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MODELING THE ACTORS IN WATER SUPPLY SYSTEMS

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ABSTRACT

A methodology is developed to reveal the dynamics of behavior and interactions among actors (stakeholders) in water supply systems and their effect on the technical network and the ecological and socio-economic environment. An agent-based model is under construction which allows to simulate different scenarios of the actors' behavior and to compare the results with observed phenomena (stylized facts) of Swiss cities. First results further clarify the significance of demand trend analysis. We envision the model in a final stage as being helpful to tackle the task of illuminating the diffusive claims, expectations and interactions of the actors involved. Knowledge about these processes is crucial to uncover bottlenecks hindering the sustainable development of our water supply systems into the future. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Agent-based modeling; behavior and interaction of stakeholders; complex system; infrastructure; simulation; socio-economic interface.

INTRODUCTION

While developing the infrastructure of the water supply system during the last couple of decades, problems of interaction between human water use and the natural water cycle were in general solved by applying an "end-of-pipe" approach: for each environmental problem arising (e.g. water scarcity, deterioration of water quality) or for each new service demanded by the people (e.g. sufficient water even during peak hours), the problem has been solved by focusing on technical issues: purification plants were built, water mains expanded, or new water sources exploited. Since the development of a functioning water supply system was significantly responsible for a high quality of life, the usage of all kinds of resources was rarely questioned. The rules simply required us to apply the best available technology, which determined the standards written in regulations. Uncertainties such as the future water demand were compensated by applying a worst-case design strategy. An event of water delivering shortage or a local failure of some installations was not accepted (or supported by regulations). Since water demand was rising constantly, this strategy worked perfectly: capacities were well adapted to demand at any time. The system expanded continuously, which also represented a win-win situation for the actors involved: customers received the services required, engineers had work, business for utilities was growing, etc. Now, the existing system can generally be characterized by a supply-oriented concept: demand is satisfied uninfluenced (Guy and Marvin, 1996), requiring consequently a large resource-intensive infrastructure network with long life-expectancies of its elements (Larsen and Gujer, 1997). Also, when looking at water supply systems of cities, we can frequently observe several phenomena. These phenomena can be seen as "stylized facts", which may be defined as robust patterns often resulting from social interaction and which are thus hard to transfer and reproduce experimentally.

- *Large capacity reserve:* In recent years, the trend of the demand pattern is decreasing (more efficient household technology, reduction of water using industry, water recycling). Due to the life-expectancy and the risk averse policy, it is difficult to adapt (downsize) infrastructure capacity, resulting in large capacity reserves.
- *Aged infrastructure:* Maintenance and renewal of the infrastructure was often neglected as the focus of the water network development was on expansion. Hence a high percentage of water mains are older than their life-expectancy. Bursts of pipes occur frequently and are a permanent concern of water managers (Kamm, 1993; Wieman, 1993).
- *Ratio peak to average demand:* The ratio between the size of water mains determining peak demand and average demand is 2-4 in urban areas. Although as a consequence the water mains are most of their time underutilized and thus used inefficiently, it is remarkable that this situation seems to be widely accepted.
- *Water-productivity:* The amount of water we demand depends strongly on the household technology, transforming the water into the services required (e.g. toilet flush, dishwasher). Several studies have been conducted which showed that the technology would be available to reduce water usage up to 50% without loss of life-quality (e.g. Mönninghoff, 1993).

Today, almost without exception across the water industry, managers face the challenge of meeting high quality and environmental standards while reducing costs. Balancing system performance against cost of the system is in principle nothing new, but the discussion has dramatically focused on this issue in recent years (e.g. Lehmann, 1994; Duckworth and Clarson, 1997; Hertzler and Davis, 1997). While costs are high due to depreciation, interest and the expensive replacement of aged infrastructure-elements but water consumption is decreasing, the consequent rising water fees (per volume of water) attract the attention of the public. This challenge becomes aggravated by the pace of change on all water business. While in the past water utilities could develop under rather stable or at least foreseeable socio-economic conditions (time-scale for change 30 years), the environment in which water utilities operate today is no longer easy to predict (time-scale for change 5-10 years). The uncertainty of the influence of factors such as critical public opinion, customer expectations, changes to the political and regulatory environment, the introduction of evolving technology or the dynamics of water demand is substantial (Fig. 1). Even the reaction of the consumers to the constantly rising water fees is hard to predict: A worst-case from the viewpoint of the water utilities is that rising water fees would lead to a water-saving consumer-reaction which in turn stimulates prices again. Wiederkehr (1997) condenses these phenomena to "a society which is emotional and highly media-conscious".

