DAWN: A platform for evaluating water-pricing policies using a software agent society

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Abstract: Lately there is a transition in water management: policy makers leave aside traditional methods focused on additional-supply policies and focus on water conservation using demand control methods. Water Agencies use water-pricing policies as an instrument for controlling residential water demand. However, design and evaluation of a water-pricing policy is a complex task, as economic, social and political constraints have to be incorporated. In order to support policy makers in their tasks, we developed DAWN, a software tool for evaluating water-pricing policies, implemented as a multi-agent system. DAWN simulates the residential water demand-supply chain and enables the design, creation, modification and execution of different scenarios. Software agents behave as water consumers, while econometric and social models are incorporated into them for estimating future consumptions. Scenarios and models can be parameterized through a friendly graphical user interface and software agents are instantiated at runtime. DAWN's main advantage is that it supports social interaction between consumers, which is activated using agent communication. Thus, variables affecting water consumption and associated with consumer's social behavior can be included into DAWN scenarios. In this paper, DAWN's agent architecture is detailed and agent communication using ontologies is discussed. Focus is given on the econometric and social simulation models used for agent reasoning. Finally, the platform developed is presented along with real-world results of its application at the region of Thessaloniki, Greece.

Keywords: Agent-based simulation; Water-pricing policy; Decision Support Systems; Autonomous Agents

1 INTRODUCTION

1.1 Background

Policy making for water management is in general a demanding task. It involves in-depth study of all factors and conditions including water consumption demands and water assets availability. Even more, it requires critical ability and expertise for identifying the consequences of a certain policy in effect. Support to this procedure is provided by scientific methodologies and tools that simulate the water management cycle. Simulation tools are used to model the water management dynamics on a certain system. Their use supports policy-makers to estimate future effects of a certain policy on the system. The overall goal of a simulator is not to forecast the exact state of the modeled system, but to explore how the system will evolve because of a specific policy. In this work, we focus on water management in urban areas. Pricing water in urban areas is a complicated task, as economic, social and political parameters have to be considered. Water-pricing policy design involves the investigation of water-demand and its correlation with water price. In studying the residential water demand, researchers have utilized a variety of statistical and econometric techniques, and they have focused on finding the appropriate demand management policies that offer incentives in saving water [Mylopoulos et al., 2004].

In order to support policy makers in such tasks, we developed DAWN, a software tool for evaluating water-pricing policies, implemented as a multi-agent system. Policy-makers and analysts, the actual users of DAWN, can specify water-pricing scenarios and evaluate them through a software environment. In this paper, we present the DAWN platform and demonstrate its capabilities to simulate social interactions among consumers and to explore how the total water consumption may be affected. Quantitative results, obtained through DAWN simulations, can be used by analysts for further evaluation of the pricing policies.

1.2 Agent modeling for water management

DAWN employs an agent-based approach to model the residential water-supply chain. Agent modeling has been used for water-management simulations. Consider the FIRMA (Freshwater Integrated Resource Management with Agent) project, where agent models are used for the simulation of natural, hydrological, social and economic dimensions of water resources management at water basins. [Gilbert, 2003; Moss et al., 2000]. FIRMA is a decision support tool for the integrated design of water management. Agents in FIRMA are used to model all stakeholders involved in a water basin demand-supply cycle. A second example is the SINUSE project, which employs an agent-based approach for integrated management of a water table system. Agent models in SINUSE are used to represent interactions between a water table and its users while taking into account the social behavior of the farmers [Feuillette et al., 2003]. In addition, Ducrot et al. [2002] are working on the NEGOWAT project, which is expected to deliver a integrated methodology using both agent models and role-playing games to address conflict resolution and negotiation for sustainable water management at a water catchment in the Metropolitan Region of Sao Paulo.

The aforementioned agent-based decision support systems have been successfully applied for medium-level water management regions, such as river-basins, water-tables or water catchments. Advancing on the way earlier research work has dealt with agent-based decision support systems for water management, we present DAWN, a software tool for simulating something different, i.e. the residential water demand-supply chain, and to a local scale.

