Optimization and Simulation in Planning of Systems of Drinking Water Supply: A Dutch Experience

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CONTENTS

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Summary

For the supply of drinking water to the provice of South Holland in the Netherlands, heavy use is being made of infiltration of surface water into the dunes. This entails that large parts of the dunes have been closed to the general public. Moreover eutrophication of the dunes caused by the polluted surface water affects the unique dune ecology. Hence there is much protest against the use of the dunes and alternative supply systems for drinking water have to be considered.

The choice is difficult because many possible sources and production techniques are available, some very promising, but still under development. Also there are many criteria available such as costs, quality, reliability, ecological value, recreation, energy, public health, production of waste materials and institutional aspects. One has to reckon also with existing installations, long delivery times, uncertain demand, complicated managerial systems at various levels - national, provincial and local governments as well as individual companies. Many different kinds of decisions are involved concerning demand, maximally allowed extractions of groundwater, size of basins, pipelines, purification plants, contracts between interested parties, etc. Given the fundamental nature of the choices to be made and the time constants involved in change of drinking water supply systems and demand a time horizon of 30 years is appropriate.

About two years ago (spring 1979) the analysis of the various policies was entrusted to a combined team of the Delft Hydraulics Laboratory (DHL) and the National Institute for Water Supply (RID). Two approaches were adopted, simulation and optimization. Simulation was new to the clients. In the mean time we are approaching the end of a, as it looks now, succesful policy analysis.

In the simulation model the development of the drinking water supply system of South Holland is simulated for the next thirty years given a policy strategy, a certain demand of drinking and subpotable water and some scenario assumptions like discount rate, water quality standards, increase of energy prices. An alternative policy strategy generates an alternative development over time

of the supply system.

This development includes changing capacities and productions of reservoirs, pipelines, treatment plants, etc. The consequences of these developments are computed in terms of the effects on the objectives.

In fig. 3 an overview is given of the last version of the model. Besides the production and the capacity module also the quality module is of central importance. This module describes the change of water quality in different purification steps and the adjustment of the purification system when final quality does not meet the standards. Such an adjustment means investment (cost) and leads to higher energy consumption etc.

In the beginning of the study it has been stated that in principle there are so many strategies that it would be impossible to find all attractive solutions using only a simulation model. In order to guide the search for good alternatives and to get an impression of what an optimal solution for each objective or combination of objectives looked like an optimization model has been constructed.

The optimization model is a linear single time step multi objective model. It was expected that most of the objectives would have more or less linear relationships with the decision variables of the model. These variables concern production of potable and subpotable water projects and transport of water by pipelines. The following objectives are considered: costs, water quality, reliability, public health, damage to nature and energy consumption.

Both models are used in an interactive way. On the one hand results of simulation runs concerning waterquality, energy, costs and public health are used to estimate coefficients of objective functions for the optimization model. On the other hand the simulation model is used to detail and to develop dynamic patterns of "optimal" solutions.

Some of the experiences with the use of both models until now are:
- The fear of not being able to find all attractive solutions with only a simulation model proved to be rather pessimistic. After a first analysis it turned out that only about 20 essentially different policy strategies could be identified. The optimization model added some solutions but mostly they

were inattractive for all the objectives not in the objective function.

- The optimization model is not suited to find all non-inferior solutions because of the large variety of combinations of objectives.
- Comparing results of simulated "optimal" solutions with the original solutions from the LP model, it proved that costs and reliability calculations in the latter were rather inaccurate caused by assumptions about linearity and time independance.
- The alignment with actual policy is much better in the simulation model than in the optimization model.
- The optimization model is useful for quick insight and broad screening of alternatives.
- The simulation model first has been written in DYNAMO (III). DYNAMO was abandoned because of technicl difficulties. Experiences with a second sophisticated language (ACSL) were disappointing because most team members were not sufficiently familiar with ACSL so that comminication was hampêred. Finally structured programming in FORTRAN was used to the content of all.
- Presentation of results from simulation proves to be difficult. Representatives of interests prefer optimization results to simulation. They only worry about a limited number of objectives.
- Systems analysis as a whole has guided the study. It has indicated which substudies are needed and with what level of detail and accuracy. In a complicated study like this, this is an important role for systems analysis. The models and the input needed are a focussing point and form the real integrating part of the study.

1 Introduction

In this paper we report on our experiences with a case study where simultaneously both system dynamics and optimization were applied. In the introduction the problem definition is described.
In the second chapter we give some more background information. The third chapter deals with the pros and cons of the followed approaches, as well as the expectations held by the two research teams. In the fourth chapter we present a short description of the constructed models. The fifth chapter is about the practice of the project. We end with some conclusions.

