Interaction analysis of stakeholders in water supply systems

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Abstract An analysis of the characteristic goals, strategies and rules of behavior of relevant stakeholders allows the efficacy and potential risks of past and current engineering and management concepts to be estimated. The study is driven by the observable shift from security to cost-centered strategies by water utilities and the difficulties of balancing technical and financial needs in an uncertain future. Its benefits include a methodology with a twofold result. With the aid of domain knowledge from experts involved in a participatory process, the interactions of a subset of stakeholders are quantified and documented in a rule catalog. This leads to an improved understanding of their decision-making rules. An agent-based model comprising these stakeholders' rules of behavior in subsequently development. Once the model is validated with data sets from a real utility, multiple-scenario testing helps to explore different strategies and can be used to generate ideas for developing flexible management and design schemes. Despite the complexity of the system described, simple model rules which are repeated annually can replicate the general development of both capacity and cost-related parameters. Scenario simulations show the effects of different management strategies on key parameters such as capacity, water price and financial debt.
Keywords Actor behavior; agent-based modeling; flexibility; infrastructure; management strategies; rule-based communication; urban water management; water utility

Introduction

A surplus of *hard* technical knowledge is currently available in many disciplines as against a death of *soft* cybernetic and behavioral knowledge. We know *how* to purify water to the highest standards and *how* to automate and regulate entire water-supply systems. But we often have difficulty in understanding *why* these technologies are implemented in preference to others or *why* policy decisions go one way rather than another. Everyone has personal feelings about the reasons for this situation, but we lack the tools to discuss and understand it more effectively. These concerns are particularly urgent in view of the current development of water-supply systems.

Let's look back a little first. The engineering rules which provided the basis for building the infrastructure of water-supply systems and the management rules which formed the basis for operating them have proved to be both appropriate and useful in the past. The ensuing system (type and size of infrastructure, management concept, organizational structure) can be used as the result of a combination of three technical and socio-economic influences: the goals and interests of the stakeholders, the environment (political stability, economic welfare, availability and quality of resources) and the technical feasibility of the available options. This development was significantly dictated by the stakeholders who influenced the technical boundary conditions through research and the socio-economic environment through political activity. It was further characterized by a continuous and steady expansion of the water-supply infrastructure and by giving higher priority to technical security than to cost considerations. Today, however, the situation has changed. The public demands cost-minimized optimization, privatization, lean maintenance and a redistribution of capacity reserves. In contrast to the past, however, consumer behavior and the resulting trend in water demand are unclear: will it be stable or drop still further?

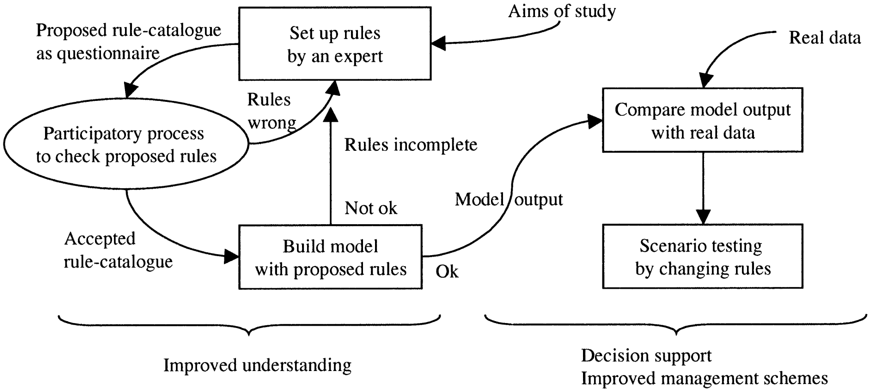

Figure 1 Outline of methodology. A process designed to improve our understanding of the stakeholders' interactions and decision-making rules leads to a model which can be used to explore alternative rules and hence help to improve management schemes

