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CLIPS based decision support system for Water Distribution Networks

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Abstract

The Water Distribution Networks (WDN) are managed by experts, who, over the years of their association and responsibility, acquire an empirical knowledge of the system and, characteristically, this knowledge remains largely confined to their respective personal domains. In the event of any new information and/or emergence of a new problem, these experts apply simple heuristics to design corrective measures and cognitively seek to predict network performance. The human interference leads to inefficient utilization of resources and unfair distribution. Researchers over the past, have tried to address to the problem and they have applied Artificial Intelligence (AI) tool to automate the decision process and encode the heuristic rules. The application of AI tool in the field of WDN management is meager. This paper describes a component of an ongoing research initiative to investigate the potential application of artificial intelligence package CLIPS (short for C Language Integrated Production System, developed at NASA/Johnson Space Center) in the development of an expert decision support system for management of a water distribution network. The system aims to meet several concerns of modern water utility managers as it attempts to formalize operational and management experiences, and provides a frame work for assisting water utility managers even in the absence of expert personnel.

1 Introduction

The day to day operation of a water distribution network is managed by skilled operators who use their experience and heuristics to adjust and control elements such as pumps and valves to ensure the water supply up to the satisfaction of consumers. As water use tends to follow repeatable patterns the operators understand what is required for normal operation but, when an unplanned event such as a burst main occurs, they often have to respond in a reactive manner, usually with scant information provided by contact from customers already impacted by the event (Machell et al., 2010).

Managers of water utilities design most of their interventions and other decisions based on intuition, rule of thumb heuristics and trial and error. These operative decisions are often vague and lack objectivity and consistency. They suffer from inefficient network management because of distribution complexities and heavy human intervention. Because of this manual management based on heuristics, there is no guarantee that resources are utilized effectively (Raghvendran et al., 2007).

Usually, the policy of global exploitation of the water-supply system is not clearly defined. The main reason is the difficulty in gathering the required information, due to the fact that it is based on the operator's experience. Other reasons are the variety of control mechanisms and the frequent changes in the water network topology (Leon et al., 2000). Difficulties in managing a typical water supply system arise on account of (i) absence of a well defined policy framework, (ii) difficulty in gathering information that is coherent and objective because, as is often the case, information is based on individual perception and experience, (iii) complexity of a typical water supply system on account of a variety of control mechanisms, and (iv) frequent changes in the network topology (Leon et al., 2000). These reasons pose great difficulties in efforts to develop mathematical models of such inherently complex systems (Walski, 1993).

Recent developments in artificial-intelligence technology make it possible, by encoding knowledge and reasoning, for a computer program to simulate human expertise in a narrowly defined domain during a problem-solving process. This type of program is designed to assist in solving problems that require the skill and expertise of a human, by the application of heuristic rules of thumb. It is generally referred to either as a knowledge-based system (KBS) or an Expert System (ES) (Chau, 2004).

Present study attempts to develop a Decision Support System (DSS) that incorporates a dynamic knowledge acquisition system driven by simulated runs of a hydraulic model, suitably calibrated and validated for the given water utility. The Expert System uses CLIPS as AI tool and integrates computational platforms such as MATLAB, open source GIS and a Relational Database Management System (RDBMS) working under the umbrella of a common User Interface. The User Interface has been designed as a PC based application using Visual Studio.Net programming language.

2 Review of some Expert Systems

The history of expert systems is rather short. The first line of expert systems was developed just 35 yr ago and their basic design has not changed since. Successful early expert systems include platforms such as DENDRAL and MYCIN. DENDRAL (Buchanan and Feigenbaum, 1978) could analyze mass-spectrogram data of chemical structures and MYCIN (Shortliffe, 1976) could diagnose bacterial infections.

The success of DENDRAL and MYCIN provided a stimulus that triggered global research initiatives towards expert system development. Liao (2004) reviewed literature on various expert system methodologies and classified them in terms of the following eleven categories: rule-based systems; knowledge-based systems; neural networks; fuzzy expert systems; object-oriented methodology; case-based reasoning (CBR); system architecture development; intelligent agent (IA) systems; ontology and database methodology. The review shows that these methodologies were developed for a wide range of problems in fields as diverse as medicine, telecommunication engineering, water and waste water engineering, robotics etc.

In the field of water management some important application of Expert System may include EXPLORE (Leon et al., 2000); OASIS (Goforth and Floris, 1991); CRITQUING Expert System (Shepherd and Ortolano, 1996); IITWSEXP (Khosa et al., 1995); Expert System treated water distribution (Bunn et al., 2001); Network Management System For Water Distribution System (Raghvendran et al., 2007); Intelligent Control System For a Municipal Water Distribution Network (Chan et al., 1999).

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Some of the ES have been described in brief as follows:

- IITWSEXP (Khosa et al., 1995): IITWSEXP was developed for the campus water supply distribution system of Indian Institute of Technology, Delhi. The expert system was built using Level 5 Object expert shell for MS Windows and was designed to provide expert diagnostics about reported problems and their troubleshooting, daily run scenarios, and static and dynamic information regarding the physical components of the water supply system of IIT Delhi. The expert system utilized a dedicated database management system and also featured components on duty rosters and staff deployment and some relevant details about supply wells on the campus.
- Intelligent Control System For A Municipal Water Distribution Network (Chan et al., 1999): the implementation model was the system developed with the expert system shell, COMDALE/X. It is a SCADA based system which uses ES for taking decisions based on economic,social and environmental factors.
- EXPLORE (Leon et al., 2000): it employs the water demand forecast to obtain an optimal daily pumping schedule. The system has been applied to the management of the Seville City water-supply system.
- Network Management System For Water Distribution System (Raghvendran et al., 2007): the CygNet has been used to implement the NMS for Water Distribution Networks. CygNet is integrated NMS (Network Management Software) software that is currently being used by VSNL and MTNL for the management of large telecom networks in India.
- ES for Control Treated Water Distribution (Bunn et al., 2001): New Plymouth District Council (NPDC), New Zealand, has implemented an Expert System to optimize the distribution of water from the water treatment plant to five bulk supply reservoirs using linear program.

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– OASIS (Goforth and Floris, 1991): Operation Advisory and Simulated Intelligent System (OASIS) was developed as a knowledge base advisory system for water management operations of South Florida Water District. It was implemented on Symbolic workstation using Common LISP and Inferencing ART.

– CRITIQUING Expert-System Approach (Shepherd and Ortolano, 1996): it provides computer based decision support system for water supply system operations of San Francisco Water Department (SFWD). The critiquing system evaluates operating plan and provides feedback which includes suggestions for improvement, warning and alternatives.

In most of these foregoing initiatives an attempt was made to transfer knowledge from the heuristic domain to the knowledge base of the expert system. Some other ES have applied fuzzy logic to process information and suggest "best practice" guidelines for the network manager. Review of literature further reveals that presently available expert systems have an extremely limited scope of applications and are confined to only those specific tasks that they are designed for, and are unable to reason broadly across fields of expertise. These ES employ static knowledge domains without the ability to store newer facts and, therefore, unable to learn. The present study employs a dynamic knowledge domain that is designed to be self learning as it accommodates newer knowledge for future guidance.

3 Water distribution system management

Municipal water distribution system are large scale and spatially extensive,composed of multiple pipe loops to maintain satisfactory levels of redundancy, governed by nonlinear hydraulic equations, designed with inclusion of complex hydraulic devises such as valves and pumps and complicated by numerous layout, pipe sizing and pumping alternatives. In addition to this system is also affected with the inclusion of new areas within the municipal limits and population increase specially in metropolitan cities.

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Further, municipal Water Distribution Networks (WDN) are seldom new. As a result of the natural process of ageing, and with frequent interventions necessitated by perceived need to meet various performance goals, water supply networks undergo physical changes that significantly impinge on their hydraulic responses. Often, these impacts result in performance levels that are well below expectations. Additionally, WDN are managed by experts, who, over the years of their association and responsibility, acquire an empirical knowledge of the system and, characteristically, this knowledge remains largely confined to their respective personal domains. In the event of any new information and/or emergence of a new problem, these experts apply simple heuristics to design corrective measures and cognitively seek to predict network performance. Understandably, therefore,the assurance of a satisfactory response of the study network to suggested interventions is often based more on hope rather than on a validated belief.