Problem definition

For the supply of drinking water to the province of South Holland in the Netherlands, heavy use is being made of infiltration of surface water into the dunes. This entails that large parts of the dunes are closed to the general public. Moreover eutrophication of the dunes caused by the polluted surface water affects the unique dune ecology.
Hence there is much protest against increasing infiltration. From different sides alternative drinking water supply systems have been suggested.
The choice is difficult because many potential sources and production techniques are available, some very promising ones still being developed. Also there are many criteria such as costs, quality, reliability, damage to nature, recreation, energy, public health, production of waste materials and institutional aspects. In addition one has to reckon with existing installations, long delivery times, uncertain demand, complicated managerial systems at various levels - national, provincial and local governments as well as individual companies. Many different kinds of decisions are involved concerning maximum allowed extraction of groundwater, size of reservoirs, pipelines, purification plants, contracts between interested parties, etc. Moreover given the fundamental nature of the choices to be made and the time constants involved in change of drinking water supply systems and demand a time period of 30 years into the future has to be considered.

About two years ago - spring 1979 - an integral analysis of the various existing policy options was setup by the National Institute for Water Supply (RID). A steering group consisting of representatives of several governmental agencies, both at the national and the provincial level, was installed. It had to approve the various study proposals and monitor the progress of the analysis. The aim of the analysis was to generate an overview of the different possible future developments of the water supply system of South Holland and to compare these in terms of the various objectives.

When the study started some knowledge about separate relationships between, e.g., sources, pipelines, quality and prices existed. However in general this knowledge was incomplete. Hence many substudies would have to be commissioned concerning detailed topics, such as, effects of different supply systems on nature, on recreation and on hydrology. The existing and newly generated knowledge would have to be integrated into a to be developed, general framework. This framework should fulfill the double role of firstly enabling the desired overview and comparison; secondly, while it was being built and tested, it would point to sensitive gaps in knowledge. In this second sense this framework would serve an important managerial role during the analysis. The generation of the framework was entrusted to a combined team of the RID and the Delft Hydraulics Laboratory (DHL). RID had a background in optimization. DHL was interested in simulation. Both approaches, optimization and simulation, were considered appropriate for the problematique at hand, and were adopted for the analysis.

2 Background information

In this chapter we give some background information about the following complicating important factors:

- organizational complexity of the study
- political complexity
- many details at a very disaggregated level
- uncertainty.

Organizational complexity of the study

The organizational setup of the study was as follows. The project leaders of the RID and the DHL together with the project leaders of the substudies formed a study coordination team. Only the chairman of this study team reported to the steering group consisting of representatives of the concerned governmental agencies at the national and provincial level. The principal task of the steering group was to grant permission or not for parts of the system study and substudies. Further this group had to decide about proposals for decision criteria, drinking water standards, etc. The group was not allowed to take any political decision. It had a bridging function between planners and consultants on the one hand and policy makers on the other hand. These last two groups did not communicate directly with each other.

As already mentioned, the system models functioned also as instruments to manage the progress of the whole analysis and to direct the substudies so that uncertainties in the final results were minimized given time and money constraints. This applied especially to the substudies on damage to nature and on recreational effects. It took much effort to keep specialists in these fields within the bounds of the systems analysis. Despite this not all specialisms have been fully integrated at this moment.

Political complexity

In South Holland three different policy levels can be recognized:

1. At the level of national and provincial agencies one has authority over the maximum quantities of water which are permitted to be extracted from rivers, from ground water reservoirs and from the dunes. At this level also one decides about standards for quality, health, reliability, etc.

2. Given the constraints set at this first level local drinking water companies can decide about mutual deliveries thus shaping the provincial networks of pipelines for various categories of water.

3. Dependent on the decisions taken at the first and second policy levels the various drinking water companies make their individual technical plans.

This analysis was directed to policy makers at the first level.

Some members of the steering group were concerned with such particular drinking water variables as costs and quality of drinking water, effects on public health, reliability of the supply system and energy consumption. Other members from different national agencies were mostly concerned with the environment and conservation of nature. Others, still, dealt with recreation. Provincial representatives were in charge of the total physical planning. Thus the members of the steering group had many conflicting objectives and interests.

Many details at a very disaggegrated level

- Both demand and supply are distributed over the province (see fig. 1). We considered 11 points of demand for drinking water, first 25, later on 34 drinking water plants, 9 plants for subpotable water including reservoirs, and separate networks of pipelines for drinking water and for subpotable water.

- Water quality from sources to the points of demand has been defined in terms of mean and standard deviation of concentrations of 12 quality parameters. For purposes of public health 11 more parameters have been considered.

- More then 10 different purification steps have been distinguished. These could be combined in numerous ways into a purification plant. Depending on the composition of the purification plant quality and cost of drinking water and damage to nature, etc. have been calculated.

- Decision criteria such as costs, quality, reliability, public health and institutional aspect had to be known for a period of 30 years not only at the provincial but also at a local level.