2 THE DAWN PLATFORM

2.1 Functional requirements

Residential water demand-supply chain involves two main stakeholders. One is the Water Utility, which constantly supplies water to an urban area and puts into effect the water pricing policy. The other is the area residents who consume water and pick up its cost. A generic scenario of this system is:

1. The Water Utility initiates a pricing policy for managing water demand.
2. The Consumers Society reacts to the selected pricing policy. Individual consumer reconsider their own water consumption with respect to water price, social influence, weather conditions and other fixed parameters.
3. The Water Utility revises its water-pricing policy in a timely fashion.

The main principle, upon which DAWN was designed, is that actual consumers interact with each other. Social activity definitely affects water consumption behavior. Thus, DAWN's core is a society of agents, serving as a sample of water consumers. This society reacts to the employment of specific water-pricing policies, simulating the dynamic behavior of the actual consumers.

Water consumer agents follow an econometric model for estimating their consumption, while a social interaction model was incorporated to define consumer social behavior. Configuration of this hybrid model is on the discretion of the DAWN user. Scenario evaluation and DAWN's agent model may be easily modified by the user, who can define all parameters required for the simulation through a GUI.

The main purposes of DAWN are to:

a. Support the evaluation of water-pricing scenarios, constituting a flexible, easy-to-use simulation tool.
b. Provide reliable results, to support the decision-making process.
c. Model the social behavior of water consumers and provide a methodology for incorporating it into state-of-the-art consumption models.

2.2 DAWN scenarios

The main objective of DAWN is to simulate the residential water demand-supply chain in order to facilitate the evaluation of water pricing scenarios. DAWN users (scientists, analysts, decision-makers) relying on their expertise and the available data need to follow a certain procedure to realize this objective. An abstract description of the DAWN simulation procedure involves the following steps:

1. **Data collection and scenario design**. A user prepares the simulation scenario by specifying a set of parameters for the water-pricing policy and the water consumption model. The scenario is input to DAWN through a GUI.
2. **System self–configuration**. DAWN processes the scenario entered by the user. The

simulation procedure is initialized and autonomous agents consuming water, within the society of agents, are instantiated.

3. **Scenario simulation.** The simulation procedure is launched. Simulation is performed in iterative steps. Each step simulates a time interval, during which water consumption is estimated.

4. **Result presentation.** While the simulation runs, the total and individual consumption are presented to the user. When the simulation is terminated, all results are saved.

5. **Evaluation of the scenario results.** DAWN scenario quantitative results are evaluated by the user. Comparison and study of the results can lead to valuable conclusions.

The aforementioned procedure is schematically represented in Figure 1.

2.3 DAWN Architecture

The DAWN functionality described in the previous section has been realized through an agent-based architecture, shown in Figure 2. All actors in the residential water demand-supply chain simulated have been implemented using agents. The Water Consumers, the Water Utility and the Meteorological Office are represented by autonomous agents, who undertake the simulation of the water demand-supply chain. In addition, the Simulator Agent (SA) is utilized to moderate and synchronize the simulation procedure. Simulator Agent is also responsible for capturing user-defined scenario specifications through a GUI.

When a new experiment is started by the user, SA sets up the whole simulation process and instantiates all agents required for the simulation. These agents include a Water Supplier Agent (WSA), a Meteorologist Agent (MOA), and a set of Water Consumer Agents (CA). During the instantiation process, SA appoints to all agents the user-specified parameters, required to realize their respective models.

Having all agents instantiated, the simulation process starts. SA facilitates the overall procedure. A simulation step starts when SA asks from WSA the total consumption for the respective time-interval. WSA contacts all CAs, informing each one about the cost of water it consumed in the previous step. Each CA utilizes the econometric and social models to estimate its new consumption. Social activity between CAs is realized via agent messaging. Water consumption econometric and social models are discussed in the next section.

