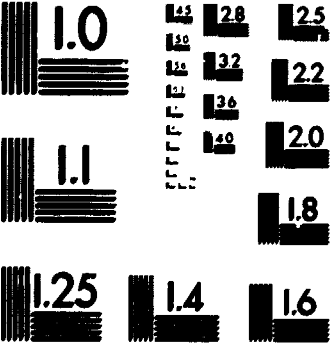

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DP/CPR/79/021

CHINA

Technical report: Training and future development in process modelling and simulation *

Prepared for the Government of China
by the United Nations Industrial Development Organization,
acting as executing agency for the United Nations Development Programme

Based on the work of John Mann,
expert in process modelling and simulation

United Nations Industrial Development Organization
Vienna

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EXPLANATORY NOTES

In this report, original monetary values have been used wherever possible to avoid distortions present in official exchange rates. However, the following may be used as an approximate guide:

\$US 1.00 = ¥ 2.34
£Stg1.00 = ¥ 3.05
£Stg1.00 = \$US 1.31
£1.00 at 1967 prices ≈ £3.00 at 1984 prices

The following abbreviation is used:

SIPAI = Shanghai Institute for Process Automation Instrumentation
103 Cao Bao Road,
Shanghai.

ABSTRACT

This report describes a 6-month mission to the Peoples Republic of China, under contract DP/CPR/79/021/11-11/31.9.B . The mission was carried out in three phases, in October and November 1982, October, November and December 1983, and July, August and September 1984.

The mission was part of a large project giving assistance to the Ministry of Machine Building Industry, and was undertaken at the Shanghai Institute for Process Automation Instrumentation, Shanghai, a research and development institute responsible to the Bureau of Instrumentation of the above Ministry.

The present project involved the training of a group of up to 8 specialist engineers in process mathematical modelling and computer simulation, together with development of a suite of related computer programs. Training took place through lectures, discussions and associated exercises, and by 'on the job' training on a practical model building of an industrial process.

Modelling of the industrial process, a glutamic acid fermenter was of value not only in training, but also in acquainting staff with the technology of fermentation. The model will be used for on-line process control in the factory concerned.

The present project also included the formulation of plans for the future development of process modelling and simulation in China, for consideration by the Ministry of Machine Building Industry.

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INTRODUCTION

The present project, DP/CPR/79/021/11-11/31.9.B formed just one part of a major project concerned with providing assistance to the Ministry of Machine Building Industry, Peoples Republic of China. The overall project development objectives were:

1. To improve productivity and product quality within various sectors of Chinese industry in an effort to restore the 12% annual industrial growth rate.
2. To strengthen the capital goods industry.
3. To modernise the country's internal industrial capital equipment to enable them to respond to the national needs of the coming decade.
4. To improve the capital equipment used in agriculture.
5. To add new technological industrial capability to help in achieving the desired national industrial growth.

With the exception of Objective 4, the present project makes a contribution in all of the above areas. The immediate objectives were stated to be:

1. To assist the Ministries of Machine Building and Agricultural Machinery in establishing, implementing, and strengthening various research and development centres, scientific laboratories and research institutes.
2. To create a cadre of Chinese scientists, engineers and technical professionals who are aware of the current "state-of-the-art" in various technologies which relate to the construction of machinery.
3. To assist the Ministries of Machine Building and Agricultural Machinery to specify and select modern hardware and software to support the activities of various technical institutes, laboratories and organisations.
4. To improve skills in areas related to metal working technology by training Chinese technical professionals.

The present project is particularly related to the first three of these objectives.

The project was undertaken in a research and development institute responsible to the Bureau of Instrumentation of the Ministry of Machine Building Industry, namely the Shanghai Institute for Process Automation Instrumentation (SIPAI). The Ministry of Machine Building Industry has responsibility for selecting and providing the equipment needs of the production Ministries, for example those concerned with manufacture through Chemical Engineering, Metallurgical Engineering, Coal Engineering, Light Industry, Power Engineering, Nuclear Industry, etc.

An essential aspect of capital equipment in the process industries is that of its instrumentation and automatic control. In these areas, the Ministry of Machine Building Industry is advised by the Bureau of Instrumentation, which in turn is advised by SIPAI and the Bureau of Automation.

The objectives of the present project were formulated as:

1. To train a group of identified SIPAI staff in the techniques of process mathematical model building, computer simulation and automatic control.
2. To develop a suite of related computer programs for mathematical model manipulation, and simulation, and control system design.
3. To advise the Ministry of Machine Building Industry on the future development of model building and simulation in China.

The present project had a total duration of 6 months. By agreement, it was divided into three phases, of 5 weeks, 10 weeks and 1[illegible] weeks respectively. The first phase commenced on the 17th of October 1982, the second in October 1983, and the third on the 8th of July 1984.

The division of the project into these three phases proved extremely effective, in that it enabled SIPAI staff to consolidate their learning, and to achieve pre-set objectives in the periods between phases. It also enabled planning and preparation for the later phases to be more effective.

RECOMMENDATIONS

1. That the present project be regarded as a pilot exercise, and that it be repeated, in a modified format, as soon as practical with a larger group of specialists, using the services of the present group of trainees and Chinese academic staff under the guidance of an invited expert.

2. That the level of process modelling and simulation activity be significantly increased to enable these techniques to fully contribute to cost-efficient, safe and orderly industrial development in China.

3. That the scope of process modelling and simulation be increased to include an emphasis on modelling for strategic industrial decision-making purposes.

4. That a suitable expert be invited to give a training course to nominated Chinese staff in the area of modelling for strategic planning.

5. That a new institute be established for specialisation in process modelling and simulation.

6. That the new Institute should work in the areas of modelling for

    (i) strategic planning

    (ii) process investigation and improvement

    and (iii) process control and automation.

I. ACTIVITIES AND OUTPUT

A. Model Building and Simulation

Mathematical modelling refers to the act of writing down the mathematical relationships which describe a physical process. This technique is particularly important in the process industries such as those which produce chemicals, glass, paper, steel, food, pharmaceutics, cement and electrical power, whether from nuclear reactors or conventional boilers. The equations not only describe the physics, chemistry or biology of the process, but may also include economic relationships, or equations describing aspects of human activity (cybernetics).

The equations themselves may vary in complexity. For any realistic representation of a process system, many such equations will be involved, and these equations must usually be solved simultaneously, since physical processes in the system are occurring at the same time. For this purpose, it is usually essential for a digital computer to be used. The act of operating on the equations in such a way that the solutions resemble the performance of the plant variables, is called computer simulation.

The twin activities of model building and simulation are fundamental to many aspects of automatic control. They represent the means by which automatic control schemes may be investigated without the expenses of purchase of equipment, installation on the plant, and experimentation on the plant. This saves time and wasteage through off-specification material as well as capital, and is inherently safer than operating a plant under unknown conditions.

B. Formal Training

Formal training took place through a set of lectures, most of which were given during October and November 1982. The set of lectures dealt with such matters as

Simulation in the process industries
Modelling in the state space
Simulation in the state space

Equation manipulation
Model behaviour and analysis
Reduction of model order
'Hillclimbing' and other optimisation methods

The lecture material was accompanied by discussions and examples and exercises.

Additional lectures and discussions were held with wider audiences, both within SIPAI and to the Shanghai Automation Society and the Shanghai Instrument Society. In addition to the above material, subject matter included steam boiler modelling as a specific example, and hardware and software for process simulation.

C. Computer Software Development

A number of computer programs were taken to Shanghai by the author, and their use described to the nominated staff in SIPAI. These were commissioned on a number of test problems by SIPAI staff on their PDP 11/03 computer both during the first phase, and during the period between phases I and II. Some additional programs were written by Sipai staff during this time, so that the final suite enabled the following computations to be made:

Equation manipulation to state space form
Matrix operations, including inversion
Roots of a polynomial
Eigenvalues of a matrix
Eigenvectors of a matrix
Integration of nonlinear differential equations
Matrix exponentiation
Simulation using matrix exponentiation
Simulation using eigenvalues and eigenvectors
Simplex optimisation
Hillclimbing optimisation

Additional development of computer programs has been undertaken by SIPAI staff, particularly in the areas of process parameter identification and simultaneous nonlinear equation integration.

D. Informal Training

As with most engineering subjects, successful modelling and simulation requires professional judgement, which is only obtained by 'on the job' training. This was undertaken during the second and third phases.

The particular example chosen was that of a fermentation process (for the production of glutamic acid). In choosing such a process, it was recognised that comparatively little modelling and simulation has been undertaken in fermentation, and that the modelling of biological processes is more difficult than the modelling of chemical or physical processes. Furthermore, the modelling of batch processes is more difficult than the modelling of continuous processes.

Biotechnology will become an increasingly important industry in China because of its strong agricultural base, and it was the wish of SIPAI to obtain experience in this field. Equally importantly, successful process modelling and simulation of an existing process can only be undertaken with an enthusiastic and knowledgeable industrial partner, and such a client was already well known to SIPAI management. This client was the Shanghai Flavours and Essences Factory, of 40 Yun Ling Road West, Shanghai.

Preparative work was undertaken in the period between Pases I and II, and a model based on factory data was developed during Phase II. The model was shown to simulate factory fermenter performance, and to be able to predict plant behaviour successfully, on the limited data then available.

Further data processing was undertaken to confirm initial conclusions during the period between phases II and III. A number of numerical techniques, including statistical methods of parameter estimation, were also applied to the model.

At the present time, much of the information concerning the plant status is laboriously obtained from laboratory analysis of fermentation samples. Phase III has therefore concentrated on developing an 'indirect-measuring' model. This uses those measurements which can be made directly on the plant, particularly by analysis of fermenter exhaust gases, and uses these to infer the results of laboratory analysis, thus reducing this work significantly. This work appears to be successful, although full confirmation is still required.

The work undertaken during phases II and III is technically advanced, and a number of papers are in the process of being written describing the work. This will disseminate the information further, particularly in Chinese industry. One such paper is reproduced in Annexe I.

E. Advice on Future Developments

Mathematical modelling and computer simulation are comparatively new activities in China, so experienced personnel to do this work are scarce. The subject possibly has greater significance than it has in developed countries, since China is industrialising rapidly, and technical personnel need to master their own and imported technology rapidly. The understanding of complex processes is facilitated by the use of mathematical language. In the Chinese language, precise technical expressions may not exist, or if they do, they may not bear an equivalent relationship to similar expressions in other languages.

The need for advice on future developments was an important objective, and this was emphasised at a meeting with Ministry personnel in August 1984. Accordingly, a detailed report was written for the Ministry (Annexe II). This report recommends the setting up of an Institute for Process Modelling and Simulation, and details its suggested modes of operation, and the necessary actions to be taken for its development, and to ensure dissemination of techniques and knowledge throughout China.

II. UTILISATION OF RESULTS

A. Formal Training

The formal training has already been utilised in devising and simulating the fermentation model described above, and in other process and process control tasks. The lecture material has already been used to produce additional computer programs to assist in this work. The group is well motivated and innovative, and has already mastered the subject sufficiently well to be producing papers for national and international conferences.