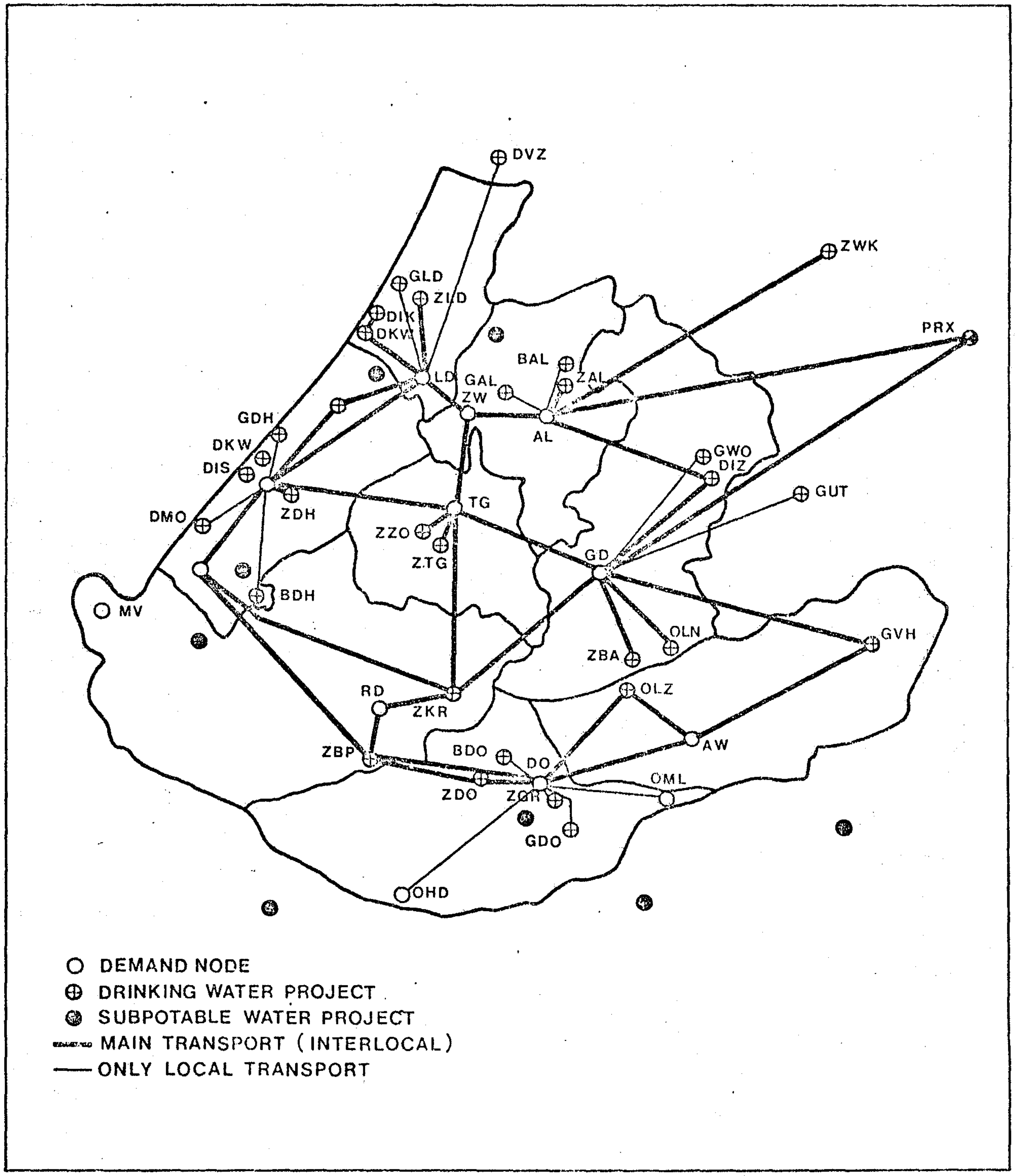

Fig. 1. Drinking water transport system.

Uncertainty

There was considerable uncertainty concerning the following important developments:

- future demand of drinking water and its distribution over the province
- energy prices
- new purification possibilities and their effects in terms of quality and cost of drinking water etc.
- quality of the various sources.

Additional uncertainty was caused by input data and such economic variables as discount rate, etc.

3 Modelling approaches

The amount of detail and the number of different decision criteria and alternatives made a modelling approach obvious. Because of the dynamic character of the problem with many non-linear relations, many objectives and many decision makers at different levels simulation was attractive. Hence initially the combined RID-DWL team focussed on simulation.
A simulation model is an analytical model, i.e., exogenously defined policies are inputs and objectives such as costs and quality of drinking water are outputs.

The RID feared that there were in principle so many potential alternative policies that it would not be possible to survey the outcome of all of them and to be sure that all attractive alternatives could be found.
Therefore to guide the search for attractive alternatives and to get an impression of what optimal solutions for the various objectives or combination of objectives look like an optimization model has been constructed. This optimization model is a policy model, i.e., given objectives it selects an optimal policy out of all possible policies.
However there were various difficulties with the optimization approach as well.