Each CA reports its water consumption demands to the WSA, which calculates the total demand. The latter is communicated to SA and presented to the user, signing the termination of the simulation cycle. Each simulation cycle corresponds to a certain time interval, defined by the user.

MOA is responsible for suppling all CAs with meteorological conditions. As weather conditions are communitywide, this information is passed to CAs through WSA. Note that the MOA intervenes in the process only if meteorological parameters are used.

The simulation process is repeated for a certain number of iterations, defined by the user. When all iterations are performed, the simulation ends. In DAWN, agent lifecycle is equal to the simulation time. When the simulation is ended, all agents are terminated.

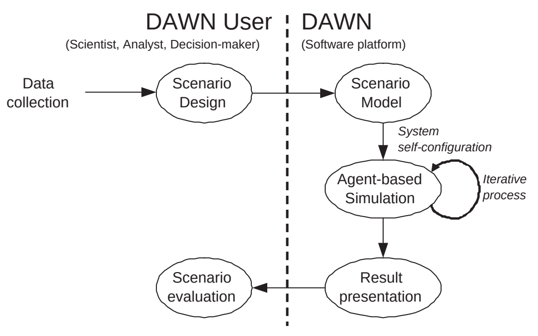

Figure 1: Functional flow diagram

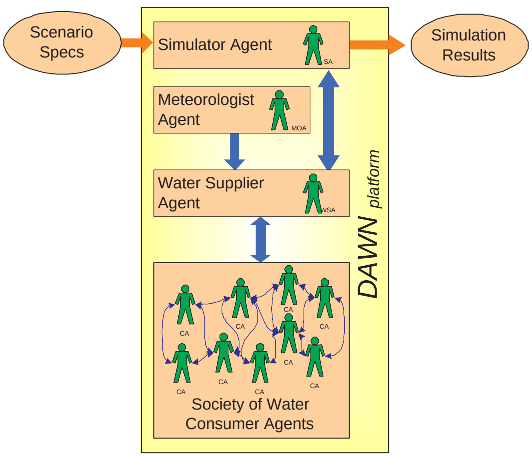

Figure 2: DAWN platform architecture

3 DAWN MODELS

3.1 Econometric model

Water demand estimation is usually formed as a generic model of the form $Q = f(P, Z)$, which relates water consumption Q to some price measures P and other factors Z [Arbues et al., 2003].

The econometric model, adopted in DAWN, specifies the water consumption Q for time interval T in the form:

$$\ln Q_T = \sum_i e_i \ln(f_i[P_{T-1}]) + \sum_j e_j \ln(f_j[Z_T])$$

where P is the price, Z are other factors influencing water demand, e is the corresponding elasticity. This model is highly reconfigurable by the system user as all variables, functions and elasticities can be specified.

3.2 Social model

In DAWN, the water consumer society is simulated as a set of Consumer Agents. Each CA represents a single consumer or a consumer group having common needs. Communication among CAs simulates the social interaction among consumers. CAs are situated on a square grid. Each CA is determined by its position on the grid. So, a single CA is identified as *CA(x,y)*, where (x, y) are its coordinates on the grid. Social interaction between CAs is limited to a *neighborhood*, in analogy with the actual social interaction, which is not communitywide. Therefore, a CA neighborhood is specified as the square area on the grid, whose center is the specific CA and its radius is defined by the *SightLimit* parameter. All agents residing in the neighborhood are supposed to be CA's *Neighbors*.

As an example, consider a 2-d grid of side equal to six, shown in Figure 3. Let the *SightLimit* parameter be one. For each CA, a neighborhood square of side three is defined. The neighborhood area of *CA(3,3)* is shown in Figure 3. The social model is realized in the neighborhood area, so *CA(3,3)* consumption is affected only by its two neighbors, *CA(2,2)* and *CA(2,4)*. Note that each agent may reside in more than one neighborhoods. For example, *CA(2,2)* is neighbor of both *CA(3,3)* and *CA(1,1)*.