The success of the group however poses the major danger to the ultimate success of the training exercise. Promotion and natural wasteage will reduce the number of able practitioners below 'threshold' level. Up to 8 people have been members of the group at various times, but already this has been depleted. It is therefore recommended that the present training be regarded as a pilot exercise, to be repeasted with suitable modifications, with a larger number of identified participants. The programme could be simpler, in that it would be devoted entirely to training. The present trainees could be used as instructors for the second group, together with suitable Chinese academics, but it is still recommended that the services of an expert be retained as overall course director.

B. Computer Software Development

This part of the exercise has already been successfully used on a number of practical problems, including the fermentation modelling work. The only danger to its future use would be through a shortage of trained staff, for the reasons indicated above.

C. Informal Training

The success of the informal training is already apparent in the quality of the work achieved.

As an industrial task however, the work is not complete in that the models have yet to be programmed into an on-line microprocessor, for data logging and control purposes. This work is currently proceeding. There is no forseeable reason why it should not be successfully completed.

D. Advice on Future Developments

At the present date, the report for the Ministry of Machine Building Industry has yet to be discussed by that Ministry. It is therefore too early to comment on its ultimate utilisation. If however it is accepted by the Ministry, it should be noted that there would be areas where UNIDO could provide technical assistance.

III. CONCLUSIONS

The present project has been entirely successful in that it has trained a group of specialists and given them practical experience in applying their newly-gained training. These specialists will form the nucleus for future development, and a realistic development plan has been formulated.

The work could not have had this degree of success without the enthusiasm and commitment of the Chinese staff involved. The author is also appreciative of the efforts of these staff to enable him to learn about conditions in Chinese universities and factories. This enabled him to approach the task with greater understanding and realism. SIPAI made every effort both socially and professionally to enable the author to maximise the professional achievements of both himself and his Chinese colleagues, for which all concerned remain most grateful.

Annexe I

MODELLING OF THE FERMENTATION PROCESS FOR PRODUCTION OF AMMONIUM GLUTAMIC ACID

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Abstract

Ammonium glutamic acid, from which monosodium glutamate (MSG) is manufactured, is formed in a fermentation broth by the excretions of the bacterium Corynebacterium Glutamicum. The modelling of this process is difficult since the model must adequately describe both cell formation and product formation, which occur separately, but in partially overlapping phases. It is shown that production plant data does not support some of the assumptions made in the literature. Adequately detailed equations may be derived to describe the system, and their parameters evaluated using plant data. This is done using a pragmatic approach. Integration of the equations gives model behaviour which is well representative of plant behaviour.

+ Department of Chemical Engineering, University of Technology, Loughborough, U.K., on secondment by UNIDO (United Nations Industrial Development Organisation).

1. INTRODUCTION

Monosodium glutamate (MSG) is an important food ingredient, where it is used as a flavour enhancer, particularly of meat products. Although traditionally associated with Japan, where about 1/3 of world production capacity is installed, and Asia, it is manufactured and widely used in processed foods in North America and Europe.

Large-scale manufacture was previously by a chemical route. In 1956, however, Kinoshita et al (1) discovered a micro-organism (subsequently named Corynebacterium Glutamicum) which excreted large quantities of glutamic acid, and this is now the preferred route for the manufacture of ammonium glutamic acid (AGA), and hence MSG.

The fermentation route being of recent origin, many problems still remain to be resolved. In particular, factory fermentations may exceptionally take only 28 hours, but may also take as long as 70 hours.

The present work is therefore aimed at producing a model capable of describing the fermentation process, and the identification of the parameters in that model. Later work will be concerned with using the model for predictive purposes, for control, and ultimately for optimal control.

The work was done on a 150 m^3 fermenter at the Shanghai Flavours and Essences Factory+, using data obtained from normal factory production log-sheets, backed up by a data logger (JS-200 computer system) installed by the Shanghai Institute for Process Automation Instrumentation (SIPAI)

+- 40 Yun Ling Road West, Shanghai, China.

2. BACKGROUND

The glutamic acid fermentation process is, in effect, a batch biochemical process. In the process, the micro-organism produces and excretes glutamic acid, which is then converted to ammonium glutamic acid in the fermentation broth by virtue of the presence of ammonia. The principal substrate is glucose, with nitrogen being provided by either ammonia solution, or urea. Inorganic salts are also required. In effect, over-production of glutamic acid by the cell causes excretion of the excess, and this is aided by the deliberate limitation of biotin in the broth (Tanaka et al, (2)).

Production of glutamic acid, at least as far as excretion is concerned, occurs subsequent to cell growth, rather than concurrently with it, so it is in Classification II proposed by Gaden (3). In this respect it is more complex than the baker's yeast fermentation kinetic systems investigated by Wang et al (4,5,6,7). In practice, the system is made more complex by the partial overlapping of the cell growth phase and the glutamic acid excretion phase (8,9,10).

After cell production has ceased, glutamic acid production and excretion continues, with concurrent depletion of glucose and nitrogen-containing substrates. The fermentation process is normally stopped by deliberately allowing the nitrogen-containing substrate to become depleted, when the glucose concentration has fallen to around 0.6 - 0.7%.

The principal state variables describing the dynamic process of fermentation are as follows: cell concentration (X), ammonium glutamic acid concentration on the broth (P), and glucose concentration (S), together with carbon dioxide production rate and oxygen consumption rate.

The first three state variables describe the overall process, but are difficult to measure on-line, with presently-available technology. The last two state variables, being more readily measurable on-line, are therefore very useful in establishing a mathematical model which can be used to measure X and P indirectly.

Figure 1 shows typical factory data, illustrating the interactions between X,S and P (from Feng (13)).

3. STRUCTURE OF THE MODEL

We now proceed from the theoretical mechanisms previously discussed to set up the structure of a mathematical model for the ammonium glutamic acid (AGA) fermentation process. The following discussions start from the assumption that in spite of the acknowledged complexities of the AGA fermentation process, it can still be described as following two macro chemical pathways, namely

Glucose + Oxygen + Urea (or Ammonia) → Cells + Carbon Dioxide + Water + Byproduct I

and

Glucose + Oxygen + Urea (or Ammonia) → AGA + Carbon Dioxide + Water + Byproduct II

Both byproduct I and byproduct II will almost certainly be mixtures of chemicals.

From figure 1, it can be seen that the microbial propagation phase is well advanced by the time that AGA production commences. Therefore, microbial propagation and product formation can be considered separately, before joining these two aspects of the model together.

Microbial Growth

It is generally considered that microbial growth follows an exponential growth law, such as

$$\frac{dX}{dt} = KX \qquad (2.1)$$

Although this would describe the initial part of the X - curve, (figure 1), it would not describe the apparent subsequent 'flattening' of the curve. This reduction in cell growth rate to zero is clearly not because of substrate limitation, but rather because the microbial population is self-limiting, a situation better described by the equation

$$\frac{dX}{dt} = K_1 X \left(1 - \frac{X}{X_{max}}\right) \qquad (2.2)$$

This equation has been suggested by Riccati in general studies of population dynamics, and appears satisfactory in that

$\frac{dX}{dt} \rightarrow 0$ as $t \rightarrow \infty$. It is less than fully satisfactory in that

$\frac{dX}{dt} \neq 0$ at $t = 0$, since it is usually observed that the inoculated

micro-organism does not start multiplying immediately after placement in the fermentation medium. This requirement will be considered later. In the meantime, it should be noted that the solution to equation 2.2 is given by

$$X = \frac{X_o e^{K_1 t}}{1 - \frac{X_o}{X_{max}}\left(1 - e^{K_1 t}\right)} \qquad (2.3)$$

where X_o is the cell concentration at $t = 0$, and X_{max} is the maximum cell concentration attained. In addition, suppose that X has the value of $X_{max}/2$ when $t = t^*$. Then it may be shown that $e^{K_1 t^*} = (X_{max} - X_o)/X_o$, so

$$K_1 = \frac{1}{t^*} \ln\left(\frac{X_{max} - X_o}{X_o}\right) \qquad (2.4)$$

Thus, the two constants K and X_{max} in equation 2.2 may readily be determined from experimental data.

As mentioned previously, there is a period of zero cell growth after inoculation into a new medium takes place, during which time the cells adapt to their new environment. This is observed both from production plant log-sheets, and in the laboratory.

This situation may be dealt with by introducing a 'dead-time'. Thus the cell propagation equation (2.2) may be written as two equations

$$\frac{dX}{dt} = 0 \quad \text{where} \quad X(t) = X_o , \qquad 0 \leq t < \tau_1 \qquad (2.5)$$

and

$$\frac{dX}{dt} = K_2 X (1 - \beta X) \qquad t \geq \tau_1 \qquad (2.6)$$

where

$$K_2 = \frac{1}{(t^* - \tau_1)} \ln \left(\frac{X_{max} - X_o}{X_o} \right) \quad \text{and} \quad \beta = 1/ X_{max}$$

This particular cell growth model is easy to use when fitting existing data, since two of the three parameters (τ_1 and β) are evaluated independently of each other. However it should be noted that both K_2 and β depend on X_{max}, and can therefore only be determined after cell growth has ceased (see figure 1).

Product Formation

Product formation from cells may now be considered. Yamashita(8) and Wu(10) have shown that total glutamic acid formation is given by the equation

$$\frac{dP_T}{dt} = \frac{K_3 S}{K_4 + S} X - K_5 \frac{dX}{dt} \qquad (2.7)$$

where K_3, K_4 and K_5 are constants. In this equation, the term $\frac{K_3 S}{K_4 + S} X$ describes the expression of excess glutamic acid by the cells, and an allowance $K_5 \frac{dX}{dt}$ is then made for the accumulation of glutamic acid within cells, by virtue of their increase in mass concentration X.

The term $K_5 \frac{dX}{dt}$ (equation 2.7) will clearly be zero for much of the fermentation, by examination of figure 1. Since the material inside the cell is glutamic acid, whereas the material in the broth reacts to become ammonium glutamic acid, there is some difficulty in dealing with equation 2.7.

One possible way around this difficulty, which results in a slightly simpler model without distorting accuracy, is to rewrite equation 2.7 as

$$\frac{dP}{dt} = K_6 \frac{S}{K_7 + S} X \qquad (2.8)$$

where P then represents the concentration of ammonium glutamic acid in the broth.

Examination of factory data consistently shows that there is a delay time for the formation of AGA, it being commonly assumed that only mature cells excrete AGA. This factor may be incorporated in the model by introducing a time delay τ_2 into equation 2.8, thus

$$\frac{dP}{dt} = 0 \text{ , } P(t) = 0 \text{ , } \qquad \text{for } 0 \leq t < \tau_1 + \tau_2 \qquad (2.9)$$

and
$$\frac{dP}{dt} = \frac{K_6 \, S \, X(t - \tau_2)}{K_7 + S} \qquad \text{for } \qquad t \geq \tau_1 + \tau_2 \qquad (2.10)$$

Substrate Consumption

Substrate (glucose) consumption clearly takes place in two parts. One part is to satisfy the requirement for cell growth, and the other is to maintain energetic metabolism of the cell, thus

$$(\Delta S)_T = (\Delta S)_G + (\Delta S)_M \qquad (2.11)$$

It is usually considered that consumption of substrate during cell growth is expressed by

$$\left(\frac{dS}{dt}\right)_G = \frac{1}{Y_G} \frac{dX}{dt} \qquad (2.12)$$

where Y_G, the 'yield coefficient' is defined by

$$Y_G = \frac{X}{(\Delta S)_G} \qquad (2.13)$$

Most authors consider Y_G to be a constant, implying that the composition of young cells is identical to that of mature cells, and that the same metabolic pathway is used throughout the cell formation phase. These assumptions may need to be reviewed, but so far there is no indication in factory data that they are invalid.