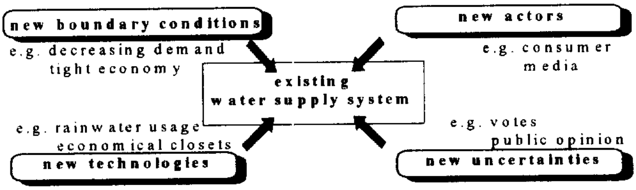

Figure 1. A new situation (e.g. decreasing demand trend) and new influences of a dynamic but uncertain environment (e.g. public opinion) challenge the renovation and the further development of the existing infrastructure.

The major problem in order to cope with this situation is the fact that the infrastructure such as water mains or storage tanks have long life-expectancies (50 to 80 years). This contributes to the inflexibility of the system and requires water utilities to plan and forecast far ahead - clearly, a quite difficult task within the environment described. Eliminating uncertainty by infrastructure size may be viewed an impractical and uneconomical strategy today. Although a failure of the system would expose the utility and its directors to public dispute (Duckworth and Clarson, 1997), a non-failure policy may do the same. Let's take a look at the limitations of a "larger than necessary" system:

- *Cost:* While locally the size of infrastructure does not affect total costs significantly, the *overall* size is a crucial parameter in determining cost when adding up all the parts (Hertzler and Davies, 1997).
- *Lock-in effects:* Since the infrastructure is very capital intensive, a once built part binds capital for a long period of time. This creates lock-in effects, which makes it difficult to change strategies and the direction of management. Once built, the capital is spent, fixed and affects the development of nearby network elements (Geldof, 1995; Edenhofer *et al.*, 1997).
- *Incentives for innovations:* Innovation normally increases the performance of a system, but it needs initial support. An infrastructure covering all the uncertainty with its size will neither promote incentives nor a market for innovation (e.g. water saving technology, leveling of peaks, etc.).
- *Natural resources:* Local scarcity of water and droughts are nothing new. The urgent warnings however about *global* scarcity of water *and* the effects also on regions with plenty of water (e.g. most of Switzerland) can not be overheard anymore (e.g. Food and Water Conference Engelberg CH, 1997). With respect to know-how transfer, a wise strategy must build on a water productive and thus water and resource saving management. It shall be stressed that this point is *not* an ethic one primarily.

Combining limitations of large networks with the stylized facts (phenomena) mentioned before stimulates the question whether our common supply oriented, uncertainty-covering water supply "philosophy" is flexible enough to cope with the future. We need to acquire knowledge about potential bottle-necks and develop strategies which can include the uncertain future preventing lock-ins and lost opportunities.

"In order to tackle the challenges of the future, we need to understand the development of the past". This statement makes us wonder whether we sufficiently understand the processes which lead to the attributes of the present system. We have identified two major influences (Fig. 2): On one side there is an influence that we may summarize as "technology", resulting from technical and scientific knowledge of the engineers, who design the system. That's the part we understand to a rather high degree. On the other side, there are several effects which we may characterize as "claims and expectations", resulting from different interests, incentives or duties of the actors (stakeholders) involved. That's the part we understand poorly, although we suspect that the behavior and interactions of the various actors may be crucial for the direction, in which the system was developed. So far, this type of research within the field of water supply is, though emerging, not yet often performed (e.g. Geldof, 1995; Jeffrey *et al.*, 1997; Barreteau and Bousquet, 1998).

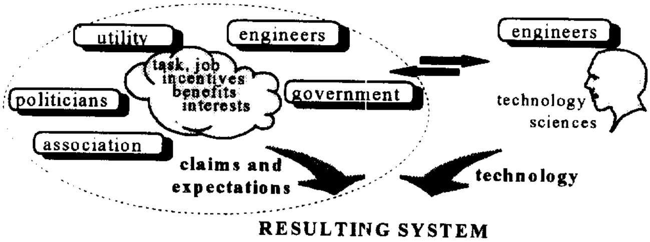

Figure 2. Two major influences contribute to how the system is built. While the "technology" part is well known, the "claims and expectations" part is poorly understood. The resulting system involves e.g. infrastructure capacity, quality of resources, pattern of water demand etc.

In this work we want to challenge our understanding of the interactions between the macroscopic dynamics of the system (e.g. observed capacity, demand pattern) and the microscopic interactions of its sub-systems, the actors. Research questions to be addressed include the following.

