

# MODELLING THE DISCRETE ORDERING OF HYDRO-ELECTRIC PROJECTS - THE ARGENTINIAN CASE

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## INTRODUCTION

The purpose of System Dynamics modelling is the study of the mechanism, especially including managerial policies, which govern the evolution of a socio-economic system through time, and in the face of a changing external environment. In particular, the analyst seeks to identify the processes which enable the system to benefit from opportunities and defend itself against threats.<sup>1, 2, 3</sup> The concept of designing policy structures for controllable systems is the essence of the approach,<sup>4</sup> allied to powerful methods of system description,<sup>5</sup> and an efficient simulation technique.

When analysing the long-term behaviour of an organisation as a whole, it is usually necessary to treat the process of capacity addition. In some cases, this has been represented as a mechanism of the ordering of capacity, subject to constraints, in such a way as to eliminate, within a planning horizon, a foreseen gap between capacity required and expected to be available<sup>6</sup>. This paper deals with the problem of modelling these processes for the addition of hydro-electric capacity to the electrical generating system in Argentina.

An earlier investigation of energy modelling by Naill<sup>6</sup>, represented the electrical utility companies in the USA investing a stream of money. The magnitude of that stream, divided by a cost coefficient, produced a corresponding flow of generating capacity, delayed to represent construction. That model is very aggregated and, indeed, can be criticised on other grounds.<sup>7</sup>

In the electrical industry, as Zepeda pointed out<sup>8</sup>, it is hard to believe that the size of capacity units will be constant over a long period. He, therefore, introduced plant size, using a TABLE function<sup>9</sup>, so that size grew with the simulated time of the model. He was, however, legitimately able to regard the plant size as constant at any given moment.

Hydro-electric (HE) Capacity is an example where non-uniformity of the equipment is the rule rather than the excep-

tion. Every project has its own capacity, output/capacity ratio, unit capacity cost, construction delay, etc., and these parameters are mainly determined by the location of the project itself. So, the modelling problem is to find adequate equations for handling the selection of project after project, and tracing the individual characteristics of each one through the system modelled.

Such a system contains a mixture of discrete events (ordering, or not, a given project at a particular time), discrete and different magnitudes (practically every parameter for each project), and continuous processes (the generation of electricity, and revenue, after completion, and incurring expenditure during construction). Such mixed processes have generally been difficult to represent in continuous simulation models, and the common recourse has been a very high level of aggregation which has exposed the model to serious inaccuracy. However, recent work on the modelling of coal face operations<sup>10</sup>, in which it was necessary to represent discrete changes of state and random duration in a state, as well as unpublished work on problems of air defence, suggested that the assumed limitations of continuous simulation were not as severe as had been supposed. This paper, therefore, examines the technical problems of modelling the discrete addition of hydro-electric capacity, as part of a wider analysis.

The following solution is based on the assumption that there exists a precedence order in starting the different hydraulic projects belonging to a particular basin. That precedence order is suggested by the physical aspects of the exploitable area, leaving to the manager the timing of the execution of the project.

## THE ARGENTINIAN CASE

The present configuration of the electricity capacity generation of the Argentine Republic, is strongly based in oil and gas consumption, which represents 64% of the installed capacity, against 30% from hydro-electricity and 6% nuclear<sup>11</sup>. The hydraulic potential of Argentina has been estimated at 191,000 Giga watt hours/year<sup>12</sup>, and specific projects exist which would yield a theoretical annual output of 136,000 GWH/Y approximately<sup>13</sup>. Only 9,614 GWH/Y of that identified potential are being actually produced. Clearly

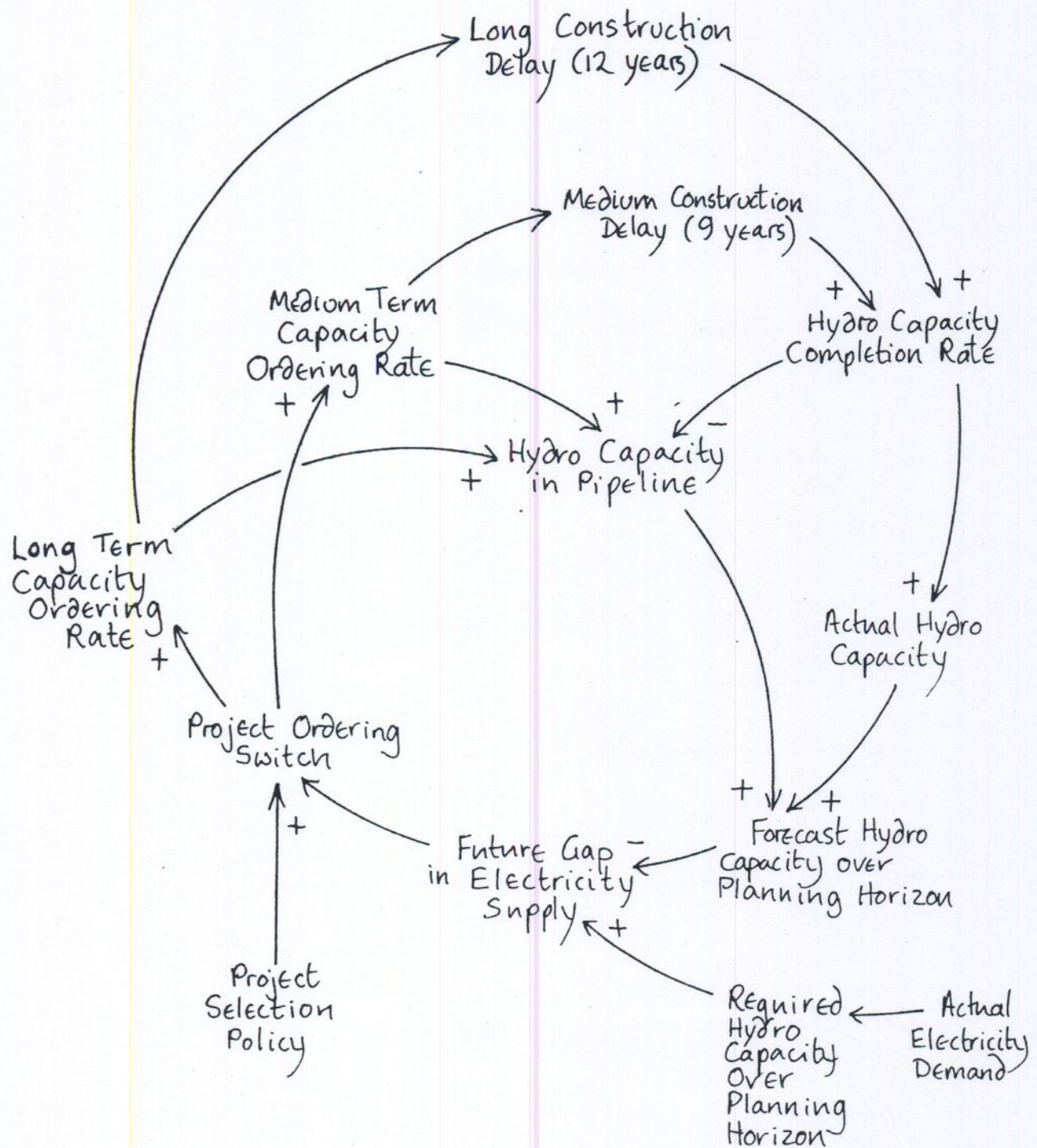


Figure 1. Influence Diagram of the Basic Feedback Loop Controlling Capacity Growth (Simplified)

the development of Hydropower is an important possibility for Argentina.