- There were so many objectives and these objectives could be combined in so many alternative ways that also the optimization approach could never cover all the attractive solutions.
- The many objectives required multi-objective programming. However the distance between planners and policy makers was too large to make estimates of reasonable weights for objectives feasible. Hence normal multi-objective programming was impossible. Moreover the process of assignment of weights to objectives would not correspond to the actual real desicions to be made.
- In stead of one decision maker as is normal in optimization there were many decision makers at different levels.
- The dynamics of the problem would have to be handled by means of dynamic programming.
- There were essential non linearities in the system.

In order to deal with all these complications a very sophisticated optimization approach would have been necessary. This would have led to a very complicated model with probably not very accurate results. Notwithstanding these difficulties it has been decided that a relatively simple linear optimization model would be built for a broad screening of alternatives.

4 Structure of the models

Simulation model

Before the study started DHL constructed a simple simulation model with 2 points of demand, 3 plants, production and costs in balance sheets. The purpose was to acquaint water resources planners with simulation and to get a first insight in the problem.

In the first year of the study (1979) the combined DHL-RID team built a second model consisting of 4 modules: demand, production and capacity, quality and costs [see fig. 2].

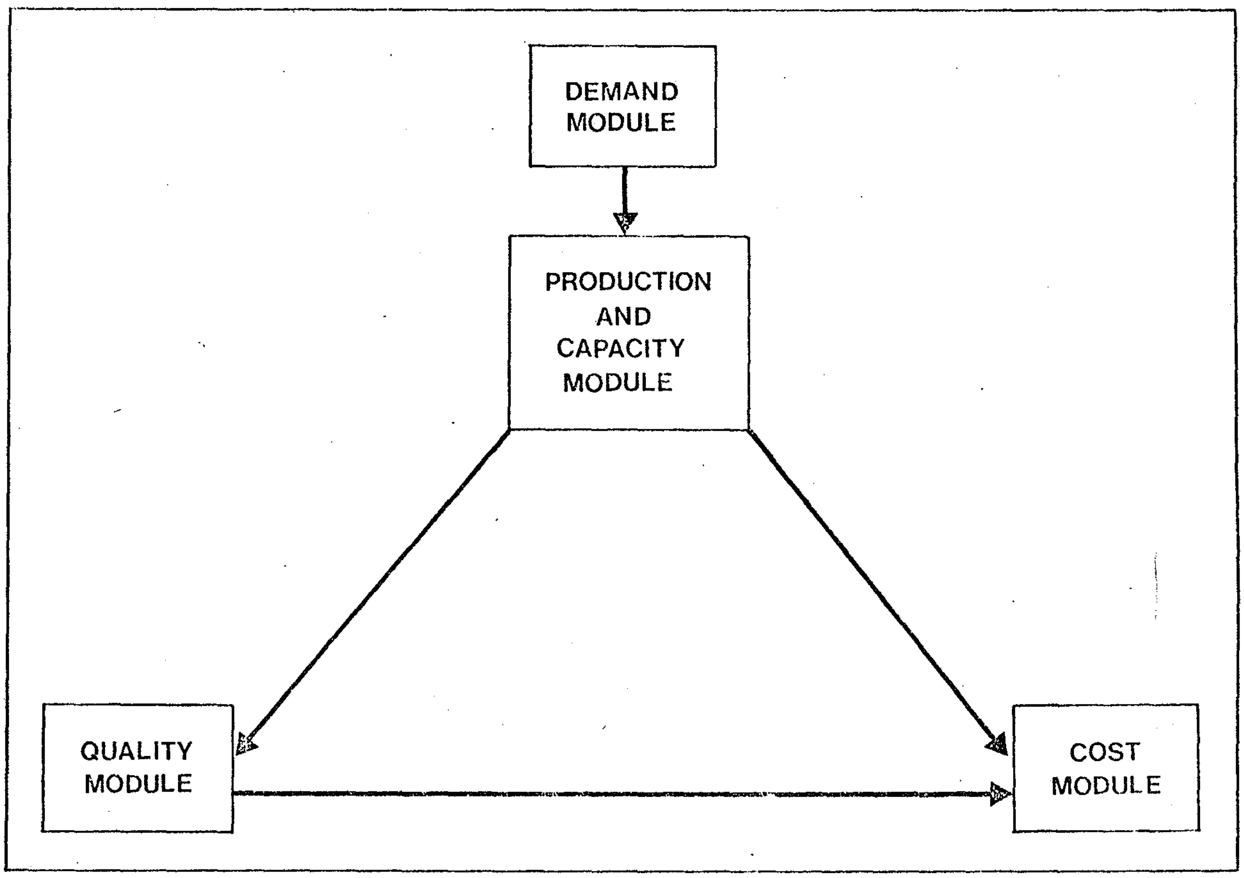

Figure 2 Basic structure of second simulation model

The central piece of the simulation model was the so called production and capacity module. An important element of this module was the adjustment mechanism of capacity to demand (see figure 3).