Yamashita et al (8) assumed that consumption of substrate for metabolic purposes $(\Delta S)_M$ would be in two parts, namely

(i) consumption to produce AGA, and

(ii) consumption for respiratory purposes.

They postulated that the former would be proportional to the formation of AGA, whereas the latter would be proportional to cell mass.

In our examination of factory data however, we can find no evidence for the latter conclusion. Using data abstracted from Feng (11) and Feng (13), figure 2 has been constructed, showing proportionality between AGA formation and substrate consumption. If there were a term of practical significance proportional to total cell mass, the result would be a progressive reduction in the gradients of the characteristics in figure 2; indeed, factory log sheets, if anything, sometimes indicate the reverse.

We have therefore assumed that there is a single cell metabolic rate, resulting in respiration being proportional to glutamic acid excretion. Thus the total consumption of substrate may be written

$$-\frac{dS}{dt} = K_8 \frac{dX}{dt} + K_9 \frac{dP}{dt} \qquad (2.14)$$

where $K_8 = 1/Y_G$, from equation 2.12 .

It has to be noticed that a moderate amount of by-products is generated during both the cell growth phase and the AGA formation phase, in addition to CO_2 and water. So far we do not clearly know the molecular formulae of these by-products, although stoichiometric calculations give some indications. The assumption that the molecular formulae of by-products of cell growth and of AGA formation are invariant must be made. This is not unreasonable in view of the apparent constancy of yield factors, as evidenced for example by Figure 2.

Hence, K_8 in equation 2.14 includes implicitly a factor additional to theoretical requirements, to account for by-product formation (BPI) during cell propagation, and K_9 includes implicitly a similar factor for BPII formation.

Summary of Assumptions

The assumptions and simplifications implicit in the model are summarised as:

1) The curves shown in figure 1 are typical of all AGA formations. Although there will be batch-to-batch variability resulting in displacement of the curves, the fundamental shapes will remain invariant.

2) The whole of the fermentation process, despite its complexity in reality, may be summarised by two chemical reaction formulae. These take place independently, except that both consume the same substrate, and cell production must precede AGA formation.

3) There is a time period, which could in theory be zero, required for the organism to adapt to its new environment after inoculation into the production fermenter.

4) The cell does not commence to generate AGA until the cell grows to a definite age.

5) No change in viable cell concentration takes place after the period of growth has ceased.

6) Substrate is only consumed for cell growth (and associated by-products) and AGA formation (and associated by-products).

7) Substrate consumption for cell respiration is proportional to substrate consumption for AGA production.

3. DETERMINATION OF MODEL PARAMETERS

The equations describing the system may be summarised by

$$\frac{dX}{dt} = 0 \quad , \quad X(t) = X_0 \qquad \text{for } 0 \leq t < \tau_1 \qquad (2.5)$$

$$\frac{dX}{dt} = K_2 X (1 - \beta X) \qquad \text{for } t \geq \tau_1 \qquad (2.6)$$

$$\frac{dP}{dt} = 0 \quad , \quad P(t) = 0 \qquad \text{for } 0 \leq t < \tau_1 + \tau_2 \qquad (2.9)$$

$$\frac{dP}{dt} = \frac{K_6 S X(t - \tau_2)}{K_7 + S} \qquad \text{for } t \geq \tau_1 + \tau_2 \qquad (2.10)$$

$$\frac{dS}{dt} = -K_8 \frac{dX}{dt} - K_9 \frac{dP}{dt} \qquad (2.14)$$

It is now required to determine the parameters τ_1, τ_2, K_2, β, K_6, K_7, K_8, and K_9. A pragmatic method will be described here, but a statistical identification method would be an alternative approach.

Firstly, it should be noted that equations 2.5 and 2.6 are independent of the state variables S and P. β is readily determined from the steady-state value of X (X_{max} from equation 2.2). With $\tau_1 = 0$, K_2 may also be readily determined (Termed K_1 in equation 2.4).

As τ_1 is increased, K_2 is also increased, in such a way that

$$K_2 = K_1 t^* / (t^* - \tau_1) \qquad (3.1)$$

which is a direct result from equation 2.4 . Figure 3 illustrates the application of equations 2.5 and 2.6, together with equation 3.1 to fermenter cell growth data. Since it is difficult to obtain accurate plant data for cell concentration X, τ_1 may generally be determined sufficiently accurately by inspection.

In a similar manner, τ_2 may generally be determined from inspection. It will be noted that, in equation 2.10, $\frac{dP}{dt}$ is dependent on S, and that in equation 2.14 $\frac{dS}{dt}$ is dependent on $\frac{dP}{dt}$.

It might therefore be assumed that the parameters in equations 2.10 and 2.14 would have to be determined simultaneously. Such however is not the case, since data for S already exists, and this can be used in equation 2.10 to determine K_6 and K_7.

A pragmatic approach to the determination of K_6 may be adopted by noting that X is constant for much of the latter part of the fermentation, when P is changing most rapidly. Hence, putting K_7 equal to zero and measuring the maximum gradient $\frac{dP}{dt}$ of the product curve, gives a good estimate for K_6.

If such an equation is then integrated using plant data for S, it will be found to have a reducing in the latter stages of fermentation due to substrate depletion, but inadequately so. Increasing curvature may be given to the P-curve by increasing K_7, but the value of K_6 must be simultaneously increased to compensate for this. In this way, it is possible to repeatedly simulate equations 2.9 and 2,10, using for example the method described by Peng and Cui (12), progressively making the integrated equations approach the plant data.

The parameters in equation 2.14 are in principle simple to determine pragmatically, since $\frac{dX}{dt}$ is zero for a significant time during the fermentation, and furthermore $\frac{dP}{dt}$ is also zero initially. It is however important to note that K_8 and K_9 could be determined from stoichiometry, particularly if the chemical compositions of the 'lumped' byproducts were known. Without this information, chemical stoichiometry can only give upper and lower bounds for K_8 and K_9.

The parameters K_8 and K_9 may also be determined with considerable accuracy by plotting factory data in the form of figure 2, when K_9 may be derived from the gradient of the plot of AGA vs substrate consumed, and K_8 from its intercept with the substrate axis.

5. RESULTS AND DISCUSSION

Using the results described in Section 3, model parameters have now been determined for a number of production runs of the 150 m^3 fermenter described in Section 1. The integration method was that of Peng and Cui (12). One such simulation is presented in Figure 4.

The same methods have also been applied to the 50 m^3 fermenter described by Feng (13), with the results presented in Figure 5.

Given that factory data is always more variable in nature than laboratory data, it can be seen that adequate plant simulations have been obtained.

Where the model is not completely satisfactory is in its assumption that all cells will take the same length of time to mature (τ_1) before commencing propagation. This would have only a small effect on the substrate (S) response and the product (P) response.

6. CONCLUSIONS

It has been shown that the complex biological phenomena involved in the production of ammonium glutamic acid can be described in sufficient detail mathematically to represent realistically full-scale plant behaviour.

The method of determining the model parameters has proved effective, although it would be less-well suited for on-line model up-dating for plant prediction purposes. For this reason, a statistical identification method has been developed, and will be the subject of a later paper.

7. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of the staff of the Shanghai Flavours and Essences factory, particularly Mr Feng Beng Bao for many helpful discussions.

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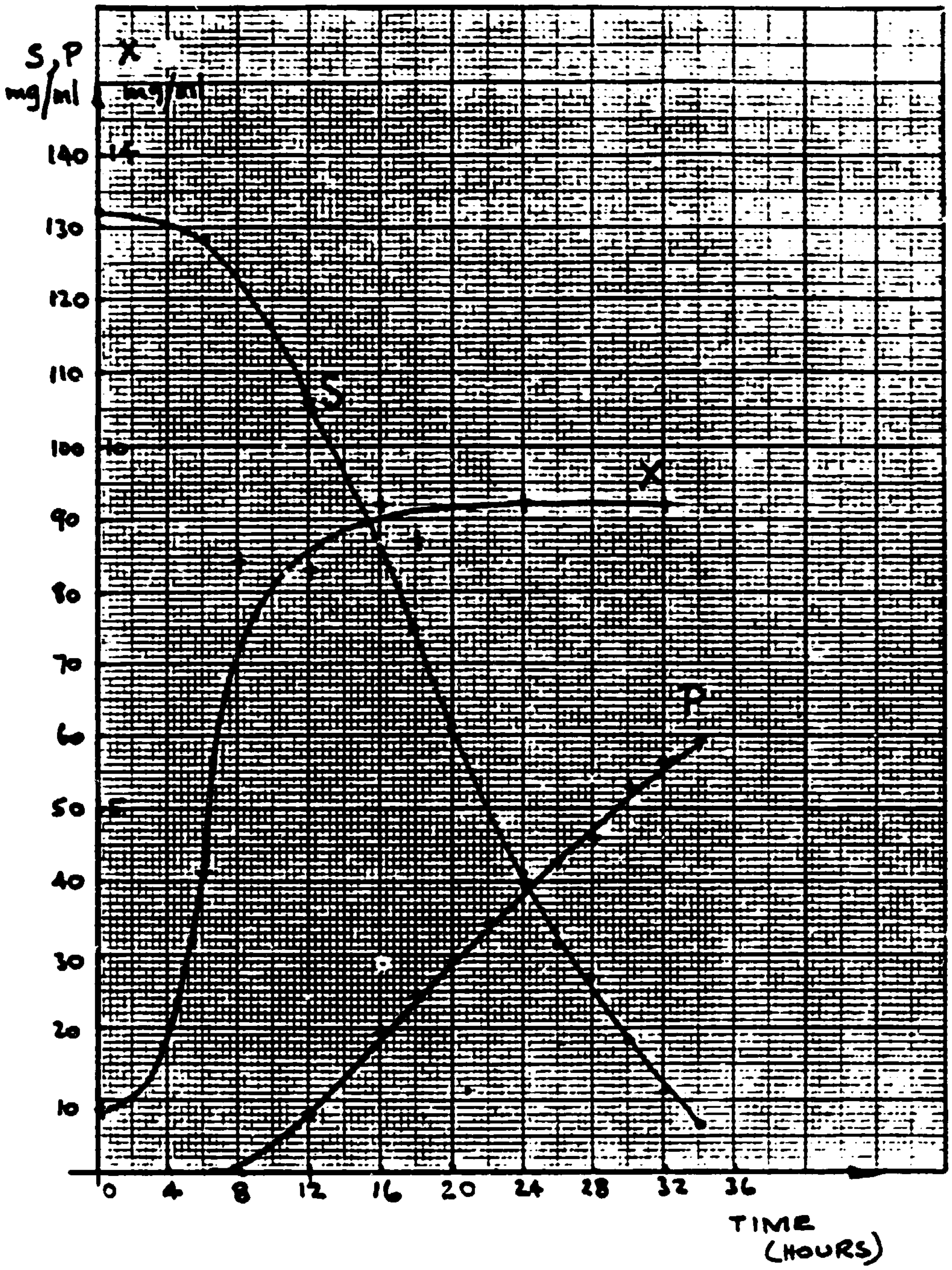

