Predicting Water Demand in a Small Mediterranean Country

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Abstract
Based on the Rosen's definition (Rosen 1985), anticipation "is based on having a predictive model of the system you're trying to control ...". In case of complex systems, for which analytical models either do not exist or are based on too strong assumptions, anticipation is based either on simulation models or mental models. The paper deals with one particular simulation study whose main objective is to form a part of a decision support system for water management. In particular water demand related processes and their links to economy of a small Mediterranean country are studied and simulated. Simulation models are expressed by system dynamics and implemented by the visual simulation tool Powersim™.
Keywords: simulation, system dynamics, visual tools, water consumption, economy.

1 Introduction

Water is an essential element of household consumption, and an input into production processes. In general, it does not have close substitutes. Unlike in Middle East countries where most of water is still used for irrigation with expected growth of domestic use (Martin 1999) most of the billed water consumption in Malta is for final, domestic consumption, the remainder being taken up by agriculture, industry, services, tourism and government. Less than one-half of the country's water output originates from renewable ground-water sources, the remainder is provided by energy very demanding reverse osmosis plants. Water production and distribution in Malta is provided by Water Services Corporation (WSC). Another related simulation study has been carried on to study groundwater extraction and replenishment processes (Cassar et al. 2000a) and reverse osmosis desalination as such (Cassar et al. 2000b). So it is obvious that understanding and prediction of water consumption patterns in a country where water is a scarce commodity subsidized by government is very important. Prediction of future behavior of any (real or fictitious) system has to be based on its model. Generally there are three types of models that might be used for this purpose (Zeigler 1984), (Sterman 1991).

Analytical models express the relevant facts and relationships by mathematical equations whose solution gives the answer to the question.

Simulation models are based on description of the system's structure together with basic relationships among its components. The answer is obtained from an experiment that runs the model and observes its behavior.

Mental models are based on relationships kept and processed directly by our brains.

All three types of models have their advantages and disadvantages and there are situations where any of them could be the best one or the worst one respectively. A very instructive and clear discussion on this topic can be found for example in (Sterman 1991). With respect to our problem the choice seems to be as follows. Analytical (mathematical) models are very good for optimization of static problems, but typically fail when applied to dynamic complex systems, mainly due to very strong assumptions. Mental models represent the experience of experts. It is difficult if not impossible to assess their quality and validity. Expert's intuition can prove to be the best available prediction or it can fail totally. Generally the validity of mental models in predicting future behavior of complex systems is very limited. So it seems that construction of a simulation model was in our case the only feasible solution.

The simulation model is supposed to form a core of a "what-if" answering tool able to predict water consumption in various situations and to modify water distribution regulations if necessary. Since the very beginning it was clear that the task would not be easy. In water consumption there are many actors with different behavioral patterns that are based on factors that are often difficult to quantify. Even if quantification is possible, data are often not available in required amount and quality. Under such circumstances a logical questions arouse: "Is it meaningful to build such a simulation model? Will the results be credible?" An honest answer was "we do not know". Nevertheless we are convinced that the effort in all such cases is not wasted. Strict requirement for exact data would stop mathematical and computer modeling whatsoever. Most practical models contain data that are just rough estimates and the only support to the credibility of results is some sensitivity information. So strictly speaking our effort was justified by two facts. Even a simulation model that is not accurate and whose results have to be taken with great care (by the way, are there other simulation models?) is better than nothing. Better than an extremely simple and flawed mental model (Sterman 1991). Second fact was the educational and analytical output of the simulation study. It is well known that too often simulation study is the first case when the system is properly studied and described. Qualitative results represented by better understanding of the system and its behavior are sometimes more useful than the answers to the original problem. In our case we believe that identification of actors involved in water consumption, identification of their parameters together with their quantification represents an important contribution to the understanding of water consumption processes.

Regarding the tool used the choice was almost obvious. *System dynamics* developed at the MIT in late fifties (Forrester 1961) is a tool intended to support simulation of complex dynamic systems made of many related components.

The simulation study described in this paper is a part of the project "Medwater – A Decision Support System for Water Management in the Mediterranean Region" coordinated by the University of Sunderland with participants from Cyprus, Malta, and Norway. The paper's objective is a description of system dynamics based simulation methodology explained by practical examples and not the technical details of the model.

