AN INTERACTIVE SIMULATION

OF A RENAL UNIT

by

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Thesis submitted for the degree of Doctor of Philosophy of the University of Southampton.

- 1984 -

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ACKNOWLEDGEMENTS

I should like to express my debt to the late Professor K.D. Tocher who inspired me to use the discrete event simulation approach. I am very grateful to Dr. A.K. Shahani, who took over the role of supervisor, to Mr. J.G. Crookes of the University of Lancaster who has given much advice and support and to Professor A. Polak, consultant physician and former director of Portsmouth Renal Unit, who has been extremely helpful.

I also wish to thank :

- present and some former staff of Portsmouth Health District, especially those of the Renal Unit and the finance, pharmacy and pathology departments,
- Dr. N. Selwood of the European Dialysis and Transplant Association,
- Dr. T.G. Feest, renal physician of Exeter Renal Unit,
- Mr. R.M. O'Keefe, a former research colleague at the University of Southampton,
- Dr. T.A. Davies, my husband, for his support and interest.

The typing is by Joanne O'Malley Secretarial Services and artwork by the Teaching Media Department of the University of Southampton and Mr. M.A. Davies.

I acknowledge the financial assistance from the Science and Engineering Council who not only provided the initial two years' grant, but extended it for eight months to enable me to finish the work.

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF MATHEMATICAL STUDIES

OPERATIONAL RESEARCH

Doctor of Philosophy

AN INTERACTIVE SIMULATION OF A RENAL UNIT

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This dissertation describes and discusses an interactive microcomputer model of the treatment of chronic renal failure by dialysis and transplantation.

There is an unmet demand for the treatment of this condition, particularly in the older age-groups. A model of the treatment system is needed by planners in order to explore the implications of meeting the demand, giving different priorities to available treatments and changing the balance between home and hospital treatment. Previous models have been constructed, but they omit important elements from the system, have poor credibility, lack robustness and are not easy to use.

This discrete event simulation, developed at Portsmouth, describes the system more realistically, including resource use and constraints, the arrival of kidneys and the matching of donors with recipients. The concept of 'shadow entities' is developed and used.

The model was verified and validated using techniques which included using a tabular display while the simulation was running. The model is easy to use, and robust both to different data requirements and extreme policy changes.

Interactive simulation runs, based on different admission policies and priorities for dialysis, are described, together with their use in the costing and budgeting of renal failure treatment services.

Chapter 1

THE NEED FOR A MODEL

1.1 INTRODUCTION

1.1.1 Modelling a health system: renal failure treatment as an example

In the hospital service, the organisation of patients' visits, their use of hotel facilities when in hospital and the choice of their treatments are major factors which influence the use of health service resources. Models which describe the activities of people over a period of time, however, may be complex. In the Health Service, not only may different treatment strategies be applied to apparently similar patients, but patients under treatment may well be making several demands on the system at the same time. For example a patient may be booked for radiotherapy, may be occupying a hospital bed and may be undergoing investigations involving doctors, nurses and expensive equipment. An example of such a complex set of interacting processes are those stemming from the treatment of chronic renal failure.

Indeed, treatment of patients with kidney failure in a Renal Unit is typical in this respect, for such patients require kidney machines, day and inpatient beds and operations. Kidneys are vital organs one of whose main functions is continuously and efficiently to remove harmful chemicals from man's blood stream. Infections, autoimmune disorders and other conditions may damage the kidneys and cause renal failure in some people. A proportion of people will die unless a substitute for their own kidneys is available. They may receive one of the following treatments, which will be explained in more detail later on:

i) haemodialysis (1.2.1)
ii) renal transplantation (both (i) and (ii) have been available in the United Kingdom since the 1960s (1.2.3))

iii) intermittent peritoneal dialysis, which is usually used only as a temporary measure or

iv) continuous ambulatory peritoneal dialysis (C.A.P.D.) which has become established as an alternative long term treatment in more recent years (1.2.2).[1]

Patients accepted for treatment by a Renal Unit with an integrated dialysis/transplant programme may change from one type of treatment to another (Figure 1.1). Each of these treatments makes distinct demands on Health Service resources, requiring different drugs, operations, pathology tests, fluids and expensive equipment. The way in which the Renal Units are organised and the emphasis they put on the different treatments varies considerably from one to another [2] and may change considerably over a short period of time (6.5.1). The system is thus both complex and fluid, making the planning of renal services and the evaluation of different policy decisions extremely difficult.

1.1.2 Planning Problems

Coming to grips with plans and policies for treating chronic renal failure has been a preoccupation of health planners for well over a decade. Many problems may be identified, but few hard solutions have been put forward. The major problems are:

i) as many patients with chronic renal failure are relatively young, there is considerable public pressure to make treatment available;

ii) the technology for the treatment of this disease continues to change, year by year;

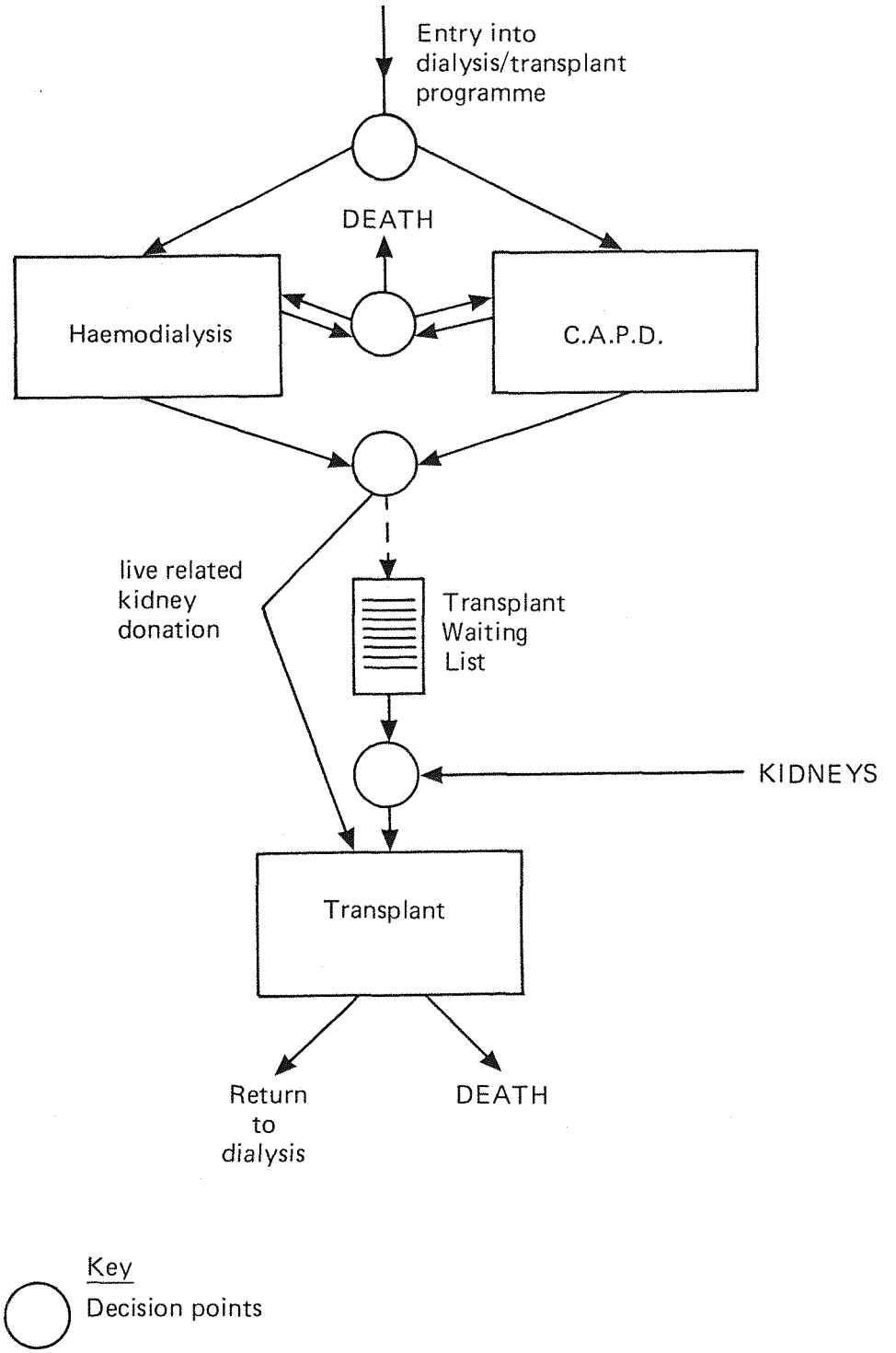
iii) there is an "unmet need" for treatment;

iv) nobody has established an "ideal" mix of treatments to be provided by the health service in this field;

v) as finance for health service projects reaches its limits, it becomes more important to decide on improved patterns of organization to make the best use of the resources which are available. (see below).

Figure 1.1

The Decision Process in the Treatment of Patients in a Dialysis/Transplant Programme



1.1.3 Financial Problems

The finance allocated to the hospital service in England in the Government's annual budget is divided between the 11 Regional Health Authorities. The Regions then allocate money to District Health Authorities for:

i) District hospital services,
ii) community services,
iii) Regional services such as Regional laundries and
iv) specialties providing services to the whole Region such as Radiotherapy, Plastic Surgery and Renal Units.

Since the money for the Regional specialities is administered by the Districts providing the service, not only is there competition between the Districts and the Regional specialties for finance, but also competition for resources between the District services and the Regional Services at District level. This is exacerbated by the lack of specialty costing and poor budgeting procedures in the Health Service [2].

Renal Units were established in the late 1960s and early 1970s to treat patients with severe renal failure on a dialysis/transplantation programme. Partly due to their success in keeping alive patients who would otherwise have died, the Renal Units have made increasing demands for finance each year. They are almost certainly not unique in this respect, but their relatively recent introduction and their separate and particular requirements for specially trained nurses, a day ward with machines, machines for homes, fluids for dialysis and drugs for transplant patients, make them a readily identifiable target for attempts at cost saving or at least at cost control. Such attempts are becoming more common.

In order to predict or control costs, however, one needs a clear policy for the allocation of treatments to patients and a means of forecasting future resource use and the consequent costs, based on that policy. Those planning the service thus need not only a credible and flexible model for planning, but also one which can be used to predict the patient related workloads of the various hospital departments and hence costs.

1.1.4 Why a model is needed

Given the planning and financial pressures already identified, it is little wonder that since the early 1970s considerable effort has been devoted to making models of parts of the dialysis/transplant programme, in order better to understand and control the way in which it is developing. Chapter 2 is devoted to examining ways in which these problems have been tackled both by myself and by other workers during the last decade and to concluding that none of these approaches has been satisfactory.

The remainder of this Chapter 1 contains:

i) a brief review of the research studies which have set out to determine the potential demand for treatment (1.2),
ii) a greatly simplified description of the dialysis and transplant treatments (1.3),
iii) a description of the operation of an integrated dialysis/transplant program (1.4) and
iv) an explanation of the reasons why Portsmouth Renal Unit was chosen as a test bed for this study (1.5).

1.2 THE NEED FOR TREATMENT

In 1971, Farrow et al [3] predicted that the number of patients on treatment would level off within 10 years. The annual reports from the European Dialysis and Transplant Association [4,5,6,7] (see footnote) show, however, that there is not only an increasing number of patients on the life saving treatments available on the dialysis/transplant programmes in Europe, but also increasing numbers of patients have been admitted each year.

Only knowledge of the incidence (the rate of occurrence per head of population) of renal failure can place an upper limit on the potential demand for Renal Unit facilities. Renal failure has many possible causes including: polynephritis, glomerulonephritis, stones, nephrosclerosis and diabetes mellitus. The studies (listed in Table 1.1) show that these diseases effect men and women to a different extent although the overall incidence is much the same.

Footnote: The 1983 [1] report does not appear to continue this trend but it was based on an incomplete set of returns.

TABLE 1.1

Incidence of end-stage renal failure in patients fulfilling criteria for acceptance on a dialysis transplant programme.

Authors	Date	Place	Age range	Population (millions)	Incidence rate (per million) (i)	(ii)
Branch et al.[8]	1971	South Wales	0..60	0.12	39	38
Mc.Geown[9]	1972	N.Ireland	(5..60 (5..55	1.50	38 33.3	37
Pendreigh et al.[10]	1972	Scotland	(0..54 (0..64	5.20	38 52	44
Mc.Cormick[11]	1973	S.E.Scotland	(0..54 (0..64	1.17	35 40	37
Moden et al.[12]	1975	Israel	15..59	4.5 *	41 *	41
Karatson et al.[13]	1975	Hungary	15..55	1.56	33	36
Dombey et al.[14]	1975	Nottingham, England	(0..50 (0..55 (0..65	0.75	29 39 45	41

(i) the incidence rate for the age range in column four.
(ii) the estimated incidence rate for the age range 15..59.
* the figures quoted in the paper were age related indicies for the Jewish population. They had to be adjusted, therefore, to the estimated total Jewish population.

In these studies, authors wanted to identify the subset of patients who met certain criteria which they considered would make them suitable for treatment on a dialysis/transplant programme. The studies were based on case notes and laboratory reports and, in some cases, questionnaires to doctors about living patients. Table 1.1 shows considerable agreement between the studies whether in the United Kingdom or elsewhere, although some are small and local, and others are large and nationwide.

The figures quoted from the Israeli study[12] were based on the number of people the authors considered definitely needed dialysis. There was another group (an additional 25%) whom they thought might have benefited from dialysis but who had other co-incident diseases such as diabetes or severe heart disease reducing their life expectancy and making their inclusion in a dialysis/transplant

programme unlikely. All of the other studies excluded such patients, although the exact criteria differed between studies.

Table 1.1 shows that opinions about the upper and lower age limits of patients thought suitable for dialysis differed considerably between authors. In Britain children are normally treated separately from adults but there is no lower age limit. Numbers of children needing treatment on a dialysis/transplant programme are small (approximately 1 per million per year) but because the probability of renal failure increases with age[8], the incidence rate is quite sensitive to the upper age limit.

In recent years, Israel and various European countries such as Belgium and Italy have been treating considerable numbers of patients in older age groups. In other respects, too, the criteria for admission to dialysis/transplant programmes have been relaxed in the past decade; it is now, for example, commonplace to accept diabetic patients for treatment[1].

Based on the studies done in the United Kingdom [8,9,10,11], a figure of 40 per million population is often quoted[2,15] as being the target for the annual intake of Renal Units. This should include most patients under 60 years old who fulfil the tight criteria of these studies, but as these criteria are no longer applicable, this figure must be regarded as a lower limit of potential demand rather than an upper limit.

The number of new patients in United Kingdom accepted for dialysis/transplant programmes in 1979 was 21.6 per million population, varying from 14.02 per million in Wessex Region to 30.0 million in East Anglia[16]. Even the best served area was admitting considerably fewer than 40.0 per million per year, and very many fewer than Israel's acceptance rate of 51.9 per million per year and Belgium's of 48.2 per million per year. The main difference between the various countries related not to the incidence rates of renal failure (see above), but to the acceptance criteria of the older age groups for treatment[16]; the elderly in Britain being very poorly served. Thus the 1979 figures indicated that there was considerable unmet demand for treatment in the United Kingdom, particularly in patients aged over 55 years. The figure for the acceptance rate for all age groups had increased to 26.7 patients per million population in the 1982 European Dialysis and Transplant Association report[7] which was, perhaps, a slight improvement.

1.3 THE TREATMENTS

1.3.1 Haemodialysis

Blood is passed from the patient, lying on a bed or couch, through tubing into the artificial kidney and back into the patient's body. Unwanted chemicals from the blood pass through a dialysis membrane in the artificial kidney into the dialysis solution. Patients receive dialysis two or three times a week for several hours each session. The connections, therefore, between the patient's blood supply and the machine have to be re-made frequently. To facilitate this the patients receive surgery (access surgery) before starting haemodialysis treatment.

Patients generally start haemodialysis treatment in a Renal Unit where there is a day ward with several machines. In Britain, once the patients, together with a helper (spouse, parent or friend), have learned to master the art of haemodialysis, most patients have a machine installed at home (home dialysis). The room housing the machine must have its own water supply, water softener, a separate electricity supply, a telephone, a washable floor and a bed.

In more recent years, some Regional Health Authorities[2] have established minimal care units, which have "minimal" staff in attendance. Patients using these units do not have a machine installed at home.

More detailed descriptions of haemodialysis are given by Merrill[17] and by the Office of Health Economics[18].

1.3.2 Peritoneal Dialysis

In order for dialysis to take place, dialysis solution is introduced into the patient's peritoneal cavity (in his abdomen), the peritoneum itself acting as a dialysis membrane. In order to be effective, the dialysis solution must be changed before equilibrium between the chemicals in the blood stream and the dialysis solution is reached.

Intermittent peritoneal dialysis (I.P.D.) has been available for many years but is not very widely used as a long term treatment.

Continuous ambulatory peritoneal dialysis (C.A.P.D.), on the other hand has, since 1979, become increasingly used as alternative to dialysis and transplantation[1]. Patients have a permanent

indwelling catheter inserted through their abdominal walls before they start treatment, in order to effect a connection between the peritoneum and the bag of dialysis solution supported under their clothes. The bags have to be changed every six to eight hours.

C.A.P.D. patients are particularly susceptible to peritoneal infections and may therefore make considerable demands on hospital inpatient facilities.

1.3.3 Transplants

Patients have to wait for a suitable kidney to become available before they may have a transplant operation. They are, therefore, usually treated with dialysis first. Most kidneys for transplants in this country are obtained from people who have died (cadaver kidneys), whose relatives have given permission for their use. Some patients, however, are given one of the two kidneys of a living close relative (live related kidneys).

The recipient patient's immune response must be reduced with drugs and modified by matching between his and the donor blood if his body is to be prevented from rejecting the transplant, causing him to become very ill and to die unless the transplanted material is removed very quickly.

The following factors influence the success of a kidney transplant.

i) Drugs. The immune response is reduced if the patient takes certain drugs such as steroids or Cyclosporin A. Transplant patients have to take immunosuppressive drugs from the day of the transplant until it fails or they die.

ii) Blood groups. The ABO blood groups should be compatible (see Table 1.2).

TABLE 1.2

Compatibility of Donor and Recipient Blood Groups

Blood Groups of recipient	Percentage occurrence	Donor blood groups compatible with recipient	Percentage occurrence
O	47	O	47
A	41	O, A	88
B	9	O, B	56
AB	3	O, A, AB, B	100

It has been suggested that a further blood group (called the Lewis group) should be matched[19,20,21], but this is not generally done in Britain.

iii) HLA genes. There is strong evidence, despite the poor statistical design of most of the studies[22], that good matching of the human lymphocytotoxic antigens (HLA) between patient and donor reduces the probability of rejection of the transplanted material (the graft). There are A and B HLA antigens[23,24,25,26,27] (one of each from a person's mother and father) plus the more recently discovered DR antigens which maybe even more important[25,28]. These antigens do not occur independently of each other[29] and so the probability obtaining any particular combination of A,B and DR antigens is almost impossible to estimate, but it is extremely small. There is rarely, therefore, exact matching of these antigens between kidney donor and recipient.

iv) Lymphocytotoxic antibodies. Patients can become sensitised and produce antibodies to foreign matter in contact with their blood. For instance they may become sensitised to particular HLA antigens after a blood transfusion, pregnancy or a transplant operation. Some lymphocytotoxic antibodies to HLA A and B antigens can be identified, and so patients awaiting transplantation are screened for them. A patient's antibody level (or index) is an estimate of the probability (based on tests using a panel of sera acquired from a variety of people) that he will produce these

antibodies to a donor's tissue. A sensitised patient who produces lymphocytotoxic antibodies to the serum of a potential donor will not usually be given the kidney, because it is thought that the antibodies are likely to cause the transplant to be rejected.

v) Blood transfusions. It used to be thought[30] that patients wanting transplants should not be given a blood transfusion if at all possible in order to avoid sensitisation. There is now considerable evidence, however, that patients who have received blood transfusions have a much greater chance of a successful transplantation than those who have not[24,30].

vi) The relationship of the patient and donor. Patients receiving kidneys from close relatives (with compatible blood groups and good HLA matches) are more likely to have successful transplants than those who have kidneys from unrelated people who have died[16].

vii) Previous transplants. Opinions differ as to whether patients receiving second transplants can, on average, expect worse[31,32] graft survival than those patients receiving first transplants[33]. More recent data show that those receiving third transplants can certainly expect poorer transplant (graft) survival[7].

viii) Age and state of health. Not surprisingly, older people and patients with other health problems, such as diabetics, have worse survival figures than younger and comparatively fit people[34].

ix) The skill of the surgeon and the history of the donor kidney. Taking into account the age of the patients and the HLA groupings Morris[35] showed that the differences in patient survival rates between transplant centres was significant. This implies that skill of the surgeon is an important variable factor.

Apart from a few patients (usually some of the younger ones) who receive kidneys from living relatives, patients in Britain have to wait for cadaver kidneys. The donors of kidneys and the recipients generally have compatible blood groups, negative cross-matches (no lymphocytotoxic antibodies) and at least two matching HLA A, B

and DR antibodies.

Patients can live a reasonably normal life with a successful transplant, despite the need to take drugs for the rest of their lives. The quality of life of most patients is considered better than that of haemodialysis patients[36].

1.4 THE SYSTEM

This section will describe the system of treating patients on a dialysis/transplant programme, explaining the decisions that have to be made at each stage. These are shown in outline in Figure 1.1.

1.4.1 Choice of dialysis treatment

By the time the kidneys fail two important decisions will have been made:

i) whether the patient should be admitted to the dialysis/transplant programme and
ii) whether he should receive haemodialysis or C.A.P.D.

These decisions will depend on the availability of resources, the age and health of the patient, and his or her home circumstances. Both dialysis treatments require a reasonable level of intelligence and attention to hygiene. The criteria for selecting patients, almost certainly differ between renal consultants and between Renal Units.

When a patient's kidneys are failing and he (or she) is thought suitable for treatment on a dialysis/transplant programme, his kidney function will be monitored regularly at hospital outpatient visits. If he is to have haemodialysis treatment, access surgery, well in advance of the time when he is expected to enter the programme, will be arranged. A patient selected for C.A.P.D. treatment must be fitted with an indwelling catheter, which may be done as an out-patient procedure. Some patients are admitted to hospital several times and are operated on more than once before they start treatment.

If patients starting haemodialysis are to have their homes fitted with machines then they need:

i) regular committed help from a relative or close friend
and ii) appropriate housing, which may be provided by the Local Authority.

If, on the other hand, the Renal Unit provides indefinite hospital haemodialysis or minimal care units, the type of housing a patient has is much less important.

In some Renal Units, C.A.P.D. is a preferred treatment to haemodialysis[2]. In most units providing C.A.P.D. treatment, C.A.P.D. patients are likely to include:

i) people living by themselves,
ii) patients with vascular problems in whom it is difficult to create access for haemodialysis,
iii) diabetic patients and
iv) patients who for some reason cannot cope with haemodialysis.

C.A.P.D. patients thus include a disproportionate number of older patients and patients with other medical problems.

1.4.2 Constraints on the provision of dialysis treatment

Patients who need haemodialysis may have to wait for a space to be available in the Renal Unit before they are able to start regular treatment. After a period of time using machines in the Renal Unit as day patients (i.e. on unit dialysis), patients are considered ready to be trained (usually with the help of a relative or close friend) to become independent of nursing help. A trained patient can then progress to home dialysis (or to a minimal care unit if it is available). Even after leaving unit dialysis, a patient may attend the unit for occasional dialysis sessions or for long periods of dialysis if he needs inpatient treatment or has persistent medical or domestic problems.

There is thus competition for unit dialysis resources, which can lead to complex scheduling problems. These are particularly apparent in Portsmouth Renal Unit, where patients attend for dialysis twice a week (spaced by two or three days) unless they are training, during which time they attend three times a week.

There are no practical resource constraints on the provision of C.A.P.D. treatment, bags and fluids being readily available. There may, however, be arbitrary limitations at some Renal Units on the numbers of patients to be treated. After a few days of training, which may be done an outpatient procedure, a C.A.P.D. patient can live a reasonably normal life at home.