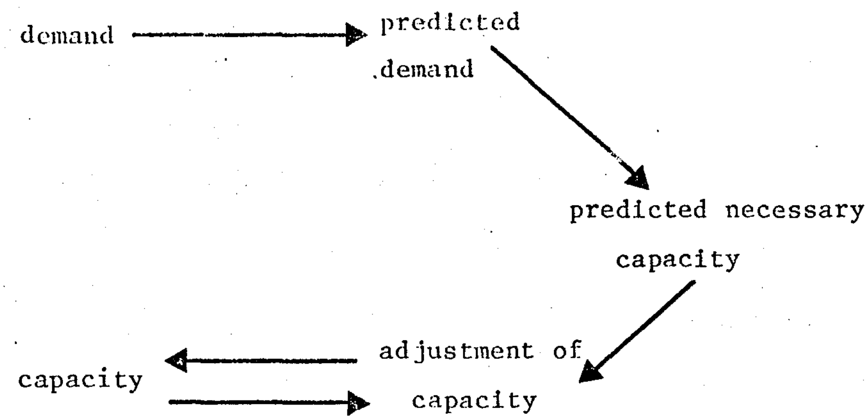

Figure 3 Capacity adjustment. (The arrows indicate causal influences)

The demand was assumed to be independent of costs. It always had to be met. Hence demand could develop according to its own rules.
Along with the demand module a forecasting mechanism was included. This introduced deviations of forecasted demand from realized demand. As a consequence sometimes capacity and demand did not fit precisely.
Using this construction it was possible to simulate the historical developments of capacity and demand very accurately. This enabled us to study appropriate planning mechanisms, which were deemed important given the historical uncertainty of demand.

An other important part of the production and capacity module, missing in figure 3, is the allocation of demand to supply points. It occurs six times: for actual demand and both for short and long term forecasted demand for both subpotable water and drinking water. (A distinction between short and long term forecasts had to be introduced because of the different planning horizons for purification plants and pipelines.)
The allocation mechanism operates on the basis of preferences of demand points for suppliers and the other way around. A precise sequence of prefered deliveries from supply points to points of demand is setup. According to this sequence demand is allocated to the corresponding supply points as far as is still needed and possible. This allocation mechanism and the preferences on which it is based turned out to be clearly understandable and can easily be interpreted in reality. Important is also that the preferences underlying the allocation are mostly determined by the drinking water companies who largely agree on their values. In the model a policy is determined by setting prefer

ences for the deliveries and maximum capacities for the supply points. The latter quantities are in the hands of our clients.

Corresponding tho these policies the simulation model generates solutions i.e. time dependent water supply systems. There effects in terms of the decision criteria such as costs and quality were all derived starting from the production and capacity module.
In the first year of the study about 100 plants and pipelines were considered. Numerous array manipulations had to be executed. First we tried to use Dynamo-III with some FORTRAN-subroutines. Unfortunately Dynamo-III did not perform to its specifications and we lost 4 month and also much of our impetus. Finally we decided to use an other sophisticated language, ACSL (Advanced Continues Simulation Language).However, in the beginning of the second year of the study the experiences with this language were disappointing too because most team members were unfamiliar with it and the communication stagnated. Furthermore the differences between forecasted demand and realized demand caused endless confusion to those team members who were more familiar with the optimization approach. Therefore we built a third simulation model using structured programming in FORTRAN in which demand and forecasted demand were taken from the same demand scenario which was supposed to be perfectly known. Five new modules for effect calculations of production and capacity developments were added. An even higher number of plants and pipelines have been considered. In figure 4 an overview of the last version of the model is presented without further comment*.

The optimization model is a linear single time step multi objective model. The objectives are assumed to be linearly dependent on the decision variables of the model. These variables are productions and transports of drinking water and subpotable water.
The following objectives were considered: costs, water quality, reliability, public health, damage to nature and energy consumption.

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* Bresser, A.H.M. and Pluym, W.K. "Multi-objective planning of the water supply for the province of South Holland", Leidschendam, RID, 1981.