2 Building the Model

There is a vast literature related to system dynamics based methodology of building simulation models. See for example (Cover 1996), (Kirkwood 1998a,b). The basic idea expressed by the author himself is: "System dynamics uses concepts drawn from the field of feedback control to organize available information into computer simulation models" (Forrester 1991). Next chapters will try to show how the basic principles of system dynamics have been applied in our simulation study.

2.1 The Problem

All simulation studies and software projects generally have to start by the problem specification. In our simulation study the problem was this: "answer various queries about water consumption at national level in various situations". This sentence is of course far from exact problem specification, but it is very typical for simulation studies that nothing more is in fact available. Identification of factors that influence water consumption is one of the outputs of the simulation study; their exact list cannot be expected as a part of the problem specification.

2.2 The Simulated System

We never simulate the whole real system. Using the problem specification as a criterion we select only those parts of reality that are relevant and then we simplify them. Simplified description of relevant parts of the reality is called the *simulated system*. There is unfortunately no simple guide how to create it. We have to consider everything that is relevant and we have to ignore the rest. This is easy to say, but to do it represents probably the most difficult part of simulation. Due to recent development of visual simulation tools like Extend™ or Powersim™ converting a simulated system into a simulation model is very often just drawing by mouse on the screen. Even if programming is necessary user-friendly simulation languages together with program development tools support the work very much. So the hard work has been moved to the early stages where the simulated system is specified. The problem is that often we do not know what is relevant. Take domestic water consumption. Among others there are two factors that certainly affect it: price of water and family income. These two are related to each other through national economy in a very complex way. So shall we incorporate a simplified model of national economy into our water consumption model or shall we make these two factors exogenous? Simple answer does not exist. By making a variable exogenous we can break an important feedback loop. On the other hand incorporating more and more variables into the model (making them endogenous) can result in a big unmanageable simulation model. The solution is as almost always a sensible compromise.

After starting work on the simulated system we found out that we need some *decomposition* that is a precondition of successful modeling of all large-scale systems.

In our case a sensible decomposition seems to be the one based on different sectors. Considering the different characteristics and behavioural patterns of the various users of water, six different models with their own exogenous and endogenous variables were developed to cater for these differences:

- Household sector
- Manufacturing sector
- Services sector
- Tourism sector
- Agricultural sector
- Government sector.

This categorisation is neither comprehensive nor complete, as for instance; the manufacturing sector would itself comprise a diverse set of activities that cannot be easily classified into one. Thus, the categorisation also reflects limits to the extent of data availability as well as modelling resource constraints.

The latter two considerations were however not considered in deriving each of the six models described above. In particular, the complexity of the conceptual framework was not reduced simply because data relating to specific issues do not exist. Sections of the models that cannot at present be supported by data were left exogenous or redundant for the time being, to be potentially used when more data becomes available. The paper (Borg et al. 2000a) contains a brief description of all sectors. Here we shall present just typical examples. After creating all sectored models they have been integrated into one water demand model.

To create a simulated system we need a language to formulate it. There are very many both formal and informal tools for this purpose. In our case the language was the system dynamics itself. System dynamics defines two graphical system description languages at two different levels of abstraction. There are no special names for these two languages, so let's call them by the names of the products of their use: *causal loop diagrams* and *flow diagrams*. Description of these two languages covers the essence of system dynamics. Many examples can be found for example in (Kirkwood 1998a). All diagrams presented in this paper were created by Powersim™ 2.51 (Powersim Corporation, AS).

2.3 Causal loop diagrams

Causal loop diagrams describe the system at a very abstract level. The work starts by identification of various factors or components and their relationships. Factors are represented by textual labels, relationships by arrows. There is no quantification except the positive and negative nature of relationships that is distinguished by labeling arrows by + or - signs. The relationships typically represent causations and the fact that sequences of causations often close explains the name "causal loop". Big diagrams contain many interconnected loops and also open causation chains. Loops with odd number of negative arcs tend to reach an equilibrium, so they are called *balancing loops*. Loops with even number of negative arcs (or none) are called *reinforcing loops.*

They do not reach equilibrium because a fluctuation eventually returns back with the same sign. Values of factors then grow exponentially. Situation is of course complicated if a factor participates in several loops. Figure 1 shows the causal loop diagram of water demand related factors of an average household.