This shift from stability to uncertainty conflicts with the long life expectancy of the infrastructures and requires the application of more flexible design and management concepts (Beck, 1997; Geldof, 1995; Guy and Marvin, 1996; Jeffrey *et al.*, 1997; Larsen and Gujer, 1997; Tillman *et al.*, 1999). Decision-support systems (DSS) have been increasingly developed to assist water managers' choices (e.g. Herz, 1998; Moss, 1998). However, *existing* infrastructure networks are inert and it is no simple matter to change existing habits or planning/management schemes that have evolved over many years. Because the stakeholders' internal incentives, goals and interests also add to driving the system in certain directions, it seems important to focus on these aspects. Such an integration of technical and social viewpoints has received increasing attention in recent years (Moss and Pahl-Wostl, 1999) but is rarely applied to the field of urban water management in general and water supply systems in particular. The aim of this study is to develop a methodology which can provide an insight into stakeholders' interactions and decision-making rules.

Outline of methodology

In this methodology (Figure 1), specific rules describing how stakeholders characterize their typical interests and behavior are proposed by an expert and subsequently exposed to criticism in a participatory process. In order to check the correctness of these rules, we build a model and compare its output with real data. Once we have enhanced our understanding and validated the model, the effects of alternative rules on the water supply system can be simulated. This scenario testing also forms an important part of the methodology because it allows us to demonstrate the significance of focusing on these driving forces.

Stakeholder interaction

A general overview (Table 1) reveals numerous stakeholders who influence each other and hence the whole water-supply system, including objects (e.g. infrastructure). Exogenous influences also play an important part in the development of the system. Various time scales (year, day, hour) as well as different types of flux contribute to the system complexity. These may consist either of data (information, policy, proposals etc.), or of various types of material (water, energy, particles, money etc.). Each stakeholder has his own interests and supplements the data by his own security factors in agreement with engineering principles. The table also reveals links which are not easily quantifiable (e.g. influence of the media).

The links in this table are at first sight not surprising to stakeholders in the real world. As soon as they discuss them in more detail, however, many stakeholders have their own – often diverging – opinions, their own view of reality. A model of these interactions thus

Table 1 Stakeholders, domain objects, exogenous influences and the links between them. Information is passed on (from row to columns) either as data ("D"), material ("M") or both ("B"). The circled link between the stakeholders of the engineering company (consulting as well as constructing) and the utility will be tracked below. Stakeholders marked in italics take part in the participatory process, entities marked with bold numbers are included in the model (below)

Legend:
D = Data, information, policy, proposal
M = Material (water, energy, particles, money)
B = Both (D and M)

		flux	1 State	2 Politicians	3 Utility	4 Eng. company	5 Consumers	6 Prof. Assoc.	7 People, public	8 Farmers, agri.	9 Fire service	10 City planner	11 Media	12 Neighbors	13 Infrastructure	14 Drainage sys.	15 Sanitary inst.
Stakeholders	1	State, administration		D	B	D				D	D				D	D	D
	2	*Politicians*	D		D		D		D	D	D	D		D			
	3	*Utility (public works supply)*	M	D		B	D	M		B	M		D	M	B		B
	4	*Engineering companies*	M	D	(B)			M							M	M	
	5	*Consumers*		M	D	B				D							D
	6	*Professional association*	M	D	D	D				D	D				D	D	D
	7	People, public opinion		D	D		D	D					D				
	8	Farmers, agriculture		D	M											M	
	9	Fire service			M	D		D				D					
	10	City planner (demographics)		D	D			D									
	11	Media		D	D		D	D	D								
	12	Neighbor cities		D	D												
Domain objects	13	Infrastructure (pipes, works)			M						M					M	
	14	Drainage system		D	M												
	15	Sanitary house installations			M		M									M	
Exogen. influence.	16	Economic pressure	M	D	M	D	D										
	17	Resource availability		D	M					M			D				

provides a very helpful framework and a common platform for discussion which allows critical links to be highlighted and tracked.

Since the detailed analysis of the stakeholder interactions needs to be developed step by step, only a subset of stakeholders is included in the participatory process (in italics in Table 1) and the resulting model (bold numbers in Table 1) as outlined in Figure 1. In the following, we shall focus on the sample of the link between a utility and an engineering company (marked by circle).