Patients who fail to cope with one form of dialysis for medical or psychological reasons may change from peritoneal dialysis to haemodialysis or vice versa. The failure rate on C.A.P.D. treatment is particularly high[1] and if there are insufficient haemodialysis resources, these patients may die. Failure on dialysis is shown as a decision point on Figure 1.1.

1.4.3 The transplant list

A decision has to be taken, early in dialysis treatment, as to whether a patient is suitable for transplantation and should be put on the cadaver transplant list (Figure 1.1). The decision is based on the following criteria:

i) the patient's age - some Units impose an upper age limit,
ii) the type of renal disease - some systemic diseases will damage the newly transplanted kidneys in the same way as they damaged the original kidneys,
iii) the general state of the patient's health e.g. mental disease or heart failure might be a contra-indication to transplantation and
iv) the patient's own wishes.

A patient with a relative who is willing to donate a kidney, is in good health and fulfils certain matching criteria, will usually receive a transplant in the first few weeks of treatment. He is unlikely to have his home fitted with a haemodialysis machine before he receives a transplant.

Other patients, thought to be suitable for transplantation, are added to the cadaver transplant list when they are considered fit enough to be transplanted. If they have to wait a long time for a kidney, they may have to be removed from the list temporarily or permanently for medical or social reasons.

1.4.4 Allocation of cadaver kidneys

There are two sources of cadaver kidneys:

i) those harvested locally by the transplant team,

ii) those from the UK Transplant service, who provide a clearing house for cadaver kidneys from all over Britain and occasionally from the rest of Europe and the U.S.A.

Each Renal Unit is expected to donate some of its kidneys to the UK Transplant service. When UK Transplant receive a kidney, their computer list is scanned for compatible patients with a good HLA match. The kidney is then sent to a particular Renal Unit for a specific patient. It is up to the local unit to check that the donor and recipient sera do not, together, produce lymphocytotoxic antibodies. This system is particularly valuable for patients who are highly sensitised or have rare HLA antigens who might otherwise have to wait a very long time for a good HLA match.

1.4.5 Transplant Failure

Patients who were on home dialysis, prior to transplantation, may retain their machines for a few months in case they have an early transplant failure. After that the machines become available for other haemodialysis patients (i.e. they are recycled).

Most patients who reject their kidneys do so within the first six months but others do so months or years later. They then have to return to haemodialysis or C.A.P.D. treatment. After a period of time they may again be put on the transplant waiting list. These patients may have a raised antibody index as a result of the transplant rejection.

1.4.6 Hospital treatment

Patients from any form of treatment may need admission to hospital for inpatient treatment. In particular, patients who change treatment (e.g. from C.A.P.D. to haemodialysis) generally do so in hospital. It is also likely that a patient who dies would do so in hospital.

A patient has to make outpatient visits which may be as frequent as once a week or as infrequent as once every six months, depending on his state of health.

1.5 PORTSMOUTH RENAL UNIT

The model described in this dissertation was developed at Portsmouth Renal Unit which was both convenient for and also has strong links with Southampton University. Portsmouth Renal Unit is expected to provide a service to the whole of Wessex Region, a population of nearly three million. The intake of patients to the dialysis/transplant programme has changed from 14.07 per million population in 1979 to 25.7 per million population in 1982, an increase of more than 50%. The problems of increasing numbers of patients making demands on a limited budget are thus particularly severe in Portsmouth.

Following the publication of my previous work, based on Oxford Renal Unit[37], the director of Portsmouth Renal Unit expressed an interest in using a modelling approach. The adaptation of my Oxford model in an M.Sc. thesis[38] was useful, but in common with most previous work in this area (2.3), is an inflexible 'one-off' study with poor modelling of resource use. More work was required, in order to meet the needs of Portsmouth Renal Unit.

1.6 SUMMARY

There was a need for a flexible model which was easy to use, to update, and to adapt to new situations and Renal Units. The model needed to be locally based so that Renal Unit staff and other involved with planning their services, could use it explore the implications of different policies on the need for resources.

Chapter 2

PREVIOUS MODELS

2.1 INTRODUCTION

2.1.1 System boundaries

Chapter 1 explained the need for models in planning dialysis/transplant programmes and described the treatment of patients on such programmes. Many previous attempts at models have indeed been made. In order to assess such attempts, we must first define the system which they model.

The drawing of system boundaries is a useful way of identifying which components under study are to be modelled directly (the system) and which are to be left out, or to have only an indirect influence on our model (the environment): this is a distinction made by Ackoff[39].

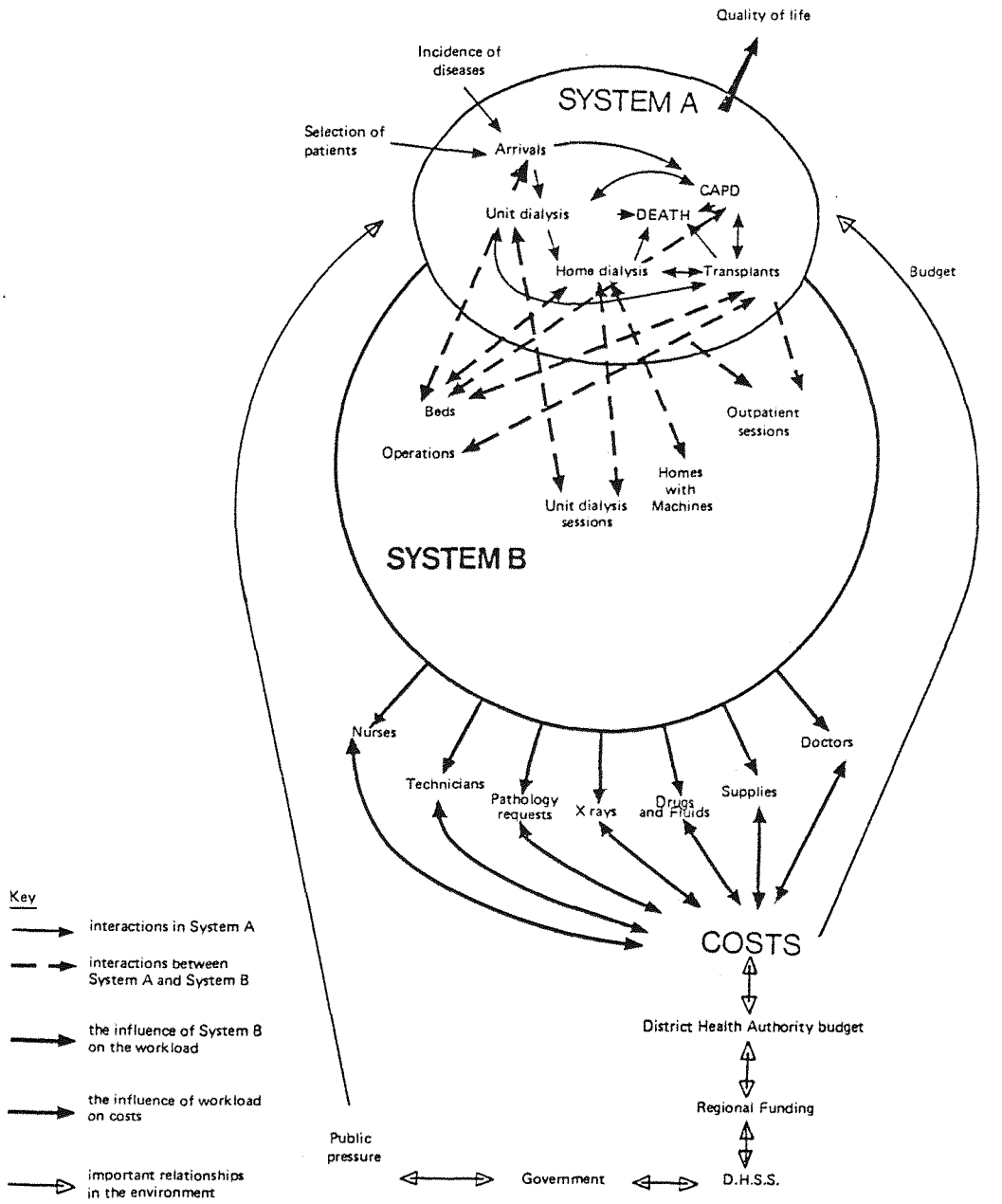
Figure 2.1 shows system boundaries drawn to define two different systems of the treatment of patients on a dialysis/transplant programme. The boundary of System A includes only the patients and their treatments, but the larger System B includes resources such as inpatient facilities, haemodialysis machines and outpatient visits. System A is easier to model but, unlike System B, does not include the resources and their constraints. As we have seen, however, the raison d'etre of models of renal failure treatment is their potential use for planning and financing such services. All previous models have, however, been confined to System A and have been unable thereby to accommodate the more realistic requirements identified in Chapter 1. This is a major limitation of all previous work, which we shall now go on to consider further on what is assumed to be its own terms. I shall reserve an answer to the question of how to model System B until Chapter 3.

2.1.2 The previous models to be considered

Table 2.1 shows a classification of past models of patient treatment on a dialysis/transplant programme. The following categories have been used: deterministic, Markov, semi-Markov, synchronous

Figure 2.1

A Systems Diagram of the Treatment of Patients on a Dialysis/Transplant Programme



simulation and discrete event simulation. These will be described in more detail in 2.3

TABLE 2.1

Models of Dialysis/Transplant Programmes in the last 15 Years (all based on System A)

Authors	Dates	Type of model	Time unit	Renal unit or population	No. of states
Farrow et al.[3]	1971	Markov	months	London Hospital, England.	26
West et al.[40]	1974	simulation(1)	months	Cardiff Royal Infirmary, Wales.	7
Cooper et al.[41]	1973	Markov	months	Washington, U.S.A.	12
Davies et al.[42]	1975	Markov	months	King's College Hosp., London, England.	25
Mc.Bride[43]	1975	Markov	months	Victoria, New S.Wales, Australia.	23
Pliskin et al.[44]	1976	deterministic, Markov, simulation(1)	years	Boston, Massachusetts, U.S.A.	5
Davies[37]	1978	simulation(1)	months	Oxford Region, England.	5*
Rimm[45]	1978	simulation(1)	months	Wisconsin, U.S.A.	6
Chambers[38]	1979	simulation(1)	months	Wessex Region, England.	60
Wood et al.[46]	1980	simulation(1)	months	N.W.Region, England.	9
Roberts[47]	1980	simulation(2)	-	Indiana, U.S.A.	-
Shah et al.[48]	1981	semi-Markov	-	N.E.Thames Region, England.	12
Ludbrook[49]	1981	Markov	months	England and Wales.+	28

\+ the data were from the North East Thames Region.
* there were additional states to take account of non-geometric survival.
simulation(1) = synchronous simulation.
simulation(2) = discrete event simulation.

The rest of this Chapter will:

i) describe criteria evolved for assessing the value of these models (2.2),

ii) summarise the important features of these models (2.3)

and iii) assess them against the listed criteria (2.4).

2.2 CRITERIA FOR ASSESSING MODELS

2.2.1 All relevant parts of the system

The relevant parts of the system to be included (assuming that we are modelling System A) are the treatments, the transitions between treatments and the arrival rates of kidneys for transplants. It will be seen that whether the arrival rate of kidneys is assumed to be directly related to the transplant waiting list, or independent of it, influences the type of modelling technique that can be used.

2.2.2 Reflection of system properties

It is desirable for any model accurately to reflect the important system properties so that there is confidence in the results from the model. The model characteristics that may be relevant for System A (Figure 2.1) are described below.

i) Survival distributions. The survival distributions used in the model should, if theoretical, be a "good fit" and, if frequency distributions, should be based on reasonably large samples.

ii) Constraints. If there are upper limits on the availability of treatments, these should be present in the model. Unit dialysis facilities are certainly constrained and so is the availability of kidneys for transplants.

iii) Patient characteristics. Patients' ages, and to a lesser extent their treatment history, certainly influence their selection for different treatments and their survival on those treatments (Appendix F). Other patient characteristics, such as blood group and antibody index become important if the matching between donor and patient in the selection of patients for transplants is to be modelled (1.3.3). Clearly these characteristics should remain with the patients throughout the simulation and should not be sampled anew each time a patient has a transplant. Only in this way can the difficulties of particular individuals in getting transplants, and their effects on the system, be realistically modelled.

iv) The time unit. The time unit of the model should be chosen such that important events, and their corresponding resource implications should not be missed by the model. For example most patients spend less than four months (see Appendix F) on unit dialysis and therefore to determine with any accuracy the use of unit dialysis facilities, the time unit should be no longer than a month, certainly not a year. The time unit should be even shorter if activities such as inpatient treatment, lasting only a matter of days are to be taken into account.

2.2.3 Variability

Because the time patients spent on different treatments is variable, estimates of future patient numbers and their corresponding resource use must be regarded as samples from distributions. The model should be able to produce good estimates of the means of the relevant results.

2.2.4 Credibility

In order to have confidence in the model, those using it should not only be able to appreciate the model assumptions and their implications, but also understand in some detail how the model works. They are then able to check to their satisfaction that the model behaves in all important respects as the system does in practice. The more complex the model, particularly in the mathematical sense, the more difficult it may be to establish its credibility with the user. Its credibility is also dependent on a good reflection of system properties (2.2.2).

2.2.5 Robustness

If the model is used at different points in time or at other Renal Units from where it was developed originally, different policies may have to be incorporated or the survival distributions may need to be changed. It should be possible to accommodate these changes by simply altering the model's input data but failing this, any changes made to the model itself should be minimal.

2.2.6 Ease of use

A model should not have to remain in the hands of an operational research scientist but should be able to be used with ease by those in need of it. It should be possible to enter data for new runs with very little effort.

2.3 PAST MODELS

2.3.1 Simple deterministic models

Simple deterministic models have no underlying assumptions about randomness or variability. Typically, the numbers of patients on different treatments are multiplied by transition rates based on previous data, to determine the numbers at the end of the coming time period (usually a year). This process is repeated several times to forecast several time periods into the future. Such an approach described as "balance sheet model" is reported to have been used at Trent Regional Health Authority[50], is the basis of the predictions made by the South East and South West Thames Regional Health Authorities[2] and is probably prevalent at other Regional Authorities. It is a very simple approach to a complex problem.

Pliskin's model[44] with deterministic difference equations was a little more sophisticated. The proportions of patients failing from each of the states: haemodialysis, functioning transplant, first year cadaver transplant and first year live related transplent, were assumed to remain constant from year to year. The number of admissions to start on dialysis, to have live related transplants and to have cadaver transplants, however, could be separately entered into the model for each year. These projections were used to determine "average needs", for example, the number of unit dialysis beds that would be needed each year.

2.3.2 Markov and semi-Markov models

Markov and semi-Markov models are stochastic processes the predicted results being assumed to be the outcome of a series of random experiments. These are explained in depth by Cox and Miller[51]. In the context of renal failure, the Markov chain is based on a matrix of transition probabilities of patients going from one treatment state

to another in one time unit. It is assumed that the transitional probability of a patient, going from one treatment state to another at the end of one time unit, is independent of what happened to him in any previous time units. Thus the probability of a patient remaining in the same state remains constant from one time unit to the next (i.e. geometric survival) and the transition probability from that state to any other state in each time unit is also constant. There is an underlying assumption, therefore, that the number of patients predicted to pass from one state i to another state j, in one time unit, is proportional to the number of patients in state i at the beginning of the time unit.

The first models of the treatment of patients on a dialysis/transplant programme, were Markov models (Table 2.1). In 1972, I adapted the original method of Farrow et al. of the London Hospital[3] for King's College Hospital[42] and at much the same time McBride[43] developed a similar model in Australia. The flow chart of the model I used is shown in Figure 2.2. The key transition states corresponded to the treatments: unit dialysis, home dialysis, functioning transplant and home dialysis after rejection (C.A.P.D. was not available then). Patients were not completely homogeneous but were divided into those suitable for transplantation and those who were not and, moreover, those who had had transplants went into different states from those who had not. The time scale was monthly and the one absorbing state was death.

To account for non-geometric survival distributions and different transition probabilities in the first few months after a change in treatment, most of the key transition states were subdivided into discrete monthly states (in which the transition probability of remaining in the same state P_{ii} was zero) followed by a recurring monthly state in which there was geometric survival. The number of transplants performed was assumed to be proportional to the number waiting for them.

Cooper and Blagg[41] took account of as many as 9 possible treatments categories which were: "center", home training and home peritoneal dialysis and the same for haemodialysis, cadaver and live related transplant and "conservative" treatment (i.e. no replacement therapy). There were two absorbing states: death and "transfer out", and a twelfth unused state for the population from which the patients were drawn. Unlike my model, there was no division of patients into

categories and no subdivision of states to account for non-geometric survival.

FIGURE 2.2

Davies's Markov chain model of the dialysis/transplant programme at Kings College Hospital (1975)

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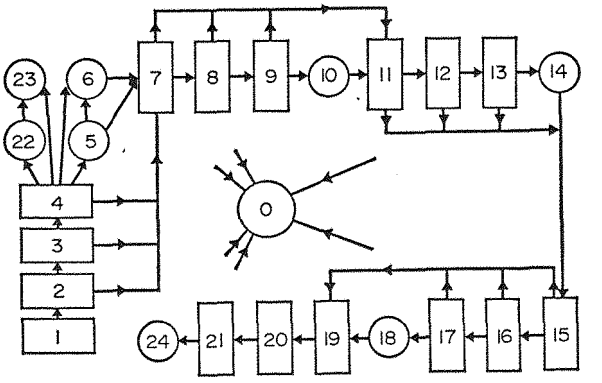

0 *Death*
1–4 *Unit dialysis (training)*
5 *Unit dialysis (waiting for transplant)*
6 *Home dialysis (waiting for transplant)*
7 *Transplantation*
8–10 *Transplantation (subsequent months)*
11–13 *Rejection (returned to dialysis)*
14 *Dialysis (waiting for second transplant)*
15 *Second transplantation*
16–18 *Second transplantation (subsequent months)*
19–21 *Second rejection*
22 *Unit dialysis*
23 *Home dialysis*
24 *Home dialysis.*

Pliskin's Markov model[44], developed from his deterministic model, was rather different from the others. It comprised a series of Markov chains with annual transitions from each of the four states described in 2.3.1. The new Markov chain started in each projected year, not only introduced new patients for dialysis, but also patients to have live related and cadaver transplants. Thus there could be independent arrivals of kidneys each year. In addition to the drawbacks of having yearly time periods and geometric survival in each state, his model would only run satisfactorily while the transplant rate was lower than the annual rate of acceptance of new patients onto the programme.

Ludbrook's[49] recent Markov model has developed from the original London Hospital Model[3]. Her model is greatly complicated, however, by the subdivision of the states into patient age groups which requires the very weak assumption that the transition probabilities are proportional to those for each age group. She uses data from the North East Thames Regional Health Authority for a nationwide economic analysis, taking no account of local or regional variations, which are known to be considerable.

In a semi-Markov model, the transition probabilities (instead of being constant as in a Markov model) are time dependent continuous distributions. By using a semi-Markov model, Shah et al.[48] were able to relax the assumption of geometric survival in each treatment state without having to subdivide the treatments into several states. In Shah's model there were two of each of the following states: home haemodialysis, hospital and home peritoneal dialysis, corresponding to before and after a first transplant. There were also two transplant states, first and subsequent transplants, and two absorbing states for transfers and deaths. The model was, in principle, very similar to the early Markov models[3,42,43] but expressed in more concise and elegant mathematics.

In using my earliest model[42] to make predictions of future resource needs, I was able to show that the demand for unit dialysis facilities would very soon exceed supply. Although these results were of interest at the time, the use of the model was severely limited because it was impossible directly to vary or constrain either the transplant rate or any other resources. The same drawback affected all other Markov and semi-Markov models (except Pliskin's, which has other limitations).

2.3.3 Synchronous simulations

A simulation is an imitation of reality in which natural variability is represented by sampling random numbers. Synchronous simulations "slice" time into regular periods (they are sometimes therefore, called time slicing simulations). At the end of each time period a decision is taken as to whether each item in each state should stay put, or proceed to another state. New arrivals may also be generated. In order to generate means and variances of results, the simulation must be run several times with the same parameters but different random number streams.

Problems that can be formulated as Markov models can also be

formulated as synchronous simulations. The simulations are more flexible, however, and can easily incorporate constraints and independent arrivals into the system.

West et al.[40] and Rimm[45] developed very simple synchronous simulations of dialysis/transplant programmes. Transitions between some of the states: unit dialysis, home dialysis, functioning transplants and death were assumed to have constant monthly probabilities. The first four months of the unit dialysis state and the transplant state were separated from the remaining months to account for different transition probabilities in the first few months of treatment. Transitions from unit dialysis to home dialysis and from any state to a transplant state were assumed to have constant monthly rates. Thus there was assumed to be a constant supply of kidneys which were all able to be used as soon as they became available. Pliskin's model[44], based on his deterministic and stochastic models, was very similar to West's and Rimm's but included live related transplantation as well as cadaver transplantation.

My 1976 model[37] of Oxford Renal Unit and Chambers's subsequent model[38] of Portsmouth Renal Unit incorporated a simple matching procedure which slowed down the use of kidneys very considerably when the numbers waiting for transplants were small. A flow diagram of the Oxford model is shown on Figure 2.3. My model was more detailed than West's in other respects too:

i) patients were divided into those who were suitable for transplantation and those who were not and
ii) many more discrete monthly states were used to take account of non-geometric survival distributions.

Wood et al.,[46] also used a synchronous simulation to plan services for North West Region. One of their objectives was to examine the benefits of minimal care units where patients could share machines rather than having their own individual machine at home. They assumed geometric survival from each treatment state. Patients were grouped into three independent categories:

i) those suitable for home dialysis and transplantation,
ii) those suitable for home dialysis but not transplantation and iii) those not suitable for transplantation.

Each of these had a different route through the simulation.

FIGURE 2.3

Davies's synchronous simulation model (1978) of a dialysis/ transplant program at Oxford.

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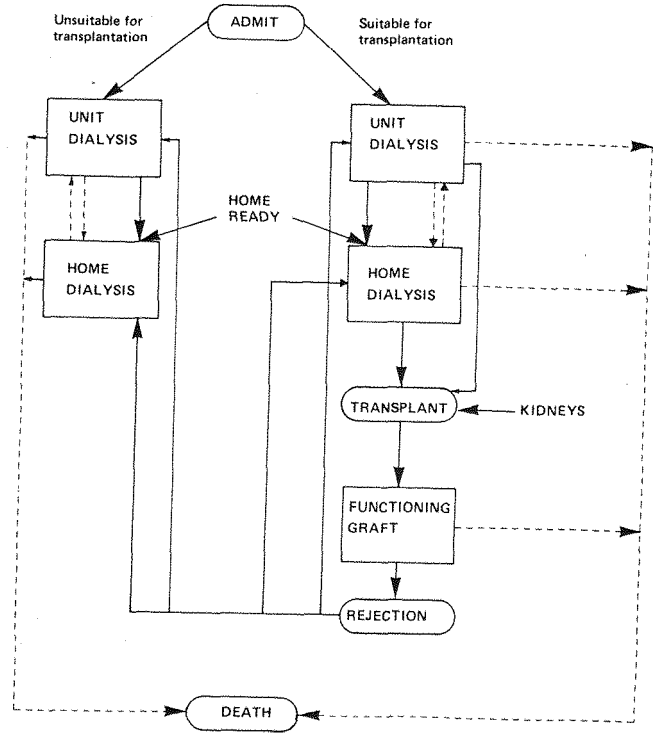


2.3.4 Discrete event simulations

Discrete event simulations capture discrete changes at particular points in time for the selected variables. These models are usually asynchronous (i.e. the simulation only "looks" at the variables at the points in time when they are undergoing a state change and not at the end of every time period). Because individuals can be ascribed attributes which influence their route through the simulation and the length of time spent on any activity, this technique is very powerful and flexible. However, the simulations can become very large and cumbersome and for a moderately large and complex system to be modelled

with any efficiency it is desirable to use a purpose built language or package.