Figure 1. Typical Factory Data

S = Substrate
X = Cells
P = Product

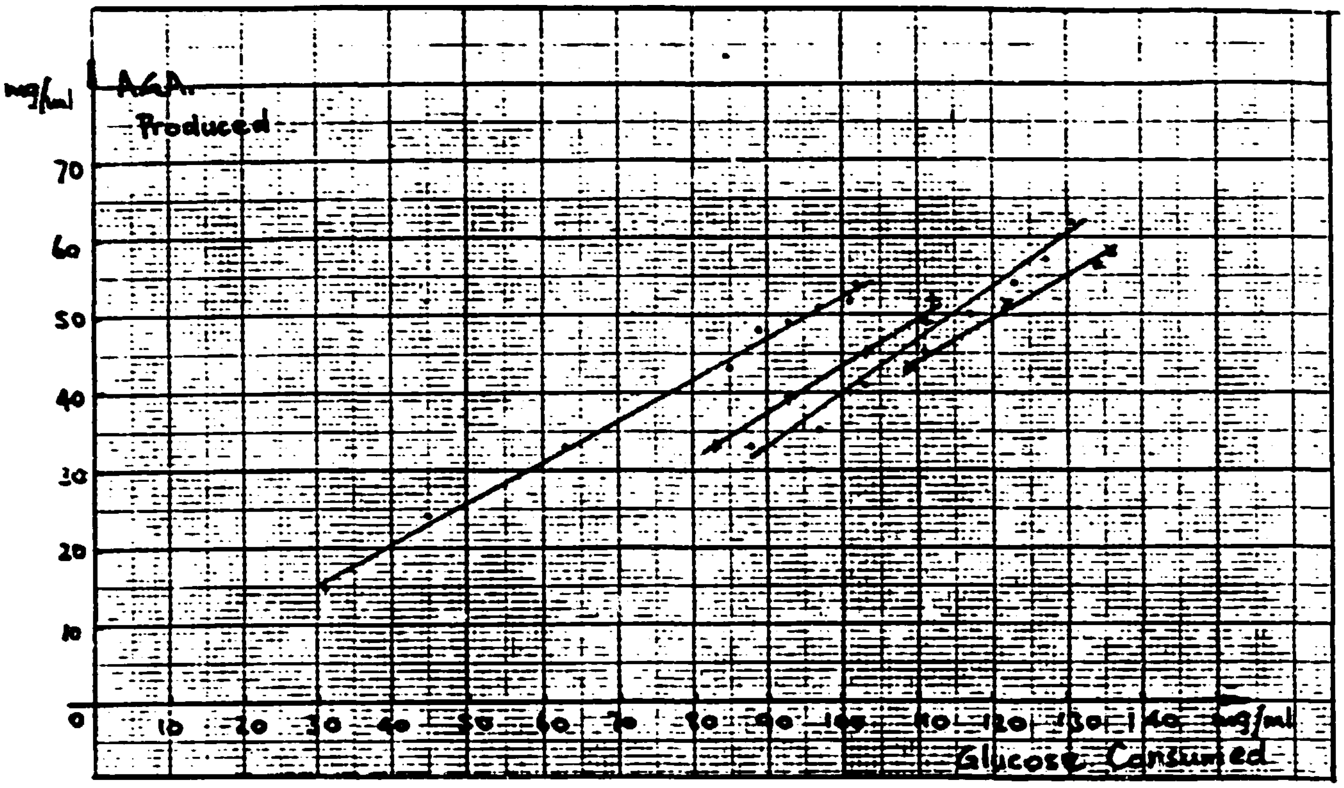

Figure 2. Relationship between Product and Substrate

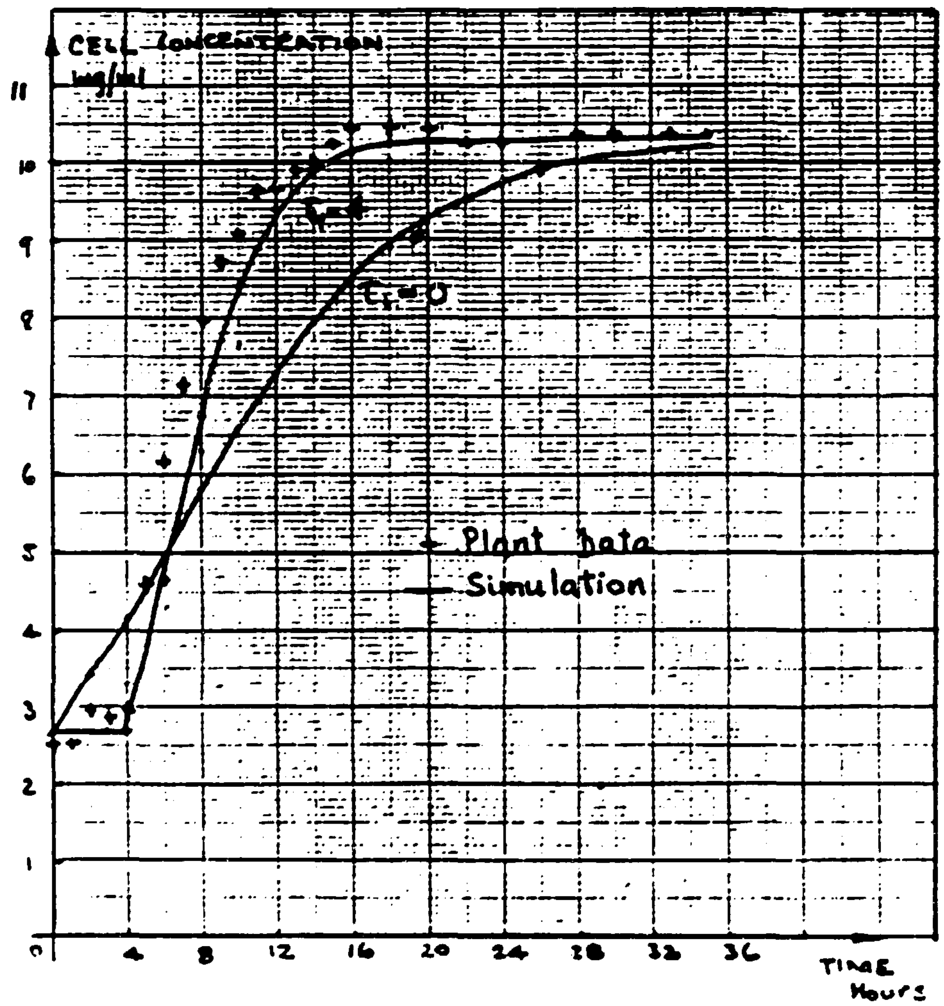

Figure 3. Modelling Cell Growth Data

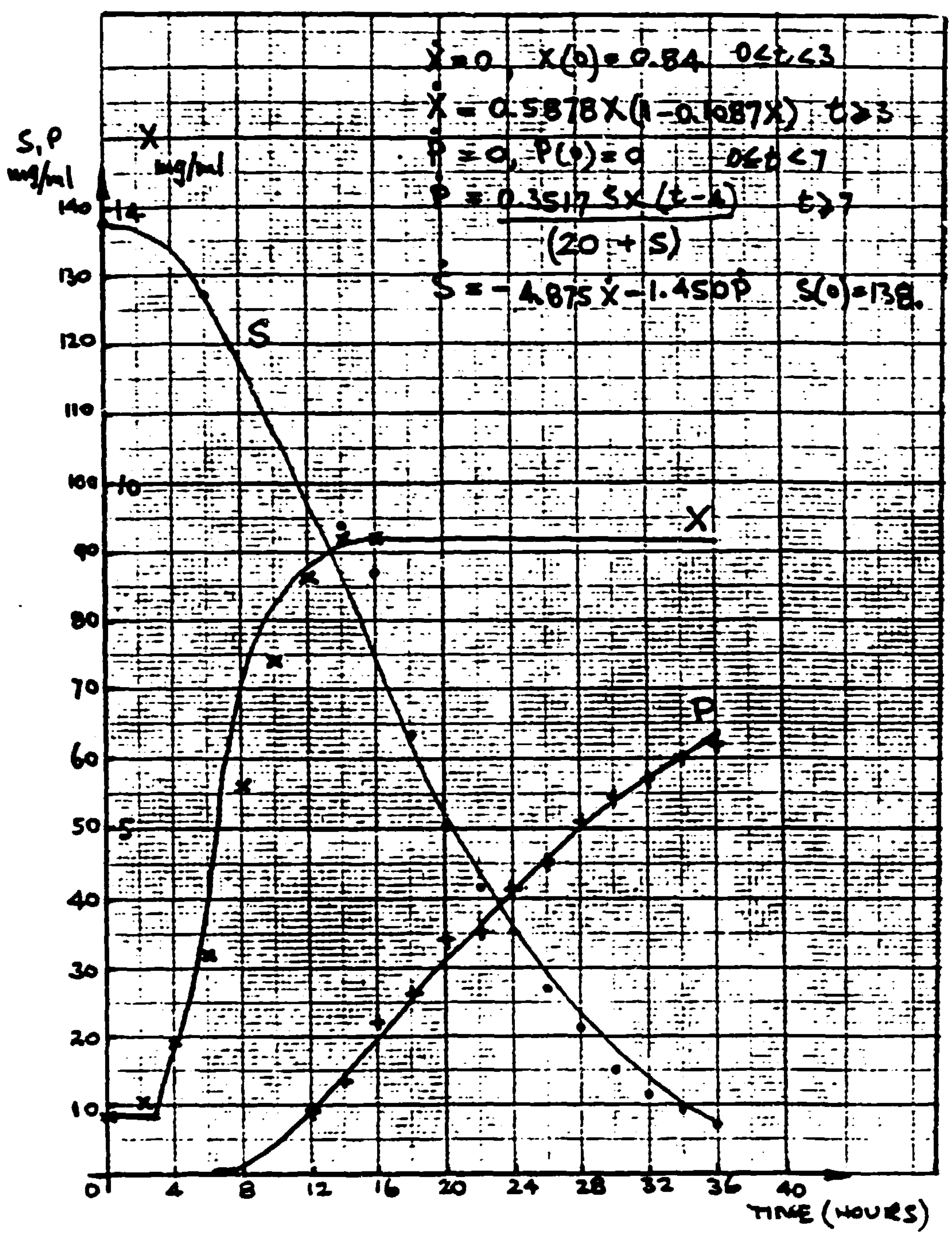

Figure 4. Model Fitted to Data for $150m^3$ Fermenter

S = Substrate — Model
X = Cells •,+,x Factory Data
P = Product

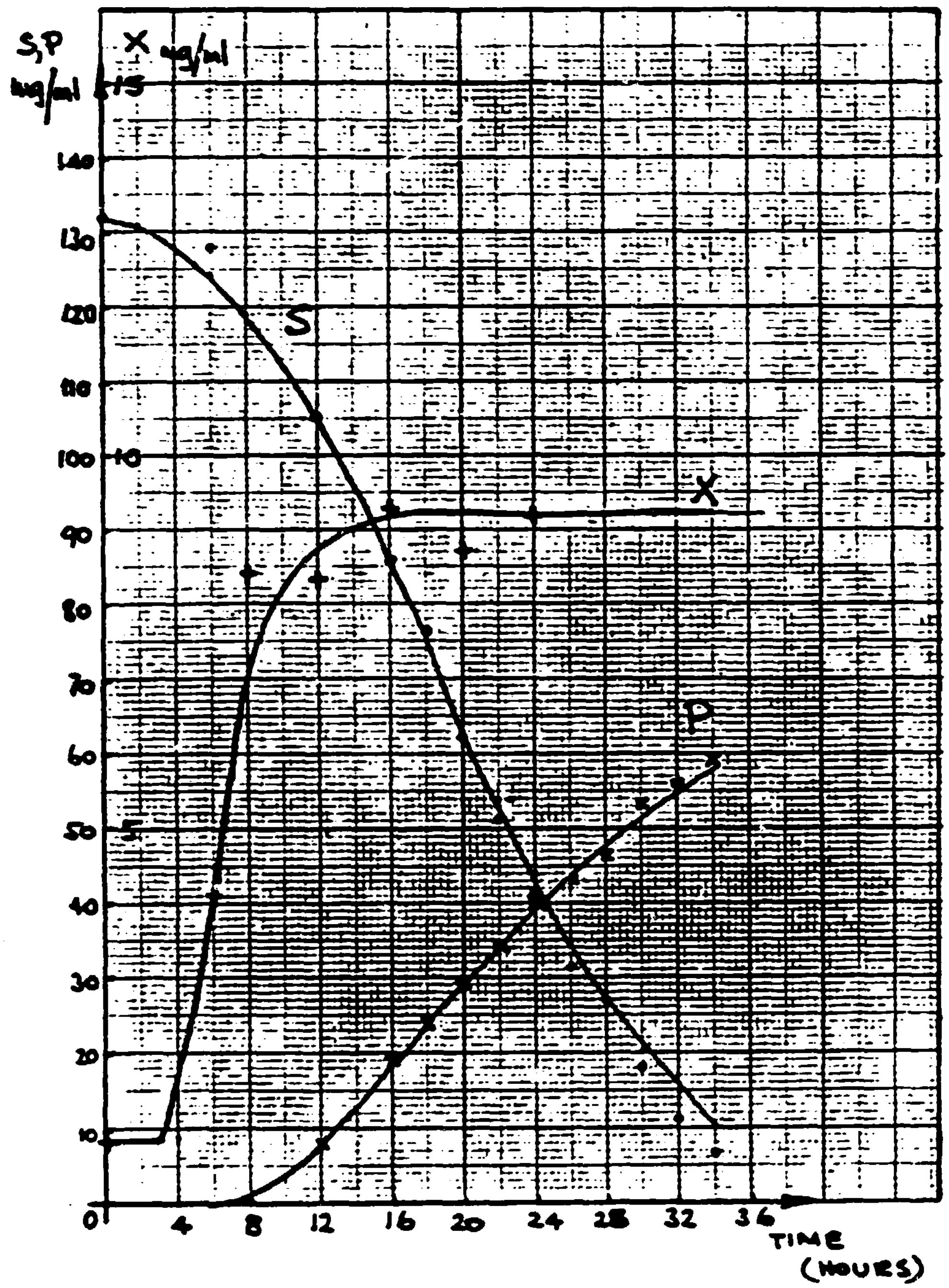

Figure 5. Model Fitted to Data for 50 m^3 Fermenter (Feng, Reference 13)

S = Substrate

X = Cells

P = Product

—— Model

·,+,x Factory Data

Annexe II

THE FUTURE DEVELOPMENT OF MATHEMATICAL MODELLING AND COMPUTER SIMULATION IN CHINA

A report for the Ministry of Machine Building Industry, Beijing, Peoples Republic of China

by

Professor John Mann, UNIDO expert working on UNIDO contract DP/CPR/79/021/11 - 11/31.9.B for the Ministry of Machine Building Industry.

August 1984.

SUMMARY

Mathematical Modelling and Computer Simulation are defined and the contributions which these techniques could potentially make to safe, efficient and cost-effective industrial development in China are described. These contributions fall into three broad categories, namely

(i) modelling for industrial strategic planning purposes

(ii) modelling for process and process operational improvement

and (iii) modelling for automatic control and automation

It is shown that in all three of these areas, the financial benefits from modelling activities far exceed the costs involved, and it is concluded that a very large expansion of these activities in China is entirely justified. This could best be achieved by setting up a central Institute to work on industrial modelling problems and to concurrently train staff seconded from Ministries and Industries, so that the techniques become more widely used, and their benefits more widely felt.

The running costs of the proposed Institute have been estimated, and suggestions made for its organisation, lines of communication, funding, and modes of operation.

SUMMARY OF RECOMMENDATIONS

1. That an Institute be set up to apply mathematical modelling and computer simulation to solving China's industrial expansion problems. (Paragraph 7.4)

2. That the Institutework in the three areas:

   Industrial strategic planning model building
   Modelling for process and process operational improvements
   Modelling for automatic control and automation (13.1)

3. That the Institute be made directly responsible to the Ministry of Machine Building Industry. (7.15)

4. That the Ministry of Machine Building Industry bear the initial costs of setting up the Institute, and act as its 'financial guarantor'. (7.17)

5. That the Institute undertake work for Industry, operational Ministries, the Bureau of Instrumentation, and the Ministry of Machine Building itself. (7.16)

6. That the clients of the Institute should bear the full costs of studies made on their behalf. (7.16)

7. That the Institute initially be based in the premises of the Shanghai Institute for Process Automation Instrumentation, and draw on its staff and equipment resources. (8.3)

8. That staff for the Institute consist of both professionally trained mathematical modellers and staff from Industries and other Ministries. (7.6)

9. That, in addition to undertaking modelling tasks the Institute should be responsible for training, and for disseminating modelling and simulation knowledge into Industries and Ministries. (7.3)

10. That Nuclear Engineering should have a high priority for modelling activi'ies. (8.4)

11. That, in addition to modelling for strategic planning, attention initially be focussed on two priority industry sectors. (8.7)

12. That ultimately a range of.process industries should be the subject of modelling activities. (7.5)

13. That staff for initial training be identified and nominated by all appropriate organisations, as well as the Ministry of Machine Building Industry. (7.2 & 7.6)

14. That such staff should ideally be numerate engineers, augmented as necessary by mathematicians, physicists, chemists and microbiologists (7.6)

15. That an intensive course of training for these identified staff take place in China using both Chinese staff and an overseas expert. (11.6)

16. That an additional intensive course in model building for strategic planning, for identified staff, take place in China using the services of an overseas expert. (11.7)

17. That further training take place in selected organisations overseas. (9.3)

18. That senior staff in all appropriate Ministries make themselves familiar with the potential of modelling techniques in their own areas of responsibility, by attending lectures and by an overseas study tour. (9.6)

19. That the resources available in Chinese Universities be fully used in the work of the Institute. (11.3)

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* Page numbers refer to original report, shown at the bottom of each page in this Annexe.