In the present day scenario, managers of water utilities face numerous difficulties on account of the following reasons: expert scientific knowledge is not readily accessible; expert scientific knowledge is not available in user friendly manner and; the tacit, undocumented expertise required for operation of a water supply system may be lost when experienced personnel leave due to retirement or transfer.

For the decision-making process within water utilities, it is now necessary to identify basic modeling tools for analyzing pipe networks and making decisions for efficient planning, design and operation. The basic one is network analysis (simulation) which allows complex water supply and distribution networks to be examined under a variety of current and future operating conditions. A number of off the shelf packages are available that allow tailor made simulation models to be constructed for a water companies specific requirements. Popular packages include EPANET (US Environmental Protection Agency), AQUIS (7T), Infoworks (Wallingford software), SynerGEE (Advantica) and WaterGEMS (Bentley).

These simulation software packages enable the implementation of mathematical models of a Water Distribution Networks that combine the physical laws governing

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the networks with the equations that relate pressure and flow for each operational element (Machell et al., 2010). Computer models are now largely used for hydraulic study of water distribution systems. The results from the model must bear close resemblance to the actual performance of the hydraulic system (ECAC, 1999) i.e. these models must be calibrated.

There are new demands on water-resource staff to apply the existing tools properly and intelligently, including providing appropriate input parameters. However, with the recent advent of artificial-intelligence technology, personnel can be trained to fulfil this requirement. A computer with sufficient knowledge storage and a user-friendly interface can be consulted as an expert; as a result, it is a suitable KBS application. Moreover, there are usually few specialists with a thorough understanding of numerical modeling of flow and/or water quality. The KBS enables staff to become acquainted with up-to-date simulation tools and fill the existing gaps between researchers and practitioners in the application of recent technology (Chau, 2004).

4 The Decision Support System development process

The aim of development of DSS is to codify the heuristic expert knowledge in a form that is easily understood by the computer; enable a novice user to manage a WDN; possible real world scenarios corresponding to various design interventions are generated and results are used to enhance the scope and reach of the knowledge base of CLIPS. The preliminary exercise in the development process involved- understanding elements of WDN and their modeling; study of already existing DSS; understanding of the terminology used by the operators and experts; appreciation of the current strategies for management of a water utility. The activities posed less difficulty since the authors have been associated with the operation and maintenance of large water distribution network. The authors are familiar with the terminologies used in the WDN management and have developed several heuristic rules for management of WDN.

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5 System prototype development

Since DSS is to be applied on a WDN, it is imperative to have a modal case study of a WDN. Anytown Network (Walski et al., 1988; Kapelan, 2002) as shown below in Fig. 1 is taken as the model case study. The network consists of 35 pipes assembled in a fashion that they form 19 loops. As the present study deals only with steady state analysis, the tanks at nodes 501 and 502 in the original network have been changed to reservoirs.

An important aspect of the system prototype development is the selection of hardware and software used in the system implementation. The proposed DSS is developed as PC based application in Visual Studio.Net environment. Visual Studio.NET is a complete set of development tools for building ASP Web applications, XML Web services, desktop applications, and mobile applications etc. and all use the same integrated development environment (IDE), which allows them to share tools and facilitates in the creation of mixed-language solutions. This framework provides a clear, object-oriented, extensible set of classes that enables you to develop rich Windows applications. Additionally, Windows Forms can act as the local user interface in a multi-tier distributed solution.

6 Decision Support System framework

A Module is the basic building block of the DSS. The DSS has modules for Calibration, Simulation, Daily Run and Information. The complex task of Computation, Data handling, visualization and decision of each module is handled through MATLAB, SQL server, MapWinGIS and CLIPS. Figure 2 shows basic framework of DSS.

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7 Support tools for DDS

Before discussing the basic building blocks of DSS, it is imperative to list and describe its associated supporting tools and platforms. Following section describes some of the tools integrated with DSS.

7.1 Relational Data Base Management System

Before a model of WDN is built, data pertaining to the components of WDN must be collected from different sources. Data should be collected and stored in a format that is readily available to modelers, planners and decision makers and easily understood by computer. Before an actual water distribution system can be modelled or simulated with a computer program, the physical system must be represented in a form that can be analyzed by a computer. This normally requires that the water distribution system first be represented by using node-link characterization. Such representation of data is voluminous and requires some efficient data base management system to manage the data intelligently by providing structures for storing data and methods for extracting information from it. Relational databases have the further advantage of allowing specifying how different data relates to each other. In the present study a Relational Data Base Management System (RDBMS) for WDN has been developed using Structured Query Language (SQL). All necessary tables have been created in SQL. The tables are linked to each other through a primary key. One such link is shown in Fig. 3 where pipe ID (pid) is common in pipe and pump table.

7.2 CLIPS knowledge base and inference engine

CLIPS is a type of computer language designed for writing applications called expert systems. CLIPS (short for C Language Integrated Production System), developed at NASA/Johnson Space Center, has recently shown increasing usage. CLIPS is a forward-chaining rule-based language that resembles OPS5 and ART, other widely

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known rule-based development environments. Figure 4 shows the basic components of CLIPS, which are essential for an ES and its implementation in ES.

- User Interface: the mechanism by which the user and the expert system communicate.
- Fact-list: a global memory for data. Inserted as pipe-facts, node-facts, valve-fact etc. into the memory of clips.
- Knowledge-base: contains all the rules used by the expert system. For instance, consider the following partial rule that is used by the system.
- Inference engine: makes inferences by deciding which rules are satisfied by facts, prioritizes the satisfied rules, and executes the rule with the highest priority.
- Agenda: a prioritized list created by the inference engine of instances of rules whose patterns are satisfied by facts in the fact list.

The CLIPS is a fact driven environment where rules are fired depending upon the pattern matching. CLIPS does not have its own database and facts stay in the memory of the CLIPS during its active state only. As soon as the CLIPS environment is closed all facts are removed from its memory. Therefore, a mechanism was required through which facts are inserted into the memory from the database. This was achieved through creation of classes and sub-classes. In CLIPS the deftemplate construct is used to create a template which can then be used to access fields by name. The deftemplate construct is analogous to a record or structure definition in programming languages such as Pascal and C. In the ES, the main Class has been kept as Fact. For each of the object as Pipe, source node, demand node etc. two child classes of facts were created to capture the slot value of the fact from database. For example, as shown in Fig. 5 below, for pipe object, 1st Child class is DRAFPipe which specifies the slots to be used in the fact and 2nd child class DRPipe which is child of DRAFPipe.

The deftemplate shown in Fig. 6, for pipe details is inserted into CLIPS environment and values of slot are passed from the database and then pipe fact is inserted into

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the memory. If the inserted fact matches with the already existing facts then chaining mechanism of CLIPS fires rules. When using an ES, two kinds of integration are important: embedding CLIPS in other systems and calling external functions from CLIPS. CLIPS was designed to allow both kinds of integration. The easy addition of external functions allows CLIPS to be extended or customized in almost any way. The integration of CLIPS with Visual studio.Net has been accomplished through ClipsNet.dll.

7.3 MATLAB platform

Visual studio.Net framework along with CLIPS and SQL server cannot perform complex mathematical computations required for different modules the DSS for management of WDN. Therefore to impart computational capabilities, a purely mathematical platform MATLAB, has been integrated with WAMAN. The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects. Today, MATLAB engines incorporate the LAPACK and BLAS libraries, embedding the state of the art in software for matrix computation. The ES-WAMAN uses stand-alone COM components created by MATLAB compiler. Each of the COM components is used in VS.net as class which can perform desired computation using data from SQL and send back the results to .Net environment.

7.4 Hydraulic Network Solver (HNS)

The DSS being developed has modules on calibration, simulation and daily run which require repeated solution of mathematical model of pressurized WDN. The possibility of linking public domain network solver, EPANET (Rossman, 1993) through DLL was examined and it was felt that an in-built solver would be economical in terms of computer time. Therefore, based on Todini and Pilati (Todini and Pilati, 1988) improved gradient method, a HNS was developed in MATLAB and incorporated in Visual Studio.Net through COM component.