Roberts[47,52], who used a discrete event simulation in modelling the treatment of patients with renal failure was putting into a use a simulation language he had written. The language, based on FORTRAN, is said to be coded easily from a detailed network diagram. The system itself is very simple, having three treatment states only: unit dialysis, home dialysis and transplantation. A patient starts treatment on haemodialysis and if suitable for transplantation may, after a period of time, have a cadaver or live related kidney transplant. If this fails, he returns to dialysis with no opportunity for a second transplant. There is no modelling of peritoneal dialysis and there is no independent arrival of kidneys for transplantation and matching of patients with kidneys. The model does, however, use data on patients' ages and suitability for transplantation to influence their passage through the system. This extremely powerful technique has not been used to its full potential by Roberts in this model.

2.3.5 Other Approaches

It might be possible to produce a stochastic model which, with constraints and independent arrivals of kidneys, gave a better reflection of system properties than Markov or semi-Markov models. Not only would it be, in all probability, more mathematically complex and therefore less credible, but also it would still be impossible to give patients characteristics and thus to model matching of kidney donors and recipients.

An optimising approach such as mathematical programming could be considered. In health care, however, it is difficult to identify suitable objective functions, or even appropriate resources to constrain. Whether formulated as objectives or constraints, patient satisfaction and life expectancy under different treatments should not be ignored and yet are very difficult to measure. This is unlikely to be a fruitful area to pursue in modelling more complex systems such as the treatment of patients on a dialysis/transplant programme.

2.4 COMPARISON OF THE PAST MODELS

2.4.1 All relevant parts of the system

All the models included all the treatments available in the particular system they were modelling. It is understandable, for example, that peritoneal dialysis was left out of many of the models because it was only after C.A.P.D. became feasible that it was used in this country, as an alternative to haemodialysis (see Chapter 1).

The independent arrival of kidneys to match with patients is almost impossible to model using a Markov or semi-Markov chain unless entered into separate chains, as done by Pliskin[44]. It is straightforward, however, with a synchronous simulation or even a simple deterministic model. Modelling the patient and donor matching is more complex and needs a simulation model.

2.4.2 Reflection of system properties

i) Survival distributions. Using a Markov model, treatment survival distributions must either be assumed to be geometric, or by subdividing the treatment state into discrete states (in which $P_{ii} = 0$) followed by one non-discrete state (in which $P_{ii} \neq 0$), to have a geometric tail.

In using deterministic difference equations or synchronous simulations there is a further possibility, that patients transfer from one state to another at a constant rate which is therefore independent of the number of patients in any state. The arrival of cadaver kidneys for transplantation can thus be modelled more realistically.

The use of the semi-Markov model overcomes the restrictive requirement of geometric survival in each state but, on the other hand, provides no obvious way of modelling independent influences on the system such as the donation of cadaver kidneys.

These problems can be overcome by using a discrete event simulation where there are few limitations on the type of distribution that may be used[53].

ii) Constraints. Using a Markov or semi-Markov model it is difficult to describe constraints on treatment availability or resource provision. With deterministic difference

equations it can only be done by introducing a constant supply of a resource. Although no upper limits were placed on the availability of any treatment in the simulations discussed in this chapter, constraints can be introduced quite easily into synchronous and discrete event simulations.

iii) Patient characteristics. In all the modelling techniques discussed, except discrete event simulation, patients have to be treated as one homogeneous group with respect to age, treatment history and the probability of receiving any particular form of treatment. Patients can certainly be divided into groups to take account of different attributes, and can progress through separate sets of states but this can complicate the models considerably, and the assumptions that are made. Ludbrook's[49] Markov chain model is a good case in point. Even so, the models cannot give patients the individual characteristics necessary for realistic modelling of matching of patients and donors for transplants.

iv) Time unit. In the Markov chain and time slicing techniques there has to be a fixed time unit at which the events are assumed to happen. All except Pliskin[44] (with a time unit of a year) used a time unit of a month which is quite reasonable for modelling System A. It was unclear what time unit was used by Roberts[47,52], but for discrete event simulations, this unit can be made very short without it having a detrimental effect on the simulation's efficiency.

2.4.3 Variability

No account can be taken of variability in the deterministic models. In stochastic models it should be possible to calculate the variances at the same time as the means. The variances in the models lack conviction, however, not so much because they are based on complex formulae, but because they are based on the assumption of complete randomness which, due to the presence of constraints, is fallacious.

As simulation results are dependent on random numbers, simulations must be run several times with the same parameters but different random number streams in order to generate means and variances of results.

Variance reduction techniques[54] can be used to enable a simulation model to give better estimates of means of results, but none were reported as having been used in the models described in this Chapter.

2.4.4 Credibility

The deterministic models, the simple Markov models (such as Cooper and Blagg[41]) and the simple synchronous simulations (such as West[40]) are easy to understand but lose credibility because of their poor reflection of system properties. On the whole, the more effort that has been made to reflect the system properties in the stochastic models or the synchronous simulations, the more complex and less credible they become. Some examples are as follows: the proliferation of states to fit the available distribution data (Farrow[3], Davies[42], McBride[43]), or more mathematical complexity (Shah[48]).

The logic of a discrete event simulation, however, can follow very closely that of the system being modelled. If it has a good reflection of system properties, therefore, and is written or documented in a way that is easy for the user of the simulation to follow, then it should have good credibility.

2.4.5 Robustness

The simple models (with a poor reflection of system properties) are limited by the sweeping assumptions they have to make. The more complex a Markov chain model or synchronous simulation becomes with, for example substates and branches for patient sub-groups, the more dependent it becomes on the data available at a particular unit. This can be seen in the difference between the structure of the Markov chains of Farrow[3], Davies[42] and McBride[43]. These problems arise because of the need to overcome the restrictive assumptions of the modelling techniques.

A discrete event simulation has few restrictive assumptions and is much more flexible and, for example, its structure is independent of the distribution of time between events. It is inherently more likely to be robust than a synchronous simulation or a Markov model.

2.4.6 Ease of Use

Ease of use relates to the implementation of the modelling method rather than the method itself. Of the studies discussed in this Chapter, Pliskin's deterministic model was the only one that was reported as being designed to be easy to use.

2.5 CONCLUSION

In summary, the past models were very limited in use for the following reasons:

i) They modelled System A, which excludes the resources patients use, and the constraints on those resources.

ii) Many were used for large population groups, ignoring important local differences among decision criteria and survival data, comparing one Renal Unit with another.

iii) Even assessed as models of System A, they did not meet the criteria listed in this Chapter. In particular, they were without exception all deficient in reflecting the system properties. They were neither robust nor were they designed for local staff to enter and change data in order to explore the implications of different policies.

iv) The modelling techniques selected for use in previous work have undoubtedly in most cases determined the assumptions which were made. Some of these assumptions were very dubious, particularly those relating to kidney matching and the transplant rate (2.4.2).

v) In addition to the foregoing, there is no published evidence as to be verifiability or validity of such previous models (I did in fact make some attempts to verify my Oxford model[37], but these results were not published).

Results produced by any of these models must, therefore be treated with extreme caution, especially if they are to be used for planning services. Chapter 3 describes selection of a system, choice of a modelling technique and the definition of a model designed to overcome these problems.

Chapter 3

THE SIMULATION MODEL

3.1 THE SYSTEM BOUNDARIES

Chapter 2 identified the weaknesses of previous studies. The problem was not only with the methodology but with the definitions of the system boundaries, which in all cases were too restrictive. This chapter will describe how the system was extended (3.1), and why and how it was described as a discrete event simulation.

3.1.1 Previous models

Previous models, described in chapter 2, dealt only with the transition of patients between treatments on a dialysis/transplant programme (System A in Figure 2.1, page 16). Resources such as unit dialysis machines and inpatient beds, were outside their system boundaries. In some instances, the authors measured the use of resources indirectly on the basis of predictions of the total numbers of patients on the different treatments. These predictions must be unreliable, however, because such models cannot:

i) constrain resource availability or
ii) model in detail the varying extent resources are used during different stages of a patient's treatment.

3.1.2 Definition of the system

The purpose of this study is to provide a model for local use, to predict the future implications on the resource use of a dialysis/transplant programme, under different assumptions about:

i) decision criteria for choice of treatment,
ii) arrival rates of patients,
iii) kidney availability and
iv) the provision of resources.

In order to make credible predictions of resource use the system boundaries have to extend beyond those used in previous models, to include all the patient activities that can cause expensive resources (such as nursing, staffing, pathology tests, drugs, fluids and other supplies) to be used. Ideally, the system boundaries must be extended beyond those in System A to those of System B (Figure 2.1). The additional activities of System B include:

i) the use of unit and home dialysis machines,
ii) inpatient treatment,
iii) operations and
iv) outpatient attendances.

I defined the system to include all of these, with the exception of outpatient attendances whose influence was the least and for which data collection was the most difficult. Some of the additional modelling requirements were:

i) organisation of competing demands for and scheduling of unit dialysis facilities,
ii) organisation of competing demands for inpatient facilities,
iii) time periods of days, or even shorter, between events,
iv) representation of patients who were using facilities and resources (such as inpatient beds and unit dialysis machines) while concurrently surviving on, and transferring between the different types of dialysis and transplantation.

A modelling technique was sought which not only fulfilled the requirements listed in 2.2, but could also reflect these system properties of the extended system.

This chapter describes:

i) the choice of discrete event simulation and the computer techniques deployed in building the model (3.2),
ii) an overview of the whole model (3.3),
iii) a detailed description of the discrete event simulation of Portsmouth Renal Unit (3.4, 3.5),

iv) the difficulties which were discovered in modelling within this particular discrete event simulation framework and alternative approaches that were considered and rejected (3.6) and

v) a summary (3.7).

3.2 DISCRETE EVENT SIMULATION

3.2.1 The choice of technique

Discrete event simulation, described briefly in 2.3.4, is a powerful and flexible technique in which changes which occur in the system to be modelled are assumed to happen at discrete points in time. It can:

i) use parametric or empirical distribution data,
ii) allow the imposition of constraints,
iii) take account of patient characteristics and
iv) use any appropriate time units.

It has the additional advantages that models can be both credible to the user and robust. I, therefore, chose to use a discrete event simulation modelling technique.

In order to use the technique to take account of the difficulties inherent in modelling a patient system (1.1), I had to find a discrete event simulation package that, by not forcing the user into adhering rigidly to a particular structure, could be adapted and augmented easily.

3.2.2 Simulation terminology

Simulation terminology varies considerably between authors. For some concepts and terms, such as shadow entities (*shadow entities* hereafter) I have found no written reference. Some of the more comprehensive descriptions (e.g. Kreutzer[55]) are so full of jargon words that they are difficult to understand. Mitchell[54], however, gives a clear account of the basic concepts. In my description, I shall distinguish specialised simulation words by putting them in italics and words referring to parts of computer programmes in capital letters.

i) *Time*. Simulation *time* is advanced in discrete steps and, therefore, there has to be a *time* advance mechanism. The smallest subdivisions of *time* used in a simulation are called *time beats*. These may be as small as microseconds or as large as years, depending on the time scale of the system being modelled. The phase of the simulation in which the *time* is advanced called the *executive*. Although its mechanics depend on the simulation method and language, simulated events are always performed in the time order in which they are due to happen. *Time* can never go backwards.

ii) *Entities*. The components of the simulation are called *entities*. Examples of *entities* in my system are: patients, inpatient beds, unit dialysis machines. An *entity* has *attributes* (i.e. information about that particular *entity*) and changes to these *attributes* have to be modelled at the discrete points in time. The most important *attribute* is the *clock*, that is the *time* at which the next happening or change to that *entity* is due to take place. *Entities* which have this *attribute* are called *active entities* and those that do not are *passive*. *Active entities* are often called simply, *entities* (Birtwhistle[56]) and I too, shall use this terminology.

Entities may have an integer *attribute* which can be used to identify uniquely members of a group of similar *entities*. This is called the *attribute number*.

Permanent entities are those that are present throughout a simulation and *temporary entities* can be created and disposed of as required.

iii) *Resources*. *Resources* are groups of *passive entities* which are indistinguishable from each other and, as a group, have only two *attributes*: the number available and the number in use. *Resources* are used by *entities* in some discrete events and these events cannot take place unless there are sufficient *resources* available. Thus *resources* are used to model constraints. When *resources* are used by an *entity*, they are *booked* and when they are released again they are *unbooked*.

iv) *Events* and *Activities*. A distinction will be made between an *event* and an *activity* although these terms have, to some extent, become confused in the literature. I shall follow Tocher's[53] use of the word *activity* to mean a change to the *entity attributes* at one point in time. An *event* is a group of related *activities* that happen at one point in time, one *activity* setting off a train of others (see Mitchell[54] for a more detailed explanation and examples). Every happening starts and finishes with an *activity* (e.g. a hospital stay has an admission and a discharge). When a starting *activity* takes place the *time* for the finishing *activity* which may be fixed or be sampled from a distribution, is set. While the *entity* is waiting for the finishing *activity* to take place, the *time* of the finishing *activity* is kept on the *entity's clock*. The *entity* is said to hold the *time* and to be *engaged* to the finishing *activity*.

Entities may either be sorted into *time* order when they are *engaged* to an *activity*, or they may be unordered and the *times* on the *clocks* be searched when required. If more than one *activity* is due to happen at the same time, the order in which these are performed may affect subsequent *activities*. The structure of the simulation should, therefore, facilitate the formulation of independent *activities*.

Pacers are types of *activities* which recur according to a particular time pattern. *Pacers* are used to generate arrivals into the system.

A finishing *activity* or a *pacer* takes place at *time* set on the *entity clock*, regardless of the availability of *resources* and the state of the simulation as a whole. By contrast, *conditional activities* are dependent on the availability of *resources*, *entities* or on another type of condition (e.g. day of the week).

v) *Queues*. *Entities* may need to be grouped into sets for some common purpose. Such sets are called *lists* or *queues* and they are usually created to identify those *entities* waiting for a *resource* or *entity* to be available for use in a *conditional activity*. The *queues* may be maintained in the order of arrival of *entities*, in which case arriving *entities* are added to the *tail* of the *queue* and withdrawn from the

head (i.e. the *queue* is *beheaded*). *Queues* may be *rotated* to withdraw *entities* from other places in the *queue*.

vi) *Fetching*. When an *entity* is *engaged* to an *activity*, there may be circumstances, unforeseen at that time, which cause this *engagement* to be interrupted. The *entity* must then be withdrawn from its *engagement* and be made available for some new and different *activity*. It is said to be *fetched*.

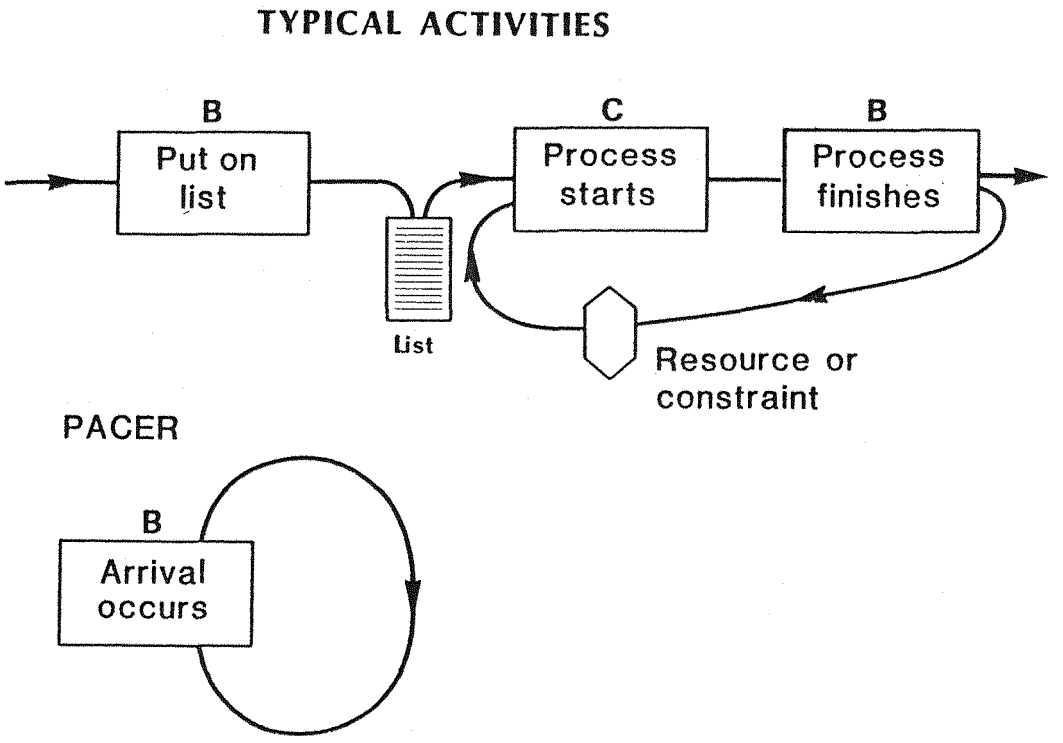
vii) *Shadow Entities*. *Entities* may need to be engaged to more than one *activity* at once. An *entity* cannot *hold* more than one *time* and so another *entity*, called a *shadow entity* is introduced to *engage* to one of the *activities*. The *shadow entity* has to have an *attribute* to identify it with the *entity* which it is *shadowing* so that the *attributes* of the main *entity* can be changed, if necessary, when the *shadow* takes part in an *activity*.

viii) *Wheelcharts*. The structure of a simulation may be illustrated diagrammatically by a *wheelchart* (or an *activity* flow diagram). The short and simple term *wheelchart* (invented by Tocher[53]) is appropriate because the life cycles of *entities* and *resources* appear as circles which meet together when the *entities* co-operate together or as *resources* are used. They appear, therefore, like gear wheels in a machine.

The simple *wheelcharts* in Figure 3.1 show how they may be used to represent *lists*, *resources* and *activities*.

FIGURE 3.1

Activities in a Wheelchart



3.2.3 The three phase simulation method

Different simulation methods in use include the event based methods, the activity based methods, the process system and the three phase method.

In activity based simulations, every *activity* is scanned at each *time beat*. If *activities* are found ready to be performed, then following their execution, the *activities* are repeatedly scanned to see whether the conditions for any *conditional activities* have been satisfied and should be performed. Following an *activity* scan with no execution of *activities* the *time* is advanced one *beat*.

By contrast, in the event based simulations, the *executive* is concerned only with identifying when *non-conditional activities* should be performed. Each automatically sets in train related *conditional activities* (the whole complex of *activities* being called an *event*).

This is much more efficient in computer time than the activity approach because no unnecessary *activities* are attempted. It does, however, become extremely complex to program if there is competition for *resources* or *entities*. Similar problems arise with the process system (see Crookes[57]).

In the three phase method, devised by Tocher[53], the *activities* whose conditions for performance are only dependent on *time*, are called *bound* or *B activities* and the *conditional activities*, *C activities*. The three phases are sequenced like this:

1) advance the simulation *clock* to the *time* set for the performance of the earliest *B activities*,
2) perform the *B activities* for that *time beat*,
3) test each *C activity* to see whether the conditions for its performance (such as the existence of a *queue* or the availability of *resources*) are satisfied and if so perform it.

Robert O'Keefe and I have explained this in more detail with examples[58].

Mitchell[54] and Crookes[57] prefer the three phase method to the other methods for the following reasons:

i) It is more efficient than the activity method because *B activities* are separated from *C activities* and are only attempted when they are due to be performed.
ii) Though less efficient than the *event based* method, because all *C activities* are attempted at each *time beat* in which a *B activity* is performed, it is easier to program. The computer system automatically performs the consequences of the performance of each *B activity* (i.e. the *C activities*) without the programmer having to work them out, together with their interactions, himself.
iii) It is more robust because the effects of *state changes* (i.e. availability of *entities* or the existence of *queues*) are taken care of by the *C activities* which are independent modules. Thus any additions or changes to the program are likely to cause much less disruption to the logic than they are in the event based and process view where the *conditional activities* are not logically separate from the *bound activities*.

3.2.4 The simulation package

Two packages based on the three phase activity discrete event simulation method were readily available.

First, at Southampton, in parallel with my study of the Renal Unit at Portsmouth, Professor Tocher was developing a simulation package for the University's ICL 2970 machine in rational FORTRAN (RATFOR). It was based on GSP[59], the simulation language he had developed at the British Steel Corporation. The combination of working with this language in its unfinished and poorly documented state, and the slow turnround of runs from the mainframe computer proved unsatisfactory.

Second, John Crookes of Lancaster University gave us a much smaller simulation package for use on an Apple II microcomputer. This package is available as a set of precompiled Pascal library units[58]. Although the list processing and sampling facilities of this package are less comprehensive than those in the RATFOR package, I decided to use this system because it had the following advantages:

i) It was written for a microcomputer, whose advantages have been well documented[57,60]. In this case, the almost unlimited time available on the Apple II microcomputer compared with the University's rather overloaded time sharing systems was a considerable advantage. Its portability was also very convenient because it enabled me to take the computer to the Renal Unit for demonstration purposes.

ii) It was written in UCSD Pascal[61] which like RATFOR is a structured programming language but unlike RATFOR does not need to be pre-compiled to another language. Amongst the advantages Robert O'Keefe and I[58] have listed are: portability between computers, economical use of computer memory both in compilation and in running; and the structure of the written language which, when well written, reads somewhat like English (making for ease in removing errors and documentation).

iii) As well as the compiled programs, the Pascal text was available, so it was possible to amend and augment the text of the programs in order to tailor them to the particular problem under consideration.

In addition to the main program which includes the *executive*, there are five Pascal library units (groups of pre-compiled functions and subroutines, called procedures in Pascal[61]), which can be called by any program declared to be using those units. These units are:

ENTITIES - to create and control the *entities*,

QUEUES - to create and manipulate *queues*, adding to them, *rotating* or *beheading* them etc.,

SAMPLING - to generate random numbers to sample from histograms, normal and negative exponential distributions,

HISTOGRAMS - to create histograms of data gathered during the simulation,

SCREENS - to provide routines concerned with screen control.

I substantially modified all the units for my purpose (see Appendix A.1). During development, I supplemented the ENTITIES and QUEUES units and reorganised them in order to create more library space, (calling them SIMULATE and INITIAL) while not, however, changing the original procedures and functions. Robert O'Keefe and I largely rewrote the SAMPLING unit and he completely rewrote the SCREENS unit. The output from the simulation was written to file for further analysis and so the HISTOGRAMS unit was not used.

3.2.5 The computer hardware

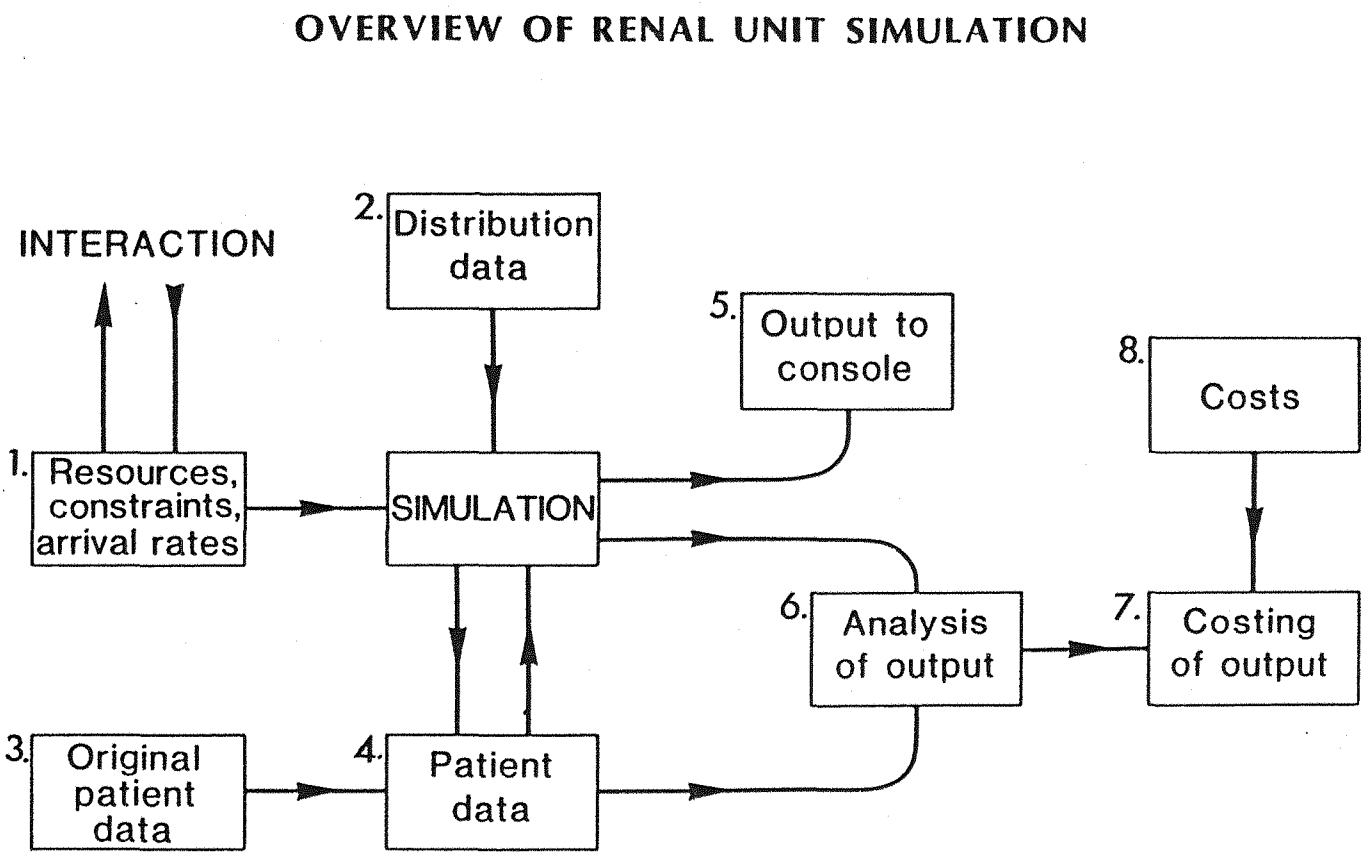
The hardware includes an Apple II microcomputer with a 16K language card for use with Pascal, a monitor and two disk drives. Using an Axlon Ramdisk 320, which is a disk emulator with 320K bytes of storage, speeds up the running simulation considerably by storing the files that have to be accessed during the run (i.e. the data files and program coding for overlaying). The program is speeded up further by the addition of a Stellation Two speed up card[61].