The possible HE projects in Argentina fall, geographically, into four clear groups: the Parana basin on the border between Argentina, Uruguay, Paraguay and Brazil – the Patagonian basin, and two regions in the Andes, Cuyo and Neuquen.

The Plata projects are large, 2580 MW average, with high total costs, though the unit output cost is very attractive, compared with smaller projects. Long construction delays, 12 years, and international agreements about shared rivers are typical of these projects, together with excellent output/capacity ratios, which should give lower operating costs.

On the other hand, the Cuyo System is characterised by small projects, 277 MW average, with the exception of one project. They have medium output/capacity ratios, low overall costs, but they are the more expensive projects in terms of unit capacity cost. Medium construction delays, 9 years, are typical of the Cuyo System.

The Neuquen and Patagonia systems are very similar groups, with average projected capacities of 1070 MW and 880 MW respectively. The main difference between them is the construction delays. Obviously, Patagonia is less known and planned, and its exploitation is nil, due mainly to cost of the energy transmission to the energy markets, nearly 2000 km from the projects, and lack of regional demand.

The projects must be treated *individually* rather than as group averages, because the variation between projects is very large.

## THE BASIC FEEDBACK CONTROLLING LOOP

A simplified influence diagram is shown in Figure 1, where there are two negative loops controlling the capacity growth. The outer negative loop is followed when it is decided to build up capacity in the Plata of Patagonia systems, which require the longer construction delay. Similarly, the inner negative loop regulates quicker projects, in the Cuyo or Neuquen Systems.

## PROJECT SELECTION POLICIES

The selection of particular projects to fill the anticipated needs of the Argentinian electricity generation system in the heart of one modelling technique and this section explains the rather complicated factors which must be considered.

In an ideal world, or if we were prepared to assume away a good deal of the complexity of the Argentinian case, the problem could be depicted as shown in Figure 2. The Forecast Required Capacity FRC, which includes a margin for reserve capacity, will grow between Now and Now + CDEL, where CDEL is the project construction delay. If all has gone well with earlier forecasts and decisions, there will be sufficient capacity already under construction to make the curve for Forecast Available Capacity, FAC, follow the required curve FRC until just before Now + CDEL. At that point a gap should appear which can be filled by ordering, at Now, enough projects to fill the gap.

The complications arise in the real case because there are two construction delays, 9 years or 12 years depending on the hydro electric basin being developed. In addition, because the