THE FUTURE DEVELOPMENT OF MATHEMATICAL MODELLING AND COMPUTER SIMULATION IN CHINA

1. Introduction

1.1 The present report results from the author's experiences and observations during a 6-month UNIDO contract, working for the Ministry of Machine Building Industry. The six-month period was divided into three phases, and took place in 1982, 1983 and 1984. During these periods the author was additionally able to visit a number of factories, research institutes and universities. Discussions were also held at a senior level in the Ministry of Machine Building Industry. The knowledge gained during these visits and discussions is drawn upon heavily in writing this report. The present report concerns only the process industries.

2. Background

2.1 Mathematical modelling refers to the act of writing down the mathematical relationships which describe a physical process. The equations may be based on absolute laws, such as those of conservation of mass and energy and momentum, or they may describe functional relationships, such as the proportionality between voltage and current expressed by Ohm's Law. The equations necessary for description of a particular process, or part of a process system, may come from Engineering, Chemistry, Physics, Biology or Economics, and may include models of human behaviour. The equations may describe the flow of energy (heat, electrical, mechanical, fluid, chemical or biochemical energy), or the flow of mass, or momentum, or the flow of information.

2.2 A number of equations will be required to describe a single system. These equations will be a combination of algebraic equations and differential equations. Both kinds of equation may be either linear or non-linear.

2.3 In some ways, these equations are very similar to the equations which engineers use when designing a process system. Much of the information will be the same, but the approach is different. An engineering designer is usually interested in a very specific design, whereas a mathematical modeller will build greater generality into his model to allow for unusual operating conditions. The engineering designer is interested in process plant which does not exist, except as a concept; the mathematical modeller may use his model to investigate both plants which have not yet been built, as well as existing plants, or combinations of these.

2.4 In high technology projects, the engineering design team and the modelling and simulation team would work closely together. In the process industries, these projects would also include a control team and an instrumentation team. The field of mathematical modelling and computer simulation is so broad however that it would be wrong to think of it only in the context of engineering design, control and instrumentation.

3. Reasons for Modelling and Simulation

3.1 To make a comprehensive model which describes every aspect of a process or process system would be a very time-consuming task. It is therefore very important that the precise reasons for making the model be formulated, so that irrelevant equations are excluded and so that full attention is directed towards making the relevant equations sufficiently detailed and accurate to fully represent reality. Some reasons for undertaking a mathematical modelling and computer simulation assignment could be:

(i) To aid capital investment decisions.

3.2 Some capital investment decisions are simple ones. For example, a steel-making plant which does not have coke-making ovens will want to instal its own coke-ovens. The necessary size, the coal requirements, and the value of the coke-oven gas can all be calculated in deciding on the cost effectiveness of that investment decision.

3.3 A more difficult decision could occur in an electrical power distribution network. the addition of one new power-station, or generating set within a power station, will require also additional switchgear and high-voltage cables, which can be costed. As a result, power transmission on other cables in the high voltage grid will be reduced, increasing the reliability in those cables in overload situations and reducing the need for capital expenditure there. Different sites for the new power station will therefore have different physical effects, and therefore different costs and different benefits. An additional complicating factor would be the anticipated growths of power requirements in different parts of the grid.

3.4 In the past, all alternative investment decisions could not be examined, nor could the full consequences of these decisions. The result was that the best value for money was not obtained, and frequently there were consequences which had not been investigated, resulting in disruptions elsewhere, and the need for yet more unforseen capital investment. Mathematical modelling enables the decision-maker to minimise these undesirable consequences.

(ii) To improve process safety.