3.3 AN OVERVIEW OF THE MODEL

Figure 3.2 shows that the simulation program is central to the model. It is also essential, however, to provide data for setting the starting conditions and distribution data and to produce output for analysis. Before describing the simulation itself, I shall give a brief

description of the input and output. In this, I shall refer to the numbers of the boxes on the diagram (Figure 3.2).

FIGURE 3.2



3.3.1 Components of the system - conventions

Patients, kidneys and other aspects of the dialysis/transplant programme are important components of the system to be modelled. I shall therefore need to refer to patients and kidneys both in the context of the simulation, and in the context of real life. When I refer to them as if they were objects and parts of a computer programme, I shall, to reduce confusion, use quotation marks, e.g. "patients", "kidneys".

3.3.2 Input data

The simulation program needs data: the arrival rates of "patients", the arrival rates of "cadaver kidneys for transplantation", the availability of resources such as "inpatient beds" and "unit dialysis machines", the presence of constraints and the timetables of "unit dialysis" and "operating theatre sessions" (box 1). The user enters these directly into the simulation programme at its start (4.2.1). He can also interrupt the running programme to change them (4.4.1).

3.3.3 The distribution data

Cumulative distribution data (box 2) have to be available to the simulation program for sampling lengths of stay, survival times and numbers which determine the decisions about "patient treatment" to be taken during the simulation. I have written a program (4.6) for entering and editing histogram, survival or discrete data. It will also validate the distribution data and create a file of cumulative distribution data from the empirical data.

3.3.4 The patient data

Data about each "patient" has to be referred to throughout the simulation. The necessary information includes his "age", "blood group", "antibody index", number of previous "transplants", "suitability" for various "treatments" and some "treatment history". A tailor-made database program (4.7) is used to enter data about the patients on the dialysis/transplant programme (box 3) onto a file of patient records. At the beginning of each run, the simulation program reads the file to set the starting conditions and duplicates it (box 4). It changes the copied file whenever simulated events happen to "patients" and adds new "patients" to it when necessary. The file of records of "patients" can, after the simulation run has finished, both be read by the database program and be used for further analysis (box 6).

3.3.5 Output to the computer console

While the simulation is running the computer console displays a table showing the numbers of "patients" using the different *resources* and the length of the *queues* (box 5). The information is updated

every "day" (4.4.2).

3.3.6 Analysis of output

Data about the use of *resources*, *queues* and numbers of "patients" are collected and saved on a disk file while the simulation is running. This is then available for further analysis (box 6) and costing (box 7). The costs and the costing model are described in Chapter 8.

3.4 THE SYSTEM IN SIMULATION TERMINOLOGY

Section 3.2.2 shows how I use simulation terminology in this dissertation. I shall now show how these concepts were applied to modelling the treatment of patients in a dialysis/transplant programme.

3.4.1 *Time*

A *time beat* in "days" is suitable for measuing "inpatient lengths of stay". A subdivision of "days" is, however, more appropriate for *booking* "unit dialysis machines" and "operating theatre time". If time units are shorter than "days", therefore, the predicted times to "death" are quite likely to exceed the maximum integer, 32767, held by the computer. The *time beat* is therefore in "days" and in order to time-table "unit dialysis" and "operating theatre sessions", the program associates three "shifts" with each "day": morning, afternoon and night.

3.4.2 *Entities*

"Patients" are *entities* (see 3.6.1) and so that the simulation program can refer to the "patient" file (3.3.4), the "patient" record number on the file is equal to the "patient" *attribute* number. The "patient" *attributes* are listed in Table 3.1.

"Patients" are treated as permanent *entities*, but it is possible for the running simulation to create new "patient" *entities* if there are insufficient *entities* available from recycling the "patients" who have "died".

The only other *entities* used in the simulation are those for *holding* the *time* generated by the *pacers* and the *shadows* (see 3.4.7).

TABLE 3.1

Patient attributes held in the patient record

treatment	: new, unit dialysis, home dialysis, C.A.P.D, live related transplant (first 6 months), cadaver transplant (first 6 months), functioning graft (after 6 months), dead.
age group	: 1..5
blood group	: A, B, O, AB.
antibody index	: 0..100.
date of birth	: date.
date of last change in treatment	: date.
in a hospital bed	: true or false.
ward name	: nephrology or transplant
operation needed	: emergency, routine. : none, access, catheter, live related transplant, cadaver transplant, nephrectomy.
machine at home	: true or false.
on transplant waiting list	: true or false.
no. of transplants	: 0..10.
preferred dialysis	: haemodialysis, C.A.P.D.
trained for home dialysis	: true or false.
suitable for live related transplant	: true or false.
suitable for cadaver transplant	: true or false.
haemodialysis shifts	: Monday..Sunday. : am, pm, night.
will die	: true or false.

The only other *entities* used in the simulation were those for holding the *time* generated by the *pacers*.

3.4.3 *Resources*

The following were regarded as *resources* in the simulation:

i) the number of people on unit haemodialysis ("unit dialysis places") (see 3.6.3 for the reason for including this resource),

ii) the number of patients on the training course (1.4.2) for home haemodialysis ("training places"),

iii) the number of operations in an operating theatre session ("units of operating time", see footnote),

iv) the number of haemodialysis machines in the Unit available for each unit dialysis session (1.4.2) on each day of the week ("machines"),

v) the number of cadaver transplant operations that can be carried out in any one day ("transplant units"),

vi) the number of inpatient beds, identified as being in one of two hospital wards ("nephrology" and "transplant" "beds"),

vii) the number of home haemodialysis machines and

viii) the number of C.A.P.D. places.

3.4.4 *Activities*

The sequence of *activities* is explained in 3.5.

The numerical ordering of the *B activities* in the *executive* is purely for reference purposes, whereas those of the *C activities* determine the order in which they are to be performed. A priority rating can, therefore, be given to *C activities*.

3.4.5 *Queues*

In this simulation "patients" always go into a *queue* when waiting for a *C activity*. All *queues* with the following two exceptions are operated on a "first come, first served" basis:

i) "patients" may have to be extracted from the middle of the "cadaver transplant" *list* and

ii) "patients" waiting for "transplants", having been allocated a "kidney" are put at the *head* rather than the *tail* of the *queue* for "inpatient treatment".

Footnote: This is a device to give different weightings to different types of operations and to constrain the number which can be done in a session.

3.4.6 *Fetching*

The "arrival" of "cadaver kidneys" is independent of the "patient" *entities* and so recipient "patients", have to be *fetched* from their existing *activities* (see 3.5.6).

Fetching is also necessary as a result of the use of *shadow activities* (3.4.7).

3.4.7 *Shadow Activities*

While "patients" take part in the "day to day" *activities* of, for example, "inpatient admission" and "discharge", the *shadows* are engaged to longer term *activities* including:

i) *holding* the *time* of "failure" on a "treatment" (possibly resulting in "death"), predicted at the start of that "dialysis" or "transplant" "treatment",
ii) *holding* the *time* for a "patient" on "unit dialysis", to start "training" for "home dialysis",
iii) *holding* the *time* for the *activity* in which a "patient" is put on the "cadaver transplant" *list* and
iv) *holding* the *time* for a "patient" who has had a "transplant" to graduate to the "treatment" category, "functioning graft" (after six months).

3.5 ASSEMBLING THE SYSTEM COMPONENTS

The "patients" in the system may be thought of as passing through a succession of "treatment" states. Figure 3.3 shows the transfers between: "C.A.P.D.", "unit haemodialysis", "home dialysis", "transplant" (including: "live related transplant", "cadaver transplant", "functioning graft") and "death". "Treatment failure" is indicated by a dotted line.

This section describes the system as a *discrete event* simulation using the *wheelcharts* of:

i) the inpatient subsystem (Figure 3.4) and
ii) the whole system (Figure 3.5).

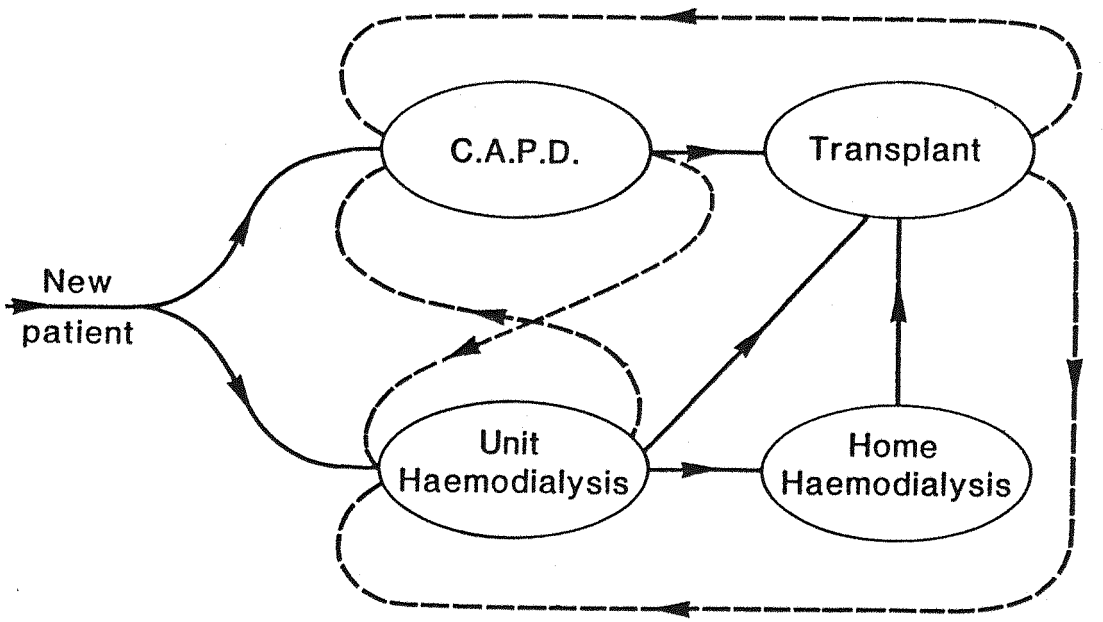
The *activities* and *lists* are on these Figures. Figure 3.5 can be unfolded for reference (page 61).

The data used for sampling *times* for *activities* to take place and for determining decision criteria in the simulation are described in 5.4.1.

Convention: the *lists* are called L1, L2 etc. in the text and on the *wheelcharts*.

FIGURE 3.3

TREATMENT ON A DIALYSIS/TRANSPLANT PROGRAMME
A FLOW DIAGRAM



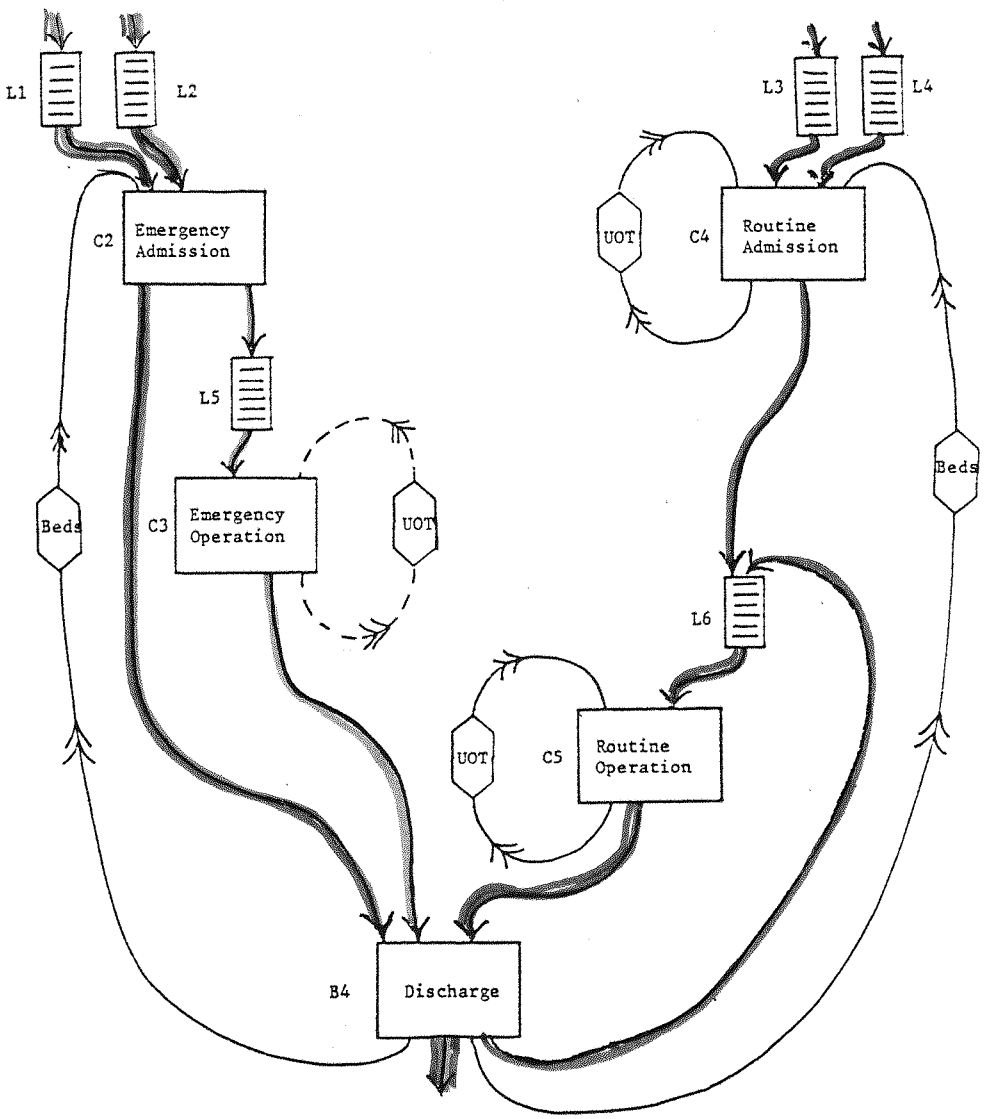
—— progression

—— failure

Note : death occurs from any state

FIGURE 3.4

Wheelchart of the Inpatient Subsystem



Key

UOT Units of operating time

Activity does not have to wait for resource to be available

Emergency admission, emergency operation

Emergency admission, routine operation

Routine admission, routine operation

Emergency admission.

3.5.1 Inpatient Treatment

The inpatient system is almost freestanding (3.6.1) from the rest of the system and of more general application. The *wheelchart* in Figure 3.4 shows the sequence of these *activities* and the complex interrelationship between them. The simulation of the whole system (Figure 3.5), however, makes use of only four routes through these *activities* (letters in brackets show the notation used in Figure 3.5) which are:

i) "emergency admission" with no "operations" (E),
ii) "emergency admission" with an "emergency operation" (EE),
iii) "emergency admission" with a "routine operation" (ER),
iv) "routine admission" with a "routine operation" (RR).

"Patients" on any "treatment" who require "admission" to hospital are put into one of four *lists:*

- "emergency" or "routine admission" to the "nephrology ward" (L1, L3),
- "emergency" or "routine admission" to the "transplant ward" (L2, L4).

i) Emergency Admission (C2). "Patients" on L1 or L2 start the EMERGENCY ADMISSION when there is a "bed" available in either "ward" (for preference in the "ward" on the *list* in which they are waiting). A "bed" is *booked* and if the "patient" record says that an "emergency operation" is needed (route EE), the "patient" is put in L5. Otherwise he is *engaged* to the *activity* DISCHARGE (routes E and ER) with "length of stay" (on the *entity clock*) dependent on his "treatment" (Table 3.1).

ii) Emergency Operation (C3). If there are any "patients" in L5 an EMERGENCY OPERATION takes place. If it is on a day in which a "routine theatre session" is due to take place, then the "patients" *book* "units of operating time" (in competition with the "patients" needing "routine operations"), otherwise the "operation" takes place without competition. The "patients" are then *engaged* to the DISCHARGE with a "length of stay" dependent on the nature of the "operation" (Table 3.1).

iii) Routine Admission (C4). "Patients" are put on L3 or L4 if they need "routine operations" and therefore ROUTINE ADMISSION only takes place on "days" preceeding "routine operating sessions". A "patient" will be "admitted" (i.e. removed from the *list* and *booked* a *bed*) if there is a "bed" available in either "ward" (the one whose *list* he is in, for preference), and there are sufficient "units of operating time" available on the subsequent "day" for the necessary "operation". Once admitted, he is then put in L6 to wait for ROUTINE OPERATION (route RR).

iv) Routine Operation (C5). If there are sufficient "units of operating time" available on days of a "routine operating session", waiting "patients" are removed from L6, have their "operation" and are *engaged* to DISCHARGE. The "length of stay" is dependent on the nature of the "operation".

v) Discharge (B4). The name of the *activity*, DISCHARGE, is a little misleading because if the "patient" record indicates that the "patient" needs a "routine operation" (e.g. route ER), then the "patient" does not leave the inpatient subsystem but is put on L6 for a ROUTINE OPERATION and retains his "bed". If no further "inpatient treatment" is indicated, however, the "bed" is *unbooked* and the "patient" leaves the inpatient subsystem by being put on one of the *lists*, L13..L19, according to his "treatment" (Table 3.1).

3.5.2 Arrivals into the system

We saw in 1.4.1 that patients in need of treatment on a dialysis/transplant programme may be identified several months before starting treatment, during which time they may have several hospital admissions and need at least one minor operation, either to provide access for haemodialysis or to fit an indwelling catheter for C.A.P.D. In the modelled system, "patients" have one "emergency admission" and one "routine operation" before beginning "unit haemodialysis" or "C.A.P.D. treatment".

ARRIVAL (B1) is a *pacer*, creating "new patients", giving them *attributes* (Table 3.1) and putting them on L7, for START TREATMENT (C14). START TREATMENT determines whether a "patient" needs an "access" or "catheter operation" depending on whether "haemodialysis" or "C.A.P.D." is his "preferred dialysis treatment" (Table 3.1).

With a requirement for an "emergency admission" and a "routine operation", the "patient" then enters the "inpatient subsystem", ER (3.5.1).

On leaving "inpatient treatment" the "patient" is put in L11 for PLAN TREATMENT (C13). In PLAN TREATMENT, "patients" are either put in L21, for START UNIT HAEMODIALYSIS (C9) or L10, for START C.A.P.D. (C19).

3.5.3 C.A.P.D. treatment

It will be recalled (1.4.2) that following the start of C.A.P.D. treatment patients have a few days training, often as outpatients, before coping independently at home. As the training period is brief and comparatively inexpensive, it is not described in the model. If, however, it should at some future time be thought to be an important constraint it could be easily included (3.7). Patients on C.A.P.D. may require inpatient treatment at any time.

In the model, both "new" (3.5.2) and "failed patients" (3.5.7) may be added to L10 for START CAPD (C19). In START CAPD each "patient":

- changes his "treatment" to "C.A.P.D.",
- has a *shadow entity engaged* to FAIL TREATMENT (B3),
- if "suitable for transplantation" has a *shadow entity engaged* to CADAVER TRANSPLANT LIST (B12),
- if not already in the "inpatient subsystem", *engages* to NEEDS INPATIENT ADMISSION (B2).

He goes through a cycle of "inpatient treatment", GO HOME (C15) and NEEDS INPATIENT ADMISSION (B2) until either the *shadow entity engaged* to FAIL TREATMENT (B3) becomes *active* and the "patient" has to go (or be *fetched*) to that *activity* (3.5.7), or the "patient" has a "cadaver transplant" (3.5.6).

3.5.4 Unit dialysis treatment

In this section I shall describe the activities of the new patients or failed patients (those who have suffered a rejected transplant or have failed C.A.P.D. treatment) who start unit dialysis, prior to long term haemodialysis treatment. Those patients established on home dialysis, needing unit dialysis sessions are discussed in 3.5.5.

In 1.4.2., I explained that, in Portsmouth, patients have dialysis twice a week spaced by two or three days, except for those undergoing a course of haemodialysis training who need three sessions a week. Patients must not miss any dialysis sessions.

In the simulation, therefore, a "patient" *books* "machines" for particular "sessions" and keeps those "sessions" each "week", even while he may be waiting for different "sessions" to become available (e.g. while waiting to "train"), until he no longer needs them.

"Failed patients" on L20, are given priority over "new patients" on L21. START UNIT HAEMODIALYSIS (C9) is performed if there are both sufficient "unit dialysis places" and also sufficient "machines" available at the right frequency and acceptable spacing throughout the "week". In START UNIT HAEMODIALYSIS, each "patient":

- changes his "treatment" to "unit dialysis",
- *books* "unit dialysis places" and "machines",
- has a *shadow entity engaged* to FAIL TREATMENT (B3),
- if "suitable for live related transplantation" *engages* to PUT ON LIVE RELATED LIST (B13),
- if "suitable for transplantation" (and not for "live related") has a *shadow engaged* to CADAVER TRANSPLANT LIST (B12),
- if not "suitable for live related transplantation" has a *shadow engaged* to READY TO TRAIN (B6),
- if not "suitable for live related transplantation" and not having "inpatient treatment" *engages* to NEEDS INPATIENT ADMISSION (B5).

With the exception of "patients" having "live related transplants", "patients" cycle through the "inpatient" subsystem, E, in exactly the same way as "C.A.P.D. patients". A "patient's" cycle will usually be interrupted by READY TO TRAIN (B6) but may be interrupted, either by the arrival of a suitable "cadaver transplant" or else, by FAIL TREATMENT (B3). If it happens that a "patient" is having "inpatient treatment" when his *shadow* becomes *active* in READY TO TRAIN, he is put in L28, until the "inpatient treatment" is finished.

"Patients" in READY TO TRAIN (B6), are put in L22, until it is the beginning of the "week" and "training places" are available. In START TRAINING (C7), a "patient's" record is examined to see which "machines" he could release, in order to establish whether appropriate

"machines" can be made available for "training". If they are not, the "patient" is returned to L22, otherwise he:

- *books* a "training place" and "machines",
- *engages* to STOP TRAINING (B7).

A similar technique of examining the "patient" record is used in RETURN TO UNIT DIALYSIS (C8). From this *activity* the "patient" *engages* to HOME READY and hence is put on L9 to start "home dialysis".