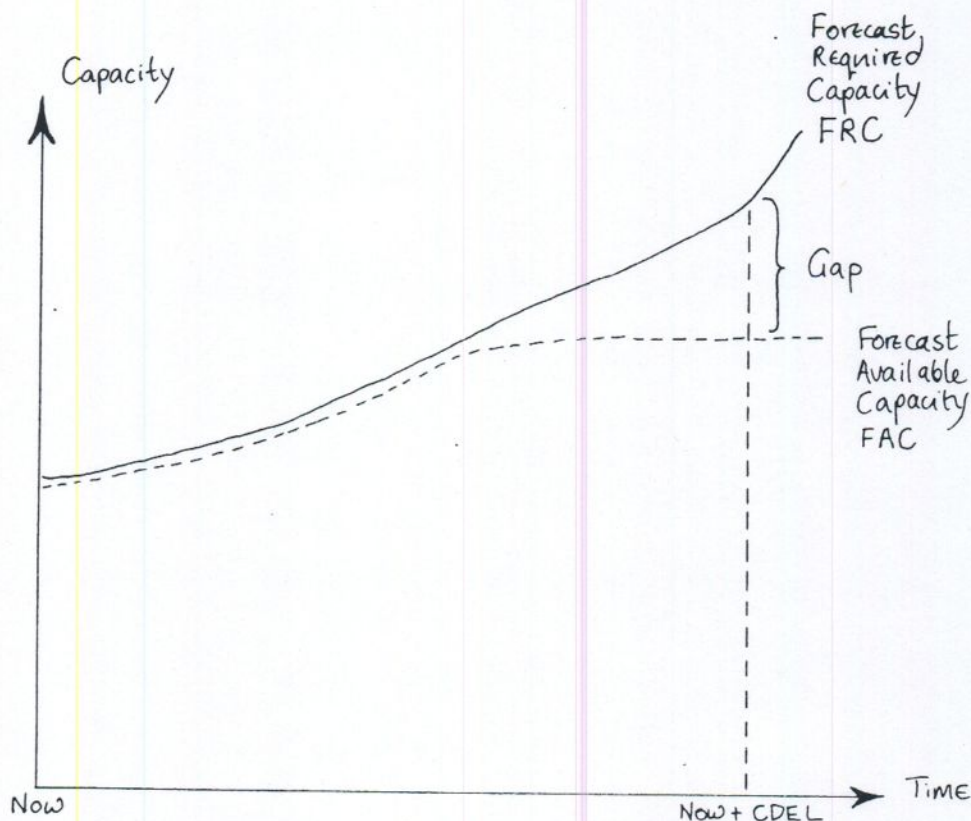


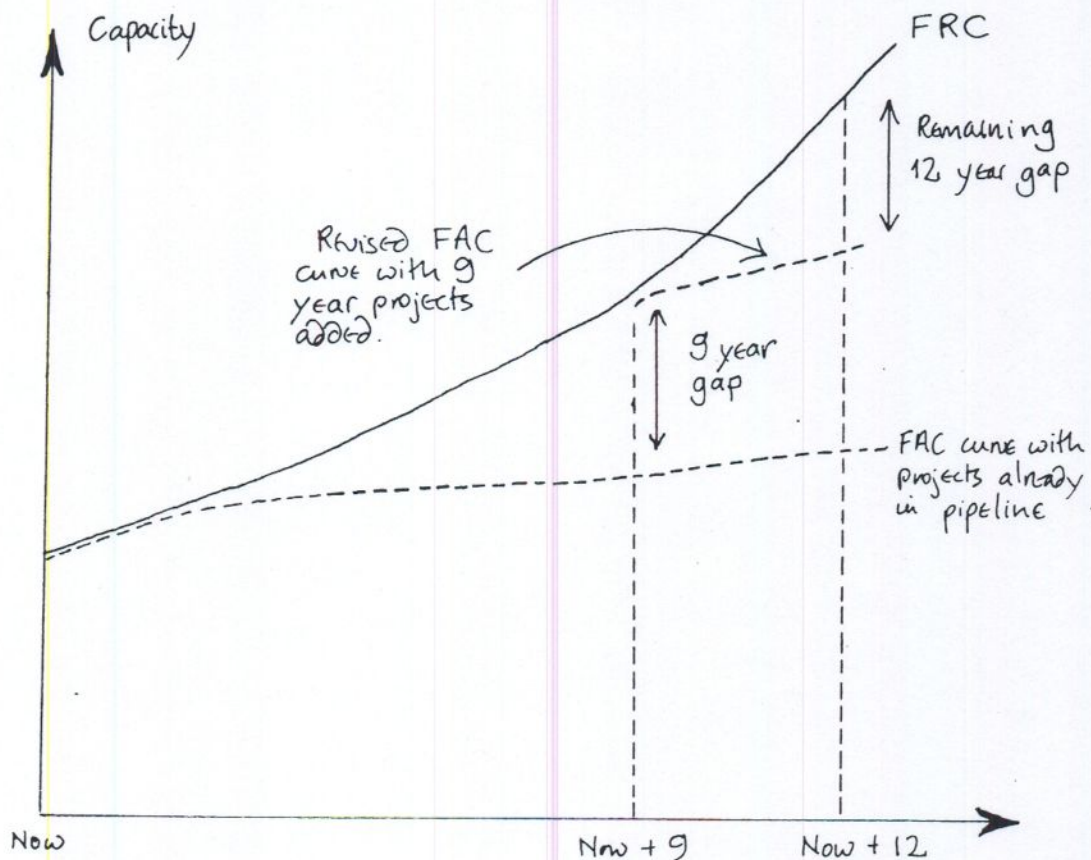
Figure 2. The Idealised Case

projects vary so much in size there is a good chance of not being able to find a project, or combination of projects which are just big enough to close the gap, even allowing for a reasonable measure of surplus capacity. If that was not enough, there is the added complication that, for engineering reasons, the projects may have to be done in a certain order so that one would not authorise, say, the sixth project which would just fill the gap, unless the previous five had already been done.

One way out of that would be to look first at the 9 year gap and order these feasible 9 year projects which will most nearly fill that gap. If FRC continues to grow there will still be some gap left at 12 years, and a 12 year project could also be sanctioned Now to fill that gap. This is shown in Fig. 3; and is called the Demand-Orientated Strategy because its emphasis is to ensure that demands are met. However, since the 9 year project generally have higher permit capacity and operating costs, it is also a higher-cost strategy.

The disadvantage of that strategy is that it does involve higher costs, generally, and the remaining 12 year gap may be so small that there are no projects capable of filling it without excessively high surplus capacity so that the decision-making processes may become locked in to a permanent sequence of 9 year projects so that the big, cheap, 12 year projects never really get developed.

The alternative strategy might, therefore, be to take the 12 year gap first and fill it as nearly as possible with the next available 12 year project. If the gap cannot be exactly filled in this way, then the remaining gap at 12 years can be projected back to 9 years and, if possible, a 9 year project found which will fill it. This 'cost orientated' strategy is shown in Figure 4 and, of course, it has the disadvantage that it may involve having to tolerate quite protracted shortages of power, though these might be met by allowing old thermal stations to run for a few years past the date at which they should have been replaced by the hydro stations.



FRC Forecast Required Capacity

FAC Forecast Available Capacity

Strategy: First fill the 9 year gap and make up any remaining 12 year gap with a 12 year project if one is available.

Figure 3. The Demand Orientated Strategy

Naturally, Figures 3 and 4 have been drawn for emphasis, and it is to be hoped that this step would turn out better than that.

In normal circumstances, the system will choose the so-called cost orientated, long term strategy, because that will produce large amount of cheap power. If however, there was a sudden increase in demand the system might be forced into heavier reliance on the more expensive medium term orientation, simply in order to produce power more quickly to satisfy imminent needs. The question then is whether the system becomes so locked in to a less attractive, but expedient, policy that it can never recover its longer-term view. We suspect that such a syndrome of expedient behaviour may be a characteristic of very large systems.

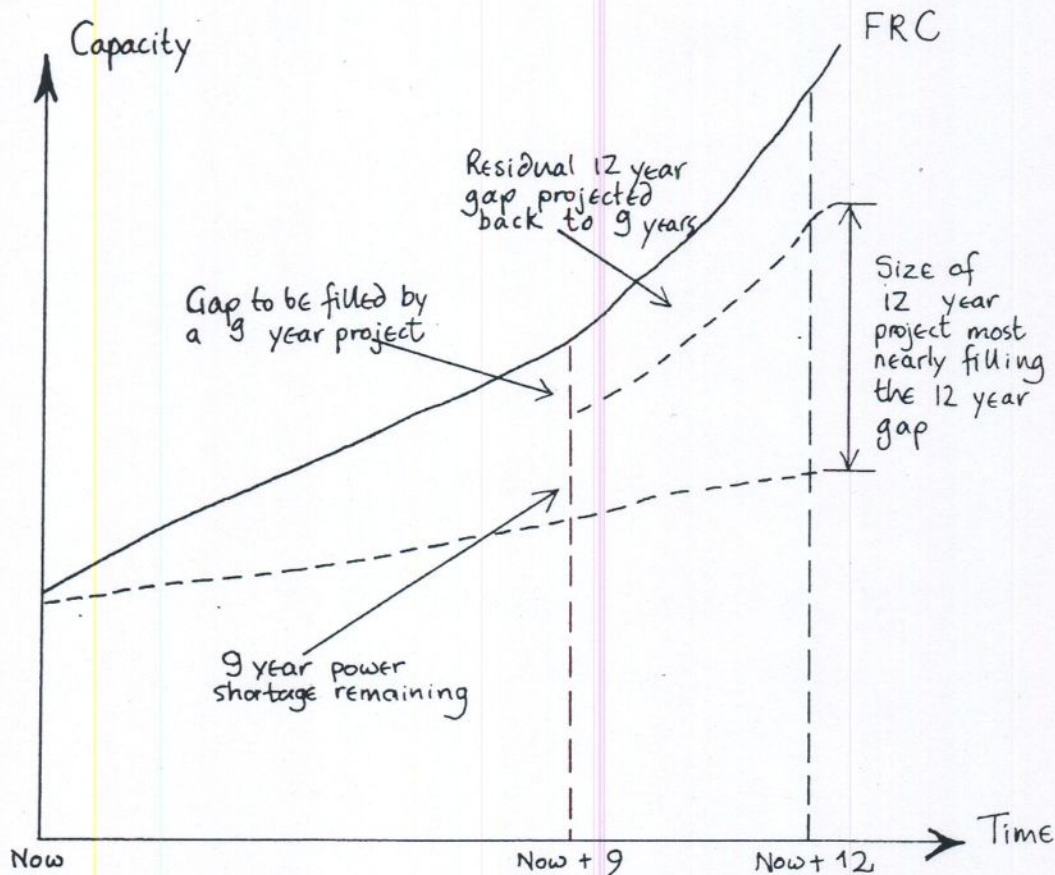
Before we can address such a fundamental policy problem we must first provide ourselves with a model which is capable of keeping track of *individual* projects as they go through the successive phases of selection, design, and construction.