Finding the rules

Each stakeholder involved is described and characterized by his typical tasks, his overall goals (interests), and the strategies he uses to achieve them. These driving forces are expressed in concrete terms by formulating specific rules which take beliefs in terms of parameter values into account. Past strategies are distinguished from present ones. As indicated above (Figure 1), an expert proposes such a set of characteristic rules. This set is then summarized and recorded in a form similar to a multiple-choice questionnaire (Table 2). This questionnaire in turn provides the basis for the participatory process. Representatives of the stakeholders described above are then involved in this process. Representatives of the stakeholders described above are then involved in this process. The questionnaire is mailed to each participant in the process: he is asked to answer the questions and mark his degree of agreement (yes, half, no). The questionnaire is subsequently discussed at a round table involving all the participants. During this discussion, the initial rule-proposing expert acts as facilitator and seeks agreement if the stakeholders have diverging opinion on a certain rule. As a result, this process transforms the rule questionnaire into a rule catalog containing unanimously agreed rules as well as rules which are wrong or only partly true. Wrong rules are sent back to the initial expert who must submit a better proposal. Table 2

Table 2 Part of the rule catalog (simplified). Each stakeholder is described and characterized by one expert. The description includes the stakeholder's tasks, goals (interests) and the strategies (past and present) he uses to achieve his goal. These driving forces are expressed in concrete terms with specific rules which take beliefs in terms of parameter values into account. During the participatory process, the stakeholders involved can agree or disagree with the proposed rules and mark their choice

Engineer of engineering company (consulting and constructing)	Agreed?		
	ok	half	no
1. Tasks:			
(a) Influence utility towards larger contracts and large-size infrastructure	X		
(b) Build infrastructure according to contract	X		
(c) Bill the utility for the corresponding costs	X		
2. Goal and interests:			
• Good reputation of company	X		
• Make profit on projects within limits of good reputation	X		
3. Strategy of past to achieve goal:			
• Large-scale infrastructure (influence towards bigger infrastructure, round off)	X		
4. Strategy of today to achieve goal:			
• Cost-saving infrastructure (cost prior to security considerations, competition)	X		
5. Rules for task a (influencing):			
• Influencing the utility results in a 10% increase in size of the received construction-job	X		
Rules for task c (bill costs):			
• The total costs of the built infrastructure element are charged immediately			X
• The total costs are spread linearly during the main construction period		X	
• If "Strategy of today": Cost-saving considerations and competition results in a reduction of overall costs of about 30%	X		

shows an example of a rule catalog in which the stakeholder representing the *engineering company* is characterized. Tasks, goals, strategies and rules are defined, thus adding further details to the links from Table 1 (circled). This example shows how two of the three tasks relate to the link between the utility and engineer. They show his intention: a) to influence the utility towards larger contracts and large-size infrastructure (as he can earn more on large contracts), and b) to bill the utility for the corresponding costs.

The model is built on the basis of an accepted set of rules. In this model-building phase it might turn out that certain rules needed to complete the model are missing. In this case, the initial expert proposes the missing rules and they are then re-evaluated. As an alternative to a round-table discussion, the stakeholders may be involved on a round robin basis, i.e. the initial expert discusses a set of rules with each participant separately. In both cases the stakeholders themselves are unable to see the specific effect of their proposed rules on the model output.

Model setup for validating interactions

The stakeholders characterized in the rule-finding process (calibration of rules) are subsequently included in a model which is used to validate the evaluated rules (Figure 2). The utility is represented by three main stakeholders: a director, a chief engineer and a head of finance. Also shown are an engineering company in the private sector, several houses standing for a cluster of consumers and the domain objects (infrastructure). An executive politician and a legislative politician are only vaguely characterized but are also included in the model. The tasks evaluated by the engineering company (Table 2) in our example appear again (circles). The company influences and bills the utility (Figure 2). The utility in turn allocates job contracts to the engineering company.