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7.5 Calibration algorithm

In recent years, several researchers have proposed different algorithms for use in automatically calibrating hydraulic network models. These techniques have been based on the use of analytical equations (Walski, 1983), simulation models (Boulos and Ormsbee, 1991; Gofman and Rodeh, 1982; Ormsbee and Wood, 1986; Rahal et al., 1980) and optimization methods (Coulbeck and Orr, 1984; Ormsbee, 1989). Techniques based on analytical equations require significant simplification of the network through skeletonizations. As a result, such techniques may only get the user close to the correct results. Conversely, both simulation and optimization approaches take advantage of using a complete model. In the recent past, the focus of the researchers has shifted from traditional analytical techniques to heuristic techniques such as Genetic Algorithm (GA), Simulated Annealing (SA), Shuffled Frog-Leaping Algorithm (SFLA) and Ant Colony Optimization (ACO).

ACOAs as a class of optimization techniques has been quite encouraging and these techniques have often been seen to outperform other heuristics based approaches when applied to some benchmark problems (Maier et al., 2003; Zecchin et al., 2005).

Considering that the calibration process involves adjustment of some key system parameters like nodal demands and/or pipe-roughness values, prior knowledge of their rational values can act as a heuristic in stochastic search procedures such as GAs and ACOAs. The authors have devised and used a automated calibration algorithm for Water Distribution Networks for internal pipe roughness using ACO.

7.6 Open source GIS platform

MapWinGIS is an open source geographic information system (GIS) and an application programming interface (API) distributed under the Mozilla Public License (MPL), built upon the Microsoft.Net Framework 2.0. The MapWinGIS components and end user application support manipulation, analysis, and viewing of geo-spatial data in many standard GIS data formats. Hence, MapwinGIS is a mapping tool, a GIS modeling system and a GIS API in a re-distributable open source. To impart the capabilities of visualization of WDN with base map, manipulation and creation of shape files, MapWinGIS platform has been integrated with Visual Studio.Net through ax-Map object.

8 Calibration module

The schematic of calibration module is shown in Fig. 7. Two sets of observed values of flow (Q) in pipes and head (H) at different loading conditions are taken as input parameters. WDN is calibrated using ACA with one set of observed boundary conditions and then validated with other set of boundary conditions. The calibrated network is saved in RDBMS for further use.

9 Simulation module

A conventional distribution network simulation model is comprised of static asset information including pipe lengths, diameters, connectivity, and network topography; and information about dynamic parameters, for example, the distribution of demand, and elements such as pumps, reservoirs and valves. Most contemporary modelling packages in current use utilise models that include every pipe down to the level of, but not including, customer service pipes. Standard daily time-varying demand relationships are estimated for different customer types, and these are summed and allocated at pipe junctions (nodes) according to the distribution of customers. The models are normally used to simulate flows and pressures over a fixed (normalised data from a specific date) 24 h period which provides enough information to be suitable for purpose (Machell et al., 2010).

Most simulation systems generate a great number of reports. The variety of data generated sometimes makes analysis and decision making tedious. A system can be conceived in which an expert system accesses the output of a simulation run and,

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based on the user's objective, chooses and retrieves the relevant data and provides a mechanism for exception reporting. This is an especially desirable feature if the analyst is not a professional but an engineer who, for example, occasionally uses simulation for analyzing complex situations. The carry out simulation studies to improve the services by adding/deleting or updating the components of WDN namely pipes, junctions, valves and pumps etc.

Figure 8 shows the schematic of the simulation module. Changes which user proposes in the WDN components makes one scenario. If the scenario exists in knowledge base then user has option to either view the details or proceed further. The non existent scenario is taken to network solver for flows and nodal heads. The values of pipe flows and nodal heads are asserted as facts in inference engine of CLIPS which fires certain rules to issue Advice/Warning to the user. The Advice/Warning along with scenario is stored in Knowledge Base of the Expert System for future guidance. Thus Expert System is dynamic and is constantly upgraded. Since the CLIPS platform does not has permanent memory i.e. the contents of the memory are lost as soon as the focus is removed from the program, the contents of all the existing simulation scenarios are transferred to the Knowledge Base of the CLIPS. To facilitate transfer of existing (previous memory) and current information (user interventions) of all the WDN components, two templates viz. "memory" and "user" are created in CLIPS. A sample of deftemplate and rules for simulation module of the DSS is shown in Fig. 9.

10 Planning module

Planners carefully research all aspects of a water distribution system and try to determine which major capital improvement projects are necessary to ensure the quality of service for the future. This process, called master planning (also referred to as capital improvement planning or comprehensive planning), may be used to project system growth and water usage for the next 5, 10, or 20 yr. System growth may occur because of population growth, annexation, acquisition, or wholesale agreements between water supply utilities (Walski et al., 2001).

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The ageing of pipes, and a consequent increase in internal pipe roughness, is always accompanied by loss of conveyance. Such a scenario is indeed realistic and confronts all water supply networks. In water utility practices, Hazen-Williams C-factor is the most commonly used parameter to represent internal roughness of water mains and by extension their carrying capacity and internal roughness of water mains (Walski et al., 1988) and the present study has also adopted this approach. The pipe roughness grows roughly linearly with time and the rate of roughness growth, a, is strongly influenced by the pH of water and the corresponding model for growth of roughness may be written as (Colebrook and White, 1937):

$$e = e_o + at \tag{1}$$

In Eq. (1), e is the absolute roughness height (L); e_o is the initial roughness height (L); a is the growth rate in roughness height (L/T); and t is the time variable (T). Using Colebrook-White (Colebrook and White, 1937) and Swamee-Jain (Swamee and Jain, 1976) approximations, Hazen-Williams C_{HW} may respectively be written as (Walski et al., 1988).

$$C_{\text{HW}} = 18.0 - 37.2 \log(X) \tag{2}$$

$$C_{\text{HW}} = 33.3 \,|\log(0.27X)|^{1.08} \tag{3}$$

where, $X = (e_0 + at)/D$ and D is the diameter of pipe. The relationship between the annual roughness growth rate, a, and the Langelier saturation index (LI) with the latter controlled by factors such as the pH of water, its alkalinity, and calcium content can be represented as Eq. (4) (Lamont, 1981).

$$a = 10^{-(4.08 + 0.38\,\text{LI})} \quad \text{for LI} < 0 \tag{4}$$

Given the age of the pipe and its diameter of old pipe, it is possible to obtain an estimate of the Hazen-Williams C-factor. Based upon the above theoretical account, as the system under goes ageing process, following things are expected to happen for any WDN:

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1. With age of the WDN, the Hazen-Williams C-value will reduce.
2. The consequent head loss in the WDN would increase.
3. The total energy requirement in the WDN for the same input parameters would as well increase.

Therefore, from the management prospective it would be interesting to have a planning module which computes the Hazen-Williams c-values for next 5, 10, and 15 and 20 yr of planning horizon and for each horizon it shall compute (a) total Energy requirement; (b) total Head loss in WDN; (c) head loss in each individual pipe; (d) variation of C-values. Above information is populated in graphical manner for the guidance of the operators. The working of planning module is shown in Fig. 10 and screen shot of planning module of Expert system is shown in Fig. 11. The planning module populates the

- Variation of Pipe flows and junction heads over different planning Horizon (Fig. 12).
- Variation of Hazen-William C-values for different groups of Pipes over the different planning Horizon (Fig. 13).
- Variation of Total Energy requirement in KW and total head loss in the system over the different planning Horizon (Fig. 14).

11 Daily run module

A water distribution system, like any large complex system, must be operated properly so that it performs at an acceptable level of service. Many water utilities use human operators whose primary function is to monitor the pulse of the water distribution system and provide system control when needed. Several methods of controlling water distribution systems are available, each representing an increasing level of automation.

The Automated control represents the case where instrumentation and control equipment are used to control the distribution system automatically. Such control can be implemented either locally at the facility or throughout the system. Typically, simple operating rules are used to determine which component is operated and how it is operated. Systems that rely on advanced control use optimization algorithms, decision support systems, artificial intelligence, or control logic to control the distribution system. Figures 15 and 16 below depicts the Daily Diagnostic Module (DDM) of the ES and a selected screen shot respectively. This module has subordinate component sub-modules for the following tasks: retrieve the status of WDN on some previous date and time (Sub-Module-I); perform daily run scenario for a given input parameters (Sub-Module-II); diagnose specific consumer complaint (Sub-Module-III).

- Sub-module-I: Every daily run for a given set of input parameters is stored in the knowledge base of the ES. Through the User Interface, we can retrieve the status of WDN on a given date and time.

