Research Grant of Hong Kong Polytechnic University (A-PE26).

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