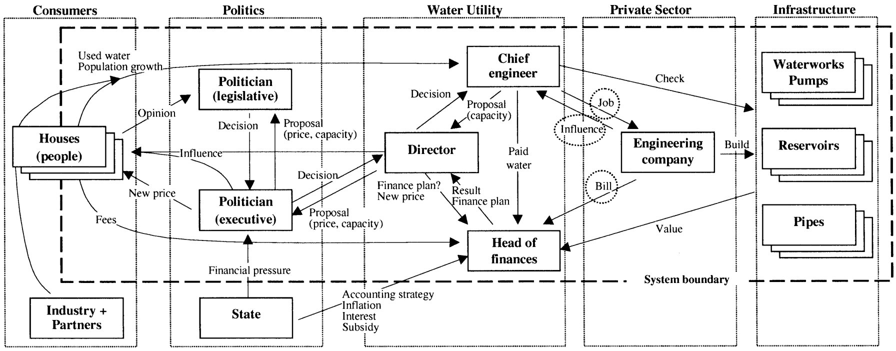

Figure 2 Model diagram showing the water supply system of a city in Switzerland in a simplified and abstract form. The model is constructed with an agent-based, hierarchical and variable structure

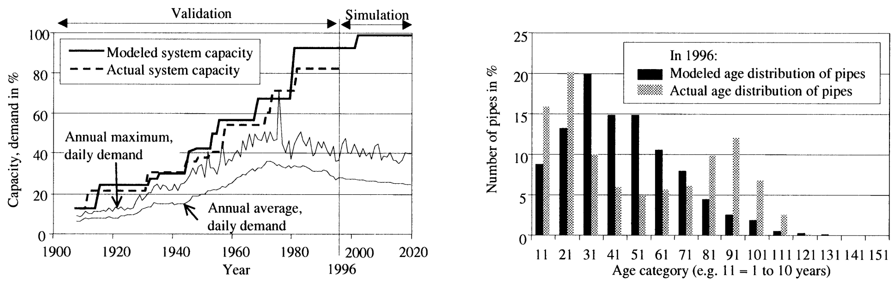

Figure 3 Left: validation of modeled system capacity up to 1996, and simulation up to 2020 assuming the same rules as in the past and a decreasing average demand trend respectively. Right: validation of age distribution of the pipes for the year 1996

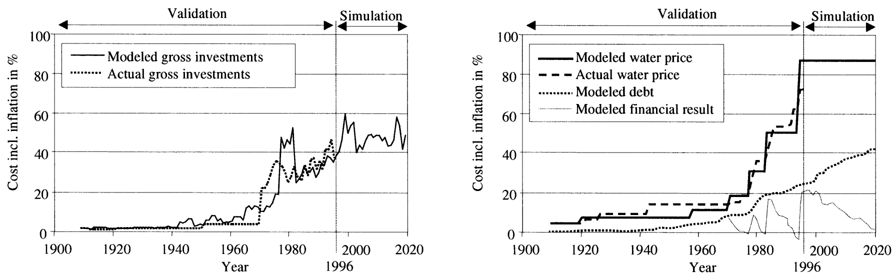

Figure 4 Validation of modeled financial parameters such as investments (left) and water price (right). Simulation up to 2020 assuming the same rules and capacity development as in Figure 3. Modeled debt and financial result are shown (right) for later comparison with Figure 5

An agent-based approach is chosen to design the model. Both the stakeholders and the domain objects (infrastructure) are modeled as agents. The structure of the model is variable. Because the modeled period ranges from 1908 through to 1996 (validation), and up to the year 2020 (simulation), the population of the city changes over time. Consequently, the number of house agents changes according to the population. In a similar way, the reservoir, pipe and pump agents change in size and in number over time according to the needs of the utility. The number of pipes also depends on the size of the city (population): 2 to 3 m main pipes are assumed per inhabitant, which represents a Swiss average. There is no geographical information system (GIS) behind the model to show the relationships between the location of the pipes and their corresponding diameters (thick near the pumping station, thinner towards the outskirts of the pipe network). The pipe diameters are thus assigned according to a given initial diameter distribution which increases in accordance with population growth.