- Sub-module-II: The schematic of this sub-module is shown in Fig. 17. This sub-module assists a network manager for ascertaining the status of the WDN for given set of input parameters. The input parameters are used by network solver to compute flow in each pipe and pressure at each head of the WDN. These computed values are compared with the observed values or values arrived under normal conditions, in the Inference Engine of CLIPS to issue warning/advice.

- This module of DDM is designed to manage consumer complaints. This module uses backward chaining process in the Inference Engine of CLIPS. Whenever a complaint is received, it identifies to which component of WDN the consumer is attached. Then using backward chaining mechanism it identifies possible cause of the complaint and suggests suitable measures to the network manager to overcome the complaint.

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12 Conclusions

The aim of the development of DSS was to explore the potential application of CLIPS for effective management of WDN. Supporting platforms like MATLAB, SQL, CLIPS and MapWinGIS were integrated under a common umbrella of Visual Studio.Net environment. Furthermore, the proposed DSS structure facilitates specialized tasks such as network modeling including its calibration. DSS has been designed to perform other routine tasks such as directed simulation runs required to monitor a network as well as to generate knowledge regarding network performance following any planned or unplanned intervention.

It has been observed that CLIPS is the suitability of the forward reasoning and matching to the application and representation of the knowledge. This simplicity of the CLIPS allows the knowledge base to grow to over any number of rules without greatly affecting the structural complexity of the knowledge or the cost of using it. The powerful CLIPS environment has facilitated the development of an DSS for management of WDN. The DSS is now being developed for maintenance of a real life WDN in the city of Delhi.

References

Buchanan, B. and Feigenbaum, E.: DENDRALand Meta-DENDRAL: Their Applications Dimension, Artif. Intell., 11, 5–24, 1978. 4

Boulos, P. and Ormsbee, L.: Explicit network calibration for multiple loading conditions, Civ. Eng. Environ. Sys., 8(3), 153–160, 1991. 13

Bunn, S., Helms, S., Hollings, B., Ltd, F., Council, N., Auckland, N., Plymouth, N., and Zealand, N.: Application of an expert system to control treated water distribution, Vodafone House, Auckland, New Zealand, sbunn@ beca. co. nz, New Plymouth District Council, New Plymouth, helms@ npdc. govt. nz, 2001. 4, 5

Chan, C., Kritpiphat, W. and Tontiwachwuthikul, P.: Development of an intelligent control system for a municipal water distribution network, Proceedings of the 1999 IEEE Canadian Conference on Electrical and Computer Engineering, Edmonton, Alberta, Canada, 9–12 May 1999. 4, 5

Chau, K.: Knowledge-based system on water-resource management in coastal waters, Water Environ. J., 18(1), 25–28, 2004. 8

Coulbeck, B. and Orr, C.: A network analysis and simulation program for water distribution systems, Civ. Eng. Environ. Sys., 1, 139–144, 1984. 13

Colebrook, C. and White, C.: The reduction of carrying capacity of pipes with age, Journal of the Ice, 7(1), 99–118, 1937. 16

Shortliffe, E.: Computer-based medical consultations, MYCIN, New York, 1976. 4

Gofman, E. and Rodeh, M.: Loop equations with unknown pipe characteristics, Journal of the Hydraulics Division, 107, 1047–1060, 1982. 13

Goforth, G. and Floris, V.: OASIS: An intelligent water management system for South Florida, AI Applications, 5(1), 47–55, 1991. 4, 6

Kapelan, Z.: Calibration of water distribution system hydraulic models, PhD thesis, University of Exeter, 2002. 9

Khosa, R., Parida, B., Singh, B., and Aggarwal, S.: Expert system for iit water supply, Master's thesis, Unpublished Undergraduate Project under Student Undergraduate Research Award (SURA), Indian Institute of Technology, Delhi, 1995. 4, 5

Rossman, L.: EPANET water quality model, Technical report, PB-93-236552/XAB, Environmental Protection Agency, Cincinnati, OH (US), Risk Reduction Engineering Lab., 1993. 12

Lamont, P.: Common pipe flow formulas compared with the theory of roughness, J. Am. Water Works Ass., 73(5), 274–280, 1981. 16

Leon, C., Martín, S., Elena, J., and Luque, J.: EXPLORE – hybrid expert system for water networks management, J. Water. Res. Pl.-ASCE, 126(2), 65–74, 2000. 3, 4, 5

Machell, J., Mounce, S. R., and Boxall, J. B.: Online modelling of water distribution systems: a UK case study, Drink. Water Eng. Sci., 3, 21–27, doi:10.5194/dwes-3-21-2010, 2010. 3, 8, 14

Maier, H., Simpson, A., Zecchin, A., Foong, W., Phang, K., Seah, H., and Tan, C.: Ant colony optimization for design of water distribution systems, J. Water. Res. Pl.-ASCE, 129, 200–209, 2003. 13

Ormsbee, L.: Implicit network calibration, J. Water. Res. Pl.-ASCE, 115, 243–257, 1989. 13

Ormsbee, L. and Wood, D.: Explicit pipe network calibration, J. Water. Res. Pl.-ASCE, 112, 166–182, 1986. 13

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Rahal, C., Sterling, M., and Coulbeck, B.: Parameter tuning for simulation models of water distribution networks, Proceedings of Institution of Engineers, 69(2), 751–762, 1980. 13

Raghavendran, V., Gonsalves, T. A., Rani, U., Kumar, S., and Narasimhan, S.: Design and Implementation of a Network Management System for Water Distribution Networks, ADCOM 2007 Proceedings of the 15th International Conference on Advanced Computing and Communications, IEEE Computer Society Washington, DC, USA , doi:10.11.09/ADCOM.2007.62, 2007. 3, 4, 5

Shepherd, A. and Ortolano, L.: Water-supply system operations: Critiquing expert-system approach, J. Water. Res. Pl.-ASCE, 122(5), 348–355, 1996. 4, 6

Swamee, P. and Jain, A.: Explicit equation for pipe-flow problems, ASCE Journal of Hydraulic Division, 102(5), 657–664, 1976. 16

Todini, E. and Pilati, S.: Gradient Algorithm for the Analysis of Pipe Networks, Computer Applications in Water Supply 1, Research Studies Press Ltd., Taunton, UK, 1988. 12

Walski, T.: Technique for calibrating network models, J. Water. Res. Pl.-ASCE, 109(4), 360–372, 1983. 13

Walski, T.: Tips for saving energy in pumping operations, J. Am. Water Works Ass., 85(7), 49–53, 1993. 3

Walski, T., Shields, F., and Sharp, W.: Predicting Internal Roughness in Water Mains, Miscellaneous Paper EL-88-2, US Army Engineer Waterways Experiment Station, Vicksburg, 1988. 9, 16

Walski, T., Chase, D., Savic, D., Strafaci, A., and Dietrich, K.: Water Distribution Modelling, Haestad Press, Waterbury, CT, USA, 2001. 15

Zecchin, A., Simpson, A., Maier, H., and Nixon, J.: Parametric study for an ant algorithm applied to water distribution system optimization, IEEE Transactions on Evolutionary Computation, 9(2), 175–191, 2005. 13

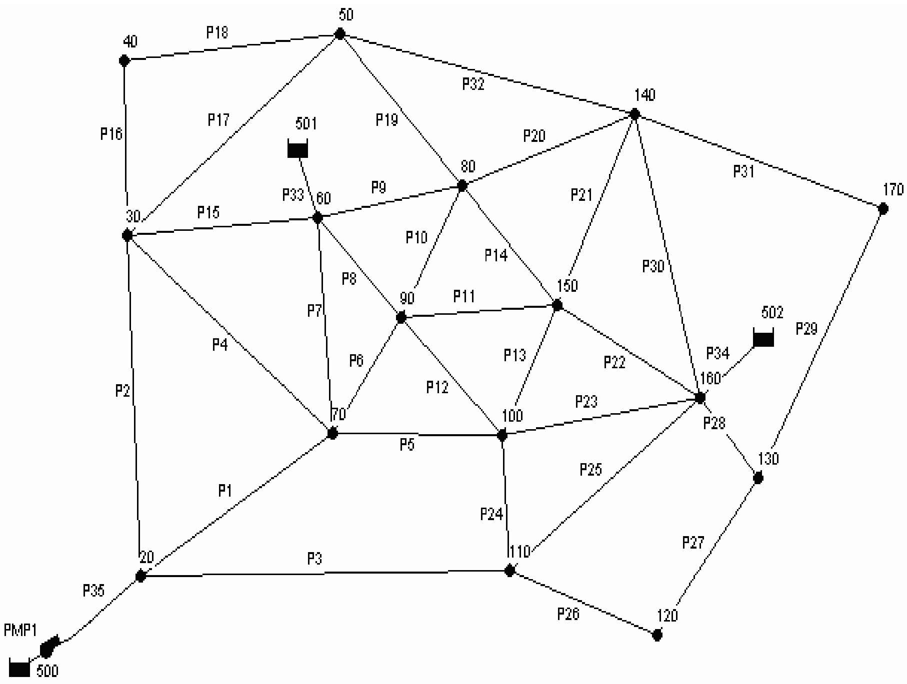

Fig. 1. The Anytown Network.