- Find an appropriate methodology to approach the "claims and expectations"-part (Fig. 2).

- Illuminate the behavior of the actors. Reveal the dynamics of interactions among actors and the effect of these interactions on the technical network and the ecological environment.
- Explore the system for bottlenecks which inhibit planners and managers operating the water supply system with increased flexibility and adaptability.
- Find good strategies (guidelines, criteria) to further develop the infrastructure under the conditions of uncertainty.

MODELING AND SIMULATION METHODOLOGY

We choose a modeling approach to enhance our "understanding" of the observed system. The goal is not primarily to provide the most accurate representation of the real world, but to enrich our understanding of fundamental behavior of the actors by reproducing some of the above-mentioned stylized facts. Several authors explored and described the processes of model building, validation and simulation within various contexts (e.g. Casti, 1977; Popper, 1980; Axelrod, 1997; Carstensen *et al.*, 1997; Troitzsch, 1997), which shall not be repeated. Instead, let us focus on the structure of the model. In recent years the terms "multi-agent modeling", "multi-agent paradigm" or "agent-based modeling" have gained significant attention, especially in the domain of social sciences (e.g. Castelfranchi and Werner, 1992; Conte *et al.*, 1997). This type of model structure is characterized by the existence of many agents, who interact with each other with only little or no central control (bottom up). A most characteristic attribute of agent-based modeling is the distinction between micro- and macro-levels (distributed intelligence). While interaction among agents takes place on a micro-level, system properties or variables emerge on a macro-level.

The application of an agent-based modeling approach seems appropriate for our purpose in a fourfold way.

- *Interaction:* We are interested in the interactions among the actors which can best be depicted using a micro-macro structure.
- *Behavior:* Our aim is to model behavior and observe the emerging system properties. Typically, behavior can be incorporated in rules of agent-based models. Actors are modeled as individual agents, characterized by typical state and behavior. These attributes may change over time.
- *Communication:* Input parameters and model structure evolve out of our prior knowledge, but also from ongoing discussions with real world actors. It is more comprehensive to discuss the rules of an individual actor than the value of a global parameter.
- *Qualitative information:* Water supply can be viewed as a complex system. As such, it is non-deterministic, involves fuzzy connections and interaction between a technical and a human system. Agent-based models can include incomprehensible, qualitative behavior.

We proceed in analogy to the Hornberger, Spear and Young Algorithm (Hornberger and Spear, 1981; Young, 1983). At the stage of our understanding of the behavior and interactions of actors, the level of intrinsic and parametric model uncertainty precludes the use of any analytical procedure to determine the "best" estimate for model structure and parameters. It is possible though to make some defensible assessments of the probable or at least allowable values of the parameters given the assumed model structure. For that we explore the range of acceptable parameters (parameter space) using sensitivity analysis (e.g. Monte Carlo) and observe the outcome of the dependent variables. They need to be within a range which is defined qualitatively depending on the specific question to be explored. Following the model building phase, the process of simulation - when interpreted as thought experiment or "idea generator" in the light of the totality of current knowledge of the system - may indicate gaps in present intuition, reveal unfavorable side-effects of well-meant behavior or suggest hot spots for further research.

A FIRST MODEL

Given the research questions outlined above, we can envision our model as one which depicts in its final version a social network including various actors (engineer, utility manager, politician, state, consumer, etc.), various time-scales (years, month, day, hour) and links to further systems (urban drainage, wastewater treatment). We start with a simple model however and let it evolve as we learn about the system.

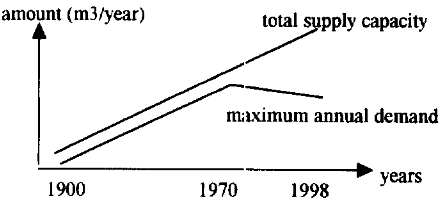

Figure 3. Typical pattern of divergence between supply capacity and demand of water since 1970.

With the first model we want to explore the first phenomenon as described above: which were the rules of the involved actors and which were the relevant constraints potentially responsible for the frequently observed pattern of diverging development of demand (annual daily peak) and capacity provided (Fig. 3)? Also, despite the decreasing trend, capacity has still expanded in recent years. The reasons for this phenomenon are most probably a combination of different effects, technical constraints (e.g. life-expectancy), the specific situation of the planning stage, political issues or uncertainty and risk considerations.

Simplification is the first step of elucidation so let us build a first most simple model, consisting of only one actor (representing the design engineer in charge). Demand is given externally out of a database (Fig. 4).