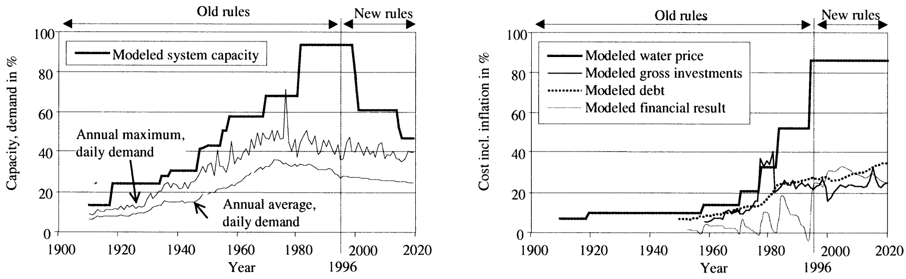

Figure 5 Simulation of a scenario in which the rules of the utility engineer and the engineering company (see Figure 2) are changed. Left – effect of new rules on capacity, right – on financial parameters. This scenario can be compared to the ones in Figures 3 and 4

Model results

Despite the complexity of a water-supply system, rather simple model rules can nevertheless replicate the general development of both capacity and cost-related parameters (Figures 3 and 4). The graphs show the general validation of the collected rules from 1908 to 1996. On the basis of the evolution of the annual maximum and average daily demand, the annually repeated rules of the stakeholders lead to the development of the system capacity (Figure 3, left. Rules as described in Tillman *et al.*, 1999) and the age distribution of pipes (Figure 3, right). Annual investments are needed to pay for these construction efforts. Their nominal development is shown and compared to the investments actually realized (nominal, Figure 4, left). Accounting principles are applied and a water tariff is calculated on the basis of income (subsidies, delivered water, connection fees) and expenses (salaries, general expenses, interest, depreciation). Figure 4 (right) shows the modeled tariff compared with the actual one as well as the debt and result development. Although there seems to be general agreement between the model and reality, parameters such as *result* which is a composite of other parameters (e.g. depreciation, interest, income, etc.) are very sensitive to minor deviations of their components from reality and are therefore not very well modeled. However, it should be noted that these are preliminary results, and further sensitivity analysis is needed in order to be confident of the robustness of the model.

A simulation of a possible further development of the modeled parameters from 1996 up to 2020 is shown, *assuming* that the *same* rules will apply as in the past and *assuming* a continuous slow decrease in average demand. Although infiltration is assumed to be zero (after 1996), investments will generally increase due to further capacity investments and increasing replacement of aged pipes. Since annual investments are higher than deprecation, the overall debt shows a continuous increase (Figure 4, right).

This scenario of simulating the further development of the water utility using the same rules as in the past can be compared with another scenario which assumes that the chief engineer of the utility changes his strategy in 1996 (Figure 5). His planning procedure now takes the risk of excessive capacity reserves into account and thus includes fewer security factors. He thus considers shutting down a single pump if his demand forecast allows for this step (new rule of utility engineer). It should be noted that this evaluation does not consider whether this is technically feasible in reality and what effect it would have on the pipe network. The demand scenario then shows that capacity would decrease (Figure 5, left). The engineering company which builds the infrastructure is now assumed to be under competitive pressure and is forced to reduce its prices, saving on buildings and own profit (=new rule of engineering company). As a result of both new strategies, investments flatten out (Figure 5, right). Nevertheless, as in the scenario in Figures 3 and 4, tariffs would still rise. Consequently, downsizing the infrastructure does not necessarily result in a short-term decrease in tariffs (also because it takes place after a price increase). However, this scenario does result in improved liquidity for the utility. In contrast to the scenario in Figure 4, tariffs would not have to be raised again in about 2022. Maintenance and depreciation may consequently be reduced, investments are smaller and thus the possibility of debt payoff increases. The utility may gain flexibility as a result of better financial liquidity.

Discussion

The methodology is characterized by a combination of a rule catalog resulting from a participatory process and the application of the evaluated rules in a model. Neither the rule catalog alone nor the model alone would be sufficient to achieve the project aims. Neither surveys alone nor interesting graphs and moving screens alone would convince stakeholders of the relevance of focussing on their behavior. Only the combined use of these tools creates an effective discussion platform leading to an improved understanding of the interactions involved: the rule-finding process is motivated by the subsequent building of a model, and the model is in turn grounded in rules which were evaluated by the stakeholders themselves.