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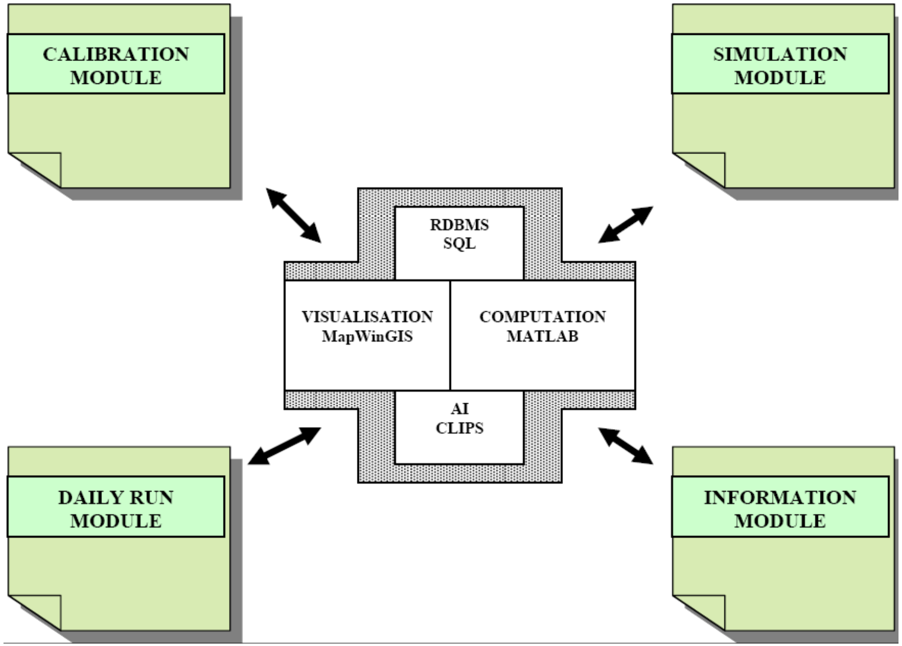

Fig. 2. Basic Framework of Decision Support System.

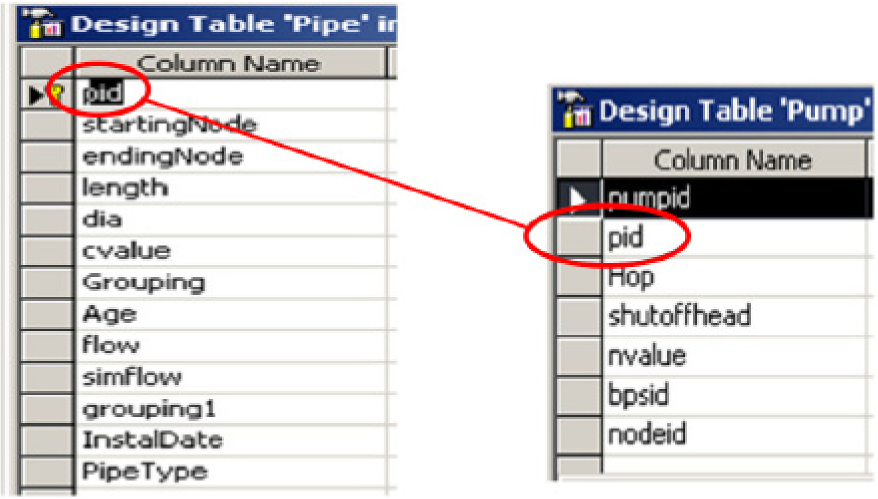

Fig. 3. RDBMS for Expert System.

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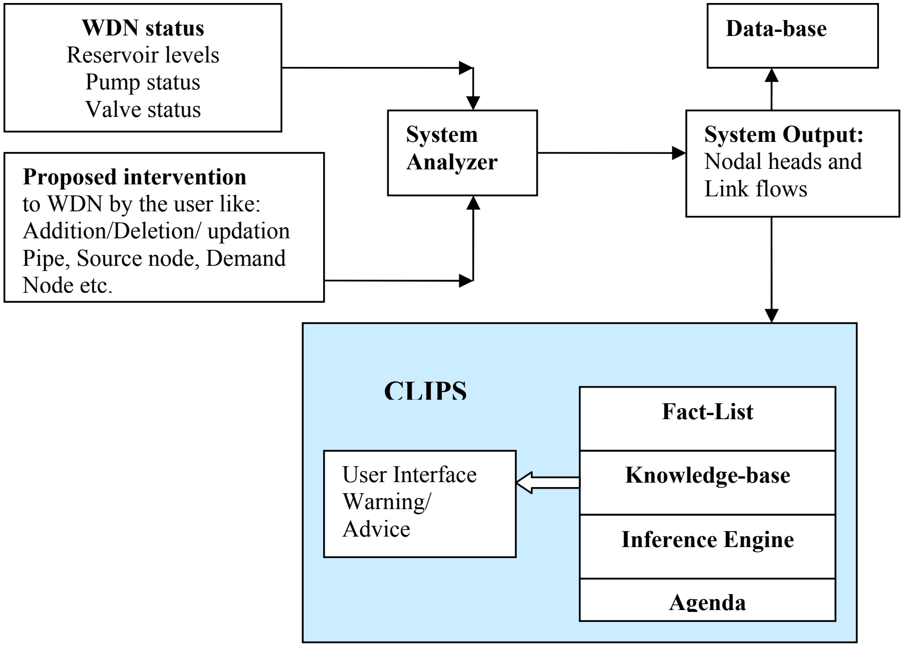

Fig. 4. Components of CLIPS and its implementation in ES.

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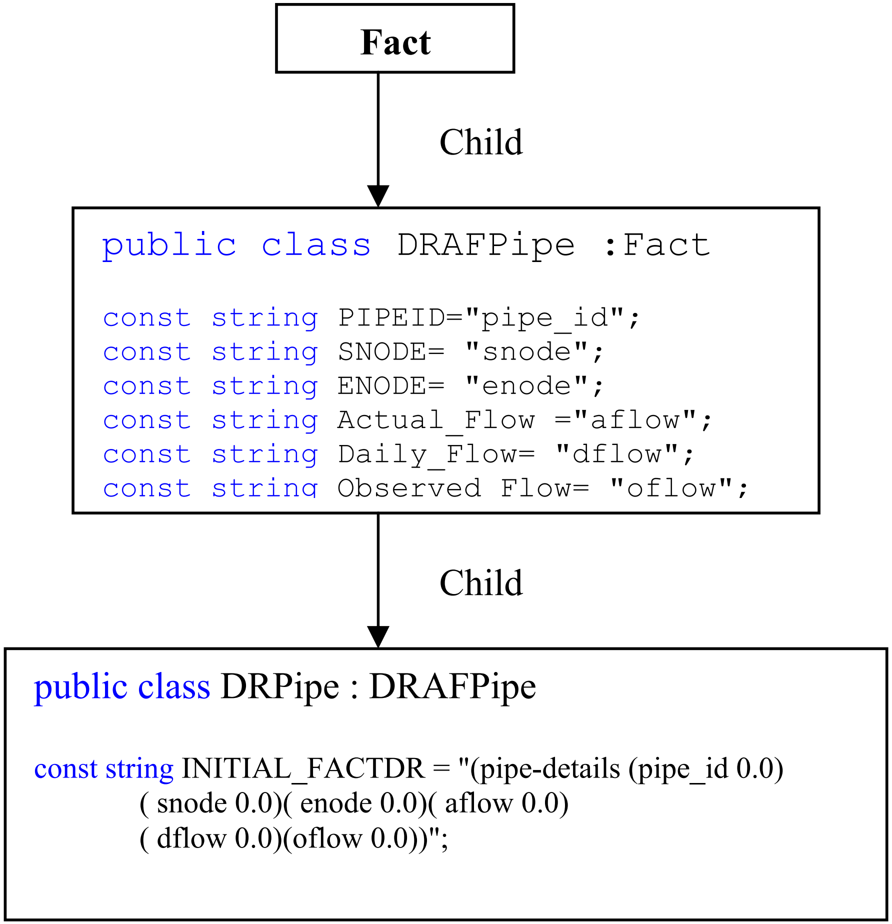

Fig. 5. Class and child Class for fact of Pipe object.