3.5.5 Home Dialysis

If home dialysis patients are admitted to hospital, they continue to need haemodialysis and have therefore to use the unit dialysis facilities (1.4.2) but they still remain in my terminology on "home dialysis". They may need unit dialysis facilities at other times too, either for ocasional sessions or for periods of a week or more.

In GO HOME (C17), each "patient":

- *unbooks* "until dialysis places" and "machines",
- *engages* to NEEDS HOSPITAL TREATMENT (B9).

The *shadow*, set in START UNIT HAEMODIALYSIS (C9) and *engaged* to FAIL TREATMENT (B3) determines the *time* when "home dialysis treatment" will finish.

In NEEDS HOSPITAL TREATMENT (B9), a decision is made between putting the "patient" on:

- L1 for EMERGENCY ADMISSION (E),
- L2 for EMERGENCY ADMISSION and needs "access operation" (ER),
- L25 for OCCASIONAL UNIT DIALYSIS (one off "unit dialysis session") or
- L24 for HOME/UNIT DIALYSIS ("unit dialysis" for "home" patient).

If a "patient" is put on L1 for EMERGENCY OPERATION, he is also put on L26 for INPATIENT DIALYSIS.

"Patients" waiting for OCCASIONAL UNIT DIALYSIS (C12) need only one "machine" to be available before starting the *activity*. They *book* the machine and *engage*, for one "day", to STOP UNIT DIALYSIS.

A "patient" on a *list* for HOME UNIT DIALYSIS (C11) or for INPATIENT DIALYSIS (C10) waits for "unit dialysis places" and two appropriately spaced "machines" to be available. He then *books* the "machines" and "unit places". "Patients" in C11 *engage* to STOP UNIT DIALYSIS and "patients" in C10 remain on "unit dialysis treatment" until the "inpatient treatment" is finished and the "patient" reaches BACK HOME (C18), where the "machines" and "unit dialysis places are *unbooked*.

3.5.6 Transplants

Patients having live related transplants are usually given unit dialysis until the operation can be arranged (1.4.3). They then have the operation in a routine theatre session.

In PUT ON LIVE RELATED LIST (B13) the "patient" record is marked to denote the need for a "live related transplant" and the "patient" is added to L4 to await ROUTINE ADMISSION which is followed by ROUTINE OPERATION (3.5.1). In ROUTINE OPERATION the patient is put on L8 to wait for TRANSPLANT (C6).

"Patients" on "dialysis" who are "suitable for transplantation" but have no "live related donor", are *engaged* to CADAVER TRANSPLANT LIST (3.5.3, 3.5.4) where they are put on L27, "the transplant list".

When a cadaver kidney becomes available, if there is more than one compatible patient, one patient is selected from the group (1.4.4). In the simulation, we assume that cadaver kidneys arrive independently and, where there are several compatible patients, the one waiting the longest receives the transplant. The complex topic of compatibility is simplified in the model by assuming that a patient and the donor of a kidney are compatible if:

- they have compatible ABO blood groups (Table 1.2),
- the antibody index (1.4.3) is less than a random number between 0 and 100.

There is a further complication in that patients on the list can be temporarily unavailable for transplantation. In the simulation "patients" on the "transplant" list are only "unavailable" for "transplantation" if they are in the "inpatient" subsystem.

In KIDNEY ARRIVAL (B14), a "transplant place" is *booked* to denote the arrival of a "kidney". MATCH (C1) takes place if "transplant places" have been booked, there are "patients" in the "transplant list", L27, and a "bed" is available. MATCH does the following:

- *unbooks* a "transplant place",
- allocates a "blood group" to the "kidney",
- tests the "patient" at the *head* of the *list* for "availability" and "compatibility", *rotating* the *list* until a "patient" has been found, or all the "patients" have been tested,
- *beheads* the *list*, if it has found a suitable "patient", and *rotates* it back to its original order,
- marks the "patient" record to denote the need for a "cadaver transplant",
- puts the "patient" on L2 for EMERGENCY ADMISSION and
- *fetches* the "patient" and his *shadows* and removes him from any *lists* that he is on (3.6.4).

In EMERGENCY OPERATION the "patient" is put in L12 for TRANSPLANT. In TRANSPLANT (C6), the "patient":

- changes "treatment" to "cadaver" or "live related transplant",
- *unbooks* any "machines" in use,
- has a *shadow engaged*, for "six months" to FUNCTIONING GRAFT (B16),
- has a *shadow engaged* to FAIL TREATMENT (B3).

In FUNCTIONING GRAFT (B16), the "patient's treatment" is changed to "functioning graft" (this affects the likelihood of a "patient" needing "inpatient treatment") (Appendix F.1).

After DISCHARGE (B4) following the "transplant operation" or "inpatient treatment" for another reason, a "patient" is added to L17, L18 or L19 for GO HOME (C20), where he is *engaged* to NEEDS INPATIENT TREATMENT; following which, he has another "inpatient admission". This cycle may be interrupted at any "time" by FAIL TREATMENT (B3).

3.5.7 Fail treatment and death

In FAIL TREATMENT the "patient's treatment" is changed to "failed", and for "dialysis" patients a decision is made as to whether the "patient" will "die" (in which case the "patient" *attribute*, "willdie" is set to true) or will:

- be added to L21 for START UNIT HAEMODIALYSIS if he has "failed C.A.P.D.",
- be added to L10 for START CAPD if he has "failed unit dialysis".

The decision as to whether "failed transplant patients" will "die" or will be added to the appropriate *list* to return to their previous "dialysis treatment" is made at the time of the "transplant" (5.4.1).

If the "patient" is to "live" his "preferred dialysis treatment" is marked on his record. If he has a "failed transplant", his need for a "nephrectomy" is also entered. All the "patients" are put in L1, for an EMERGENCY ADMISSION (C2).

Those whose "treatment" is still "failed" on leaving the inpatient system in *activity* DISCHARGE are put on L13 for DEATH. In DEATH, if a "patient's" record is marked "willdie", his "treatment" is changed to "death" and his *entity* and record are made available for reuse.

3.6 PROBLEMS AND ALTERNATIVE APPROACHES

We saw in 3.4 how the components of the system were described in simulation terms, and in 3.5 how they were assembled. I shall now describe some of the difficulties that arose in modelling the system in this way, how they were overcome and alternative approaches that were considered and rejected.

3.6.1 "Patients" as *entities*

My approach

"Patients" are the most important component in the system and the first step in describing the system was to decide whether they should

be *active entities (entities)* or *passive entities*. I decided to describe them as *active entities*, (3.4.2), with the constraints on treatment availability, described as *resources* (3.4.3).

As *entities*, "patients" had to have specific *attributes* and (in the package I used) had to be *permanent entities*. These drawbacks were overcome by:

- using the *entity attribute number* to refer to the "patient" file (3.3.4),
- adding a facility to create new *entities* while the simulation was running.

Alternative approach

Regarding "patients" as *passive entities* passing through *activities* and processed by a series of "treatments" modelled as *entities* might seem to be a more obvious way to describe the system. Without the need to have the *clock* and related *attributes*, the "patients" would take up less computer memory space. They could also be defined as having whatever *attributes* they needed (without being limited to the definition of an *entity* in the package).

The simulation must, however, keep track of the "patients" at all times, in case they need "inpatient treatment" or "unit dialysis treatment", until they leave the system after DEATH. As a result, except when "patients" are in a *list* waiting for a *C activity*, there must always be an *entity engaged* on the "patient's" behalf to an *activity* at all times. If the "patients" had been *passive*, therefore, I should have had to have created rather artificial *entities* such as a "functioning transplant machine" to *hold* the *time* of the next *activity* of each "patient". I decided, therefore, that it was much more logical to describe the "patients" as *entities* in order to *hold* their own *times*.

3.6.2 "Inpatient treatment"

My approach

Patients require inpatient treatment before entering a dialysis/transplant programme when they have a transplant and also at other times during treatment (1.4.6). Thus patients make competing demands

for hospital admission. I showed in 3.5.1 that the inpatient system is a separate and, as far as possible, a self-contained subsystem of the simulation. It accesses "patient" *attributes* in order to determine both the "lengths of stay" in hospital and also the *lists* into which "patients" should go after DISCHARGE.

It is not, however, entirely self-contained because the *activities* in which "patients" change "treatment" should almost invariably take place while the "patients" are in hospital (1.4.6). Wherever possible this problem was overcome by organising the *activities* sequentially. For example, "new patients" pass through the "inpatient" subsystem and are then put in *lists* to start "unit dialysis" or "C.A.P.D. treatment" (3.5.2).

This approach was not always satisfactory because the sequencing of *activities* may give rise to an unrealistic gap between "treatments". "Failed patients" are, for example, put in *lists* for new "treatments" at the same time as entering the "inpatient subsystem" (3.5.7). Care had to be taken to ensure that "patients" starting the new "treatment" should not be *engaged* to any further *activities* if they were still in the "inpatient subsystem".

Even this approach was not good enough for modelling transplant operations, where the change in treatment category occurs at a well defined point in time. Here I found no satisfactory alternative to putting "patients" in *lists* to change their "treatment" from inside the "inpatient subsystem" (3.5.6) (i.e. from ROUTINE OPERATION or EMERGENCY OPERATION). Any other approach would have led to a discrepancy between the numbers of "transplant operations" displayed on the monitor and the numbers of "patients" on "transplant treatment".

The "inpatient subsystem" simulation has a general application in other Health Service systems (9.2.3).

Alternative approach

"Patients" needing "inpatient treatment" at different points in the simulation could have been added to different *lists* and have taken part in distinct but competing *activities*. Although it would then have been possible to change "treatments" from within "inpatient" *activities*, there would have been many more *lists* and considerable duplication of coding.

3.6.3 "Unit dialysis treatment"

My Approach

Unit dialysis facilities are expensive to provide and the number of machines and the extent to which they are available is a rigid constraint on the acceptance and treatment of haemodialysis patients. It was important, therefore, to model the scheduling and use of these machines realistically. In 1.4.2 I showed that patients needed to use the unit dialysis machines not only at the start of haemodialysis treatment and after a transplant rejection (3.5.4), but also for periods of time while they were on home dialysis (3.5.5).

Unlike "inpatient treatment", "unit dialysis treatment" was not treated as a separate subsystem because the "unit dialysis" *activities*, undergone by "patients" at different stages in the simulation, had too little in common. "Patients" requiring "unit dialysis treatment" are, therefore, put in one of seven *lists*, depending whether they were:

i) "new", waiting for START UNIT DIALYSIS (C9),
ii) "failed", waiting for START UNIT DIALYSIS (C9),
iii) waiting for START TRAINING (C7),
iv) waiting for RETURN TO UNIT DIALYSIS (C8),
v) waiting for OCCASIONAL DIALYSIS (C12),
vi) waiting for INPATIENT DIALYSIS (C10) or
vii) waiting for HOME/UNIT DIALYSIS (C11).

The ordering of these *C activities* reflects the priorities of the different groups of "patients" for "unit dialysis treatment".

"Patients" on "haemodialysis" must continue to receive "treatment", even when waiting in a *list*. The usual process of *booking* a *resource* in the *C activity* and *unbooking* it in a subsequent *B activity* (Figure 3.2), had to be replaced by the much more complex process described in 3.5.3.

Although START TRAINING has the highest priority of all the "unit dialysis" *activities*, it only takes place on a "Sunday" by which time all the "machines" may be booked. The *resource*, "unit dialysis places", was therefore introduced as a constraint in order to reserve "machines" for "training patients".

Alternative Approaches

Instead of having a set of "machines" for each "unit dialysis session", there could have been just one set of "machines" for all the "sessions". Instead of *booking* the "machines" in advance, all "patients" requiring "unit dialysis treatment" in a particular "session" would be put on a *list* immediately before the start of that "session". There would then have to be *activities:* PUT PATIENT IN QUEUE, START DIALYSIS and STOP DIALYSIS. All these *activities* would all have to take place two or three times a week for each "patient", with "patients" sorted into priority order on each occasion.

Although this method is conceptually more simple than the one that was used, it could easily happen that there were too many "patients" in the *queue* for some "shifts" and "patients" would then fail to have essential "dialysis sessions". To model it this way would thus have been both unrealistic and unsatisfactory.

3.6.4 *Shadows*

My Approach

The use of *shadow entities* was described in 3.4.7. Some of the complications of using *shadows* is illustrated by reference to Figure 3.5 which shows the subsystem relating to "C.A.P.D." "treatment". In START CAPD, a *shadow* is *engaged* to FAIL TREATMENT. In FAIL TREATMENT, the "patient" has to be identified and withdrawn from an *activity* or *list*. He may either be *engaged* to DISCHARGE or to NEEDS ADMISSION or he may be in a *list* waiting for EMERGENCY ADMISSION or GO HOME CAPD.

i) Identification. *Shadow entities* were given the same *attribute number* as the "patient" they were *shadowing* and when not in use, they had *attribute number* zero. *Shadows* could therefore be used to identify the *shadowed* "patient" and other *shadows* of the same "patient".

ii) Removal from *activities*. A "patient" and other *shadows* of that "patient" could be *fetched*, if necessary, from *activities* (see 3.4.6), but if the "patient" was consuming *resources*, these had to be identified on the "patient" record so that they could be withdrawn.

iii) Removal from *lists*. Retrieving a "patient" from a *list* (or *lists*) entailed searching all the possible *lists* for the "patient" and removing him if and when he was found.

Finding "patients" could therefore be an untidy and rather lengthy procedure. After the development of my program, an alternative and neater approach was developed by Robert O'Keefe in AIMS[63]. It would be instructive to rewrite my simulation in AIMS to see whether it is better than the approach described here.

The main problem in using *shadows* was found to be their large consumption of space in the computer memory at run time. This was reduced to manageable proportions by reducing the number of *shadows* used. A "patient" was only given a *shadow entity* to be *engaged* to FAIL TREATMENT, if the predicted date of "failure" fell within the timescale of the simulation.

Alternative Approach

If there were no *shadow entities*, a *time* which is now *held* on a *shadow entity clock*, would be written to the "patient" record. It would then have to be read in all subsequent *activities* (to determine the *activity* in which the "patient" should next *engage*) until the *activity* to which it was related took place. This is untidy and an unsatisfactory approach.

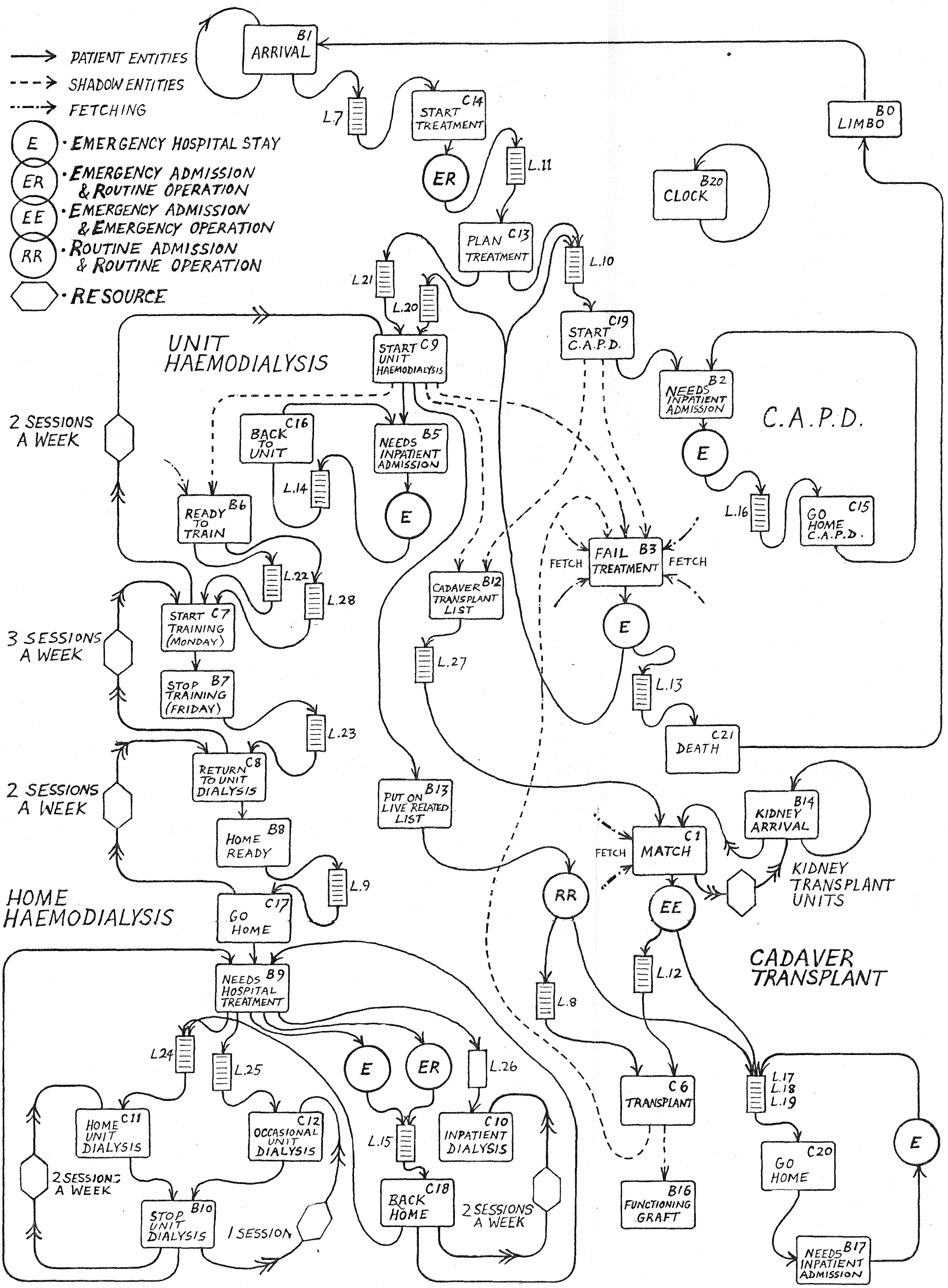
3.7 SUMMARY

I have shown in 3.5 how an extremely complex health system can be described using a *discrete event* simulation technique based on the *three phase* principle. The system includes not only patients' progress through the main types of treatments, as previous models have done (Chapter 2) but also the patient activities which directly influence the use of expensive resources, including inpatient care which is described as a distinct subsystem.

The Apple II microcomputer is an extremely small computer for such a large simulation program. Use of Pascal library units, however, enabled the programs to be overlaid to save computer memory space at run time. Further space was saved by reading and writing data into the program at run time (Chapter 4). The use of a disk emulator instead of floppy disks very considerably speeded up the transfer of this program coding and data into and out of the computer memory.

I developed *shadow entities* to describe patient survival while the main "patient" *entities engaged* in shorter term *activities*. The general application of these concepts is discussed in Chapter 9.

FIGURE 3·5 WHEELCHART OF THE RENAL UNIT SIMULATION



Chapter 4

INPUT, INTERACTION AND OUTPUT

4.1 THE COMPUTER SYSTEM

Chapter 3 describes the simulation *activities* in detail and in an overview of the model (3.3), shows briefly how the simulation program needs input in the form of resource, distribution and patient information, and provides output both on the monitor screen and on disk files for further analysis. This chapter, based on Figure 4.1, provides more detail about the relationship between these different parts of the model.

The building blocks of a UCSD Pascal program (and therefore of the simulation and supporting programs) are the library units (3.2) which, once in the system library, can be used by any program that calls them. They can also, if necessary, be overlaid to save space in the computer memory at run time[61].

Capital letters will be used to refer to the main programs, library units and group of units and other elements of the computer system shown on the labels in Figure 4.1. The numbers of the boxes in the diagram are given in square brackets. Appendix A describes briefly the content of the units used in the simulation program.

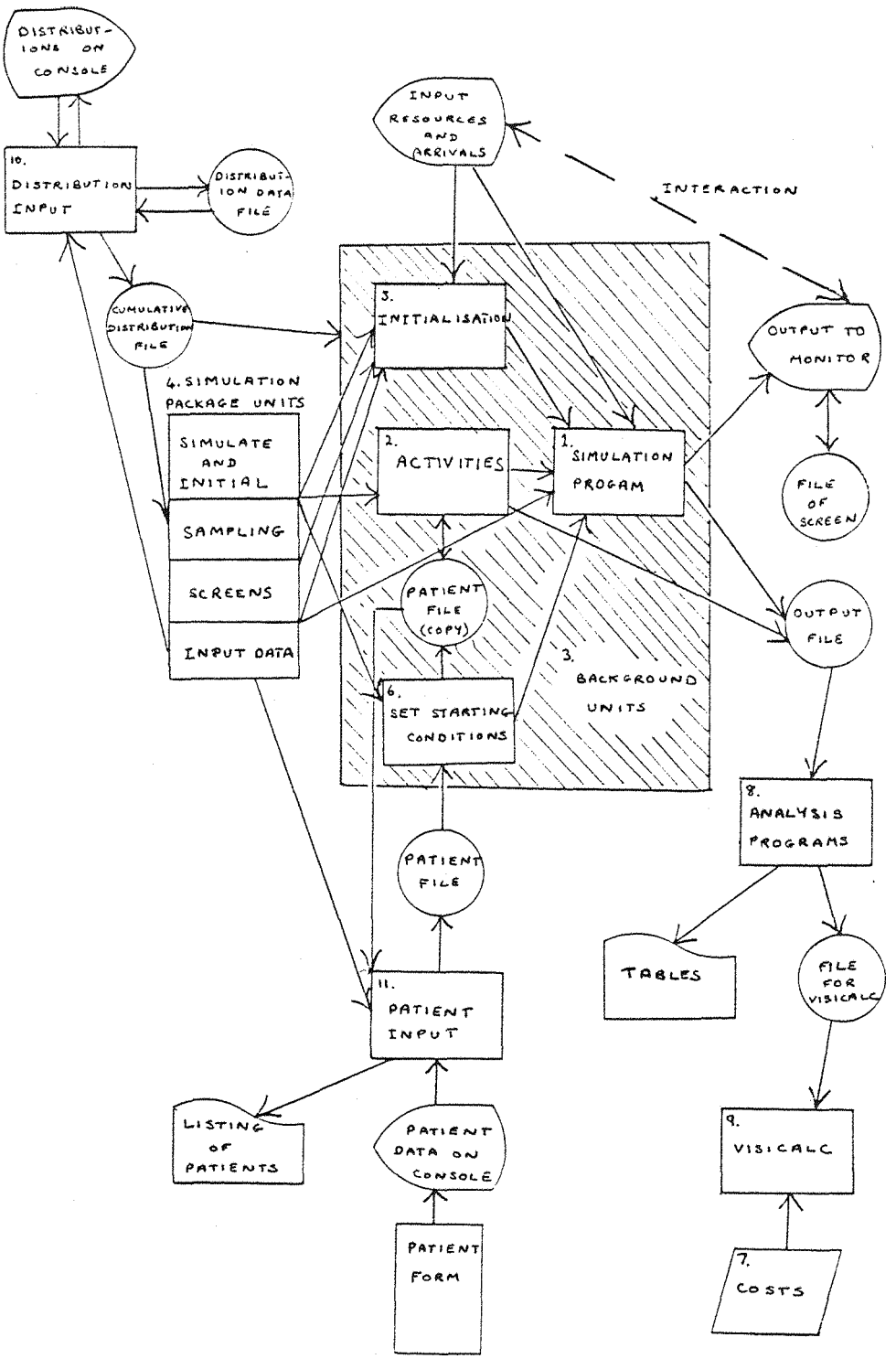
The ACTIVITIES [2] units are driven by the *executive* in the SIMULATION program [1], and uses the SIMULATION PACKAGE [4] and BACKGROUND [3] units. This chapter describes the following parts of the model (working from the centre of the Figure 4.1 outwards):

i) the INITIALISATION unit [5], driven by the *executive* (4.2),

ii) the unit to SET STARTING CONDITIONS [6], driven by the *executive*, using data from the PATIENT FILE (4.3),

iii) facilities for the user to interact with the running simulation to enable him, on viewing the OUTPUT TO MONITOR, to change model parameters and thus to influence the course of the simulation (4.4),

FIGURE 4·1 Computer System for the Renal Unit Simulation



iv) the creation of an OUTPUT FILE for the analysis of simulation data (4.5),

v) the entry of parametric and frequency distribution data (using the DISTRIBUTION INPUT program [10]) to enable sampling to take place in the ACTIVITIES units and in the SET STARTING CONDITIONS unit (4.6) and

vi) the PATIENT INPUT program [11] for the collection and validation of patient data in the creation of the PATIENT FILE (4.7).