All CAs operate simultaneously in two distinct, yet cooperative roles. CAs behave as both consumers and neighbors. The neighbor role is analogous with the actual consumer behavior to influence its neighbors, through social activities. In the agent field, this activity is modeled as an agent communication.

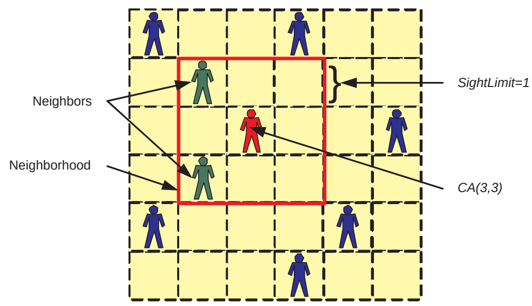

Figure 3: CA society distributed over a 2-d grid

Each CA, acting as neighbor, sends an agent message, containing its influence in the form of a *social weight*. On the other hand, each CA acting as consumer is influenced by its neighbors. It receives all social weights sent by its neighbors, and based on their sum, readjusts its water demand.

3.3 DAWN hybrid model

In DAWN the social model is incorporated into the generic econometric model, forming a hybrid model formed as $Qd = f(P, S, Z)$, where S is the social model factor. The latter is specified as a function of the social weights communicated.

The water quantity Q consumed by a CA at time interval T is specified by the function

$$\ln Q_T = \sum_i e_i \ln(f_i[P_{T-1}]) + \sum_j e_j \ln(f_j[Z_T]) + \sum_k e_{ki} \ln(f_k[\sum_N SW_T])$$

where the social model is incorporated as the sum of all social weights SW, communicated during the T-th cycle in the neighborhood N. In this way, the social interaction among neighboring agents is incorporated into the classic econometric model.

In the real world, consumers exhibit dissimilar behaviors. Each individual promotes water conservation practices at a different degree. In a similar way, changes in water demand, as a reflection of social influence, are different. Thus, in DAWN, the user is enabled to specify distinct CA types. Each type corresponds to a consumer group behaving in a similar way, thus sharing the same hybrid model. Consumer Agents of various types enable the user to simulate nonidentical social behaviors. In this way, consumers having dissimilar social behaviors can be represented by distinct consumer type agents.

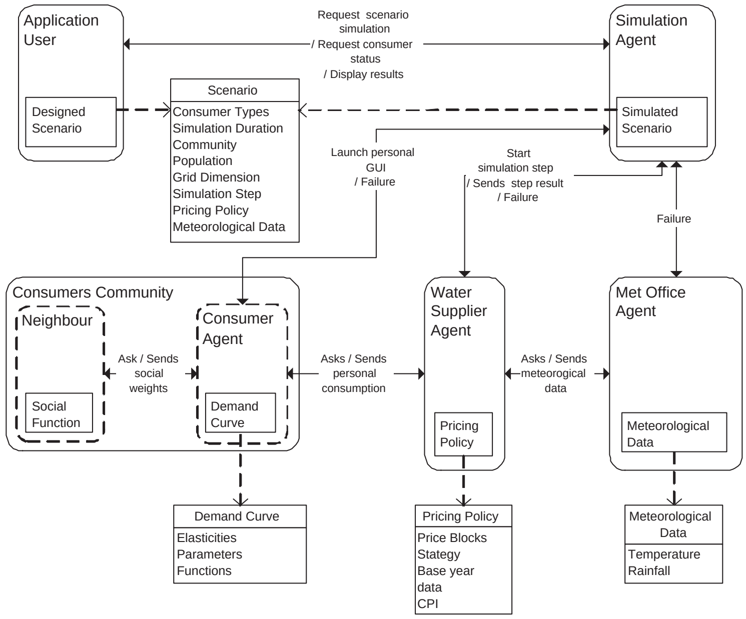

Figure 4: AORML External Agent Diagram

4 DAWN IMPLEMENTATION

4.1 Software design and ontology

DAWN model has been implemented using software agents, which were designed using the GAIA methodology [Wooldridge et al., 2000]. The software agent interaction has been specified using the Agent-Object-Relationship modeling language (AORML), introduced by Wagner [2003]. In Figure 4, the AORML external agent diagram is depicted. Each Consumer Agent realizes two distinct roles, the role of a Water Consumer and the role of a Consumer Neighbor. Each CA, in order to calculate its own demand, communicates with its neighbors, asking for their *Social Weights*, and when it is asked for its social influence replies with the appropriate weight. Additional functional activities of all agents involved in DAWN are incorporated, along with the administrative functions of the platform, such as GUI updates and user inputs.