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```
(deftemplate pipe-details
    (slot pipe_id (type FLOAT)(default 0.0))
    (slot snode (type FLOAT)(default 0.0))
    (slot enode (type FLOAT)(default 0.0))
    (slot aflow (type FLOAT)(default 0.0))
    (slot dflow (type FLOAT)(default 0.0))
        (slot oflow (type FLOAT)(default 0.0)))
```

Fig. 6. A deftemplate for Pipe details.

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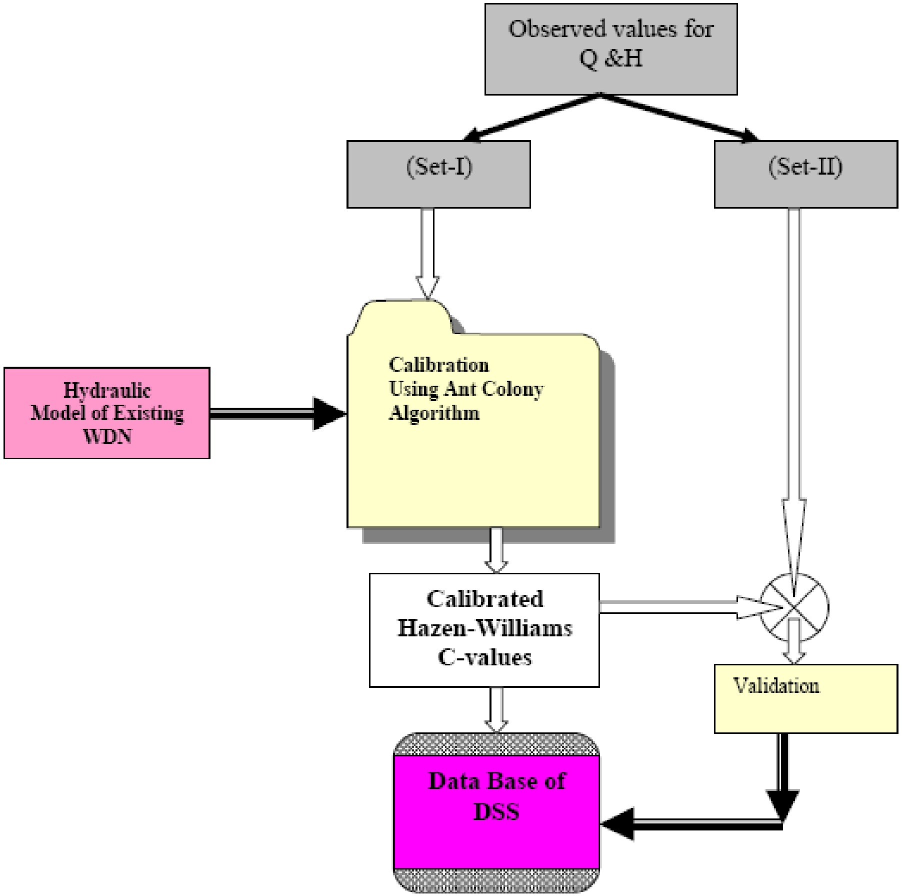

Fig. 7. Schematic of calibration module.

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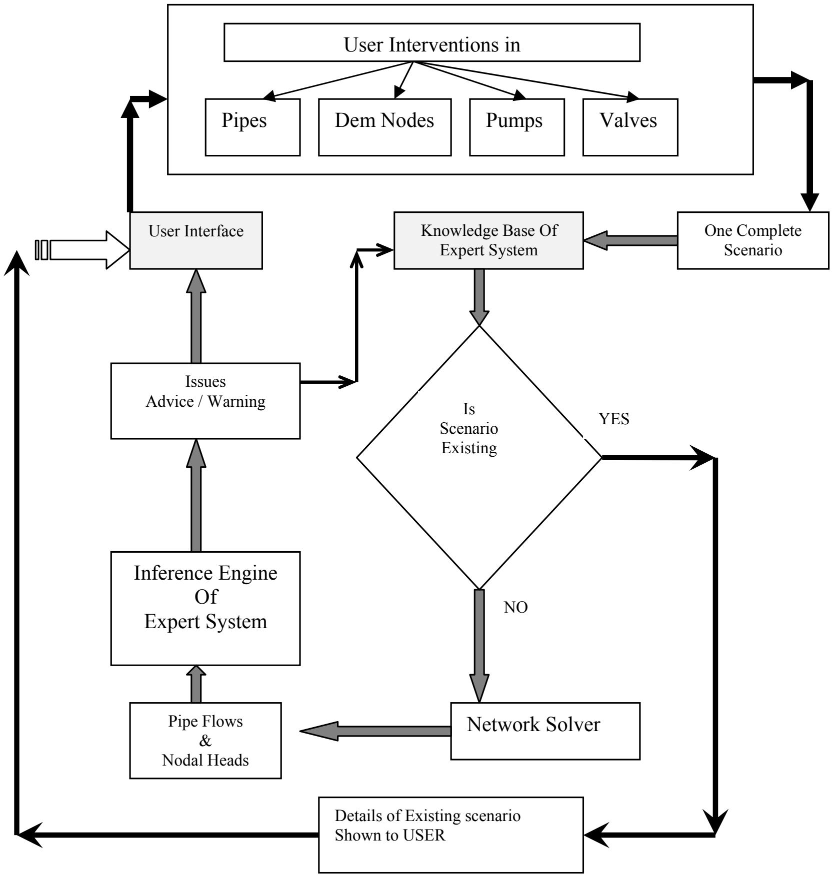

Fig. 8. Schematic of simulation module of the DSS.

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deftemplate SNmem (slot snid (type FLOAT)) (slot snhead (type FLOAT)) (slot statusSNM(type FLOAT))) (deftemplate SNuser (slot sncurr (type FLOAT)) (slot snheadcur (type FLOAT)) (slot statusSNU(type FLOAT))) ;****************************** (deftemplate DNmem (slot dnid (type FLOAT)) (slot demem (type FLOAT)) (slot elemem (type FLOAT)) (slot statusDNM (type FLOAT))) ;***************************** (deftemplate DNuser (slot dncurr (type FLOAT)) (slot deuser (type FLOAT)) (slot eleuser (type FLOAT)) (slot