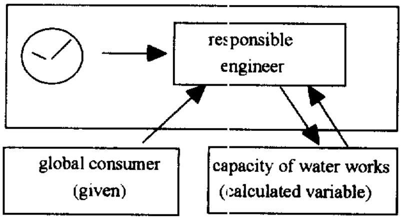

Figure 4. The structure of the model. Condition- and action rules see Fig. 5.

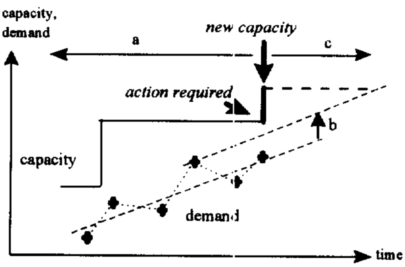

Figure 5. ***Condition rule***: current capacity < demand + 10% of demand (security, minimum of 10 units), or • nothing done since half the life-expectancy of the water works (assuming at least 2 water works). ***Action rule (rule 1)***: estimate needed capacity by extrapolating the linear regression of demand since start (period a), move regression line through peak year (b), and extrapolate to planning horizon (life-expectancy, time period c).

Every year (time step), the engineer checks the necessity to adapt capacity to recent demand developments. If, according to the condition rule, the existing capacity needs to be adapted, the action rules determine next years size of capacity (no time delay, Fig. 5).

The rule of the engineer is determined by two parameters: "planning horizon" (equals life-expectancy) and "reserve-percentage" required for safety. The following attributes characterize the model: *deterministic* (the model contains no elements of randomness), *linear* (equations of the rules are all linear), *dynamic* (the output variable (calculated capacity) evolves over time), *discrete-time* (since the agent operates with rules and not with e.g. differential equations, the model is discrete in time, the agent reacts at specific time steps), and with a *reactive agent* (we follow the agent definition described by Wooldridge and Jennings (1995). Reactive agents have no intention/goal and can not switch or adapt their behavior according to their goal (intentional agents). Neither do they include the behavior of other agents in their plan of action (social agents)).

With this rule for designing the capacity (rule 1), a pattern similar to the observed capacity emerges (Fig. 6). Although the used rule is simple, the calculated capacity follows qualitatively the observed capacity (within boundaries). Thus the fit is okay. The evaluation of the range of acceptable parameter values (parameter space) reveals that the modeled capacity lies within the boundaries if the value of the parameter "planning horizon" is chosen between 20 and 30 years and the value of the parameter "reserve percentage" between 1 and 30%.

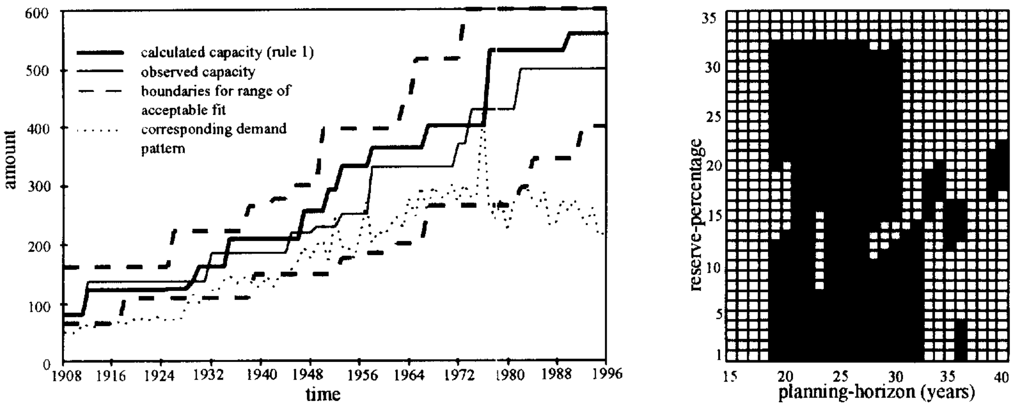

Figure 6. Left: Calculated capacity applying rule 1, observed capacity, observed demand and capacity boundaries as limits for satisfactory calculation. Parameter "planning-horizon" = 25 years, parameter "reserve-percentage" = 20%. Right: Range of acceptable parameter values (dark fields). The parameter array gets stretched out by the parameter "planning-horizon", acceptable values between 20 and 30 years, and the parameter "reserve-percentage", acceptable values between 1 and 30%.