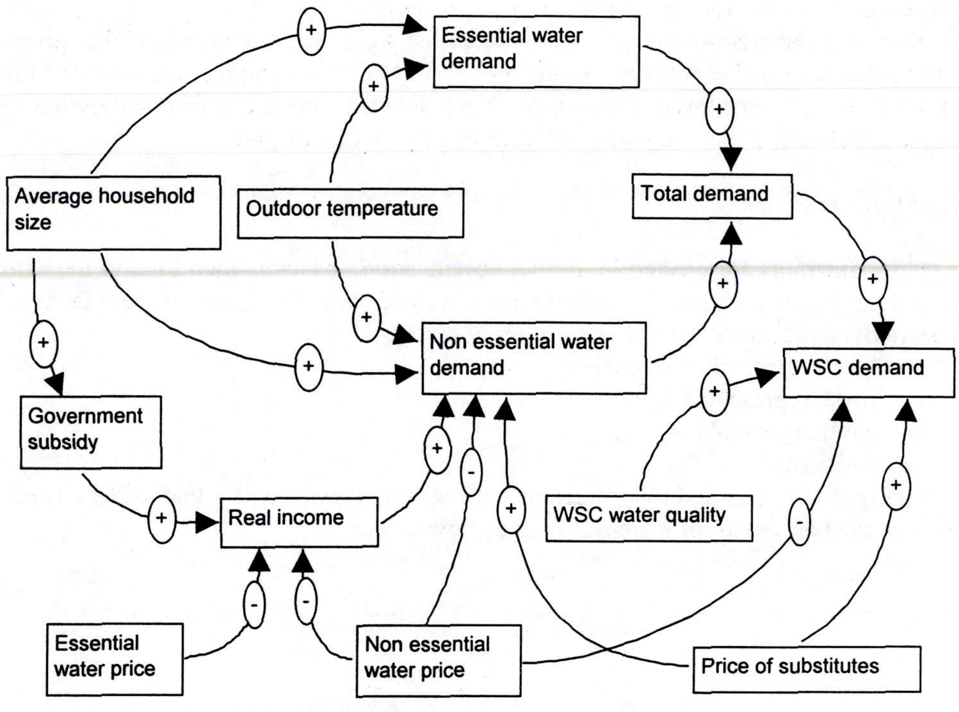

Fig. 1: causal loop diagram of an average household water demand model

A household's water demand that is provided by the Water Services Corporation (WSC) *WSC demand* is modelled as the total rate of water demand by the household *Total demand* adjusted for *WSC water quality* (relative to other sources of water supply) and for the *Non essential water price* supplied by WSC relative to the price of alternative water sources *Price of substitutes*. In this case, all water provided by WSC is assumed to be of first class quality, due to the present difficulties to create a parallel second-class water distribution system for the household sector.

The household's *Total demand* for water is made up of *Essential water demand* and *Non-essential water demand*, the former not responding to changes in prices or income. Essential demand is modelled to respond solely to the *Average household size* (number of persons) on the basis of the volume of water charged at the lower price category by WSC, and to a seasonal factor represented in the diagram by *Outdoor temperature*.

Non-essential demand for water by a household is modelled to depend on the average price of water given by the non-essential water price and the price of substitutes, household purchasing power – *Real income*, the seasonal factor, and the household size. Finally, the household's purchasing power is derived from a set of exogenous variables (not shown in the diagram) less the water service charge plus the *Government subsidy* that depends on the number of persons in the household.

Note that there is no quantification except the signs, so for example higher price of substitutes (alternative sources) means higher water demand, higher non-essential price of WSC water means lower demand, etc. Note also that there are in fact no closed loops. Some are closed in the integrated model through its economy part.

2.4 Flow diagrams

Flow diagrams are created by further specification of factors identified in the causal loop diagram. Note that so far nothing has been said about the nature of these factors. In system dynamics there are only four types of objects:

- levels (also called stocks)
- flows represented by rates
- auxiliary variables
- constants.

Figure 2 contains a simple diagram with all the above objects that will be used to explain the basic ideas of system dynamics flow diagrams.