statusDNU (type FLOAT))) ;******************************* (deftemplate Pipmem (slot pid (type FLOAT)) (slot snodemem (type FLOAT)) (slot enodemem (type FLOAT)) (slot diamem (type FLOAT)) slot lenmem (type FLOAT))) ;******************************* (deftemplate Pipuser (slot pcurr (type FLOAT)) (slot snodeuser (type FLOAT)) (slot enodeuser (type FLOAT)) (slot diauser (type FLOAT)) slot lenuser (type FLOAT))) ;*******************************	(defrule snode ?f1<-(SNmem (snid ?sn)(snhead ?snh)(statusSNM ?stm)) ?f2<-(SNuser (sncurr ?snc)(snheadcur ?snhc)(statusSNU ?stu)) => (if (and (eq ?sn ?snc) (eq ?snh ?snhc)(eq ?stm ?stu)) then (retract ?f2) (RuleSN))) ;***************** (defrule dnode ?f5<- (DNmem (dnid ?dn)(demem ?dem)(elemem ?elem)) ?f6<-(DNuser (dncurr ?dnc)(deuser ?deu)(eleuser ?eleu)) => (if (and (and (eq ?dn ?dnc)(eq ?dem ?deu)) (eq ?elem ?eleu)) then (retract ?f6) (RuleDN))) ;*************** (defrule pipe ?f9<- (Pipmem (pid ?p)(snodemem ?snm)(enodemem ?enm)) ?f10<- (Pipuser (pcurr ?pc)(snodeuser ?snu)(enodeuser ?enu)) => (if (and (and (eq ?p ?pc)(eq ?snm ?snu)) (eq ?enm ?enu)) then (retract ?f10) (RulePipe))) ;

Fig. 9. Deftemplate and Clips rule for simulation module.