In short we need to handle very discrete events in a simulation language which is ideal for policy analysis, but which has generally been used in a more continuous fashion, and at a much higher level of aggregation.

### THE MODEL FORMULATION

This section explains only the principal equation needed to inject the detailed and discrete nature of HE capacity expansion into a generally continuous simulation model of Argentinian energy policies. The line numbers which appear in the equations are the same as those in a complete listing of the model, which may be obtained from the authors.

The first 48 lines produce an exogenous scenario of exponential growth in electricity demand. In later research this scenario can be varied, because the whole point of the analysis is to examine the robustness of policy. Medium and long term forecasts are generated by time displacement of the growth pattern, and the medium and long term gaps, HMTGAP and HLTGAP, are calculated, as described earlier,



Strategy: First fill the 12 year gap and make up any remainder by a 9 year project. If one is available.

Figure 4. The Cost Orientated Strategy

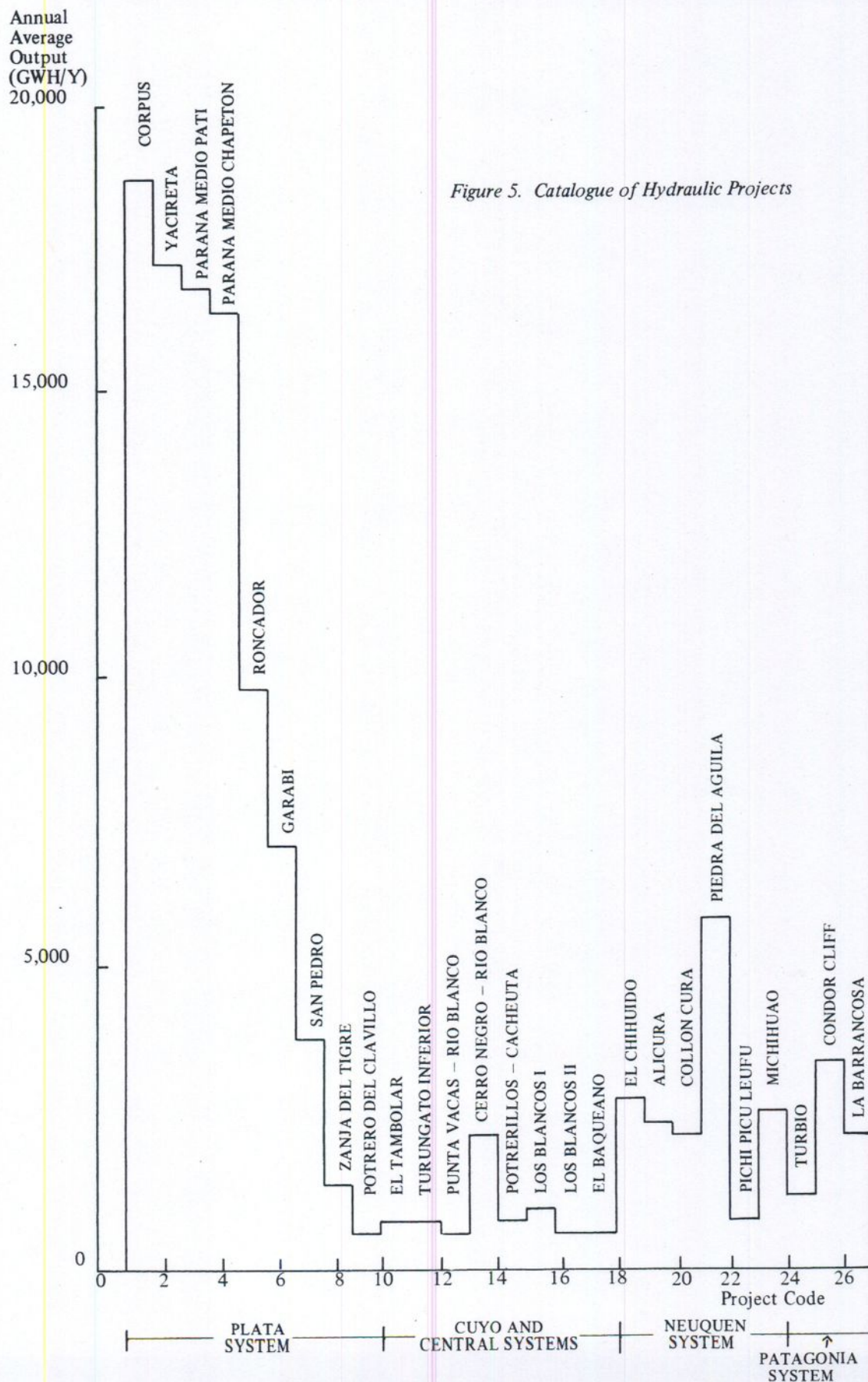


Figure 5. Catalogue of Hydraulic Projects

and constrained to be non-negative.

The HE projects actually available in Argentina are shown in Figure 5, which demonstrates very clearly why it would be unrealistic to treat HE capacity as an aggregated variable. The numbers on the X — axis are simply project codes and, within a given river basin, are arranged in an order of construction which is feasible from an engineering point of view. Naturally there might be a number of possible engineering sequences and one of the purposes of the model is to test whether any particular sequence makes the system so 'rigid' with respect to an exogenous disturbance, such as change in the rate of growth of demand, that it could engender serious imbalance between supply and demand. In other words, we wish to examine the extent to which the sequence of combination renders the system more or less capable of exploiting opportunities and defending itself against catastrophes.