An advantage of this methodology is the simple approach it offers to discuss the resulting model in a clear and structured way. The scenario simulations can thus be used to generate ideas in order to develop flexible management and design schemes. Although it is clear that these scenarios are merely exploratory speculations, they may nevertheless allow us to evaluate ideas and offer arguments to utility managers. For example, the scenario shown in Figure 5 may also be used to argue for higher tariffs irrespective of the short-term development of infrastructure size. Consequently, this process may facilitate a better exchange of ideas among representatives of different professions. The model can simulate the behavior of engineers and shows its effects on the financial state of the utility, thus combining technical and financial viewpoints.

Building a model based on a rule catalog bears some similarity to the *fuzzy logic* methodology. In particular, mathematical equations from the model are represented by *soft* sentences which make more sense to those not involved in model-building on a daily basis. Stakeholders can be encouraged in good *model thinking* when the rules are discussed in conjunction with a general presentation of the model established so far.

Although agent-based models offer prospects for social interaction, two main aspects call for special attention. Firstly, how to obtain relevant data, beliefs and rules from the stakeholders. Decision Support Systems can only reach their goals if they succeed in projecting users' ideas of a certain situation into the model tools (see also Amezaga and O'Connell, 1998; Gijsbers, 1998). So there are compelling reasons to select a participatory approach: the relevant stakeholders need to understand how the model (and its components, the agents) works as well as the level of abstraction in which their knowledge and intuition needs to be transformed into "if-then" rules. The second aspect concerns a danger which is unavoidable when working with sociological, qualitative research methods. The information received via the participatory approach may be distorted because of misinterpreted tasks, misunderstood questions and answers which were slightly elaborated due to the need for prestige (Bortz and Döring, 1995). We minimize these effects by applying a twofold strategy: (1) the same rules are exposed to different stakeholders and their reactions are compared (round robin) and (2) past rules are separated from present ones, thus allowing stockholders to dissociate themselves from past strategies where necessary so as not to distort them.

The model can replicate real data surprisingly well. However, it is neither possible nor sensible to aim for a perfect model calibration. to achieve best possible fits, many special rules and parameters would have to be included, resulting in a model which simulates total replication. All the degrees of freedom available to stakeholders cannot be included. The limits of the model must therefore be realized, and its quality should be viewed via the *structural similarity* approach of Hernberger and Spear (1981).

Conclusions and outlook

The methodology presented here seems to be effective in tackling the behavior of the stockholders, which is rarely discussed. Within the overall system, stakeholders mull over their behavior and discuss relevant links and incentives. This process alone is very helpful for understanding the overall system, and may also be compared to the ISO 9000 (International Standard Organization) procedure. The main benefit of applying for ISO 9000 certification is that the company is obliged to optimize its processes and procedures and thus usually improves its performance.

This paper cannot suggest conclusively any ways of adapting our strategies and rules for designing and operating water-supply systems in the face of an uncertain future. The development of outside economic and political circumstances has already forced utilities to change their priorities from technical security to overall cost-effectiveness. Although such dependence on outside influences is potentially dangerous, it can hardly be changed under present circumstances. However, it is far from obvious as to how Swiss utilities can apply an anticipative strategy such as demand-side management: due to political pressures not to increase prices and the declining trend in demand (and hence decreasing income), water supply volumes must be kept high. In addition, strategies designed to reduce capacity reserves are dangerous because the demand trend is uncertain and savings cannot be expected in the short-term. It is important to discuss these problems at political level.

In large parts of Switzerland, many problems arise from the transformation and adaptation of existing capacity and pipe networks to a new situation which includes declining demand, increasing political influence and financial pressures. We believe that focusing on stockholders' rules helps to provide a basis for tackling this situation. Future work will include the development of different scenarios involving alternative stakeholders' rules, counterfactual experiments and what-if analyses.

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