The analysis of data for costing and the use of VISICALC are described in Chapter 8.

4.2 INITIALISATION

At the start of a simulation run the INITIALISATION unit:

i) allocates computer memory space for *resources*, *queues* and *entities*,

ii) sets necessary variable values and

iii) gives default values for levels of resource provision and arrival rates.

Further data are entered from the keyboard and disk files.

4.2.1 Initialisation by the user from the keyboard

The variables set from the keyboard are: the *resource* levels, "unit dialysis session" and "theatre session" timetables, "patient" and "kidney" arrival rates (Appendix B) and sampling stream numbers. They can be entered quickly and simply because:

i) the presence of default values reduces the number of variables that need be set,

ii) the INPUT DATA unit facilitates program recovery following erroneous data entry (Appendix A.1) and

iii) clear instructions are displayed on the computer monitor screen.

4.2.2 Distribution data from disk files

The distribution data which are held on disk files can be entered and edited interactively using a separate program (4.6) but cannot be changed during the course of a simulation run. Two types of distributions are used to provide data for sampling in this simulation (see 4.6):

- negative exponential distributions and
- histograms.

The CUMULATIVE DISTRIBUTION FILE is a file of the histogram data in cumulative form. The INITIALISATION unit reads the means of the exponential distributions and the data points of the small histograms into the computer memory. The histograms with a large number of data points, however, are simply referenced so that the simulation program can read them from the file as and when they are needed, thus saving space in the computer memory (see 4.6).

4.3 SETTING THE STARTING CONDITIONS

Starting conditions must reflect the fact that there are patients on treatment in the dialysis/transplant programme, who have been on the programme for many years. The "patient" *entities* must already be *engaged* in *activities*, using *resources* and waiting in *queues*. The *attribute* data of these initial "patients" must also be available to the simulation program. The STARTING CONDITIONS unit both sets the starting conditions using the data on the PATIENT FILE and also copies the PATIENT FILE, adding additional *attribute* data where necessary, to provide a file for the simulation program to access and update. The collection and validation of the patient data is explained in 4.7.

Because the initial "patients" have already entered the "dialysis/transplant programme", the STARTING CONDITIONS unit samples their survival on their "present treatment" with a cumulative survival distribution, conditional upon their survival from the date when they started the treatment to the "present" time. The date of the "present" is read from the PATIENT FILE.

On reading each "patient" record the STARTING CONDITIONS unit:

- finds a "patient" *entity* whose *attribute number* equals the record number,
- sets the "patient's" age group,
- finds the number of days between "now" and the date of the last change in "treatment",
- if the "patient" is "on the transplant waiting list", adds him to that *list*,
- if he is "suitable for a transplant" but not "on the transplant waiting list" (and not "suitable for a live related transplant") *engages* a *shadow* to CADAVER TRANSPLANT LIST (B12),
- samples from the appropriate conditional survival distribution and *engages* a *shadow* to FAIL TREATMENT (B3),
- if the "patient" is "in bed" and a "bed" is available, *books* a "bed" and *engages* the "patient" to DISCHARGE (B4),
- depending on the "patient's treatment", *books* other *resources* and *engages entities* to appropriate *activities*,
- writes the "patient record" to the PATIENT FILE (COPY).

When the starting conditions have been set the simulation is ready to start running.

4.4 INTERACTION

The designer of an interactive simulation has to decide which assumptions and parameter values should be in the hands of the user to change as he wishes and which should be fixed or even incorporated into the structure of the model. In this simulation study, the decision evolved after discussions and demonstration trials with the potential users, to determine what interactive experiments they may want to carry out. If the model is, in the future, incorporated into the Renal Unit planning procedures, and used extensively, modifications may be necessary (4.8). For the present, I have limited the decisions to be made interactively to those concerning *resource* provision and to the determination of the arrival rates of "patients" and "kidneys".

It is essential to have output from the simulation on the monitor screen to show how the simulation is progressing so that interactions can be made as a direct result of what is seen on the

screen (e.g. changes in *resource* availability made as a result of long *queues* building up for those *resources*).

4.4.1 Interrupting the simulation and making changes

In order to interact with the simulation, it must be possible to stop the simulation program, perform the interaction, and continue the simulation again from the place in which it was stopped.

In this simulation, the user can stop the simulation at the end of a "day" by depressing any key on the keyboard. He is then given the option of:

- continuing the simulation with no changes,
- making some alterations or
- stopping the simulation run.

If he decides to make some alterations, the program saves the monitor screen to the disk emulator (3.2.5) using the SCREENS unit (Appendix A.1). It then provides for interaction by showing the succession of three screens used in initialisation and described in Appendix B. The user may thus make any changes he wishes to *resource* availability, timetables and arrival rates. The program then returns the saved screen from the disk emulator to the computer monitor and the simulation proceeds.

Increases made in *resource* availability and additional "unit dialysis" or "operating theatre" shifts can be immediately incorporated into the simulation conditions and constraints. Decreases in provision cannot be implemented, however, until any "surplus" *resources*, in use at the time of the interruption, have been *unbooked*.

4.4.2 The monitor screen

The display on the monitor screen while the simulation is running provides a dynamic picture of what is happening in the simulation.

The content and format of the monitor screen was designed such that:

i) the selected information for display should be pertinent to Renal Unit staff and other people using the simulation,

ii) the screen should give the user as much information as possible to enable him both to decide whether and when to interrupt the simulation to change the model parameters, and also to see the results of his changes,

iii) the information has to be expressed very concisely and

iv) the format of the screen should make the information easy to read and to understand.

A tabular format was chosen for the screen output (see Figure 4.2) rather than a graphics format (with colour pictures[60]), both to save space in the computer memory and to show clearly and concisely a wide range of information about:

i) the use of resources by "day" of the "week",

ii) the demand for resources,

iii) the total number of "patients" on each "treatment".

Demonstrations of the simulation in the Renal Unit and in the Health District have been well received and the display has been found to be clear and comprehensive and to provide adequate information for interacting with the simulation.

4.5 OUTPUT TO DISK FILE

A screen of the OUTPUT TO MONITOR and the PATIENT FILE can both be saved, as disk files, at any particular point in "time" in the simulation. They give, however, only a snapshot picture of the simulation at that point in "time". In order to determine changes over "time", simulation output must be saved at regular "time" intervals, in the way described below.

4.5.1 Collection of data

The following numbers are collected and saved to disk file at the end of each "week":

- "week" number,
- average "patient" arrivals per "week",

FIGURE 4.2

An example of a screen shown in a simulation run which has just been updated at the end of "Sunday" in 260th "week" since the beginning of the simulation.

```
      RENAL UNIT SIMULATION
              WEEK = 260
              MON TUE WED THU FRI SAT SUN
-----------------------------------------
BEDS:NEPHRO! 11  10  12  13   9   8  12
     TRANSP!  3   3   2   1   1   1   0
TRANSPLANTS!
OTHER OPS. !             1       1
-----------------------------------------
UNIT: DAY  ! 10  10   2  10  10
      NIGHT!  4   8   0      10
-----------------------------------------
                    !
NO. ON TREATMENTS!  WAITING LISTS
-----------------------------------------
 NEW            2 !   BEDS:NEPHRO      0
 HAEMO:UNIT    30 !        TRANSP      0
       HOME   119 !   UNIT DIALYSIS   54
 C.A.P.D.      48 !   TRAINING         2
 FN. GRAFT    249 !   TRANSPLANT      22
TOTAL         449
```

On the screen can be seen:

- the number of "beds" in use in the "nephrology" and "transplant" "wards" during that "week",
- the number of "transplants" and other "operations" performed on each "day" during the "week",
- the number of "patients" on each of the "treatments" listed at the end of the "day" and
- the number waiting for "beds", "unit dialysis treatment", "haemodialysis training" and on the "transplant waiting list" at the end of the day.

The output on the monitor screen is updated at the end of every "day".

- average "kidney" arrivals per "week",
- "unit dialysis sessions" per "week",
- "machines" used on each "day" of the "week",
- "operating theatre sessions" per "week",
- total "patients" on each "treatment" at the end of the "week",
- "beds" on each "ward" available for use,
- "beds" used on each "ward" on each "day" of the "week",
- "beds" used by "patients" on each "treatment" on each "day" of the "week",
- "live related" and "cadaver" "transplants" in the "week",
- "operating units" used during the "week",
- "patients" starting "home dialysis" during the "week",
- "patients" ceasing to need "home dialysis machines" during the "week",
- "patients" waiting for "unit dialysis",
- "patients" waiting for a "bed" by "urgency" and "ward",
- the size of the "cadaver transplant list".

4.5.2 Analysis of the output

The uses of the output data include:

i) the analysis of *resource* use, *queues* over "time" and user interaction with the simulation runs using a simple listing of output such as that shown in Appendix E or with the aid of graphical output (e.g. VISIPLOT[65]), and

ii) costing the output for budgeting purposes using VISICALC[66] (8.3).

4.6 DISTRIBUTIONS

The simulation program needs data from which to sample in order to determine:

i) each new "patient's"
   - "age",
   - "blood group" (1.3.3) (this also has to be determined for "kidneys"),
   - preference for "C.A.P.D." or "haemodialysis",

- suitability for "cadaver transplant" or "live related transplant" and
- "antibody index" (1.3.3).

ii) whether "failed dialysis patients" die or change "treatment" (3.5.7),

iii) the type of "hospital care" needed by "home dialysis" "patients" (3.5.5),

iv) the "time" each "patient" will spend on each "treatment",

v) "length of stay" on "inpatient treatment" and on "unit dialysis treatment",

vi) the "time" spent between the end of one "hospital" episode and the need for the next,

vii) the "time" after the start of a dialysis at which a "suitable" "patient" should be put on the "cadaver transplant list" (3.5.6)

and viii) the "time" between "patient" and "kidney" arrivals.

If suitable data were available from one or more computer systems in the Renal Unit, the problem would be only to transfer the information from one computer system to another. Because the user has to collect the decision and distribution data from several sources (see Chapter 5), it is important that they should be very easy for him to enter into a file and amend when necessary.

The patient characteristics and decision data (i, ii and iii) are simply sets of discrete frequencies. The other distributions are time dependent and may either be parametric or be based on raw distribution data. Apart from a few negative exponential distributions, the distributions used in this simulation were frequency histograms. The reasons for this approach are discussed in 5.4.1. Some of the distributions used were related to the patient characteristics (5.4).

By contrast with the negative exponential distributions, with only one data point each, the histograms give rise to storage and data manipulation problems. Use of the SAMPLING unit (Appendix A.1), however, enables:

i) large distributions to be read from disk file (preferably from a disk emulator (3.2.5)), as and when they are needed rather than consuming space in the computer memory throughout the simulation and

ii) conditional distributions to be used for sampling survival

times of "patients" already on the dialysis/transplant programme at the start of the simulation (4.3).

The SAMPLING unit is backed up by a screen orientated distribution editor (DISTRIBUTION INPUT [10]) for manually entering frequency distribution data to be validated and transformed into the cumulative form which is needed for sampling purposes. Appendix C describes its use. Its properties are:

i) the use of the INPUT DATA unit for interactive data entry (Appendix A.1),
ii) the facility to enter and edit three types of distribution from the keyboard: histogram, discrete or survival (for use with life table data), with up to 50 data points for each distribution,
iii) a choice of timescale (if the independent variable is time) of days, weeks, months or years,
iv) the facility to enter additional and to duplicate existing distributions,
v) the validation of distribution data and
vi) the creation of a CUMULATIVE DISTRIBUTION FILE.

The CUMULATIVE DISTRIBUTION FILE is then ready for use by the simulation program.

This program is flexible and easy to use. Examples are described in Appendix C.

4.7 PATIENT DATA

Patient data, for setting the starting conditions, have to be acquired (5.4.5) from a variety of sources and entered into the simulation computer system manually. In order to make it easier to collect data for all the patients from one data source and then move on to the next one rather than to finish one patient at a time, a form was designed for the collection of the data (Figure D.2, Appendix D).

The PATIENT DATA INPUT program which is a similar interactive data entry and validation program to the DISTRIBUTION INPUT program, both enables the user to enter data on to the PATIENT FILE easily and

quickly, and provides the simulation with validated patient data. Its use is described in Appendix D.

The patient data entry system comprises the following activities:

i) patient data are collected on the forms,
ii) the data are then entered on the disk file using the DISTRIBUTION INPUT program,
iii) the data are validated, errors are printed out and mistakes are corrected,
iv) in order to secure the data from casual or inadvertent changes, the user is prevented from changing the validated records unless the validation marker is removed from all the records in the file and
v) the validated records are used in the STARTING CONDITIONS unit.

Figure D.1, Appendix D, shows the monitor screen displaying a patient record into which data have been entered. The patient name and number are used for unique identification of the patient in entering and updating data, but are not used in the simulation. The other fields in the record correspond to *attributes* listed in Table 3.1 (page 44). Those *attributes* listed on Table 3.1 which are not entered manually (Appendix D) (e.g. "willdie") are allocated to the "patient" by the STARTING CONDITIONS or ACTIVITIES units.

4.8 FURTHER DEVELOPMENTS

I have designed the interactive facilities to provide for the experiments a user is most likely to want to carry out with the simulation. Examples of other interactive facilities which could be added in the future are:

i) the identification of criteria for changing "patients" from one *queue* to another when appropriate *resources* are all in use (e.g. if the *queue* for "unit dialysis" is longer than a certain value, then put the next new "patient" suitable for "haemodialysis", on to the *queue* for "C.A.P.D treatment").
ii) the facility to change decision and distribution data during the progress of a simulation.

4.9 RUNNING THE SIMULATION PROGRAM

The monitor screen is clear and easy to read. When there are 300 "patients" in the simulation, the program runs at rate of approximately one "year" per hour. Using the computer hardware, described in 3.2.5, the simulation is very suitable for short term planning, but it is time consuming to use for runs of more than two "years" in length. This problem can be overcome by the use of a more powerful computer (9.2.1).

The computer system has been designed so that it is easy for the user to enter resource and arrival data in the initialisation stage, to interact with the running simulation and to create valid patient and distribution files for use by the simulation program. An output file is available for both cost analysis and also the production of printouts for graphic displays or tables.

Although it would be much more satisfactory if the data could be prepared for the simulation directly from a computerised data collection system without time consuming and error prone human intervention, both the DISTRIBUTION and PATIENT INPUT programs are very easy to use.

Chapter 5

DATA

5.1 THE NEED FOR DATA

Data are needed both to develop the model structure and to run it. Qualitative data about how treatments are carried out, by whom, to whom, with what resources, and the priorities given to different patients, are essential for both building the model structure and also determining what quantitative data should be collected.

Three types of quantitative data are needed for running the model:

i) patient data to set the starting conditions (4.3),
ii) discrete distributions for sampling "patient" *attributes* and decisions (4.6) and
iii) survival and length of stay distributions for sampling the *time* between *activities* (4.6).

In the absence of an up-to-date and comprehensive computer data base system at Portsmouth Renal Unit, the collection of reliable quantitative data was difficult. This chapter describes:

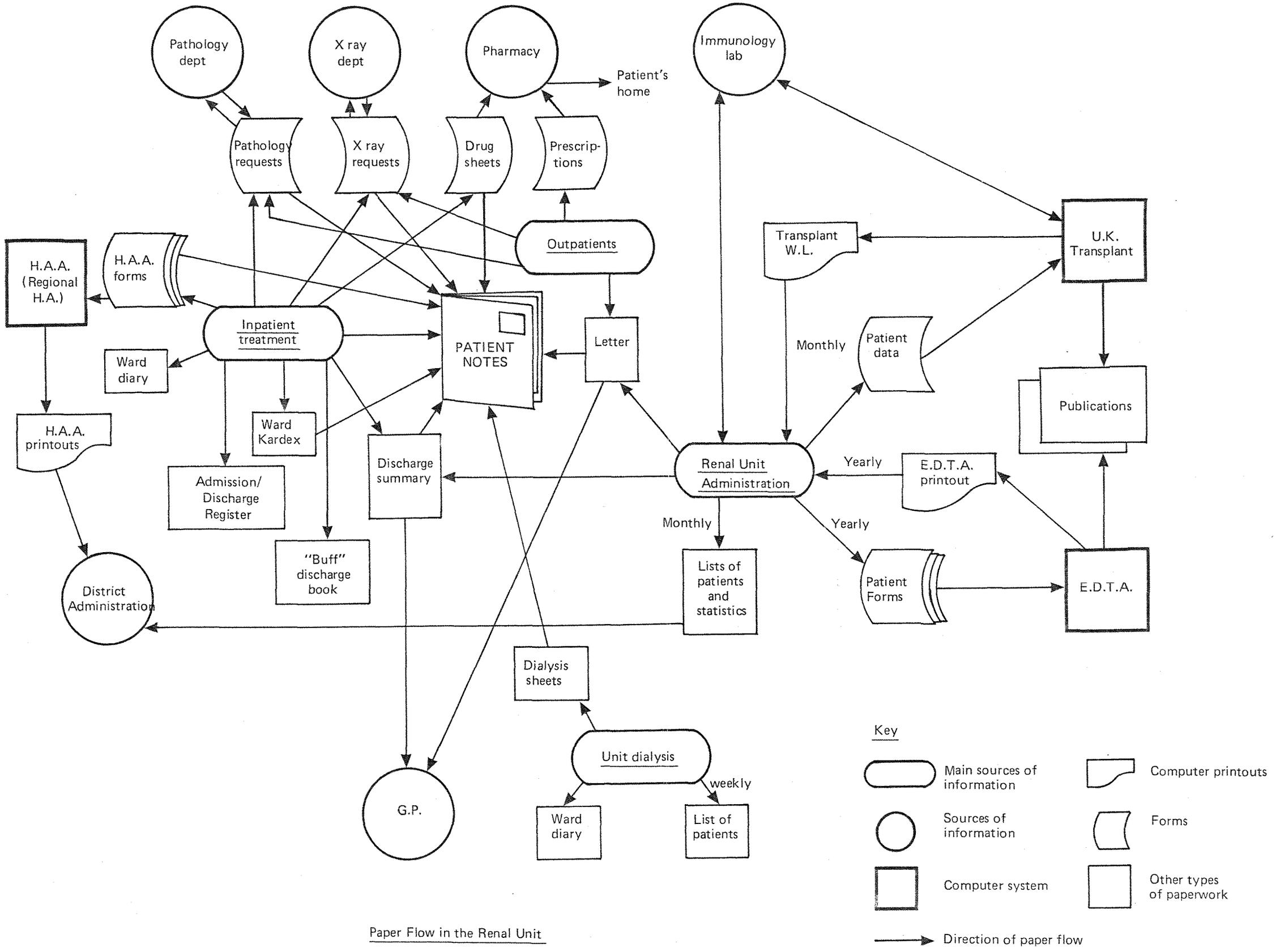
i) the data needed for building the model structure (5.2),
ii) where these difficulties arise in the flow of paper work in the Renal Unit (5.3),
iii) how the data were used (5.4) and
iv) how the paper flow might be improved in the future (5.5).

5.2 THE MODEL STRUCTURE

The detailed structure of the simulation model (i.e. *activities* and their relationship to each other), described in Chapter 3, was built up in the following stages:

i) general knowledge acquired during previous studies (2.3),

FIGURE 5.1



Paper Flow in the Renal Unit

ii) information about the system at Portsmouth built up as a result of discussions with: doctors, nurses, administrators, and finance, pathology and pharmacy staff, and also during attendance at weekly ward meetings about patients,

iii) additions and modifications made to this picture by examination of data collected in the Renal Unit (e.g. patients with a transplant which had been functioning for more than six months were less likely to be admitted to hospital than more recently transplanted patients and therefore had to be given a separate "treatment" classification).

All these stages, particularly the collection of the qualitative data, are vital to the production of a realistic and useful simulation model.

5.3 SOURCES OF DATA

This section will describe the sources of quantitative data for the simulation program. There are four important points in the system at which information is generated and collected:

i) inpatient treatment (5.3.4),
ii) unit dialysis treatment (5.3.5),
iii) Renal Unit administration (5.3.6),
iv) outpatient treatment (5.3.7).

Figure 5.1 shows that although many of the documents generated at these points are filed in the Patient Notes (5.3.1), there are other useful sources of information about patients. The local information systems, apart from a computerised chemical pathology system, are all manual but three large batch computer systems (run from outside the Renal Unit) are fed with data about Renal Unit patients (5.3.2, 5.3.3, 5.3.4).

5.3.1 The Patient Notes

A set of Patient Notes is a folder, whose filed contents include:

- medical histories taken by doctors,
- notes on progress during inpatient stays and at outpatient visits,
- prescription charts,
- results of laboratory tests,
- letters from G.P.s,
- social work reports,
- X ray reports,
- signed forms giving permission for operations,
- results of any other tests,
- copies of Hospital Activity Analysis forms (5.3.4),
- copies of discharge summaries and outpatient letters.

For long term patients such as patients on the dialysis/transplant program the folders are liable to become very fat and as a result documents may be difficult to find within the folder. It is very likely that some may come adrift and get lost. The Patient Notes, themselves, are often not to be found in the Medical Records Department. They may be on an inpatient ward, in an outpatient clinic, in a pile waiting for doctors to find time to dictate discharge summaries, waiting for clerks or secretaries to file documents or in one of many other less likely places.

The Patient Notes contain much of the information needed for the model but many of these Notes are difficult to locate in the hospital and extremely time consuming to read. They may well also be incomplete. Wherever possible, therefore, I used more accessible sources of patient information. The Patient Notes were used only for the following purposes:

i) for a sample survey of resource use for costing purposes (Appendix I) and
ii) to check information that I had received from other sources.

5.3.2 European Dialysis and Transplant Association (E.D.T.A.)

Records of renal patients, including information about patients' dates of birth, blood groups and treatment histories, are held on computer files and updated annually from forms filled in at Renal Units throughout Europe. In order to provide distribution data for

for this simulation model, I both:

i) used published statistics from the most recent E.D.T.A. Annual Reports[6] available at that time and
ii) analysed the E.D.T.A. computer file of Portsmouth patient data dating from the start of the Renal Unit until the end of 1980.

Although these two sources of information are useful and reliable, they are not comprehensive. For example, E.D.T.A. collects little information about inpatient admissions or about the use of the Unit dialysis facilities by home dialysis patients. In addition, the patient files are updated too infrequently to provide the patient data for setting the simulation starting conditions.

5.3.3 U.K. Transplant

U.K. Transplant is a clearing house for cadaver kidneys (1.4.4) which maintains an up-to-date transplant waiting list using a computer. The patient records include: patient HLA groups, antibody levels, blood groups and a classification as to whether patients are "active" on the transplant waiting list or are temporarily unavailable for transplantation. I used information from two sources, to provide distribution and patient data for the simulation:

i) published statistics in the U.K. Transplant Reviews and Reports[16,66,67] and
ii) monthly printouts of the Portsmouth Renal Unit Transplant waiting list.

5.3.4 Inpatient data

Paperwork generated as a result of an inpatient stay is of the following type:

i) nursing records such as the ward diary, the ward kardex and the admission and discharge register,
ii) entries in the Patient Notes by doctors (5.3.1),
iii) requests for tests and prescriptions (5.3.7),

iv) patient forms for the Hospital Activity Analysis (H.A.A.) computer system and

v) "ad hoc" systems such as the collection of dates and reasons for admission in a buff exercise book called the "buff discharge book".

The replication of information about inpatient admissions and discharges and the resulting transcription of information from one document to another leads to inaccuracy. The problem in the Renal Unit is exacerbated by:

i) difficulties in defining the beginning and end of the inpatient stays of some local patients who sometimes use inpatient facilities without staying overnight and

ii) lack of motivation for completing the H.A.A. form for the Regional computer system, which is poorly designed for the collection of data about chronically ill patients (e.g. there is a large space on the form for diagnosis, which is likely to remain the same from one admission to another, but little space to describe the patient's current problems).

The use of the H.A.A. computer system is, in any case, unsuitable as a source of data for the simulation because:

i) it is difficult to identify the dialysis/transplant programme patients in the H.A.A. computer system and

ii) there is a very considerable time lag between the completion of H.A.A. forms on the wards and availability of a computer file for analysis.