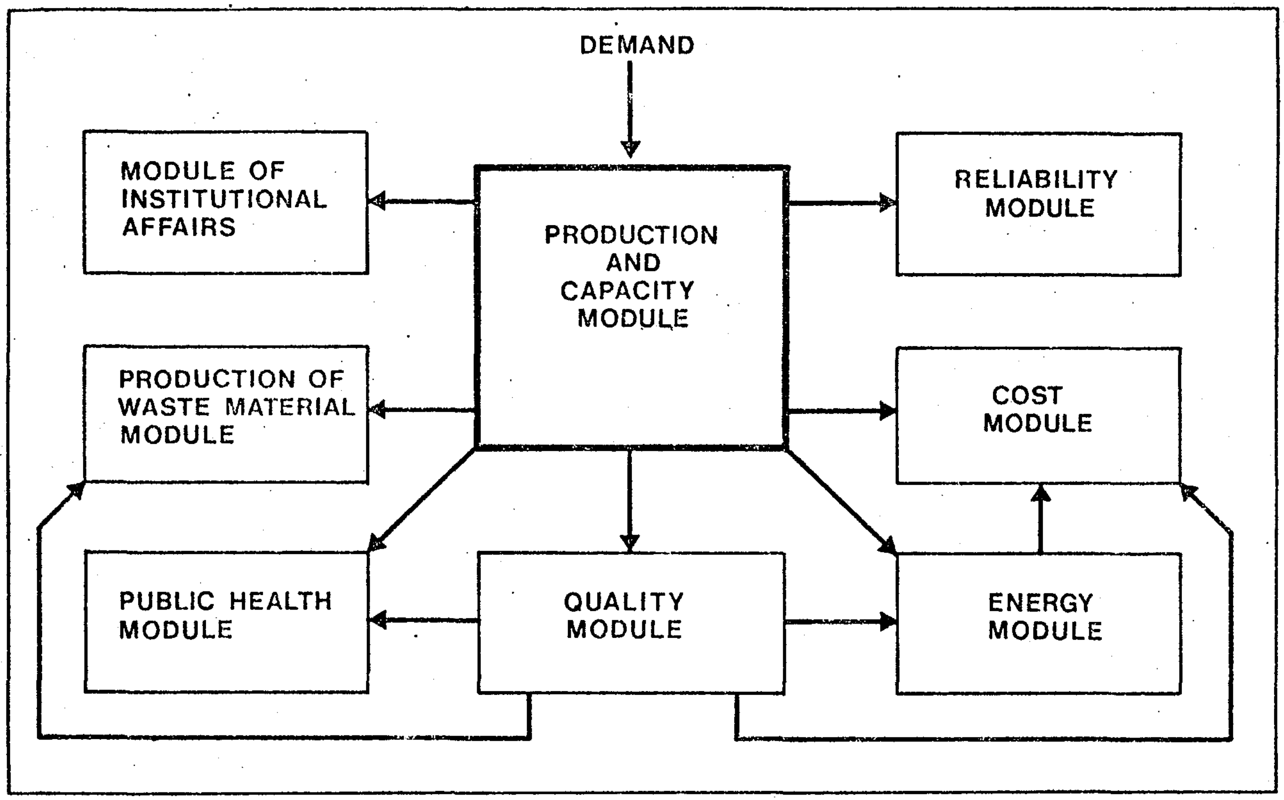

Figure 4 Overview of third simulation model

Optimization model

To give some more insight into accuracy and levels of detail we next compare the cost approaches in both models.

Costs in simulation

Fixed costs sometimes are as much as 80% of the total costs so it is important to calculate them accurately. In the simulation model fixed costs are dependent on the capacity expansion of each element (economics of scale). For the calculations of present values of solutions also the year of investment has to be known. So the total development of investments over time is computed. Calculation of fixed costs per m^3 of water is done with the so called anuity method (average unit costs, Hall* e.a., 1970). Energy costs are dependent on the production and the available pipes. Other variable costs only depend on

* Hall, W.A. and Dracup, J.A. "Water Resources Systems Engineering" Chapter 6, Water Resources Investment Timing, New York, McGraw-Hill, 1970.

production. Fixed costs per m^3, energy costs and other variable costs are summed up to total costs per m^3 (time dependent).
In order to calculate the total present value all costs are discounted to the same year (1980).

Costs in optimization

Each element of the system has coefficients for fixed, energy and variable costs. These coefficients are independent on the necessary capacity expansion. In other words economics of scale do not play any role in this approach. Also the time pattern of the investments is not computed so that it is impossible to calculate a meaningful present value.

5 Modelling practice

In this chapter we shall discuss how the models have been used during the study. Both were applied separately from each other and in interaction. Two different interaction patterns were possible.

- The simulation model generates input for the optimization model (simulation → optimization).

- By means of simulation solutions of the optimization model are detailed (optimization → simulation).

Simulation → Optimization (figure 5)

The detailed output of the simulation model could be used to calculate coefficients for the objective functions used in the optimization model such as:
- drinking water quality indexes
- public health indexes
- costs per m^3 water
- energy consumption per m^3