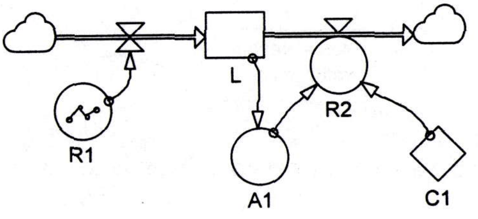

Fig. 2: an example flow diagram

Levels are objects with memory that are given initial values and that are changed by input and output *flows*. *Auxiliary variables* are used to simplify complex relationships and to represent factors with instantaneous change of values. *Constants* represent various model parameters that do not change during simulation. Arrows called *information links* represent the relationships. *Cloud symbols* represent the environment of the model. Regarding flows a cloud is interpreted either as a source of arbitrary amount of flow (the actual value being given by the rate) or as a sink where any amount of flow can vanish (again the actual value is given by the rate). The double lines are flows; the two small triangles represent rates. The actual value of a rate is given by an auxiliary variable (or a constant). The rate of the input flow to the level *L* is given by the variable $R1$; the rate of the output flow is $R2$. Variable $R2$ attached directly to the flow is just a shorthand to simplify diagrams. In Figure 2 the variable $R1$ is entered as a function given by a table - see the icon. The variable $R2$ is computed by an expression that contains $A1$ and $C1$ as operands - for example $A1+C1$. Double click on the $R2$ icon opens a dialogue window to create/edit the expression. Many standard and special-purpose functions are available. Similarly the variable $A1$ depends on the current value of L. As the name "rate" suggests, input flow increases L, output flow decreases it. Because all variables and levels can change in time, they can be considered as time functions. Level is then an integrator that with respect to Figure 2 performs exactly the following:

$$L(t) = L(0) + \int_0^t [R1(\tau) - R2(\tau)]d\tau$$

In other words the diagram in Figure 2 solves an ordinary nonlinear differential equation of the first order for a given initial value $L(0)$. So flow diagrams are in fact block diagrams made of integrators, variables and constants where the difference (input flow - output flow) is the first derivative of the function computed by the level = integrator. Compared with other block oriented continuous simulation tools there is one important difference. System dynamics modeling typically does not start with any mathematical model like for example a set of differential equations. Instead of being an input, such a model - if needed - can be extracted from a flow diagram as an output by writing equations for all levels and combining them with the equations of auxiliary variables. The opposite way is with system dynamics also possible: convert a set of equations into a block diagram made of integrators and other blocks and convert it into a flow diagram. Modern system dynamics tools have many functions including typical non-linearities to simplify this process.

To convert the causal loop diagram in Figure 1 into a flow diagram it was necessary to take several decisions. A brief outline of the more important ones follows with reference to the resulting flow diagram with self-explaining labels that is shown in Figure 3. Note also that in order to keep diagrams readable by eliminating too long links, Powersim™ allows several copies of the same object (icons with equal names displayed inside an outlined square).

First of all it was necessary to identify the type of each factor. Type of some factors was obvious, like for example constant household size. Others like for example average price of water are obviously computed auxiliary variables without memory. In our case the required output was the water demand rate, that's why there are only two levels that are in fact within the demand model not used: total water demand and demand for WSC water, both with input flow rates. All other factors are auxiliary variables computed either directly as an expression (like essential and non-essential water demand) or through a table function (government subsidy).

Second important decision is the time horizon and the time step. In Malta water is billed in three 4-months periods, so all data regarding water consumption is collected and stored accordingly. That's why in the model the time step is one 4-month period.

Time horizon is several years (we performed experiments for 10 years), but this can be easily adjusted later before the experiment.