3.5 Many simple processes can be made inherently safe by appropriate design, automatic control, and operating proceedures. More complex plant, for example in the chemical, petroleum and petrochemicals fields will be capital-intensive, and will operate with very few process operators. It is therefore important that models be used to describe these plants, both in their normal modes of operation, and in malfunction conditions, to improve overall plant safety.

3.6 Such models are mandatory in the field of nuclear power generation, where the full consequences of all possible plant malfunctions must be thoroughly investigated to ensure the complete integrity of the plant. The 'Three Mile Island' (Harrisburg) incident emphasised the need for that. In that instance, process operators completely misread the plant status, and consequently took precisely the opposite actions to the ones they should have taken, making a difficult situation into a near-disaster.

(iii) To train process operators.

3.7 The Harrisburg incident underlined the need for full operator training. Clearly, training on the plant itself cannot encompass deliberately-contrived malfunction conditions. Even in safe conditions, the production of off-specification product would be prohibitively expensive. It is therefore becomming more usual to program a mathematical model of a process into a computer, which is then used to drive the instruments on a controlpanel similar to the actual control panel, and to accept and process operator instructions. In this way, operators can be trained on a simulated plant, under both 'normal' operating conditions as well as 'abnormal' conditions. This training can even take place before the plant itself has been commissioned. It is clearly important in a country such as China, where rate of industrial expansion will result in the need to train large numbers of process operators, who do not necessarily already have an industrial background.

(iv) To investigate Automatic Control Schemes.

3.8 Historically, it has been possible to adjust the parameters on three-term controllers on the plant itself. The complexity of modern processes however means that the control schemes must be fully investigated 'off-line'. Interactions between control loops too will mean frequently that no more than minor adjustments to control loop parameters can be made on-line, and often even then only after reference has been made to the model and its simulation.

3.9 For more complex control schemes, involving for example optimal control, a model of the process is essential.

(v) To determine the cause of problems.

3.10 Frequently, problems of an unexpected nature occur during the commissioning of a new plant, or during its operating lifetime. The engineer will put forward an idea that may be causing the problem, and it can then be examined using a model, to see if that phenomenon as recorded by the plant instruments can be reproduced by the model. This is frequently a more cost-effective way of 'trouble-shooting' than dismantling parts of the plant, to examine each suggested idea in turn.

(vi) To improve understanding.

3.11 Modern processes can be so complex that their precise mode of operation can be doubtful. This particularly applies when technology has been purchased from another company, particularly if it is in another country. Even with the very best intentions, technology transfer is difficult. Where there is a language barrier, technology transfer will be more effective through the language of mathematics, and the experience of having simulated the process under discussion.

3.12 Frequently too, it will be desired to operate the purchased plant using different feedstocks, or under different conditions from those that have been used by the company from which the plant was purchased. Mathematical modelling and computer simulation is the only way to minimise the risk of damaging the plant, the production of off-specification material, and the time required for re-commissioning the plant under the new conditions.

3.13 A somewhat less dramatic, but nevertheless important result of improved understanding is that of more efficient raw material and energy utilisation, and more consistent product quality. Even if the immediate benefits from this are small, such benefits will be felt year after year. The accumulated benefits will therefore be substantial, making modelling a worthwhile exercise even in well-established industries such as traditional cement and glass manufacture.

(vii) To apply research results.

3.14 By its very nature, research experiments are confined to examining each physical phenomenon separately. It is frequently impossible to draw together the results of different investigations, other than on the production plant itself. Plant management will however be quite understandably reluctant to apply the results of research work. This is particularly true where research has indicated that a radically different set of operating conditions would be beneficial. A way to help bridge this gap can be to construct a model containing the research results, together with practical factory plant constraints. Should the factory have additional hesitations based on their own practical experience, it may be possible to investigate their fears, using the model, to assist in dispelling them. Modelling can therefore be a powerful 'sales' tool for research and development management.

3.15 A frequent benefit for research staff from the simulation exercise, is that they can readily see the benefits of their own research, in the overall context. In some cases, a result will be that the research will be redirected into more beneficial areas. The profitable direction of research is always difficult, and any tool which assists in this is well worth using.

4. The Relationship between Modelling, Simulation and Automatic Control.

4.1 From the descriptions in Section 3, it will be seen that modelling is an activity which is beneficial in its own right. It is not necessarily connected with automatic control, although in advanced control situations, instrumentation, automatic control and modelling are inseparable. Simulation is the tool by which the modelling is understood.

4.2 In modern process plants, instrumentation not only provides the information for automatic control of those plants, but also provides management information, from which more effective managerial decisions can be made. For more routine management decision making, it is possible to devise a set of rules which can be programmed into a computer, thereby leading to what is called hierarchical control, which also requires off-line investigation using modelling and simulation techniques.

4.3 In all modelling or simulation work, whether for automatic control, including hierarchical control, for process investigation or as an essential tool for top-level decision making, similar mental attitudes are required by the modellers, and the techniques and equipment used will be similar, if not identical.

5. Financial returns from Modelling.

5.1 Modelling is an activity which consumes the time of highly skilled manpower. It is therefore very important that the financial returns justify the cost. The following are some examples of costs and resultant savings:

(i) To aid capital investment decisions

5.2 In one project undertaken by the author in 1967, investment in plant for a cardboard manufacturing plant (similar to paper-making plant) was considered. The company already owned 11 cardboard making machines, making 150 different products, and was considering purchasing an additional machine, at a cost of £11M* at 1967 prices. The company wished to know which of

* Current exchange rate is £1 = ¥ 3.05

its products should be made on the new machine, to establish its specification. The author examined the technical capabilities of each of the existing machines, and hence their flexibility for manufacture of different products, as well as the company's own market predictions for eash of its products. It became clear that a 12th machine was not justified because, by rearrangingthe products on the existing machines, there would be ample capacity for the next five years.

5.3 This study required six months of full-time effort from one engineer, and resulted in a saving of £11M at 1967 prices.

5.4 The work also gave the company information concerning plant modifications which might have to be madeif the market changes did not occur as predicted, and which machines it would be necessary to modify, and how the new product mix would then be allocated between the machines to minimise energy consumption. It also gave the company management a computer model to allow it to tell 'at a glance' which were its most profitable products when raw material prices were changing with respect to each other.

5.5 The financial returns for the effort involved in this study are probably typical. They emphasise the very large benefits from quite modest investments, and explain why modelling is essential in top-level decision making.

(ii) To improve process safety.

5.6 It is difficult to put a value on process safety, and the costs of modelling will vary according to plant complexity and according to whether the plant is already in existence, and therefore many of the parameters are fixed. It is known that a team of approximately six people worked for three years full time developing a model of a novel steam generating nuclear reactor. This was before the design was finalised and many parameters had to be investigated.

5.7 A model of an established design of nuclear steam generator could require 4 man-years of work, over a two-year period. A nuclear steam generator might cost say US$ 120M. The consequences of a disaster would cost far more than this. Even the loss of electrical output from a lesser accident whilst the plant was out of commission would be substantial, say ¥ 500M for a 900MW station out of commission for 6 months, in lost revenues.

(iii) To train process operators.

5.8 Inadequately trained process operators result in excessive plant 'down-time', particularly during the first one or two years of the life of a plant, and additional maintenance costs. The products from the plant are likely to be off-specification, and therefore result in more costly 'down-stream' operations and reduced value of products.

5.9 If a high tonnage petrochemical plant, with a capital cost of say £150M has to be run at 80% capacity in the first year, the resulting loss of revenues would be of the order of £40M, or a loss of profit of £4M in that year. Additionally, if half of the product is off-specification and has to be sold at a discount of 10%, the loss of profit might be a further £8M in that year. This might well result in a loss of export earnings, a serious consequence for China.

5.10 An instrument and control panel, with interfaces to a microcomputer containing models of the plant could cost £300,000. The models themselves might take 4 - 6 man-years to develop, over a 12-month period, but this cost would be very much less if the models had already been developed for instrumentation and control studies. To this should be added the cost of training say 100 process operators over a period of 1 or 2 months.

(iv) To investigate automatic control schemes.

5.11 A process which is already under reasonable control can benefit from modelling and simulation, and the resultant improved control scheme, in a number of ways

(a) Throughput should increase. It would be unusual for the increase in plant throughput to be less than 5%, and figures of 20% are not unusual in some industries. An increase in throughput of 20% in complex processes, where hierarchical control is used, is quite possible.

(b) Energy consumption should decrease, typically by 5 - 10% in well run industries.

(c) Product quality should be more consistent.

5.12 An increase in throughput of 10% in a plant producing 1,000,000 tonnes/year of a product worth £200/tonne in sales value, with a gross margin of 10% of sales value, would result in a profit increase of £2M per year. If energy costs were 5% of sales revenue, and a fuel saving of 5% was made, the additional savings in fuel would be worth £0.5M per year. If the increase in quality means that product can be sold at a premium of 10%, the increase in profit would be £20M per year.

5.13 The costs of such an exercise might be 4 man-years of work over 12 months, plus the costs of additional plant sensors and microprocessors.

(v) To determine the cause of problems.

5.14 These modelling exercises usually have to be undertaken at short notice. In one exercise in which the author was concerned, it took one man-week of modelling and simulation to determine the cause of a problem. The plant was a small one, having cost only £1.2M, but it generated profit at the rate of £192,000 per week. The very short modelling exercise probably enabled the plant to get back into full production two weeks faster than it would otherwise have done.

5.15 A further exercise with which the author was involved, concerned the 'de-bottlenecking' of a complex production and assembly line for the manufacture of industrial lead-acid batteries. One man-month of modelling and simulation resulted in an 18% increase in throughput, which was equivalent to an increase in profits of the order of £350,000 per year.

(vi) To improve understanding.

5.16 It is difficult to evaluate the benefits from improved understanding of a process, but one approach would be to consider modelling and simulation in the context of what has been called the 'learning curve'. What people mean by this is that production costs for existing plant typically reduce over a number of years, as more is learnt about the plant and its technology, and how to manage it. It is not unusual for companies to find that they can reduce production costs by £30/tonne for example, over a number of years, which would be equivalent to a profit increase of £30M per year on a large plant.

5.17 In order to achieve this, plant modifications and additions would have to be made, incurring additional costs. Modelling and simulation can make a powerful contribution to acheiving these savings, through improved process understanding.

(vii) To apply research results.

5.18 The reluctance of industrial 'customers' to apply research results is universally observed. Repeated refusals result in low research morale and adversely affect the credibility of research management.

5.19 In one exercise in which the author was involved, a research and development project had cost at least 6 man-years of effort over a two-year period. The result was a number of reports which had been written at different times, and which the factory staff had difficulty understanding. Indeed, the research staff had difficulty in being precise about their recommendations, because different people had done different parts of the work, under different sets of experimental conditions.

5.20 The modelling work required 2 man-months of effort over a six month period. The end product was that the research results were condensed into the model, which was used to successfully 'sell' the research to the factory, therby 'saving' 6 man-years of effort. The model was also used to plan the experiments for the next phase of the research.