This rule indicates a security-strategy. The belief that a decreasing demand trend continues also in the near future is not strong. Therefore, to be on the safe side, long-term trends are evaluated and used to calculate the new capacity. On one hand, the rule ascertains the functioning of the system (enough capacity all the time). On the other hand, the rule can not respond satisfactorily to decreasing demand trends as observed since 1970.

Now we change the rule and simulate what happens if the designing engineer *would* believe in recent trends rather than taking long-term trends into account. If the designing engineer believes in a trend built of a data period of say 30 years, we observe the following pattern (rule 2, Fig. 7).

The upper boundary (Fig. 7) is the same as the one with rule 1 (Fig. 6). The lower boundary is defined as 10% less than demand (we assume that the pressure situation in the system is okay never mind a demand 10% higher than capacity). While with the application of rule 2 the increasing demand pattern in the years up to the seventies can be matched, the decreasing demand pattern after the seventies can be taken into account sooner compared to rule 1. This may lead to the first guess that with the application of a rule based on short-term trends rather than a rule based on long-term trends we can equally anticipate an increasing demand pattern but can sooner respond to decreasing demand trends.

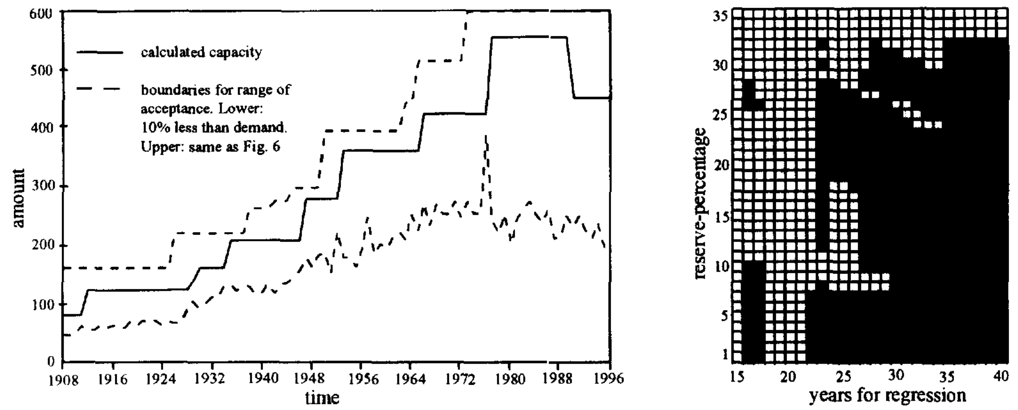

Figure 7. Left: Calculated capacity applying rule 2 with parameters "planning horizon" = 25 years, "reserve-percentage" = 20%, "years for regression" = 30 years. Boundaries as limits for range of acceptable parameters. Right Range of acceptable parameter values (dark fields). The parameter array gets stretched out by the parameter "years for regression", acceptable values between 23 and 40 years and "reserve-percentage", acceptable values between 1 and 30%. "Planning horizon" is fixed at 25 years.

In order to get more confident about how the two rules behave in different situations, four scenarios are considered to check the performance of the rules not only against existing data as above, but also against different types of demand pattern (Figs 8 and 9).

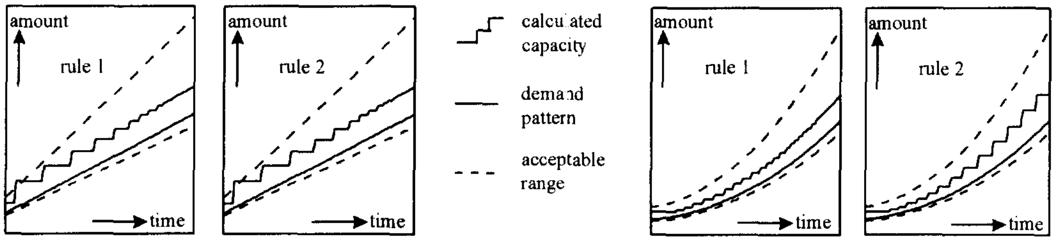

Figure 8. Left: Linear demand pattern. Both rules perform equally well as the length of the regression period taken into account has no effect. Right: Exponential demand pattern. While rule 1 increasingly underestimates demand development (new adaptation of capacity is required more and more often), rule 2 performs better.