Agent messages follow a generic ontology developed using the Protégé-2000 ontology editor [Noy et al., 2001]. Part of the WDS ontology developed is shown in Figure 5, containing the concepts of the system, along with agent Actions and Predicates. The slots of the various concepts have been configured in order to contain the appropriate information communicated by the agents. For example, Social Parameter corresponds to the Parameter concept having two slots: name, and value for describing name and value of social weights.

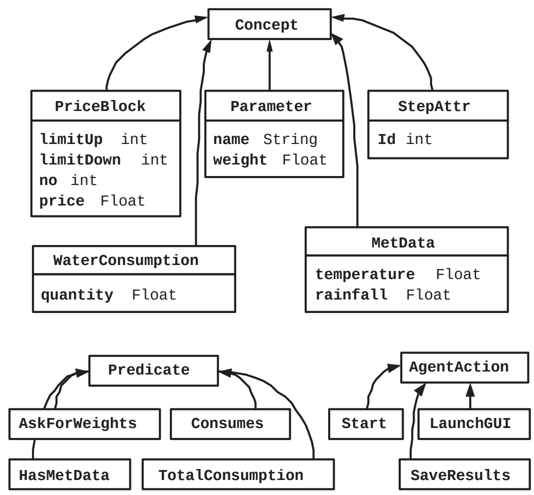

Figure 5: Water Demand-Supply Ontology: Concepts, Predicates and AgentActions

4.2 Implementation details

The DAWN platform was implemented in Java, while the development and utilization of agents confronts to the FIPA specifications [FIPA, 2002]. JADE platform has been used for agent development [Bellifemine et al., 2001].

The DAWN user is required neither to have any programming skills, nor to understand the internal functionalities of the platform. The advantages of the implemented system are its fast performance, user-friendly interface and its “open”, easy-to-parameterize implementation.

5 DEMONSTRATION

The DAWN platform has been used for the estimation water demand in the urban area of Thessaloniki, Greece. The metropolitan area of Thessaloniki comprises more than one million consumers. Aggregate data taken from the Municipal Water Supply and Sewerage Utility records have been used. Econometric models developed by experts [Mylopoulos et al., 2004; Kolokytha et al., 2002] have been extended using DAWN. A model with one hundred consumers groups clustered in four types has been simulated, evaluating a set of elective pricing policies. The four consumer agent types has been induced empirically, based on questionnaire data, acquired from a field survey on 1,356 households. DAWN hybrid model has been calibrated for the region of Thessaloniki, based on prior field studies, covering period 1994-2000. The calibrated model has been used for evaluating water pricing scenarios for the period 2004-2010. The main task was to explore the quantitative results of implementing an information and education policy in the direction of controlling water demand.

6 CONCLUSIONS

In this paper, we presented DAWN, a water management decision support system, dedicated to estimate urban water demands and evaluate water-pricing policies. DAWN can be used to explore the community's response to a water-pricing policy. It makes a step ahead in the estimation models applied in the residential water demand sector, as it considers consumers behavior and social interactions. DAWN usage has been evaluated for assisting water decision makers to estimate future water demands in the region of Thessaloniki. In particular, DAWN was used to explore social behavior and its connections with water consumption. DAWN has been welcomed by decision makers and the water experts for understanding the quantitative implications of an information and education policy.

Future efforts will build on the current framework to extend its competence. Our intention is to include other aspects of the urban water management problem, as the water availability, quality and supply costs, through the development of an adaptive behavior for WSA.

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