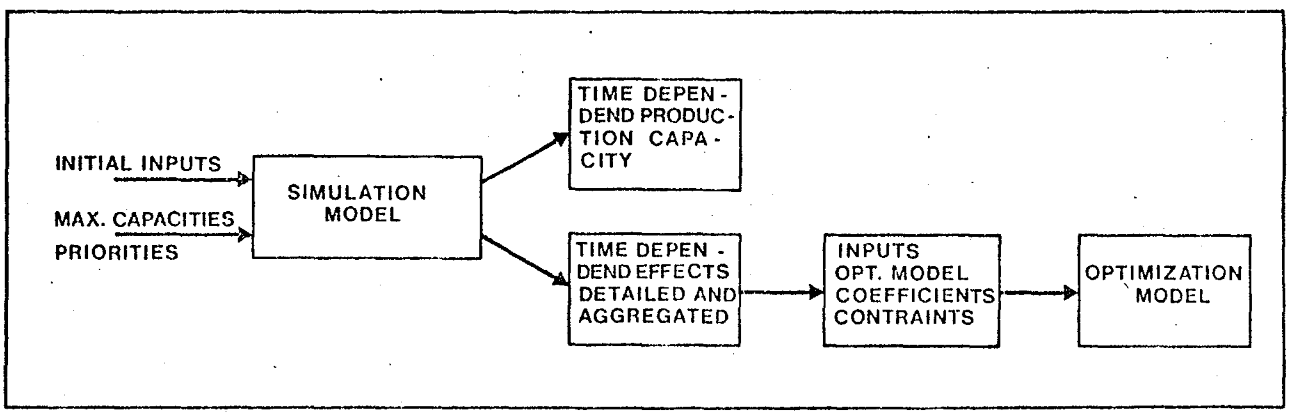

Figure 5   Relations simulation → optimization

This approach was not without difficulties. Given inprecise data, the simulation would yield a range of outputs which in turn would be used as input for an also sensitive optimization model.
In addition, it turned out that costs were rather sensitive to the chosen policy (simulation). As input for the optimization model we took mean cost

values from a great number of simulation runs.

Optimization → Simulation (fig. 6)

A solution of the optimization model could be translated into maximum capacities and a priority sequence so that simulation runs could be made corresponding with the optimization run. In this way the capacity expansion and a detailed description of effects and their developments over time could be generated.
Next results computed with the simulation model could be compared with those of the optimization model.

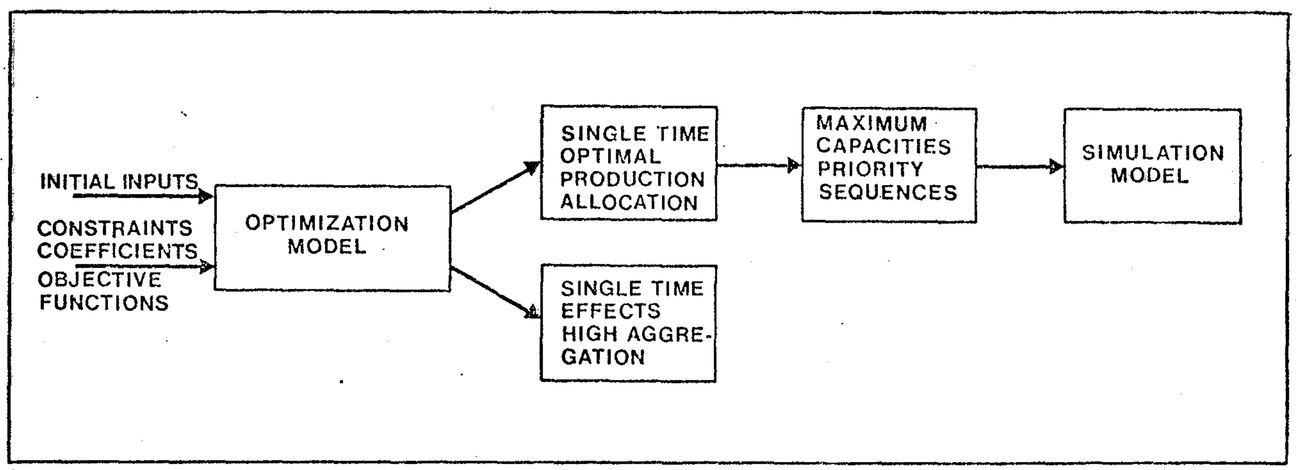

Figure 6 Relations optimization → simulation

In our modelling practice we used this second kind of interaction only a few times because of lack of time. A comparison of the optimal solution with the simulated optimal solutions showed that costs calculations of the optimization model were rather inaccurate because of the assumptions about linearity and time independency (see table 1).
Further comparisons of results on costs of both models showed that using the simulation model better solutions could be found than the cost optimal solution detected by the optimization approach. An important remark is that the

best cost criterium from the cost benefits point of view is in our case the discounted cost made during the planning period. A static model like our optimization model can never produce such a time dependent cost criterium. This is a second reason to be very careful with cost results of the optimization model.

Reliability calculations of the optimization model were less accurate than simulation calculations. So for this objective no conclusion could be drawn from optimization.