The values of Figure 5 are easily represented in the model by a square-shaped table function, which is a particular feature of the DYSMAP compiler, as follows:—

NOTE

NOTE Catalogue of Hydraulic Project Capacities

NOTE

T TPROCAP=0/18.9/17.5/17/16.5/9.9/7.16/3.68/1 17/0.22/  
0.39/

X 0.335/0.20/1.98/0.53/0.77/0.405/0.470/2.86/2.36/2.26/  
5.93/

X 0.64/2.44/1.04/3.36/2.04

NOTE

NOTE

The table is accessed by means of 4 counter variables, varying discretely, for each one of the Cuyo, Neuquen, Plata and Patagonian systems. These counters contain, at any simulated moment, the code of the next project under ordering consideration. Obviously, the counters are restricted to the area of code numbers corresponding to their respective systems. Therefore, entering using these counters, the program obtains the capacity of the next project in each river basin. Similarly, other tables might be used for introducing costs of individual projects, etc.

At this stage, the program simply adds the capacities of successive projects in the table, grouping together the entries relating to Plata and Patagonia, which have long delays and Cuyo and Neuquen, which have medium delays. In this way it can find a combination of projects which will fill any given anticipated gap between demand and capacity.

The difficult problem is to write equations which will keep track of the project capacities as they are passed through the various stages, and which will also ensure that the project code numbers are taken in the correct order, that is to guarantee that the sequence of construction of projects, which is determined by engineering considerations, is, in fact, adhered to.

This is the core of the proposed method for modelling highly discrete processes in a system which, of its nature, contains both continuous and discrete mechanisms, both of which must be represented if the model is to be adequately realistic. The procedure will be explained in detail for the CUYO case, but it is exactly the same for the remaining systems. The model structure at this point is shown in Figure 6.

The essence of our method is to use levels for the various project code numbers and counters and, to make this clearer, we have broken with the usual conventions in influence diagrams and show these levels in boxes in Figure 6.

When a project from CUYO is selected for starting, the switch CUYOPSW, for the CUYO system, takes the value 1, a level variable called Cuyo Project Counter, CYCOUNT, is activated.

The Project Counter starts at 1 and is successively increased by 1 each time a CUYO project is injected into the system. This is achieved by the following level equation, which increases by 1 during the DT following the Project Switch having a value of one.

```
L CYCOUNT.K=CYCOUNT.J+(DT/DT)*CUYOPSW.J
N CYCOUNT=1
```

On the one hand, the level counter changes itself, growing in one unit in the next solution interval DT. On the other hand, that momentary value allows the computer to find out the code number of the project listed as first preference.

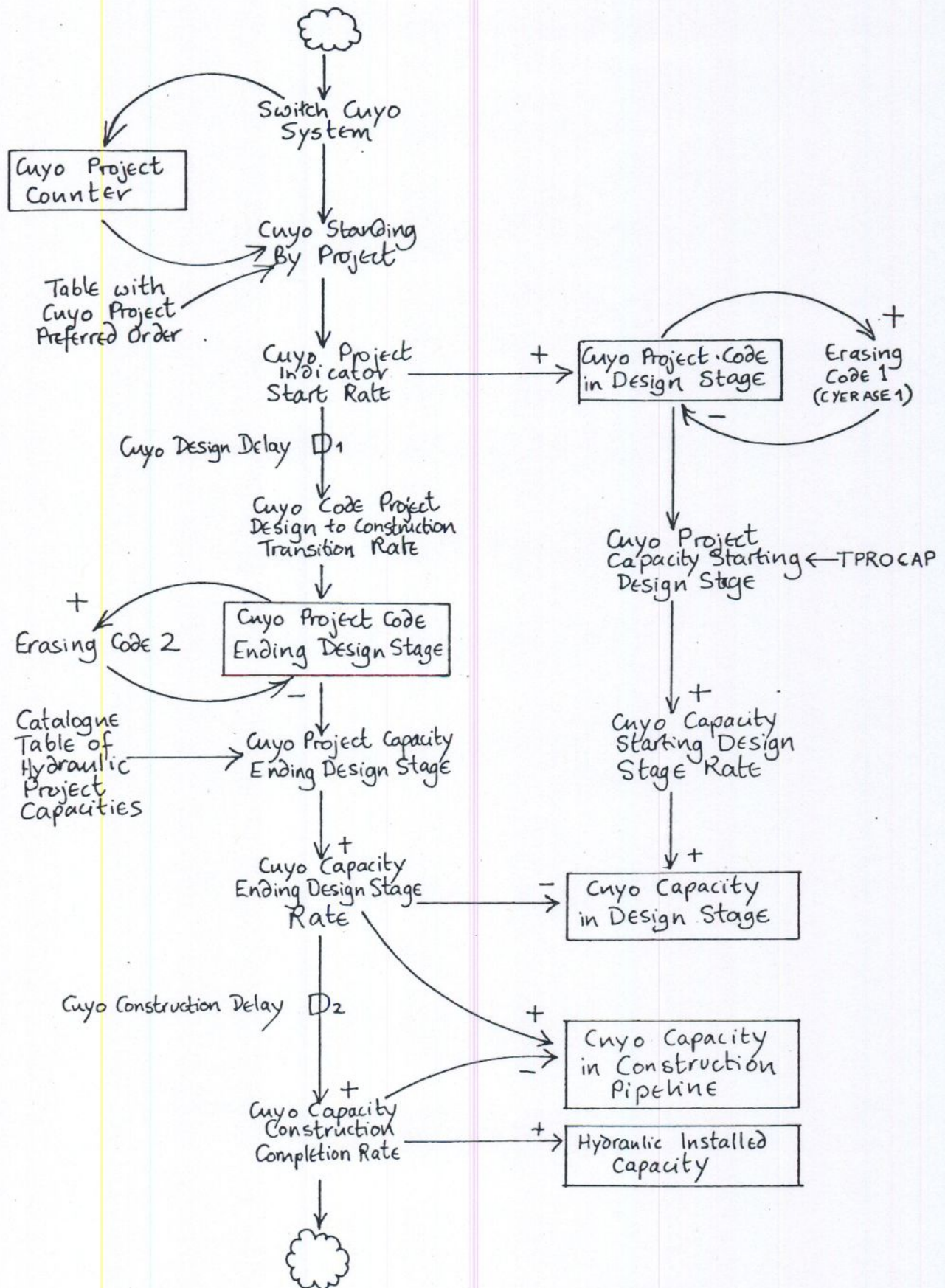
It is the function of CYCOUNT to record the number of projects so far done in the Cuyo basin, but it is also necessary to record which projects these were, that is to distinguish between the ordinal sequence of numbers and the project identified through their codes. This is done in the TCYPPO table which records the fact that there are 10 projects in the Cuyo Basin (the 15 in the TABSQ call merely provides some spare room) and that the first project to be done in Project 14, the next is 15 and so on. This table could easily be changed to represent a different sequence, with the actual sizes of the project remaining untouched in the TPROCAP table given earlier.