I decided that the most accessible form of inpatient data was in the "buff discharge" books. From these I coded the following data on 450 recorded inpatient discharges of programme patients (between 31.5.80 and 21.8.81):

- the admission date,
- the discharge date,
- the patient name,
- the type of treatment (i.e. the type of dialysis or transplant),
- the reason for admission.

This is an unsatisfactory source of data, in the long term, for the following reasons:

i) the entries in the book, on comparison with other sources of data, were found to be incomplete and sometimes inaccurate (I corrected the errors that I found and hoped that any remaining errors would not significantly affect the data entered in the simulation program) and

ii) this data collection system was set up as a temporary measure which is both unlikely to be maintained and is unavailable at other Renal Units.

Section 5.5 contains suggestions for improving the information systems in the Renal Unit.

5.3.5 Unit dialysis data

Unit dialysis data is available on the weekly dialysis sheets and in the ward diary. The sheets show the names of the patients expected to use the unit each week. Last minute changes, however, may be recorded in the ward diary but not on the dialysis sheet. I analysed unit dialysis sheets, updated by information from the ward diary, for the weeks from 5.1.81 to 11.5.81.

5.3.6 Administrative data

Renal Unit administrative staff includes the home dialysis administrator, the transplant co-ordinator and the secretarial staff who collect and publish information about changes in patient treatments, dates of transplants, installation of home machines etc. The secretarial staff also type, send copies to general practitioners and file discharge summaries and outpatient letters which summarise the pertinent facts and findings about inpatient or outpatient episodes.

Systems for the collection of data for administrative purposes have proliferated as demands have been made for information. These systems are, as far as I know, peculiar to Portsmouth Renal Unit. I found the lists of patients and statistics collected for administrative purposes to be useful for filling in patient forms and for cross checking data from other sources. Although they are limited in scope

they are kept up-to-date and are reasonably accurate. They include:

i) a list of current patients with all the dates of their changes in treatment (type of dialysis or transplantation),
ii) a list of patients by area of residence, with dates of birth,
iii) numbers of admissions and transplants by month,
iv) numbers of patients on the programme by month and
v) a classification of the patients on unit dialysis, indicating whether they are training, have a machine at home etc.

5.3.7 Other sources

Details of an outpatient visit should be recorded in the Patient Notes (5.3.1) and a letter should be sent to the patient's general practitioner (G.P.).

Requests for pathology and X ray tests and prescriptions for drugs arise out of both inpatient and outpatient visits and sometimes out of visits for haemodialysis in the Renal Unit. The results of pathology tests, X rays and inpatient prescriptions should be filed in the Patient Notes. The only copies of outpatient prescriptions, however, are usually carried away by the patients. In conjunction with the District Finance Department, I made a survey of X ray and pathology requests from the Renal wards (Appendix I).

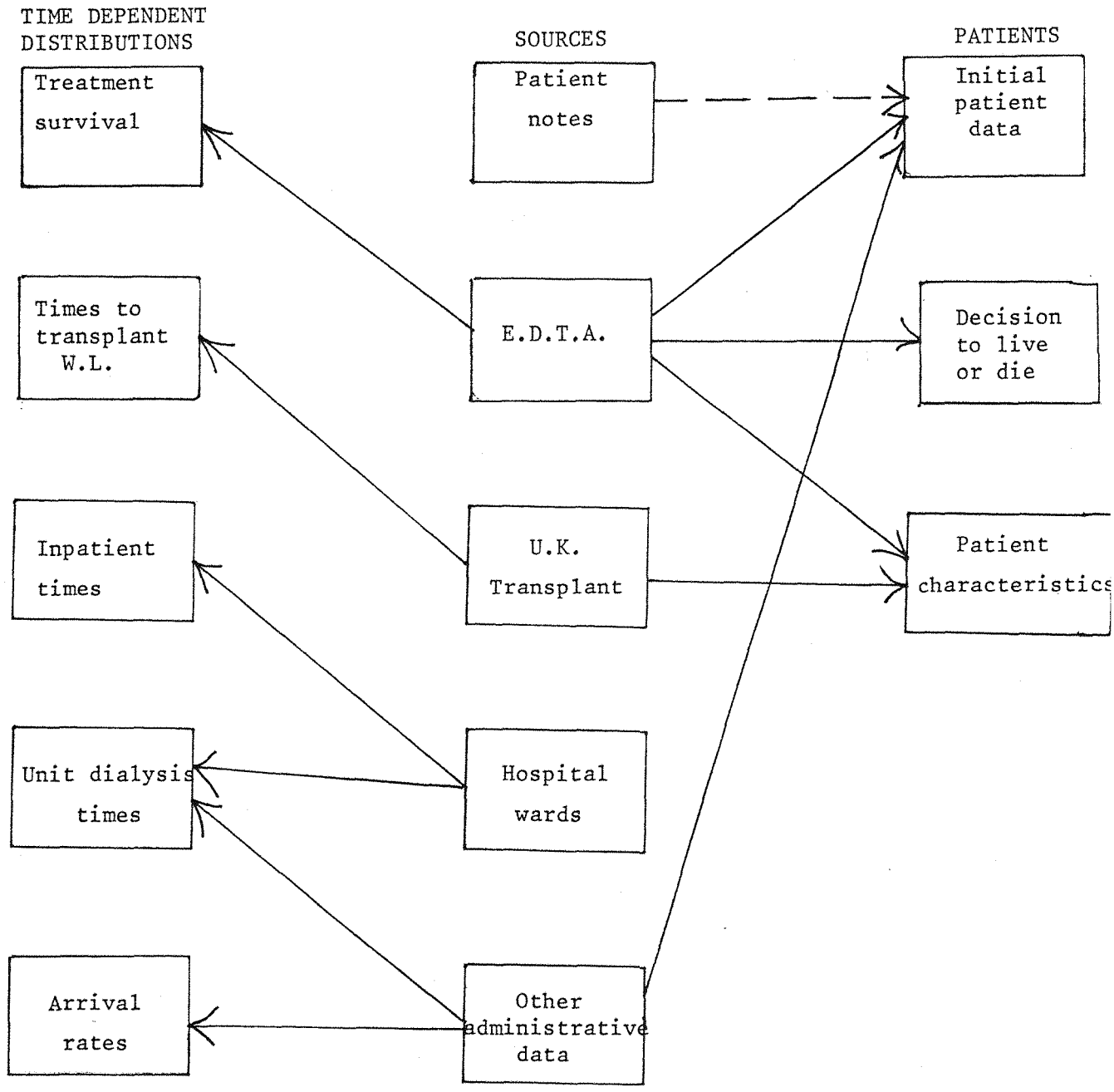
5.4 ATTRIBUTES, DECISIONS AND DISTRIBUTIONS

Figure 5.2 shows the relationship between the data sources and the data used in this simulation. The details of all the patient attribute, decision and distribution data used in the simulation are listed in Appendix F.

Previous studies (2.3.2), have found negative exponential or geometric distributions to fit poorly with treatment survival data from patients on dialysis/transplant programmes. For most distribution data of *time* between *activities* in the simulation programme, including treatment survival data, I decided to use raw frequency data rather than attempting to fit more complex functions such as Weibull distributions to the data, for the following reasons:

Figure 5.2

Sources of data



i) techniques for finding the appropriate distributions and best parameters are complex and time consuming[68],

ii) upon any changes to the published or calculated survival data, the data have to be fitted again to find the new parameters before they can be used in the simulation programme,

iii) it is quite possible that the chosen type of distribution would prove to be inappropriate either for other Renal Units or for the same Unit, at some future time when the model is updated and

iv) the additional space requirement in the computer memory due to using the raw frequency data need not be at all onerous (4.6).

5.4.1 Survival Distributions

Published survival data concerning patients with renal failure is usually presented as life table data calculated by the actuarial method[1]. The term, survival distributions, will be used to refer to the survival data of patients on the different treatments (i.e. haemodialysis, C.A.P.D., or transplantation) calculated in this way. Different survival distributions, however, can be obtained from the same patient data, by changing the definition of a "failure". Three different ways are:

i) all changes in treatment (including changes for the "better", i.e. transplants) are counted as "failures",

ii) failures in treatment are counted as "failures" or

iii) only deaths are counted as "failures".

Method (i) is inappropriate for use in the simulation model in which transplants are assumed to be offered to patients separately and independently from other patient activities.

Survival distributions of type (ii) are used for "haemodialysis" and "C.A.P.D. failure". The *activity* at the start of a "treatment" determines the "date of treatment failure". The decision as to whether a "patient" should "die" or try an alternative "treatment" is taken at the "time" of "treatment failure", in the *activity*, FAIL TREATMENT.

The probability of a patient dying after a transplant rejection is more complex, however, because it is related to the length of time

since the transplant operation took place. To overcome this, when the "patient" has a "transplant", two "times" are sampled:

- the "time" of "death" (using survival distribution, method (iii)),
- the "time" of "failure" without "death" (using methods (ii) and (iii) to get the survival distribution).

The shortest of these "times" is used to determine when "failure" or "death" should take place.

John Chambers [38] calculated actuarial survival curves for the haemodialysis and transplant patients, at Portsmouth Renal Unit. It was evident from his data that:

i) the figures for Portsmouth Renal Unit were very similar to the national figures published by E.D.T.A. and
ii) the numbers of patients in each age group were too small to produce reliable survival data for use in a model.

In order to take account of the important influence age has on patients' life expectancies, therefore, I decided to use mainly published national figures from the E.D.T.A. Annual Report[6] rather than analyse local data. Wherever possible, the survival data used in the simulation was not only broken down by age but also by whether the patient had had a transplant before or not (Appendix F.1). There were insufficient data available to take into account the other factors including those listed in 1.3.3, such as the patient's health and the skill of the surgeon.

5.4.2 Lengths of patient stays and time between episodes

The survey of using the "buff discharge book" was validated and augmented from the following sources:

i) John Chambers's inpatient data from Patient Notes[69],
ii) annual administrative statistics showing numbers of admissions and the occupancy of nephrology beds and
iii) the sample survey of Patient Notes used for costing (Appendix I).

Patients on different treatments were found to have different length of stay distributions, but there were too few patients in the survey to identify an age factor.

The time spent between admissions was much more difficult to estimate from the available data because the time periods involved were much longer. It was possible, however, to calculate average times between admissions by estimating the average number of admissions per patient (by treatment) per year. In the absence of more detailed data, I assumed they had negative exponential distributions.

5.4.3 Lengths of time on unit dialysis and time between episodes

An analysis of Portsmouth E.D.T.A. data gave the distribution of lengths of stay of patients on unit dialysis, both in the initial stages of treatment on the dialysis/transplant programme, before starting home dialysis and also after a transplant rejection. It gave little or no information, however, about other periods of unit dialysis.

The analysis of the weekly unit dialysis sheets (5.3.5) determined the frequency and length of periods of unit dialysis of patients already established on home dialysis.

5.4.4 Patient attributes and decisions

Published national and local figures were used to provide data from which to sample the characteristics given to new patients created by the simulation. The effect of age on a patient's suitability for transplantation and on his initial dialysis treatment was taken into account (Appendix F).

After a transplant rejection either or both of the following changes to the patient's characteristics may take place:

i) the antibody index may increase (1.3.3) or
ii) the patient may no longer be considered "suitable for transplantation".

In order to model the changes, the simulation program re-samples these characteristics using the same distributions as for new patients.

The antibody index, however, is sampled from the conditional distribution: conditional upon the new value being greater than or equal to the previous one.

Decisions not entirely dependent on the patient characteristics are:

i) whether "failed dialysis patients" should "die" or not and
ii) the type of "hospital care" needed by "home dialysis patients" ("unit dialysis" or "inpatient treatment").

The data for the discrete distributions were obtained from published sources and from the data collection exercises described in the previous sections.

5.4.5 Patient data for setting the starting conditions

I found almost all the information that I needed for completing the patient forms (Appendix D) by using lists of patients prepared for administrative purposes (5.3.6) together with the most recent monthly U.K. Transplant computer list (5.3.3). Information about the antibody levels of patients with functioning grafts, however, had to be acquired separately from lists of results of immunology tests from the Immunology Laboratory.

The number of patients on each type of treatment at the beginning of the simulation runs used in this dissertation can be seen on the simulation output shown in Appendix E (week 0).

5.4.6 Arrival rates

In my previous models[37,42], I have assumed that the arrival of patients into the dialysis/transplant programme and the death of people who provide cadaver kidneys, may be assumed to be random events. There is a strong case, however, for using constant arrival rates in the model (see 6.3.3).

5.5 IMPROVEMENTS IN THE PAPER FLOW

From Figure 5.1, it is clear that there is considerable redundancy in the many data collection activities in Portsmouth Renal

Unit. The ever increasing numbers of manual data collection systems puts some Renal Unit staff under great pressure to collect and provide data. If the simulation program is to be run on a regular basis, it must not give rise to yet additional manual data collection. Any requirements for data should be integrated with, and where possible, replace existing activities.

A solution involving a computerised information system might be successful in substantially reducing paper work. Its purpose and function would have to be determined in detail prior to its design or purchase, and staff would have to be prepared to abandon their redundant data collection systems. A well designed patient data base system, which could provide accurate and up-to-date information for the H.A.A. and E.D.T.A. computer systems, would save money and also be very advantageous for the provision of data for the simulation program.

5.6 SUMMARY OF DATA COLLECTION

Figure 5.2 summarises the sources of data and their use in the simulation program.

Patient data for setting the starting conditions were obtained almost entirely from lists of patients produced for administrative purposes and from U.K. Transplant waiting lists.

The sources of data for the time dependent distributions were as follows:

i) national E.D.T.A. data for the treatment survival distributions,

ii) U.K. Transplant waiting list data, for waiting time before patients starting dialysis were put on a transplant waiting list,

iii) the "buff discharge book", cross checked against a survey of Patient Notes, for the inpatient data,

iv) the weekly dialysis sheets and a file of local E.D.T.A. data, for the length of stay distributions on unit dialysis treatment and

v) the lists of patients compiled for administrative purposes, for the patient and kidney arrival rates.

The discrete distribution data were obtained mainly from published statistics.

Chapter 6

MODEL TESTING

6.1 INTRODUCTION

6.1.1 Model Structure

The discrete event simulation model describes the progress of patients through treatment in a dialysis/transplant programme (3.5). The arrival of "patients" into the system is independent of the state of the system. In order for "patient" *entities* to *engage* in "inpatient" and "dialysis" *activities*, they must enter *lists* to wait for *resources* such as "beds" or "unit dialysis machines" to become available. A "patient" may also have *shadow entities*, in order to *hold*:

i) the *time* of "treatment failure",
ii) the *time* after the start of "dialysis" when "patients" are put on the "transplant waiting list" or
iii) the *time* "patients" spend on "unit dialysis" prior to "training for home dialysis".

"Kidneys" arrive independently of the number of "patients" in the system and each is allocated to a "patient" with a compatible "blood group" and "antibody index" if such a patient is waiting.

"Patients" who "fail treatment" have "inpatient treatment" and then either "die" or start "dialysis treatment". Those failing "haemodialysis" start "C.A.P.D." and vice versa.

The model was designed to close consultation with the staff of the Portsmouth Renal Unit and was run with data based on various sources including published national figures and local surveys (Chapter 5).

6.1.2 Model Testing

i) Validation and verification. The model must be tested for validity. I shall use Mitchell's definition[54] that a model is valid if it

> "is a sufficiently good representation of the real-life system to allow conclusions to be drawn (and actions to be taken) on the strength of the results."

I shall adopt the useful distinction Hollocks[60] makes between verification:

> "does the model do what was intended?",

and validation:

> "does the model represent the real world adequately, i.e. is what was intended satisfactory?".

The model should be verified at every stage in its development (6.2) but it can only be properly validated when it is almost completely ready for use (6.5). All the previous models in Chapter 2 may have been verified, but their validity is in considerable question.

ii) Variance reduction. Another important activity is variance reduction whose purpose is to improve the efficiency of estimators (usually the means) deduced from simulation results (6.3).

iii) Robustness to assumptions. Model assumptions which may be appropriate for one Renal Unit at a particular point in time may need to be changed in other circumstances. It is important, therefore, that all independent sources of variation which might be relevant in the real world have an explicit representation in the model (2.2.5) and that any assumptions that may need to be changed are not fundamental to the model structure.

iv) Sensitivity analysis. Sensitivity analysis is performed to determine the extent to which a small change in the different model parameters will influence the results from the model.

6.2 VERIFICATION

Pascal can be written in a logically structured and transparent way which is less prone to coding errors. Nevertheless, some coding errors in a large program are almost inevitable. I tested all the BACKGROUND procedures and functions (Appendix A.2) and changes and additions to the SIMULATION PACKAGE units (Appendix A.1) outside the simulation program, to see that they did what they were supposed to do.

Testing the procedures in the ACTIVITIES units, however, has to be done in the context of a simulation program. I built a succession of simulations that became increasingly complicated at each stage and I ran the programmes under a variety of conditions (e.g. no arrivals, no transplants, no initial patients in the dialysis/transplant programme) to check that the monitor display looked sensible and realistic (4.4.2). I also tested the final program by:

i) studying the printed output shown in Appendix E and
ii) recording on a disk file every change of *activity* by every "patient" and the *time* at which this happened. I then sorted the disk file by "patient" to see whether each "patient" had a realistic "medical history".

6.3 REDUCTION OF VARIANCE

The many probability distributions used in this simulation (Appendix F) lead to frequent sampling from random number streams. The variances of results from runs using different independent random number streams are likely, therefore, to be large. This is undesirable because:

i) in the comparison of two runs with different input (e.g. two different arrival rates) it is very time consuming to determine the extent to which the differences between results are due to different sampling of random numbers, and

how much due to the different input parameters and

ii) the use of the simulation is limited if several runs are needed (with the same parameters but different random number streams) in order to obtain information for planning purposes.

This section deals with the measurement of the variability between results (6.3.1), and the exploration of different ways of reducing it by:

i) constraining the number of arrivals into the system (6.3.2),

ii) using constant *times* in the simulation instead of sampling from probability distributions (6.3.3, 6.3.4) and

iii) using different random number streams for different probability distributions (6.3.5).

I did not feel that the additional complexity, both in the model structure and in programming, of using other more complicated variance reducing techniques[54] was justified.

6.3.1 Runs with constraints relaxed

In order to obtain comparative uninterrupted runs of the simulation program, I relaxed the constraints by giving high values to the number of *resources* I made available in the simulation program (see Appendix G). In these runs, the program sampled the times between "patient" and "kidney" arrivals from negative exponential distributions (5.4.6).

TABLE 6.1

Range of results from 10 unconstrained runs of the simulation program

		Year 1	Year 2	Year 3	Year 4	Year 5
Total patients	Min.	299	310	324	337	351
	Max.	327	358	374	402	426
Functioning grafts	Min.	165	180	191	206	221
	Max.	179	209	229	242	254

Table 6.1 shows that, in 10 runs, there was a difference of as much as 17% between the predicted total number of patients on the dialysis/ transplant programme at five years.

6.3.2 Runs constrained by availability of unit dialysis machines

In practice, constraints on *resource* availability may be expected to reduce variability in the number of "patients" under "treatment". Further runs were done, therefore, in which I increased the "admission" rate but held the number of "unit dialysis sessions" and "machines" level at their previous value (i.e. 70 "unit dialysis machine sessions" per "week") and made the total "C.A.P.D." places equal to 30 (see Appendix G). In order to prevent large *queues* building up in the system, arriving "patients" were only given *attributes* and added to *queues* if there were fewer than 10 "new" "patients" waiting in *queues* for dialysis treatment. In effect, therefore, new arrivals were limited by the availability of "dialysis machines". (See footnote).

TABLE 6.2

Range of results from 10 runs of the simulation program with arrivals constrained by unit dialysis sessions

		Year 1	Year 2	Year 3	Year 4	Year 5
Total patients	Min.	316	334	337	343	351
	Max.	332	351	359	370	389
Functioning grafts	Min.	163	170	196	204	225
	Max.	174	194	207	227	235

This model, which succeeded in cutting the range of the results by approximately half (Table 6.2), is a crude representation of the limiting of demand by supply. The true situation is more complex and subtle:

i) doctors refer patients to a particular Renal Unit, with a knowledge of that unit's reputation for accepting patients.

ii) renal consultants admit patients to the dialysis/transplant programme using "medical criteria" but with a knowledge of the availability of unit dialysis facilities in the back of their minds and

iii) additional unit dialysis sessions may be made available when the demand for the existing sessions exceeds supply and queues build up.

Footnote: The order of the *C activities* was changed to give new patients lower priority for unit dialysis than existing patients.

Chapter 7 describes a more realistic use of the simulation in which additional "unit dialysis sessions" or "machines" are supplied interactively when *queues* for these facilities build up. This use, in which the arrivals are not rigidly constrained, will probably not result in a similar significant reduction in the variance, although some improvement on the unconstrained model may be expected.

6.3.3 Constant arrival rates

The results in 6.3.2 showed that the constraint on the number of arrivals (which reduced the variability of the number of arrivals) had a considerable impact on the range of the total number of "patients" predicted to be in the system. The variance in the mean number of arrivals in a time period can be reduced to zero by simply fixing the time between arrivals rather than sampling times from distributions.

The use of a constant arrival rate for "patients" and "kidneys" is less realistic (5.4.6) than the random arrival rate assumed in 6.3.1 and tends to even out peaks in the demand of *resources* ("beds" and "unit dialysis machines"). Since, however, one of the main purposes of the simulation is to test the effect of the existing constraints on the resources and to explore the need for additional resources (3.1.2), using constant arrival rates is more efficient than replicating runs for a random arrival rate with several different random number streams.

TABLE 6.3

Range of results from 10 unconstrained runs of the simulation program with constant arrival rates

		Year 1	Year 2	Year 3	Year 4	Year 5
Total patients	Min.	312	335	355	366	380
	Max.	326	351	362	389	404
Functioning grafts	Min.	166	186	203	222	228
	Max.	182	209	229	254	266

Table 6.3 shows that the range in the total number of "patients" at five years is reduced by two thirds, compared to those in the results from runs using random arrivals (6.3.1). The range of the

numbers of "patients" with "functioning grafts", however, is very similar in both sets of runs. Other variable factors, such as "transplant rejection" rates and "matching" probabilities, must have a considerable impact on the numbers of these "patients". I used constant arrival rates of "patients" and "kidneys" for all the runs subsequently described in this dissertation.

6.3.4 Fixing other "times" between *activities*

It is not realistic to fix "patient" survival "times" on different "treatments", because if the survival times of "patients" on "treatments" were set equal to the mean survival time for that "treatment" (taking into account the age group of the patient etc.), they would already have been exceeded by most established "patients", who would therefore have to be "killed off" before the simulation started.

Although the length of stay of "times" on "unit dialysis" and "inpatient treatment" can be fixed too, this would be unrealistic and lead to problems. If the mean length of stay which is very much greater than the mode (Appendix F) were to be used, most "patients" would be spending longer periods of "time" in "hospital" than patients do in practice. This would distort the rest of the model. For example:

i) "Home dialysis patients" having "inpatient treatment" need "unit dialysis sessions" (3.5.5) if they stay more than three "days" in "hospital". A fixed "inpatient stay" would result in either every "patient" having "unit dialysis" when they "stay" in "hospital" or none of them depending whether the "stay" was more than three "days" or not.

ii) More "patients" would receive "inpatient treatment" and would therefore be "unavailable" for "haemodialysis training" (3.5.5) or for "transplantation" (3.5.6).

The "times" spent on these "treatments" were not, therefore, fixed.

6.3.5 Use of random number streams

The 20 independent random number streams, available in the SAMPLING unit (3.2.4), were allocated to different groups of distributions to reduce the variance between comparison runs. The groups were chosen to minimise the number of random number streams that are affected when a parameter is changed. Thus in comparing two runs, one before a change of parameter and one after, the "times" sampled from distributions (except those directly affected the parameter change) should in most cases remain the same.