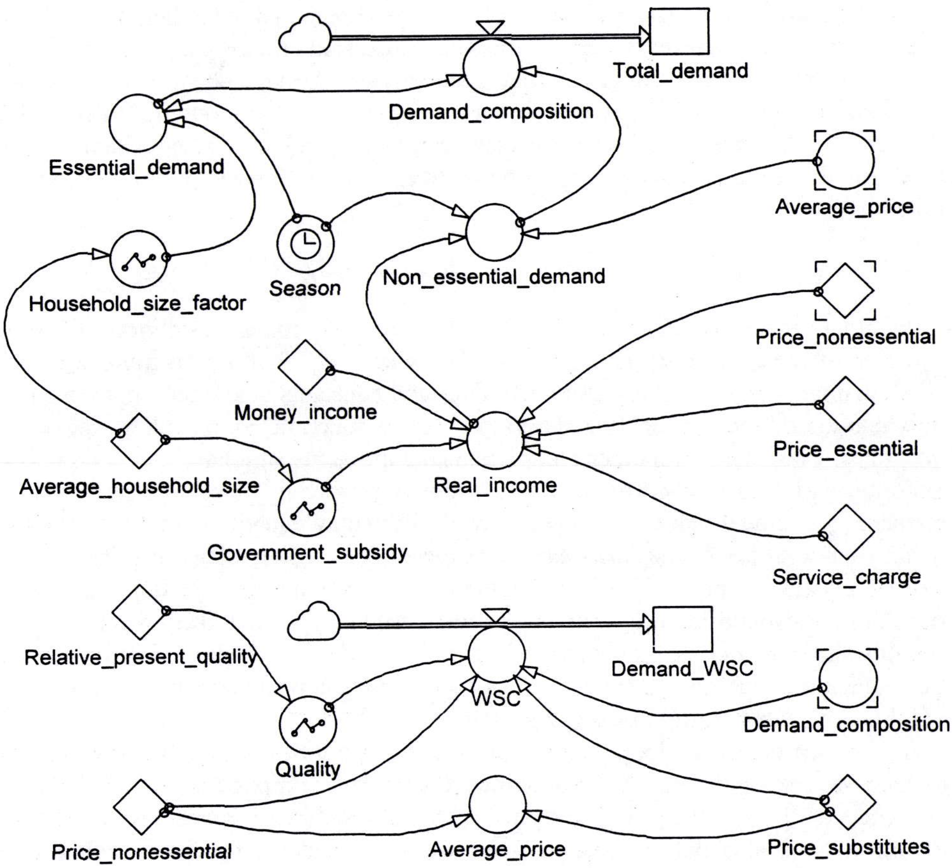

Fig. 3: flow diagram of an average household water demand model

Third problem is the exact mathematical representation of the relationships from the causal loop diagram. This was based on the analysis of available data, discussions with WSC people, and we must admit that sometimes just on intuition. Detailed list of all expressions is out of the scope of the paper, but here are some examples:

$$Essential\_demand = Household\_size\_factor * \text{IF}(Season = 1, 1.1, 0.95)$$

Household_size_factor is a function that returns water consumption given the household size. So far it is linear. *Season* incorporates seasonal effects. It is computed as (*time* mod 3) where *time* is the time step (4-month period). Note the increase during summer season number 1.

Non_essential_demand = ((Average_price^-1.65)*(Real_income^0.75)*(IF(Season=1, 1.1, 0.95))+(7*Household_size_factor_2))/7.6

Non-essential demand for water by a household is modelled to depend on the average price of water, household purchasing power, a seasonal factor, and the household size. The responsiveness of non-essential water demand to the average price of water was estimated by a regression approach at –1.65. This relatively elastic response reflects the fact that it is essential water demand that is price inelastic, and indeed whose elasticity in this model is assumed at 0. The relevant average cost of water is the weighted average of the prices of non-essential water charged by WSC and the cost of alternative water sources, with weights and price levels being determined exogenously. The response of non-essential water demand to the purchasing power of a household is by regression estimated at 0.75, a relatively inelastic response. The response of household non-essential water demand to the household size has been calibrated at 7 cubic metres per person per cycle that can be non-linear through the Household_size_factor_2.

Real_income = (Money_income - Service_charge + Government_subsidy) * (Price_essential^-0.05) * (Price_nonessential^-0.05)/1.11

Household purchasing power is derived from a set of exogenous variables, part of which is endogenised through the integration with the economic model. Purchasing power is derived as money income less the water service charge plus the government subsidy paid to households in excess of four persons, adjusted by price changes in the prices charged by WSC on essential and non-essential water. The relevant elasticities are set at –0.05, reflecting the extent of water consumption within a household total expenditure.

2.5 Integrated model

The model described in the previous chapter models one household. In the integrated model, as the first approach, the results were simply multiplied by the total number of households in Malta. The other five sectored models were since the beginning constructed as aggregates for the whole sector. The integrated demand model was then linked into a system dynamics model of Maltese economy constructed from an existing econometric model. The economy model has been simplified with respect to its expected interaction with water consumption processes. Integration of demand and economy models has closed several loops that were so far open through exogenous variables. A simple graphical user interface has been developed to make the model accessible even to users who do not know Powersim™ and to support user-friendly "what-if" analysis. It also includes a small database of model parameters.

3. Conclusion

The basic question remains – do we have a good model that contains all relevant agents and relationships among them? Are all these relationships properly quantified? Are the simulation results credible? Again the honest answer is, as always "we are not sure". The model is now being tested and the outputs are compared with available data. At the time of preparing this paper the results are not available. Anyway there are already positive outputs. Building the model has produced a detailed analysis and description of water consumption processes, probably the most detailed one that has ever been carried on in Malta. Also a conversion of an existing econometric model of Maltese economy to system dynamics (Borg et al. 2000b) whose description is beyond the scope of this paper was an experience that may be used to compare these two widely accepted approaches to modeling of large scale systems.

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