The counter will change discretely from 1 to 2, in the solution interval DT, after that in which the switch has been activated, leaving the counter showing that the second project will be next to be injected when the next project start decision is made. That value will be waiting, in turn, for the next signal coming from the switch. At the same time, the start rate indicator of the Cuyo project, CYISR has injected the code number of the first project, into another counter type level, CYCDS. Such a level contains the code of the hydraulic project, which is going to the design stage. Any previous value inside such a level is erased by a rate variable CYERASE1, fed by the level itself, and leaving CYCDS free for the next project.

```
R CYISR.KL=CUYOPSW.K*(CYSTANDP.K/DT)
L CYCDS.K=CYCDS.J+DT*(CYISR.JK-CYERASE1.JK)
N CYCDS=0
R CYERASE1.KL=CYCDS.K/DT
```

Thanks to the CYERASE1 variable, the project code in the design stage level variable, CYCDS, will have a particular code, during a solution interval time, which is long enough for setting in motion a second table function to hold the code of the project with particulars of its design, such as the theoretical annual output which appears in the TPROCAP Table mentioned earlier (Figure 5). Otherwise CYCDS takes the value zero.

```
A CYCDS.K=TABSQ(TPROCAP,CYCDS.K.O.26.1)*1E03
```



Note: The boxes indicate accumulating levels

Figure 6. Influence Diagram of CUYO Capacity Expansion

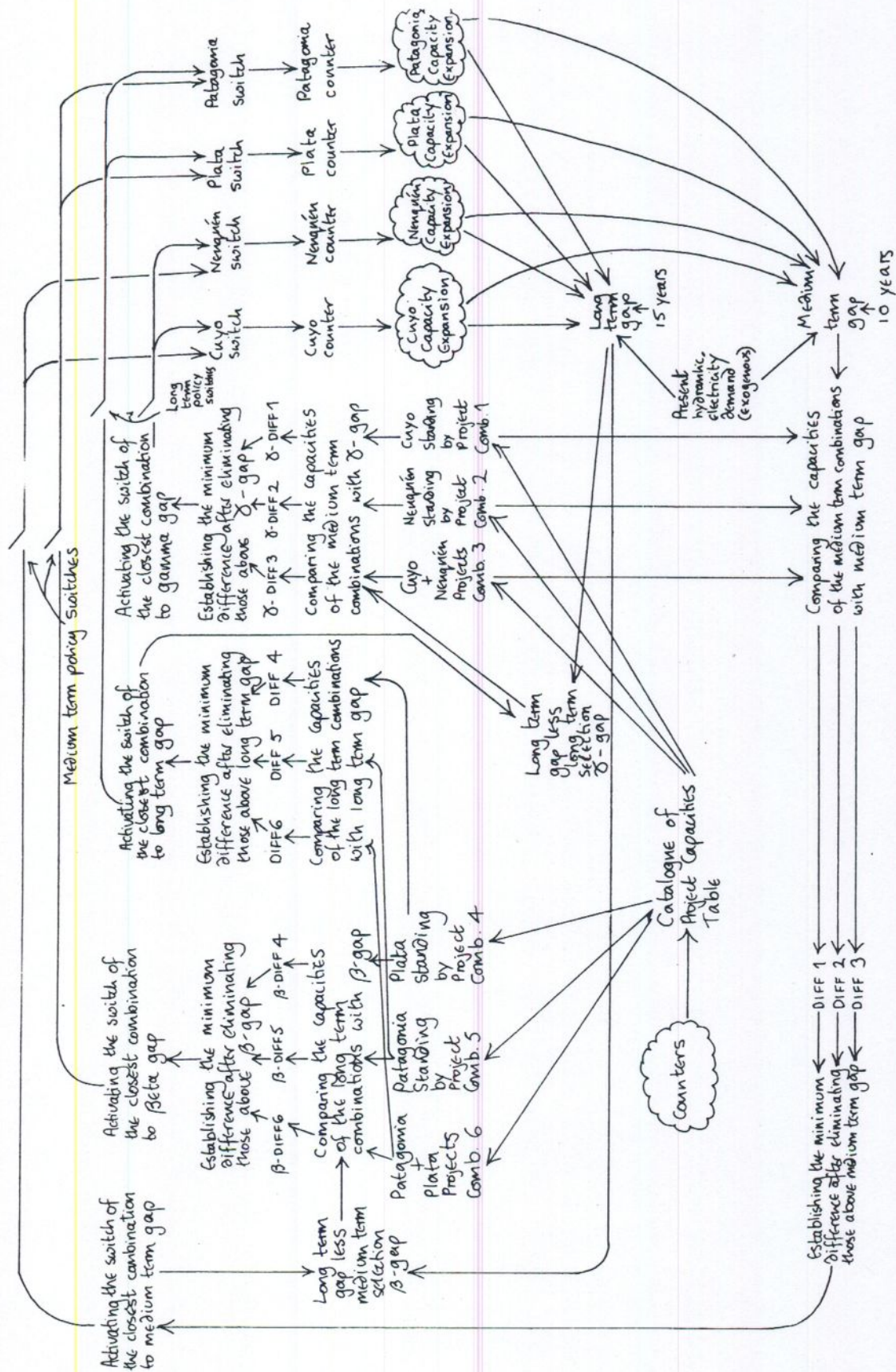


Figure 7. Medium and Long Term Capacity Growth Control Loops

The advantage of this method is that, because CYCDS only has a value during the DT following the activation of the Cuyo Project Switch, and is then returned to zero by the artificial rate variable CYERASE1, the project in question is only injected into the system once. If CYCDS was defined as an auxiliary by an equation such as

$$A \text{ CYCDS.K} = \text{TABSQ}(\text{TCYPPO}, \text{CYCOUNT.K}, 0, 15, 1)$$

it would keep that value from TCYPPO until the next time CYCOUNT changed, and that would lead to the same project continually being injected into the system, which would be double counting with a vengeance.

When a project is ordered, it is passed into a design delay which fills a level of projects in the design stage.

Depletion of that level takes place because the same Cuyo project indicator Start Rate, CYISR, which was injected into Cuyo Project code in the design stage, CYCDS, is passed through a DEADTI function, available in DYSMAP. That function creates a dead time before CYISR comes out, representing a time lag corresponding to the planning stage. For modelling reasons it has to be a pipeline type of delay.