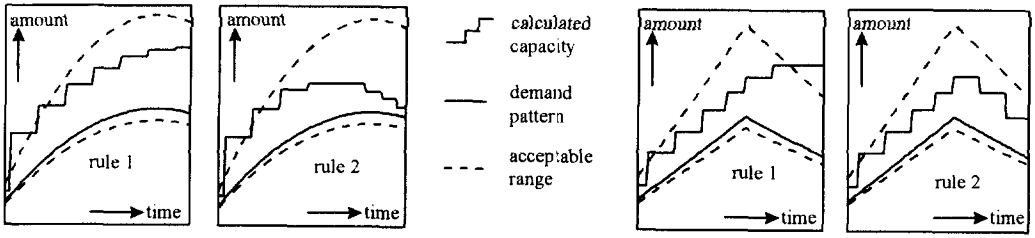

Figure 9. Left: Flattening demand pattern. While both rules overestimate demand at the beginning, rule 2 can better mimic demand towards the end. Right: Sharp bend demand pattern. Performance similar to the one with a flattening demand pattern, but aggravated.

From these scenarios we can summarize that rule 2 (short-term) performs equal or better than rule 1 (long-term). It is of course too early however to draw firm conclusions for the overall behavior of the "engineer-actor". Nonetheless these observations provide a good foundation to discuss behavior of the actors involved and their effects on the system.

OUTLOOK AND CONCLUSIONS

Future work will include the enlargement of the model. Other actors such as consumers will be depicted and the notion of demand side management (DSM) explored. Furthermore, financial issues shall be examined. To the typical model building sequence (Fig. 10) the process of defining the rules of the actors is added (Fig. 10, bold). These evolve in a process of interaction with real world actors. Important is that these rules represent an abstract, general representation of varying rules of individuals: from this body of knowledge, we extract the common denominator (institutional dynamics).

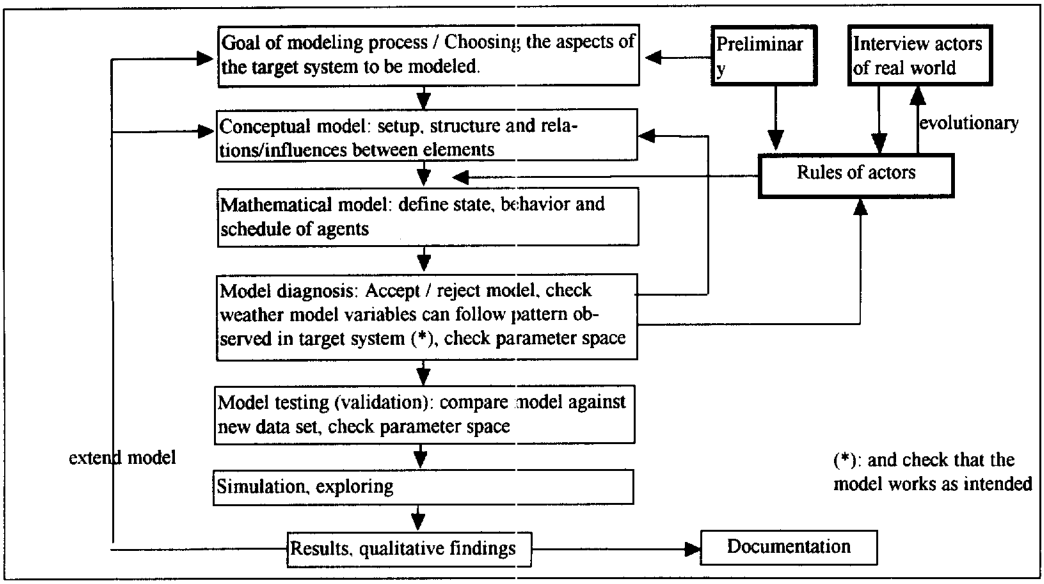

Figure 10. Sequences in the modeling and simulation process (adapted from Carstensen *et al.*, 1997).

Little work is done so far in this field, but it seems important starting to think in this direction. The task involves at least 3 major scientific fields: First, we need to understand the technical side of water supply systems: knowledge about how the system is built, the reasons why it is built in a specific way (from the technical viewpoint), and also the links of the water supply system to its related infrastructure systems (e.g. drainage). Second, this work confronts us with the field of social studies, especially with what is called the simulation of social phenomena. The results of such previous work is encouraging and appears likely to be fruitful in the future since we are concerned with technical systems in a human environment. And third, the work involves computer sciences, modeling techniques and implementation of the model with appropriate computer tools and model structure.

So far, the model and the following simulation is in the process of development. The gain from this first model will be the development of a methodology. We envision the model in a final stage though as being helpful to tackle the task of uncovering the general behavior of the actors involved as well as the diffusive interactions among them: knowledge about both is crucial for the sustainable development of our water supply systems into the future.

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