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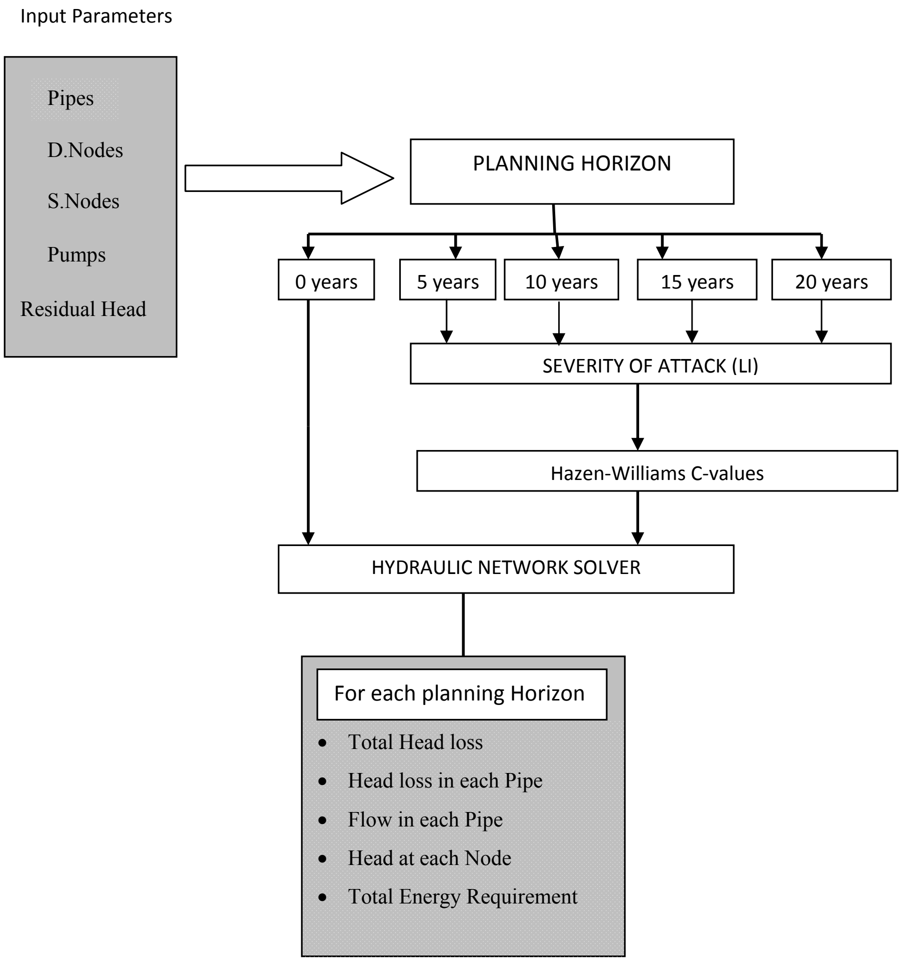

Fig. 10. Schematic of planning module.

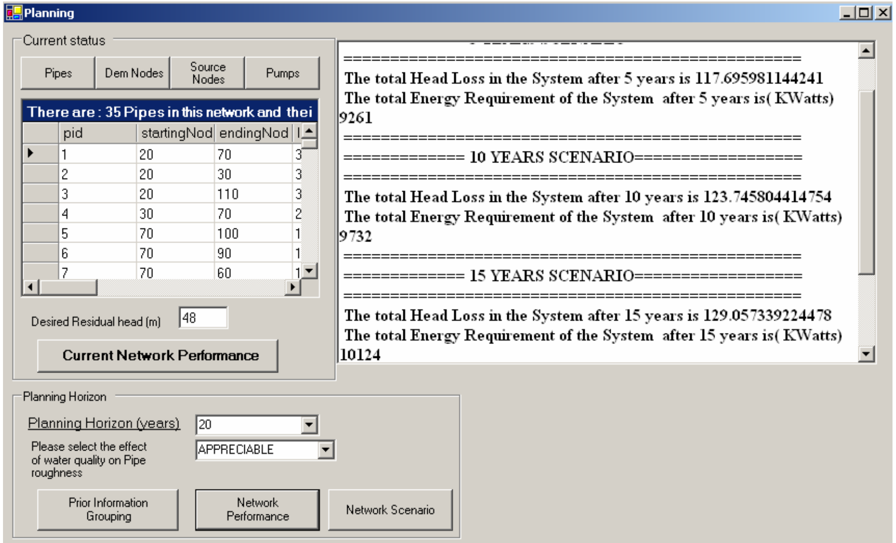

Fig. 11. Screenshot of the planning module of Expert System.

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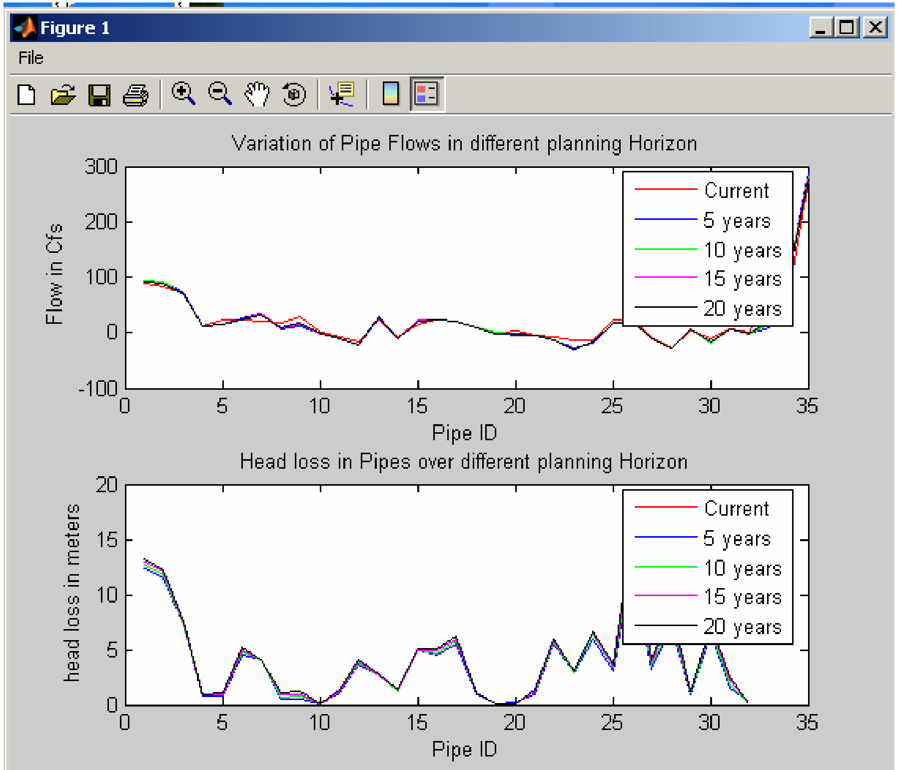

Fig. 12. Variation of pipe flows and junction heads over different planning horizon.

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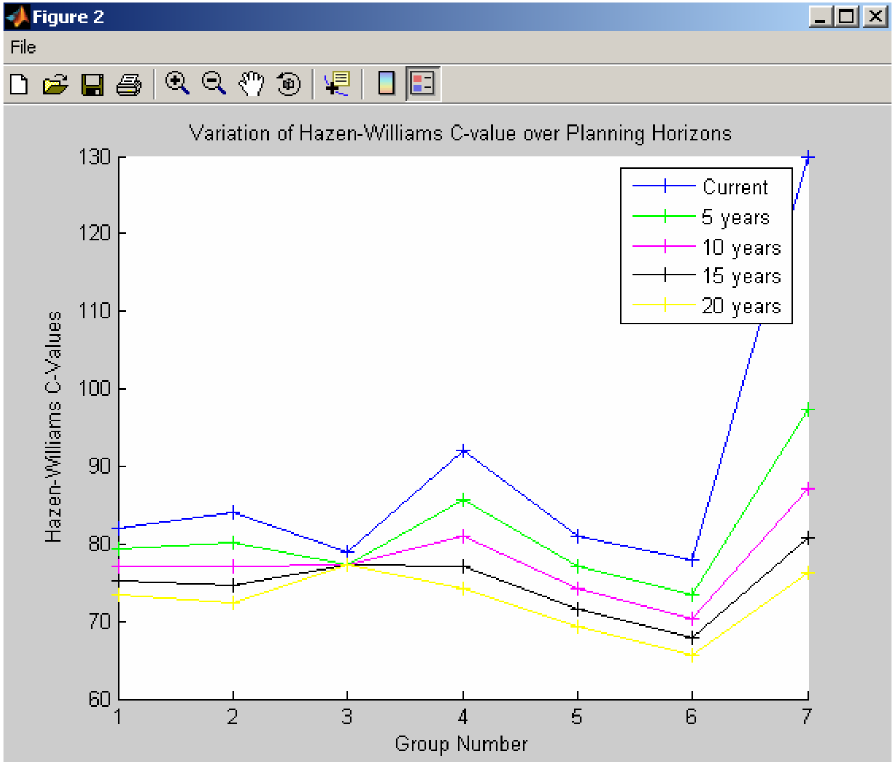

Fig. 13. Variation of Hazen-William C-values for different groups.

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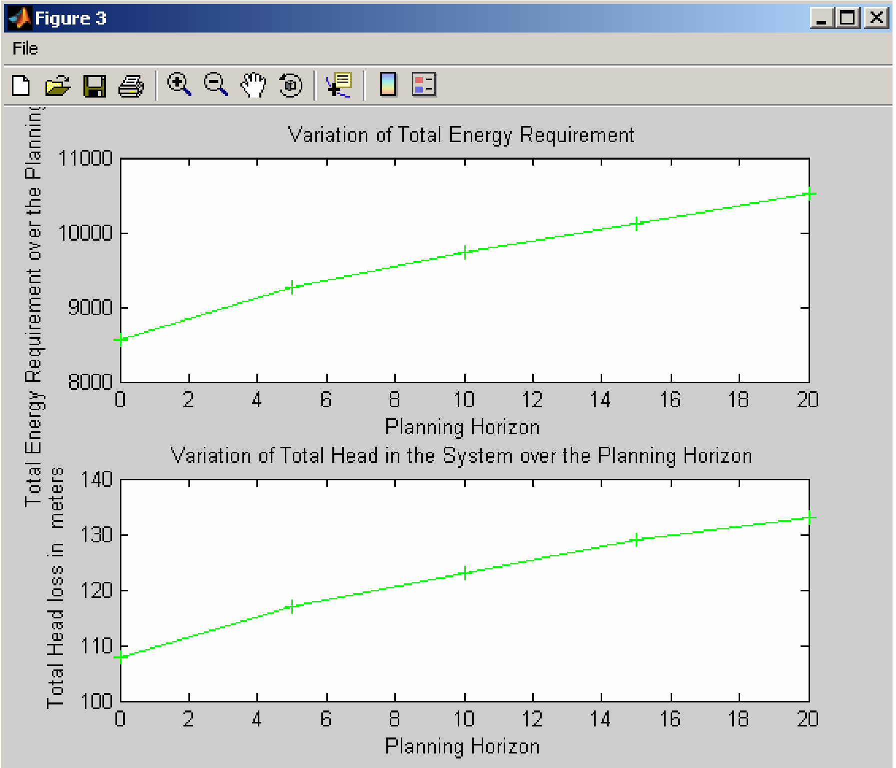

Fig. 14. Variation of total energy requirement in kw and total head loss.

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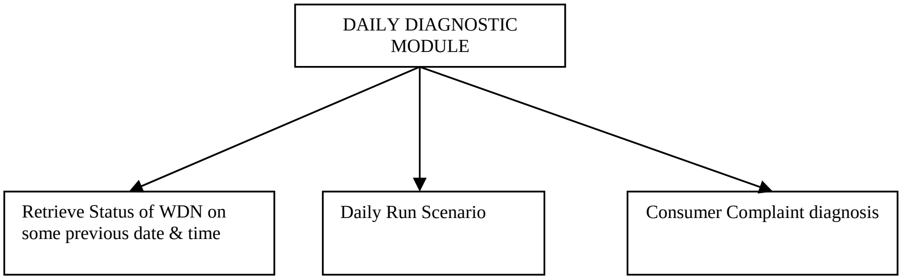

Fig. 15. Different modules of Daily Run Module.

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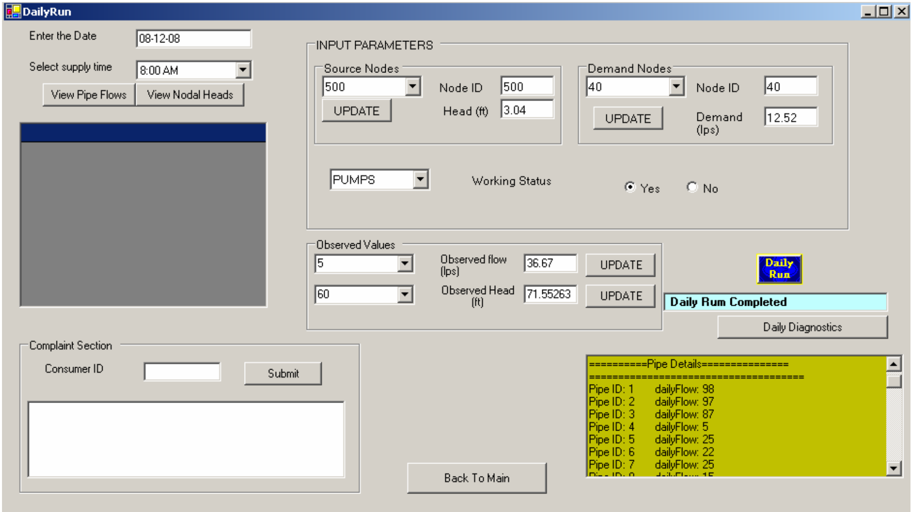

Fig. 16. Screenshot of Daily Run Module of DSS showing sub-modules.

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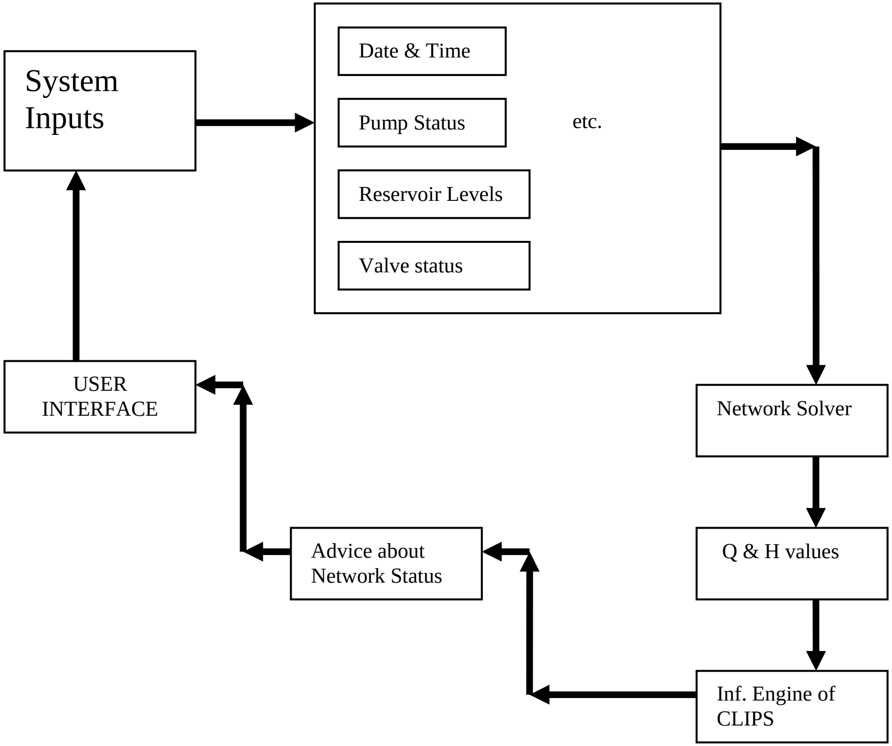

Fig. 17. Schematic sub-moduleII of Daily Run Module.

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