The capacity of projects selected, as given in the Table TPROCAP, is passed through a construction delay before eventually becoming part of the Installed Hydraulic Capacity. The advantage of our method is that it permits the use of the standard delay facilities of simulation language in such a way as to represent the highly discrete nature of the project whilst at the same time being able to use the continuous facilities for those features of the system which are truly continuous, such as financial flows. In this way, the modelling language

is bent to fit the problem, rather than the other way round.

One of the convenient features of this model is the ease of changing a desired order for another run, allowing not only for a quicker experimentation, but also for adjustment to changing external circumstances, which could make it, for example, more appropriate to start with the Parana Medio Projects, in Argentina territory, than the binational ones, in the high Parana.

Finally, the program moves to the important state variables in the system, the hydro electric capacity in design stage, in construction pipeline and installed capacity.

### THE COMPLETE MODEL

The explanation of the Cuyo Project equation demonstrates the complexity of logic which can be handled in a continuous simulation language. The total HE system is shown in influence diagram form in Figure 7. The logic is complex, because that is the nature of the system, and anything less would carry grave risks of oversimplification. Perhaps the greatest advantage of the continuous languages is that, once the logic has been represented, as in Figure 7, the equations can be written in any convenient order, without regard to computational sequence.

That is, of course, true of most languages for the simulation of dynamic systems, and it is by no means essential to use a particular language. However, in this case, the diversity of units involved made the automatic dimensional analysis package in DYSMAP<sup>14</sup> particularly useful, and the clear documentation facilities greatly facilitated model checking.

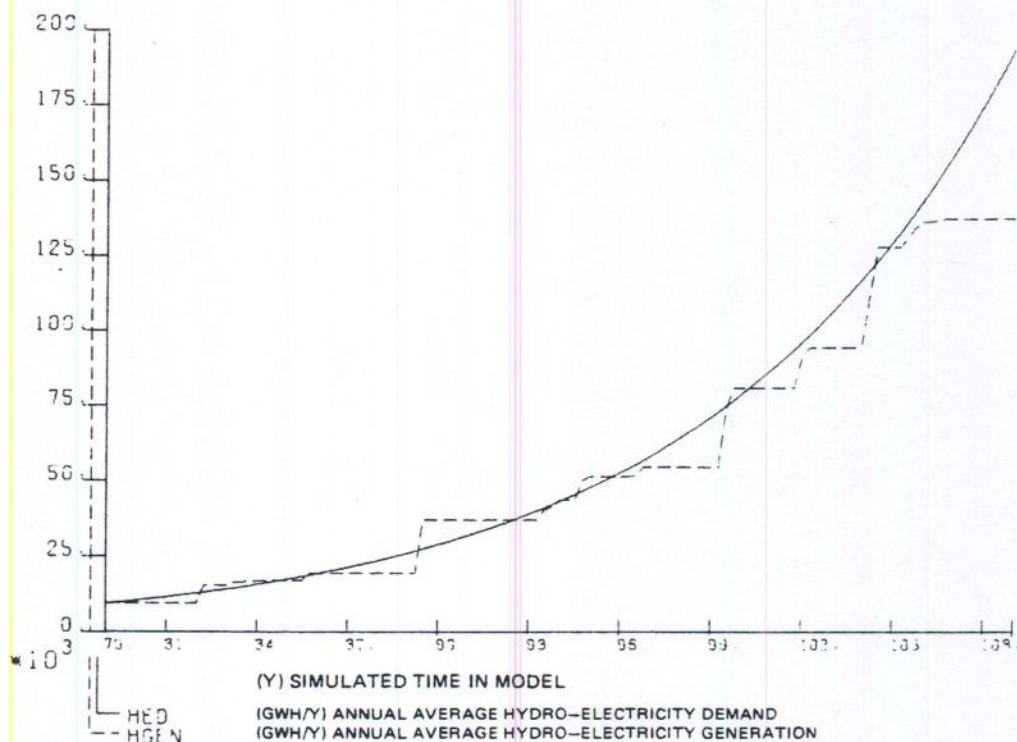


Figure 8. 10% Growth of Electricity Demand, Long Term Option Hydraulic Sector

The testing of the model described is shown in Figure 8 which demonstrates the growth of the generating capacity, when an exogenously introduced demand for capacity grows at that 10% annual rate, following the long-term strategy described earlier. The catalogue of projects is depleted before the ending of the simulation run, the last capacity addition being about the year 2007. Figure 9 exhibits the reaction of the model to the same 10% annual growth, when a medium-term strategy is maintained. Finally, if the rate of growth were 5% the system would have serious overcapacity almost all the simulated life-time of the run, as can be seen in Figure 10.

These figures, which are drawn by the CALCOMP facility of DYSMAP, have no significance at this stage beyond demonstrating that the program does actually work for each of the two broad strategic options discussed earlier. They also draw that the awful complexity of Figure 5 can be programmed into a model without having recourse to oversimplified aggregation. It is a tribute to the soundness of the original conception of DYNAMO that it can handle such a mess, and do it fairly quickly. The method described has been developed in principle in less than a couple of hours, and was programmed, debugged, and working in about three man-days.

#### FURTHER DEVELOPMENT

This paper has discussed a solution to the modelling problem of representing the managerial reality of the development of Hydro-electric potential in Argentina, in such a way as to deal both with the enormous variation between individual projects and the continuity of flow of revenue and expenditure, in a

single simulation language. We have shown how a language, which has hitherto been mostly used at a high level of aggregation can quite readily be used to represent far greater complexity. Having built a model, we naturally wish to use it and, though we hope to recount that use in full in due course, we close this paper by a brief examination of some of the policy issues which we hope to address, and a suggestion of some lines of approach which we think will prove fruitful.

It would, theoretically, have been possible to formulate this problem in dynamic programming terms, though the computational requirements could well have been enormous. Such a formulation would, however, have been open to the objections that it assumed a particular demand scenario and that it would be tantamount to deciding in 1982 which projects would be started in, say 1985. We feel, in the first case, that it is more useful to study the way in which the system could respond to the outcome of events when it turns out that the forecast has been, perhaps, optimistic. The object of an enquiry is therefore the extent to which government policy on expansion, and the engineering alternatives of different scenarios of development, make the system more or less robust, that is, capable of adapting smoothly to adverse or opportune circumstances.

As to the second objection, we feel that the only decision which can be made in 1982 is what to do and not to do in that year, and 1985 must take care of itself when we get there (if ever we do<sup>15</sup>). Naturally, what is decided in the one year will constrain the other, so we must examine the way in which sequences of decisions affect robustness.