	Dimension	cost optimal solution opt.	cost optimal solution sim.	reliability optimal solution opt.	reliability optimal solution sim.	quality optimal solution opt.	quality optimal solution sim.
cost price [year 2010]	[DFL/m^3]	1.33	1.06	1.85	1.36	1.81	1.58
reliability [not delivered quantity, year 2010]	[^{o}/oo]	0.94	1.82	0.47	1.92	1.09	1.89

Table 1 Optimal solutions from optimization model (opt.) and simulated versions of these optimal solutions

Both models were used very intensively to guide the various sub-studies. One of the first results of the simulation model was that given the priority sequence of drinking water companies and cities some parts of the province South Holland and some projects would never interact with the future water supply in the rest of the province. An analysis with the optimization model using different combinations of objectives affirmed this first result. So a lot of field work for recreation and damage to nature could be reduced. Further we used both models to define upperbounds for the capacities of projects. This again meant an important reduction of fieldwork.

Finally we found attractive solutions using only the simulation model. We already mentioned that the only policy instruments available to our clients are maximum capacities. Priorities of drinking water companies are given to them. So, in principle, only one priority sequence had to be taken into account in our search for attractive solutions. Only slide variations in this sequence caused by rather indifferent priorities had to be investigated. Varying the maximum capacity of projects systematically and using the priorities of drinking water companies it turned out that only 20 essentially different solutions could be found. An important drawback of this approach is that all kinds of undesired present practices of drinking water companies are extrapolated into the future. Disregarding some of these doubtful priorities another 5 solutions could be distinguished. Especially the simulation model helped to find out that many alternative policies of our policy makers resulted in the same solution.

6 Conclusions

Design of the study

- Early in the study much time has been spent on the definition of the policy problems, the screening of existing knowledge, and the identification of gaps in this knowledge leading to substudies. Much attention has been paid to the setup of the system study and the substudies so as to minimize the uncertainties in the final results given time and money constraints. This time proved to be well spent.

- During the study the system analysis has guided the research process. It has been used to define the substudies as to the required level of detail, allowable level of uncertainty and the kind of results needed. It has indicated what kind of new substudies should be executed and when substudies should be stopped. In a complicated study like this systems analysis has to play such a central role.

- One of the hardest problems has been the need to keep specialists in the fields of recreation and nature within the bounds of the systems analysis. This has taken much effort. Despite this not all specialisms have been fully integrated yet.

Simulation and optimization models

Instead of starting an analysis, like the one described here, by means of a complicated and detailed simulation model in order to screen alternatives and then determine precise optimal solutions using an optimization model we recommand in similar studies the opposite approach: first use an optimization model for a rough but systematic screening of inattractive options (supply points, purification methods, pipelines, etc.) and for a first delineation of substudies. After this rough screening a simulation model must be used to generate attractive solutions in great detail and accuracy, and with an explicit representation of developments over time and for further guidance of substudies.
In such an approach it is essential that the optimization model is simple so that it takes little time to collect data and to build the model.

The point is that in the political process it is necesary to apply formal methods to exclude relatively large numbers of sometimes obviously, inattractive options. Inclusions of such options in the study requires much extra effort especially in data collecting.

In our case we built both models at the same time. The screening task of the optimization model in the first phase of the study could not be executed because the model was not ready. Some substudies had been carried out before the analysis with the models showed that these substudies were not necessary. Another consequence was that the optimization model seemed to be superfluous because the screening had been done informally using only the simulation model.

- The interactive use of both models was interesting because:
  - the interaction lead to objective functions (quality, public health) or to more accurate objective functions (costs, energy) for the optimization model.
  - development over time of optimal solutions could be simulated very easily. Sometimes if necessary, optimal solutions had to be adapted to effects of developments over time.

- A serious problem was the inaccuracy of the static and linear optimization model. Comparing optimization results with simulation results concerning reliability for example it turned out that optimization calculations were too inaccurate for further conclusions.

- For the detailed calculations with the simulation model numerous data are needed. It is important to get these data in a early stage of the model building process in order to add realism to the solutions and build up confidence.

- The simulation model used structured programming in FORTRAN. All team members were familiar with FORTRAN so that communication about model details was very easy. No great structural alterations were needed after the initial stages of model building so that the inflexibility of FORTRAN was not too bothersome. Experiences with the simulation languages DYNAMO III and ACSL in earlier stages of the study were disappointing.

Results and presentations

- There are so many alternatives and criteria that it is very difficult to draw formally hard conclusions without using multi criteria analysis.

- The individual members of the steering group for the study prefered the presentation of the optimization results over that of the simulation results. The reason being that the individual members of the group were interested in only one or a few objectives and the optimization results were presented in two dimensional trade-offs. It is likely, however, that the presented optimization results have sometimes been misinterpreted by members of the committee.

- Presentation of results in objective space is not sufficient. Also concrete elements of the solutions, such as projects, have to be specified in the presentation of the results because not all criteria used in the final political decision process are explicitly stated in the study.

- The big advantages of the simulation model were its level of detail, flexibility, adaption to the political reality, and insight in the effects over time. The simulation results, however, were much harder to interpret. Since all objectives were still present and also time was important.