6. Industries which would benefit from Modelling

6.1 Traditionally, modelling has been applied in the large-scale processing industries. For example, the published literature includes models of many of the aspects of iron and steel making, including materials handling, sintering, blast furnaces and electric arc furnaces, ingot cooling and slab milling, slab reheating and sheet rolling. The optimal scheduling of steel-mill internal rail transport has also been considered.

6.2 Modelling of the wet-end of paper mills has been shown to be beneficial in improving control, resulting in more consistent product quality. In other traditional industries, such as cement and glass manufacture, modelling has been shown to reduce energy consumption, and to allow product quality to be improved.

6.3 Petroleum refining, petrochemicals, and chemicals industries, both organic and inorganic, all have similar unit operations, and all of these have been the subject of mathematical modelling exercises, for control purposes, for production planning and for overall planning decisions, including plant location problems.

6.4 Both conventional and nuclear steam generator models are reported in the literature. These may frequently be coupled with turbo-generator models. Models of electrical distribution networks are commonly used for controlling power flows in grid systems on a routine basis, and also for determining the need for additional investments in the grid system.

6.5 All of the above processes are essentially continuous systems. In other industries, batch systems are more common, and the modelling problems more difficult, but just as beneficial. Detergent manufacture and vegetable oil processing are frequently continuous processes, but the manufacture of resins, paints, pesticides, dyestuffs and pharmaceuticals are usually batch operations.

6.6 Modelling batch systems is usually more difficult than modelling continuous systems operating in their normal running state. During the start-up and shut-down periods on a continuous plant, the modelling problems are very similar to those of a batch plant.

6.7 Special mention should be made of the fermentation industries, which produce pharmaceutical materials, as well as human and animal foods or food ingredients, and which are also used for effluent treatment. So far, very little modelling has been applied to these biotechnology processes, but the benefits in improved understanding of fundamental biological and biochemical mechanisms, and in more efficient process operation and control, are likely to be profound and far-reaching in this rapidly-developing area.

7. A Format for Development in China.

7.1 To a coumtry such as China, with a high rate of industrial development, and having to purchase much technology overseas, mathematical modelling and computer simulation will be essential in aiding the evaluation, deployment and efficient operation of that technology. The need to generate finance through exports, the importance of spending the available finance in the most profitable way, and the need for efficient use of energy, also emphasise the need for very much greater efforts in mathematical modelling and computer simulation.

7.2 In looking forward, a format must be employed which enables modelling resources to be efficiently used and developed. The major tasks undertaken should be those which are of greatest importance to China, whilst not restricting initiatives in other areas. This can be achieved by initiating an accelerated programme of development in a centrally placed Ministry, or Bureau of such a Ministry. The staff for such a development however would come not only from that Ministry, but also from other Ministries concerned with these matters. These latter staff would return to those Ministries, and to the industries responsible to those Ministries at the end of their period of secondment and training. The techniques learned and experience gained during their period of secondment can thus be used at plant level. At the same time, they will inject practical knowledge into their host institution during their period of training.

7.3 It is important that the proposed Institute should not attempt to monopolise modelling and simulation of processes. Rather, it should act as a central pool of expertise from which techniques and knowledge should flow, through the training of staff, to each and every relevant industrial enterprise and decision making centre in China.

7.4 The ultimate objective should be to set up an organisation, of Institute size, concerned solely with mathematical modelling and computer simulation. Of necessity, such an Institute should have close links with instrument development, and also have access to, and enjoy the confidence of, the most senior decision-making bodies within Ministries responsible for overall planning decisions.

7.5 Such an Institute would need to be organised so that it could become immersed in the technology of particular industrial sectors, such as:

Iron and Steel
Non-ferrous processing
Minerals treatment
Nuclear Engineering
Petroleum and Petrochemicals Processing
Power Generation and Distribution

Paper and Cardboard Manufacture
Glass Manufacture
Cement Manufacture
Soap, Detergents and othe Chemicals Processing
Fermentation
Food and Food Ingredients Processing

7.6 It is envisaged that each Group would be staffed by both resident experts in different aspects of model-building and simulation, as well as by knowledgeable staff seconded to the Institute from their appropriate industries. Opportunity should also be made for the resident experts to be seconded to appropriate industries at some time during their professional careers. Staff should, in the main, be numerate engineers, together with mathematicians and, where appropriate, physicists, chemists, microbiologists and biochemists.

7.7 The size of each group would depend on a number of factors, such as the economic importance of that industrial sector, the current and future rates of investment, and the opportunities for technological development and financial improvements in those industries. Some Ministries and industries will see the need for additionally developing their own modelling, simulation and automatic control capabilities, and this should be encouraged, whereas others may prefer to rely on the central Institute for that expertise.

7.8 Supporting the above operational groups should be service sections, such as those responsible for advising on simulation software and hardware, specialist statistical and econometric techniques, training, recruitment, etc.

7.9 In making the proposals for a centralised Institute, the author is aware that no directly comparable Institute exists in the Developed countries. The problems of China however are quite different. Model building is still at an early stage of development, and needs the fostering that a central institute will give, through its leadership. China has limited financial resource for industrial development and cannot afford to purchase inappropriate technology, incorrectly sized plants, or plants which cannot operate at full capacity because of unforseen factors. Industrialisation is probably proceeding more rapidly in China than it has ever done in any other country.

7.10 The author is aware of the current organisational reforms being considered in China, and the likely decentralisation which will result. The limitations on finance for development will however still mean that more central financial control will be maintained in China than is usual in the 'laissez faire' economies of the developed countries. The proposed Institute is therefore more relevant in China than it would be in developed countries.

7.11 Modelling and simulation for investment planning requires special consideration. Where advice is being given to an industry sector, or its Ministry, there are sometimes reasons why that work should be undertaken in the appropriate industrial sector group. Where the work is being undertaken for a Ministry responsible for overall planning decisions, such as the Ministry of Machine Building Industry, clearly confidentiality must be maintained. It is therefore recommended that this take place in a separate 'Strategic Planning' group, directly responsible within the Institute to a Strategic Planning Vice-President. It is not at all necessary that this group should be geographically close to Beijing; it is more important for the group to be placed together with other engineering modellers. Indeed, the members of the group should be drawn from the more experienced members of other groups within the Institute.

7.12 The Strategic Planning Group should be staffed mainly with engineers, since the kind of model building and simulation envisaged is that which is used for dynamic engineering systems. Some economists and econometricians should also be in the group to interpret economic data but in general, the model building and simulation techniques used by econometricians are as yet less well developed than those developed for simulating engineering systems. Furthermore, it should not be the function of the Group to try to take over the econometric modelling for national planning purposes, which is no doubt already being used in China. Staff experienced in mathematics, statistics and operational research would also be desirable.

7.13 It is recommended that the Institute be managed by a Management Committee, with three Vice-Presidents, responsible for

Technical Groups, Service Sections, and Strategic Planning respectively, under the chairmanship of the Institute President. This structure is shown in Figure 1.

7.14 Consideration also needs to be given to the line of authority between the parent Ministry and the Institute. Because the Institute will be concerned with automation and automatic control, it would be proper for it to report to the Bureau of Instrumentation within the Ministry of Machine Building Industry. However, its terms of reference, as outlined, are far wider than this. If the Institute is responsible additionally for providing advice concerning efficient process operations and cost-effective investment recommendations to operational ministries, then this exceeds the terms of reference of the Bureau of Instrumentation, and the Institute should therefore report direct to the Ministry of Machine Building Industry. Furthermore, the Institute would be responsible for advising the Ministry of Machine Building Industry on matters of Strategic Planning.

7.15 For all these reasons, it is therefore recommended that the Institute should report directly to the Ministry of Machine Building Industry.

7.16 Although it is suggested in paragraph 7.15 that the Institute should be responsible directly to the Ministry of Machine Building Industry, it is not suggested that all funding should be provided by that Ministry. Where work is undertaken directly for that Ministry, for example in Strategic Planning, funding for that should be provided by the Ministry. It is anticipated that similar work will be requested by other Ministries, and funding for that should be provided by those Ministries. Advice given to the Bureau of Instrumentation should be funded by that Bureau (who may in turn wish to recover costs from other Ministries). Where advice is given to Industrial Sectors, that advice advice should be charged to those Industries.

7.17 It is therefore recommended that the Institute should receive funds from a number of sources, and not just the Ministry of Machine Building Industry. There will however be a requirement for an overall financial sponsor, particularly in the formative years of the Institute, and it is recommended that the Ministry assume responsibility for that important task.

8. <u>Short-Term Recommendations</u>.

8.1 In the short term, consideration needs to be given to how the objectives given in Section 7 can be achieved.

8.2 It is most impractical to consider setting ip a new Institution as a completely separate entity. It is better to graft the beginnings of the Institution on to an existing one, and to give it the resources needed to grow from that base.

8.3 Because of the affinity of the proposed work to that already being undertaken in the Shanghai Institute for Process Automation Instrumentation (SIPAI), this would seem to be a logical place for its development. There are already some staff trained in the specialist techniques required and, more importantly, mental attitudes in SIPAI are attuned to the concepts of interacting dynamic systems. A nucleus of staff already exists. Suitable computational facilities also exist, and the developing simulation laboratory will be an important tool. Process knowledge from a number of industries is also already in existence, but the relevance of this will depend on which industries are to receive priority treatment.

8.4 Consideration also needs to be given to the initial work area priorities. Each of the areas listed in paragraph 7.5 would amply repay modelling and simulation expenditure. The over-riding requirement for nuclear safety, together with the development of plans in China for nuclear power generation, would seem to indicate that this should be the highest priority.

8.5 The heavy investment in petroleum processing consequent upon successful exploration, indicates that this should be a priority area, together with petrochemical processing. Safety is also important in those industries.

8.6 The rapid development of China's iron and steel industry, including high-technology continuous casting, would give this industry a high priority. The likely rapid development of the biotechnology industries could also indicate a priority area.

8.7 It is recommended however that initially attention be focussed on no more than two of the above areas, one of which should be Nuclear Engineering. Resources should be made available to enable this to take place, and to enable the overall objectives to be met in as short a time as possible.

9. The Importance of Training.

9.1 As previously stated, mathematical modelling is essentially dependent on the availability of trained personnel. A training in automatic control or systems engineering is an excellent introduction, but to this must be added additional training in specialist mathematical and computational techniques. Equally importantly, successful mathematical modelling depends on professional judgement, particularly where decisions must be made regarding physical relevance and mathematical relevance. A general engineering training assists in this, but as in all engineering, professional judgement is best learnt 'on the job'.

9.2 It is recommended that an accelerated programme of training be instituted. Some of this could take place in China, but the most effective solution would be for a number of selected personnel to be trained in appropriate educational and industrial institutes overseas. Where possible, such trainees should take with them a process modelling problem of importance to their institute.

9.3 It is recognised that overseas training is expensive. The author has found from working with Chinese colleagues, and from discussions with Chinese undergraduates and postgraduates in Universities that they posess the right intellectual abilities and attitudes, and training, to make a success of their overseas training. Model building however is a multidisciplinary activity which requires a breadth of understanding across a number of areas of engineering, together with physics, chemistry and possibly biology, and combined with mathematics, statistics, computer science and possibly economics and human dynamics (cybernetics). The Chinese educational system is still oriented towards producing narrow specialists. The relationships between the above disciplines are better appreciated overseas, and therefore overseas training in modelling will be all the more important and beneficial.