This leads to an interesting point about the long-term and medium-term policy consideration discussed earlier. Most

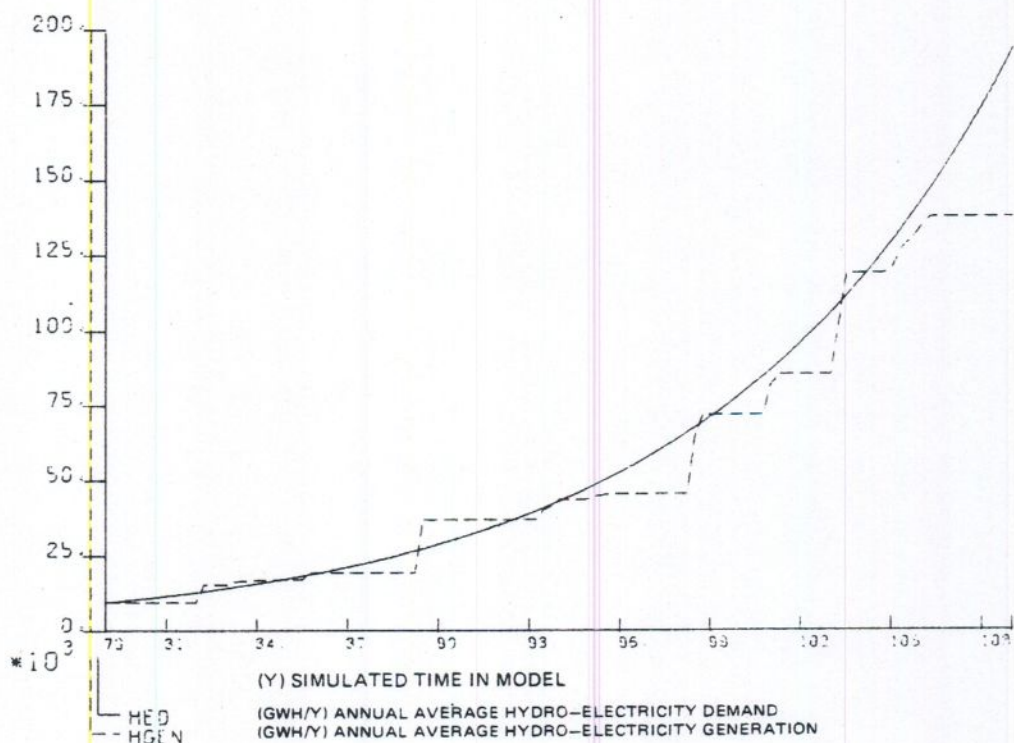


Figure 9. 10% Growth of Electricity Demand, Medium Term Option Hydraulic Sector

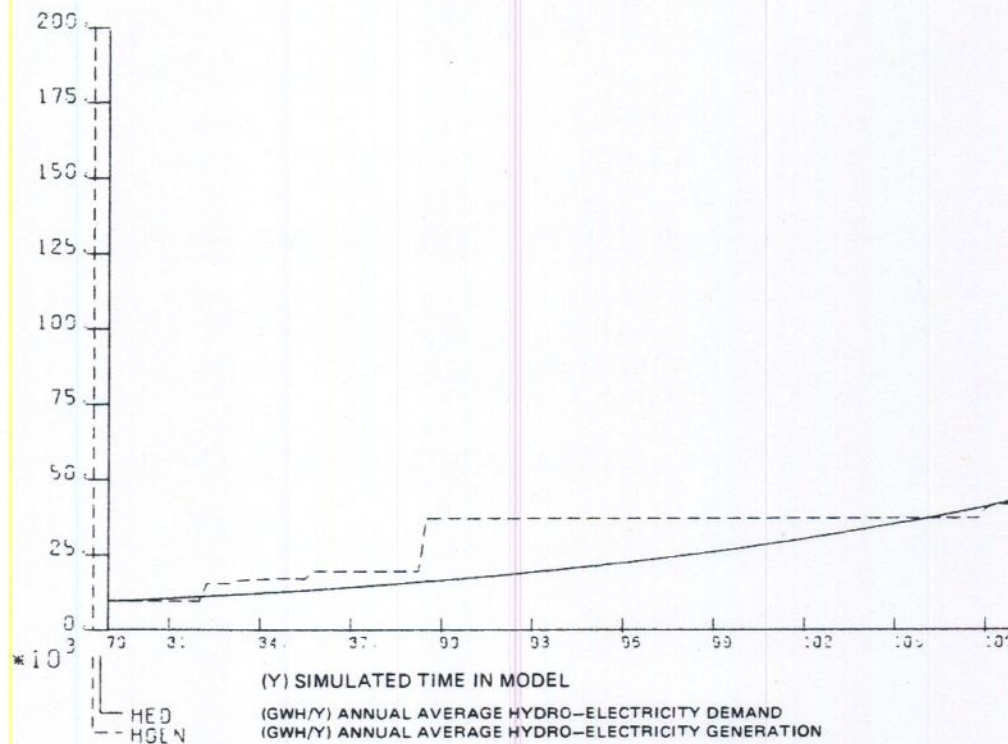


Figure 10. 5% Growth of Electricity Demand, Long Term Option Hydraulic Sector

public policy making is based, in public at least, on long-term considerations, falling back on remedial action which can be implemented in the medium term if there is some unforeseen turn of events. However, it may be that the feedback mechanisms in the system are such that, once having taken medium-term remedial action, the system becomes locked in to that, presumably, more expensive and less satisfactory mode, and cannot revert to the long-term mode even though the immediate reason which precipitated the change has long since passed. It may be, indeed, that such is the root of the West's protracted economic malaise. This is a new development in the concept of robustness which, has not, we believe, previously been recognised in this form but which is rendered tractable to analysis by the type of model we have developed.

One advantage of a relatively aggregated approach to model formulation is that it is easier to do policy design, because the model is comparatively straightforward. The disadvantage is that the policies so designed may be unsuccessful when implemented, because an aggregated model may not describe sufficiently accurately the interplay of forces in the system. In this case, we have chosen to build a rather complicated model, for the reasons explained earlier, and it is incumbent on us to face up to the question of whether the result will be too complicated to analyse either than by rather hit-or-miss simulation.

We feel, however, that there will be much to be gained by adaptation of some of the standard algorithms of control theory, the use of which in modelling managerial systems has been pioneered in work on coal clearance systems.<sup>16</sup> Finally, we see considerable promise in the use of the optimisation

facility<sup>17</sup>, which has recently been implemented in the DYSMAP simulation package.

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