9.4 It is important that such trainees should not be left in isolation during their training. They should produce regular reports, at say monthly intervals. These reports should include technical progress on the trainee's modelling problem. These trainees should be visited on a regular basis, perhaps at intervals of 6 - 9 months by an experienced mathematical modeller, when they should make a formal presentation of their progress, and discuss the details of this. Such a visit may be combined with attendance at appropriate conferences and meetings.

9.5 In the longer term, sufficient expertise will be built up in the Institute to enable most of the training to take place there. The contribution that academic staff in Chinese universities can make towards training should not be neglected.

9.6 It is also important that senior staff within the Ministry of Machine Building Industry, as well as in the operational Ministries, should make themselves thoroughly aware of how these powerful tools can assist them in their decision-making. It is recommended that such staff be briefed on modelling methods and their relevance, and that they then undertake a study tour of relevant institutions abroad. Those institutions would include universities, research institutes and commercial companies.

10. Equipment for Data Logging and Simulation.

10.1 Modelling itself can be accomplished without access to computing power. However, this soon ceases to have any meaning without the related simulation, using the equations of the model. To do this, access to a 'mainframe' computer with standard high-level language capability is adequate. The use of interactive terminals to a mainframe computer will improve the productivity of staff.

10.2 The needs for additional equipment will depend on the tasks to be undertaken. The above equipment will be quite adequate for large-scale strategic planning simulations. Since nuclear reactors are already well instrumented, adequate data will already be available. Some however will be in the form of chart recordings which will require a digitiser to transform into workable format. The ability to analyse this data using Fourier Transform methods or Auto- and Cross-Correllation methods can be achieved either by the use of specialist hardware or by use of software in a conventional computer. Equipment to undertake these tasks will soon be available in the simulation laboratory of SIPAI.

10.3 Instrumentation in the petroleum refining and petrochemicals industries is generally less comprehensive. If work is undertaken in this area, it may prove necessary to purchase chemical analytical instruments and sensors for measuring the compositions of vapour and liquid streams. High temperature sensors may also be necessary, together with 'non-invasive' flowmeters. Collection of data from these instruments will require interfacing to a microprocessor, and data storage for subsequent off-line processing in the simulation laboratory. Consideration should be given to housing the above equipment in a mobile laboratory, which could then be moved from plant to plant, as required. Specialist analytical chemists would be required to operate the equipment.

10.4 Similar remarks apply to other industrial areas, which are generally poorly instrumented, compared with the nuclear industry, even in developed countries. The problem is made more difficult in the biological industries, since biological samples must be analysed quickly, before further natural changes take place.

10.5 Much very good work can be undertaken using normal factory records, but the techniques used to deal with uncertainty in factory data will result in tho need for additional trained human resource, and will slow up investigations. Investment in software will therefore be cost effective. Similar remarks apply to investment in software for computer aided design of multivariable control schemes.

11. <u>Technology Transfer</u>.

11.1 Mention has already been made of the way in which technology transfer between Institute and Operating Ministries and their industries will take place, by secondment of staff. The regular organisation of conferences and seminars in China will also assist this.

11.2 Within the Institute, regular open progress meetings, at which progress summaries (internal seminars) are presented, should become a standard method of technology transfer. Movement of staff within the Institute will also accomplish this.

11.3 The author has found that considerable modelling expertise in specific areas already exists in some Chinese universities. Contact should be maintained with those Universities. More importantly, a mechanism should be devised whereby key academic staff in this area could be invited to the Institute to work with Institute staff on Institute problems, for periods of one or two months at a time. The institute may even wish to ensure that such academics are adequately equipped in their own University Departments to continue their work on Institute problems on their return to their Departments. This policy has been very successful in a number of U.S. Universities.

11.4 Mention has already been made of the way in which overseas technology can be transferred to China, through the training of junior and senior staff, augmented by attendance at overseas conferences.

11.5 The author is very aware that his efforts under the present UNIDO contract have resulted in the training of only a limited number of staff. This nucleus is fragile, in the sense that the small numbers may become even smaller through natural wasteage.

11.6 The present exercise should therefore be regarded as a pilot exercise. Having assessed its worth, it is now recommended that a similar training exercise be mounted for a larger number of staff, including those who are to be seconded to the Institute from Industry. Although a UNIDO expert might be used for the central aspects of the training, Chinese staff should assist, and these staff, plus the trainees would then form the nucleus of the Institute Groups.

11.7 Special consideration needs to be given to the training of staff in the Strategic Planning area, and the required technology transfer there. This has not been a part of the present UNIDO training project. It is therefore recommended that trainees be identified by the Ministry, and that the services of an expert in this area be sought. The training format should be similar to that of the present UNIDO project, namely a set of lectures on different aspects of model building and simulation of dynamic systems, with particular emphasis on strategic planning model building and simulation. These lectures should be accompanied by project work on a modelling problem of importance to the Ministry, for concurrent 'on the job' training. The length of such a training period could be around two months, provided that the problem chosen had adequate data available, and could there fore be tackled in this period.

12. Cost Projections.

12.1 At the present time, only 'order of magnitude' cost estimates are possible. If all twelve groups suggested in paragraph 7.5 were ultimately to be set up, and each group consisted of an average of 8 graduates, then a graduate staff of 96 would be involved, at least half of whom would be on secondment from their Ministries or Industries. Graduates with a specific expertise, servicing these Groups might total a further 12. The strategic planning Group might consist of a further 20 graduates, some of whom would be on secondment from Ministries and Industries. There would also be about 12 part-time 'visiting workers', as mentioned in paragraph 11.3 .

12.2 A graduate staff of 130 might require a further 70 support staff, making an Institute of 200 persons, requiring a floor area of 5,500 m^2 . At current costs, this would imply an annual Institute budget of ¥ 1.2M. The cost of the building would be ¥ 2.2 M and the capital cost of simulation hardware and software, data analysis equipment and chemical analytical equipment could be ¥ 1.5 M, which could be purchased over a number of years. Ultimately, the Institute may justify having its own mainframe computer, which would incur additional expenditure, but this should not be necessary in the short term.

12.3 The salaries for those members of staff seconded by their own Ministries and Industries would be paid by those Ministries and Industries, together with appropriate Institution overheads.

12.4 Charges made for services should reflect both direct salaries costs and Institution overheads, although this may be difficult to achieve in the short term.

13. Conclusions.

13.1 Mathematical modelling and computer simulation are important areas for the promotion of safe, efficient and cost-effective expansion of China's industrial base. The contributions these subjects make will assist automation and automatic control, together with process and process operational improvements, as well as in industrial 'strategic planning' exercises.

13.2 In all of these areas, the financial benefits will be grossly in excess of the costs of the studies.

13.3 Because of the need for an initial sound base in a related and supportive environment, it is likely that the new Institute could emerge from the present base in SIPAI. In the longer term, it may be desirable to set the Institute up as a separate entity.

13.4 The work of the Institute will be to service the Ministry of Machine Building Industry and those operational Ministries which rely on that Ministry for assistance in instrumentation, automatic control, process technology and strategic planning.

13.5 The lines of communication between the Ministry and the Institute need to be carefully considered, and the organisation within the Institute must reflect this.

13.6 Training of staff is identified as the main constraint in expanding this activity to the size where it can make an effective contribution to China's industrial development. This training will ultimately be of profound significance in the efficient technological management of China's key industries, through staff and technology transfer.

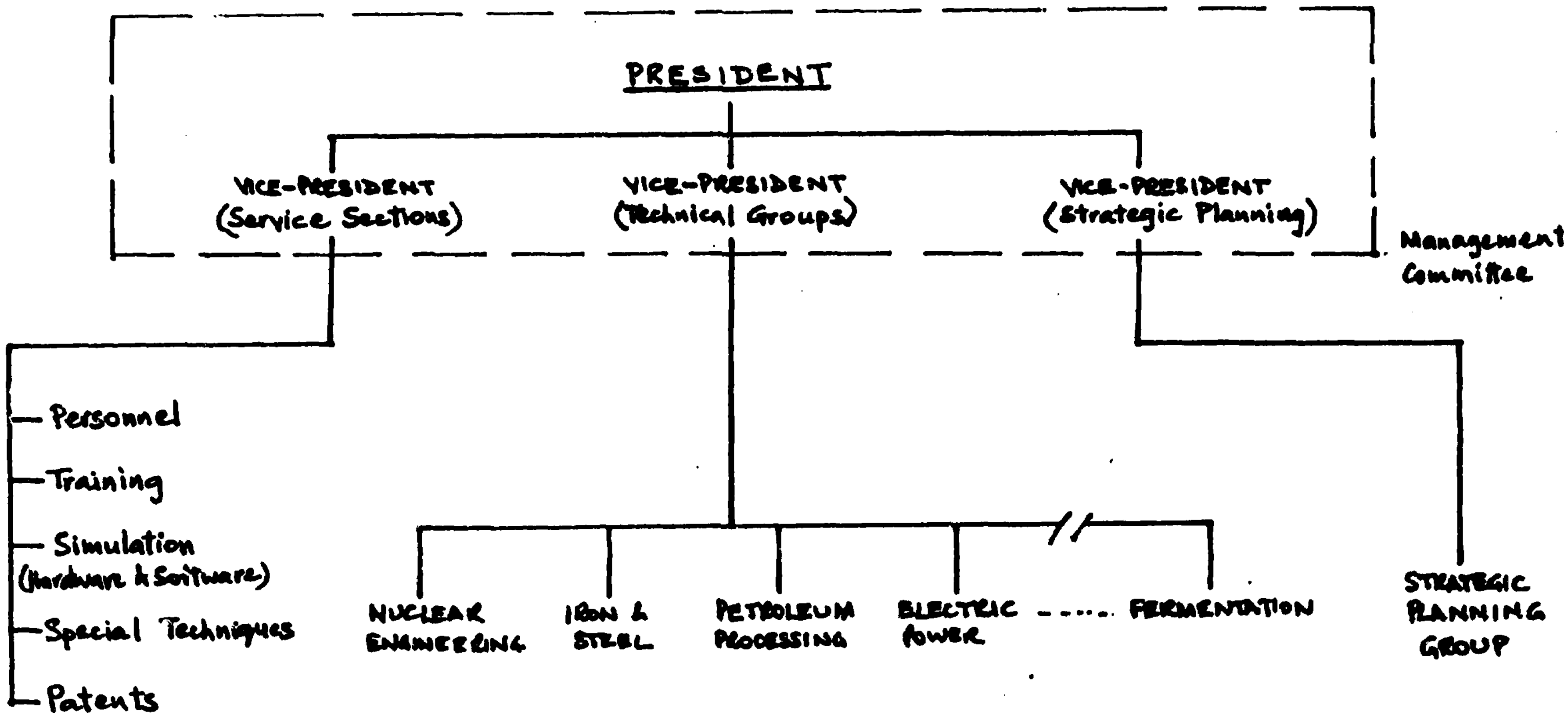

FIGURE 1: STRUCTURE OF PROPOSED INSTITUTE.