6.4 ROBUSTNESS TO MODEL ASSUMPTIONS

A credible model, however well verified, must have acceptable assumptions. There are three classes of important assumptions:

i) fundamental to the whole model that cannot be easily changed (6.4.1),

ii) part of the model structure, but due to the robustness of the three phase simulation structure (3.2.3), can be changed by making only small alterations to the program coding (6.4.2) and

iii) inherent in the data used by the simulation program, which can be changed easily by entering different distribution data using the DISTRIBUTION INPUT program (6.4.3).

It is obviously desirable that any assumptions which might need to be adjusted due to changes in Renal Unit policies or activities, should not be of type (i).

There are also implicit assumptions that any aspects of the "real world" that have been omitted from the model, are comparatively of much less importance in their influence on the system and in the use of resources than those that have been included (6.4.4).

6.4.1 Fundamental assumptions

Models using the three phase simulation structure are generally robust because changes can be made to one *activity* without having repercussions on other *activities*. The use of *shadow entities* reduces

robustness, however, because changes to the *activities* of an *entity* may affect the *activities engaged* in by the *entity's shadow* too (or vice versa). Some assumptions made in this simulation would, therefore, be complex and time consuming to change. These fundamental assumptions are:

i) the *time* of "treatment failure" (often leading to "death") is independent of all "patient" *activities*, succeeding the one in which the *time* is set and
ii) *time* spent on "unit dialysis", or the *time* spent on "dialysis" before going on the "transplant waiting list" is independent of the "amount of time" the "patients" spend having "inpatient treatment" meanwhile.

Although it may be argued that patients undergoing more frequent inpatient treatment are more likely to die or to spend a long period or time on unit dialysis before transferring to home dialysis, these relationships are not casual. (It is to be hoped, for example, that frequent inpatient treatment does not cause earlier death). The *time* set for these *activities* can, instead, be related to the "patient" *attributes* which can be changed and augmented without fundamental changes to the model structure.

6.4.2 Other structural assumptions

Assumptions which may be changed by small changes to the program coding include:

i) once a type of "treatment" has been started "patients" pursue this until "failure" or "death" regardless of the availability of *resources* or the size of the *queues*,
ii) the choice of "treatment" for a "patient" is not influenced by the availability of *resources*,
iii) the arrival rate of "patients" seeking a place on the "dialysis/transplant programme" is independent of the number of "patients" on the "programme" or of the *resources* available to treat him but can be altered by the user interacting with the program,

iv) the arrival rate of "kidneys" for "transplantation" is independent of the number of "patients" on the "transplant waiting list" but can be altered by the user interacting with the program,

v) the probability of a "patient" requiring "inpatient treatment" and/or an "operation" is only dependent on the "patient" *attribute*, "treatment", and is independent of "patient" *activities* or other *attributes*,

vi) the only intrinsic "patient" *attribute* which influences a "patient's" progress through the system is "age" and

vii) the only aspect of "treatment" history which influences a "patient's" progress through the system (i.e. extrinsic "patient" *attribute*) is whether he has had a previous transplant operation or not.

6.4.3 Assumptions in the data

Chapter 4 lists the types of distributions used in the simulation. The choice of distributions and the numbers used in the distributions were based on comprehensive data collection exercises (Chapter 5). If, however, additional information, or a proposed change in policy, were to invalidate the data in these distributions, new data can be entered using the DISTRIBUTION INPUT program.

Section 6.5 will describe a case in point which arose in practice during development of the model, because a few months after the data collection exercise the Renal Unit consultants did indeed make fundamental policy changes in the treatment of patients on the Renal Unit. There was in practice no difficulty in incorporating these in the model by alterations to the distribution data without any changes to the program coding.

6.4.4 The inclusion of relevant aspects of the real world

Section 3.1.2 describes the system that was modelled. In determining the system boundaries and identifying the elements of the system (3.4), I took care to include, as far as possible, the independent sources of variation that might at some time in the future (or at another Renal Unit) influence the treatments patients are given and their use of resources. This is a significant

improvement on previous models which used System A (see 2.1) which excluded resources and resource constraints.

If an important variable were found to have been omitted, substantial rewriting of the simulation program might be needed (particularly if it required *shadow activities*, or interacted with the existing ones (6.4.1)). It is inevitable, however, that some program adjustment will be needed as time progresses, as treatment and fashions change. It may be necessary, for example, to represent minimal care units in the simulation, if they are to be considered as a replacement for home dialysis. Due to the robust structure of the three phase simulation design, this change would require little more than a few additional *activities*.

6.5 VALIDATION

For planning purposes the model assumptions must be reasonable and the model must look and behave like the real system. Validity testing of a complex simulation with many parameters is difficult to process[54,70]. There are two main approaches to validating a visual interactive simulation:

i) the program is run from some time in the past, to the present day to see how close the predictions of the simulation are to what has happened in "real life" or
ii) the running simulation is observed, used and validated by those who may be very familiar with the system that is being modelled, using the visual information available on the monitor screen.

6.5.1 Running the program from the past to the present

The first approach is attractive because it enables statistical tests to be performed and convincing looking diagrams to be drawn. This approach is known to be unsatisfactory[70] because:

i) there are also considerable problems to be encountered in collecting the appropriate retrospective data,

ii) it only tests the forecasting ability of the model, which is not its main function. It cannot test how realistically the model behaves under different and possibly extreme policy changes.

It is a useful exercise, however, because it may identify a large discrepancy between the model forecast and the activities in the "real world". If, after a model has been structured in close consultation with those familiar with the system and verified at every stage, discrepancies may be due to either:

i) major policy changes in the validation period or
ii) differences between the way the system was said to behave by those managing it and how it actually worked in practice.

A discrepancy due to reason (i) can be turned to advantage, if the model can be made to reflect the policy changes by suitable changes to the distributions and parameters, thus showing it to be robust model which can reflect a range of circumstances.

In September 1983, I made a comparison between the numbers and types of patients in the Renal Unit between February 1983 and that date, and those modelled in the simulation program using the distribution data described in Appendix F.1 and the simulation parameters in Appendix G. Monthly figures which I collected from the Renal Unit were:

i) the total patients on each form of treatment at the end of each month,
ii) the size of the transplant waiting list and
iii) the number of admissions and transplants.

TABLE 6.4

Comparison between figures from the Renal Unit on 26.9.83 and predictions from 30 "week" simulation runs

	Simulation(1)	Figures from Renal Unit	Simulation(2)
Numbers of patients:			
haemodialysis	128	102	103
C.A.P.D.	24	49	45
functioning graft	170	184	183
TOTAL	322	335	331
Transplant waiting list	26	53	51
For 30 weeks:			
admissions	42	47	51
transplants	39	45	43

(1) run using data in Appendix F.1,
(2) run using data in Appendix F.2.

The figures in the first two columns of Table 6.4 are very different indicating that the simulation gave a poor forecast. The Renal Unit physicians, however, admitted that there had been a considerable change over the previous months and that:

i) they were putting a much higher proportion of patients on C.A.P.D. rather than haemodialysis treatment,
ii) the admission and transplant rates had increased,
iii) a higher proportion of patients were being put on the transplant waiting list,
iv) C.A.P.D. patients were admitted to hospital less frequently and for shorter periods of time,
v) patient survival, particularly C.A.P.D. survival, had improved and that
vi) the home dialysis programme was to be run down with a view to building minimal care units at some time in the future.

These policy changes and updated survival data were incorporated into the simulation model without changing any program coding and

certainly without upsetting any fundamental model assumptions (Table 6.3). Although minimal care units were not modelled explicitly, "patients" could be prevented from transferring to "home dialysis" by making no "home dialysis machines" available after the initialisation (ie in "week" 1) of a simulation run. Appendix F.2 shows how the distribution data and simulation parameters were changed to reflect the changes in policy and in patient survival. Chapters 7 and 8 show in detail the effects of these policy changes on resource use and costs.

The model can thus be seen both theoretically and practically to be robust and adaptable to some dramatic policy changes.

6.5.2 Demonstrating the simulation

The running simulation was shown in the Spring of 1983 to the following groups of people:

i) the renal physicians,
ii) the transplant surgeon and other Renal Unit staff and
iii) to some District Health Authority staff including the assistant District Treasurer, the Unit Administrator and the District Information Officer.

The staff were interested in the model and made small suggestions for its improvement.

In October 1983, using the amended distribution data in Appendix F.2, the three renal physicians and the home dialysis administrator agreed at another demonstration that:

i) the distribution data used in the model looked sensible and
ii) the simulation program behaved in a realistic way as a result of the data they entered into it.

6.6 SENSITIVITY ANALYSIS

This section shows how the simulation reacts to changes in some of the important variables and the way they interact with each other. The system is complex and the simulation does not attain a steady state for very many years. It is clearly impossible, therefore, to

explore comprehensively the whole multidimensional system, and to test the sensitivity of all the assumptions (6.4). Two approaches were, therefore, chosen:

i) a factorial analysis of the influence of three important variables in the first six months and one year of the simulation runs (6.6.1) and
ii) the effect of different kidney arrival rates with other variables kept constant (6.6.2).

The distribution data for the runs in this section were those in Appendix F.1 and the constraints and parameters are shown in Appendix G.

6.6.1 A factorial design

The use of a factorial design enables the influence of several variables to be explored with a small number of runs[71,72]. The output measures were:

i) the total number of patients under treatment, excluding new patients waiting for a place in the Renal Unit (i.e. the total number of patients whose lives have been saved) and
ii) the number of patients with functioning grafts, who could thus be expected to have a better quality of life (1.3.3).

I chose to examine the influence of three variables with a two level factorial design. Two values of each variable were chosen and eight runs were performed, one with each of the possible combinations of values of the variables, to give a broad picture of how the simulation behaves. In each of these runs I used the same random number streams and made the arrival rate of patients 70 per year (Appendix G). The variables I chose were amongst those most likely to be varied by a user: beds, unit machine sessions and the kidney arrival rate per year. Table 6.5 shows the factor levels and the average results from the four runs corresponding to each level.

TABLE 6.5

The parameters and results averaged over four runs from a two level factorial sensitivity analysis

factors	factor levels		total patients		transplant patients	
			6 months	1 year	6 months	1 year
beds	min.	17	301.8	312.8	161.8	171.8
	max.	26	299.8	312.3	166.0	175.8
unit machine sessions	min.	50	290.8	297.3	163.3	172.3
	max.	120	310.8	327.8	164.5	175.3
kidney arrival rate/year	min.	40	302.5	314.5	159.0	165.8
	max.	100	299.0	310.5	168.8	181.8

From Table 6.5 and from the analysis of main effects and interactions in Appendix H, it can be seen that:

i) The total number of patients under treatment is clearly most influenced by the availability of unit dialysis sessions (which when sessions are limited, behaves as a bottle neck) and very little by the availability of beds and the arrival rate of kidneys. An increased kidney arrival rate (with a resulting increase in the transplant rate) might be expected to relieve pressure on unit dialysis sessions and thus allow more patients into the system but such an effect is not apparent from these runs. The interactions between the different parameters are comparatively small (Table H.2, Appendix H).

ii) The number of patients with functioning grafts is, not surprisingly, most strongly influenced by the kidney arrival rate. Table H.1, (Appendix H) shows that when the kidney arrival rate is high, the availability of beds has a noticeable effect on the number of transplant patients (by constraining the transplant rate). This is confirmed by the size of the interaction between beds and kidney availability shown in Table H.2. The interaction between the kidney arrival rate and unit dialysis machine availability is, however, negligible.

6.6.2 Changing the kidney arrival rate

Whereas the provision of beds and unit dialysis sessions can be controlled and their influence on the system is fairly predictable, the Renal consultants have less control over the availability of kidneys and their use is limited by the availability of compatible patients on the waiting list. This was, however, shown to be one of the important variables in 6.6.1. In order to explore it in more detail (using the variables shown in Appendix G), I ran the simulation program with kidney arrival rates of 0, 20, 40, 60, 80, 100 and 120 per year.

Since the number of patients arriving on the transplant waiting list in the first six months in each of these runs is almost the same, a comparison can be made between the transplant rates shown in the first six months of each run. Figure 6.1 shows that the transplant rate is limited by the availability of compatible patients for transplantation when the kidney arrival rate is high. Figure 6.2 shows that the kidney arrival rate that maintains the transplant arrival rate constant is approximately 45 per year. This state of equilibrium clearly depends not only on the patient arrival rate and the proportion of patients thought suitable for transplantation, but also on the size of the transplant waiting list. The smaller the waiting list, the higher the kidney arrival rate has to be (and the more kidneys that cannot be matched) in order to maintain the equilibrium.

6.6.3 Conclusion

The system is very sensitive to the provision of unit dialysis sessions (which act as a constraint on the number of admissions). It is also sensitive to the kidney arrival rate, although it becomes decreasingly sensitive when the kidney arrival rate is large compared to the number of patients available for transplantation. The system is less sensitive to the provision of beds but because transplant operations cannot be performed when the transplant beds are full, fewer beds do cause the number of patients with functioning grafts to be smaller than it would otherwise be.

FIGURE 6.1

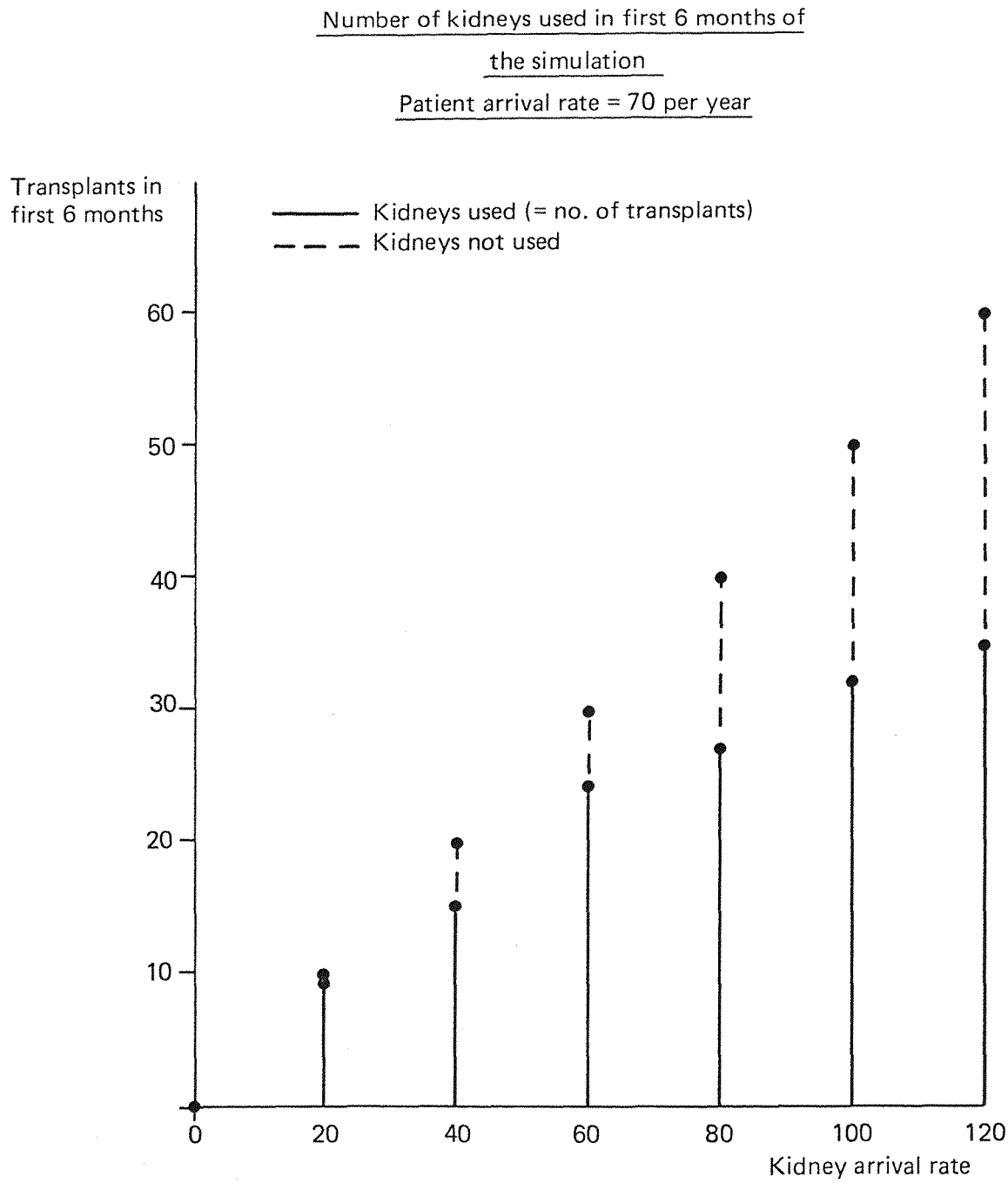
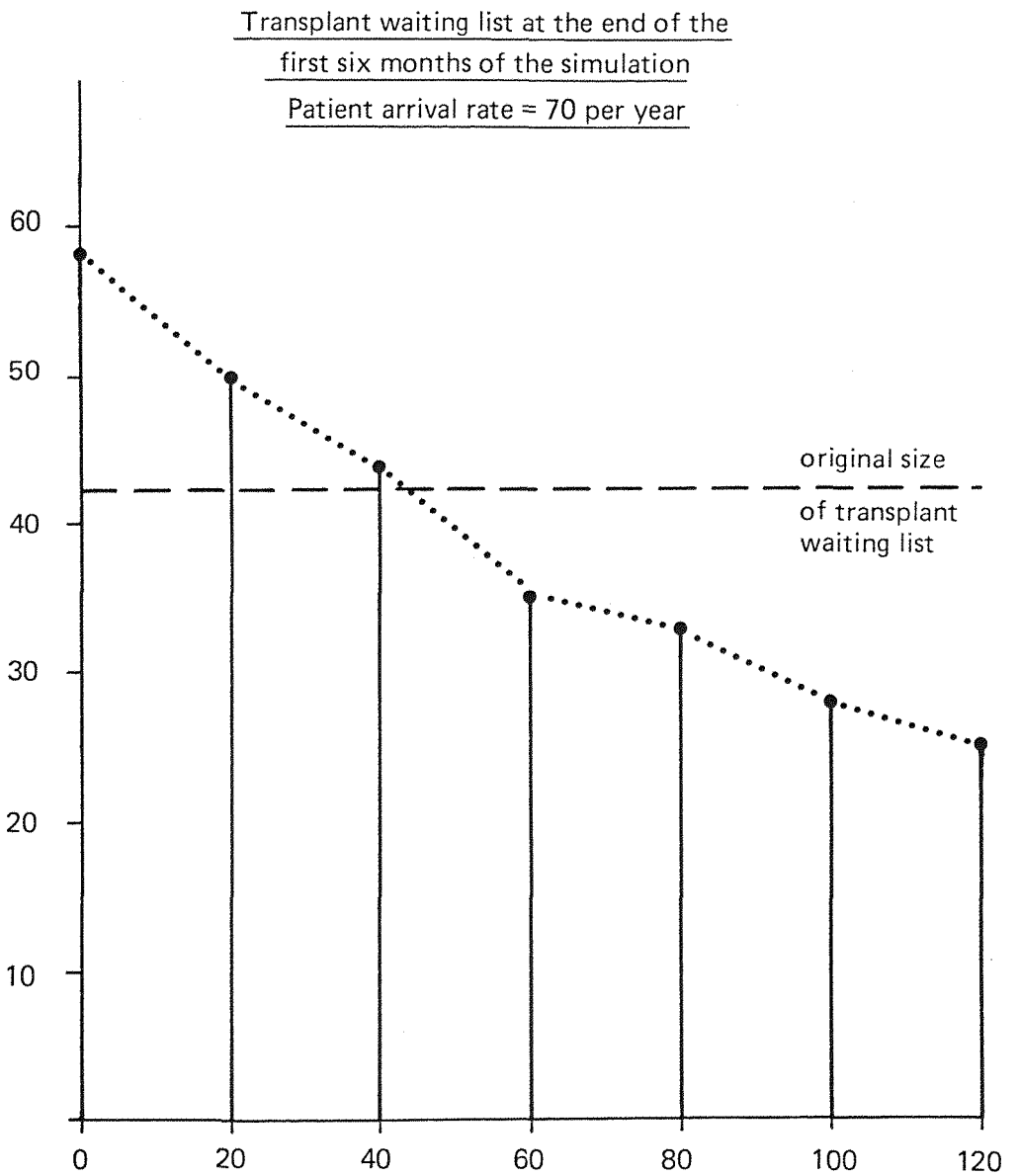

Number of kidneys used in first 6 months of the simulation
Patient arrival rate = 70 per year
Transplants in first 6 months
Kidneys used (= no. of transplants)
Kidneys not used
60
50
40
30
20
10
0
20
40
60
80
100
120
Kidney arrival rate

FIGURE 6.2


Transplant waiting list at the end of the
first six months of the simulation
Patient arrival rate = 70 per year
60
50
40
30
20
10
original size
of transplant
waiting list
0
20
40
60
80
100
120

6.7 SUMMARY

The tabular output on the monitor screen during a run provides valuable information with which to verify and validate the model in a similar way to graphical output[60]. This is a valuable addition to conventional program testing and simulation validation techniques, both of which have limitations when used in testing a complex simulation program (6.2, 6.5.1).

The use of variance reduction techniques enables consistent and comparable runs to be made, thus facilitating the use of the simulation for determining the expected outcome of different Renal Unit policies and other changes in the data.

The complete change in Renal Unit policy in the past few months has demonstrated the robustness of the model. In the next chapter I shall show how the model can be used to examine the benefits and implications of such policy changes.

Chapter 7

USE FOR PLANNING

7.1 PLANNING PROBLEMS

The growth in numbers of patients on treatment on dialysis/ transplant programmes has resulted in increasing demands for Health Service resources each year (1.2). Planning services for a dialysis/ transplant programme is complicated by the different treatments available and the movement of patients between treatments. These problems are particularly acute at Portsmouth Renal Unit where:

i) the number of patients to be accepted on the programme in the past four years has almost doubled (Appendix F.3),
ii) there is a need to increase the number of admissions still further to meet the estimated potential demand for treatment in Wessex (1.5),
iii) the numbers of cadaver kidneys made available for transplantation (Appendix F.3) continues to increase.

There have been some major policy changes in the operation of the Renal Unit in recent months (6.5.1) including:

i) the use of C.A.P.D. rather than haemodialysis, whenever possible, for patients starting treatment on the dialysis/ transplant programme and
ii) the gradual run-down of the home dialysis programme.

7.2 THE SIMULATION RUNS

This chapter will describe four interactive simulation runs in which the following policy options were explored:

i) introducing the recent policy changes in which most new patients are started on C.A.P.D., rather than haemodialysis treatment (i.e. C.A.P.D. is the first choice treatment) but continuing the provision of home haemodialysis machines to

trained haemodialysis patients (7.2.1),

ii) retaining the previous emphasis on haemodialysis treatment in which the majority of new patients were started on haemodialysis rather than C.A.P.D. treatment (7.2.2),

iii) using the policy in (i) but increasing the admission rate in steps at approximately 40 week intervals until the provision of services reaches the level of approximately 40 per million population (7.2.3) and

iv) using C.A.P.D. as the first choice treatment as in (i) but running down the home haemodialysis programme by stopping the transfer of unit haemodialysis patients to home haemodialysis (7.2.4).

Appendix G shows the constraining values entered at the start of these simulation runs. The initial "patient" and "kidney" arrival rates were 90 per year, which were the same values as those used in the validation run (6.5.1).

I interrupted the simulation run when long *queues* built up for *resources* in order to relax the appropriate constraints or change parameters. Section 7.3 describes the implications of each simulation run on the demand for the following resources:

i) unit haemodialysis machines and sessions (7.3.1),

ii) inpatients beds (7.3.2),

iii) home dialysis machines (7.3.3),

iv) the provision of kidneys for transplantation (7.3.4), based on the assumption that sufficient kidneys would be made available to keep the transplant waiting list reasonably stable and

v) routine operating sessions (7.3.5).

For (i) and (ii), the simulation program was run for five "years", but in running (iii) and (iv), the program was stopped after three "years" because by then the implications of the policy changes had already become apparent.

7.2.1 Continuous peritoneal dialysis as first choice treatment (Run A)

This run was to explore the probable demand for resources if C.A.P.D. were to remain the first choice treatment as it has been in

recent months. No restriction was put on the availability of "home dialysis machines".

Figure 7.1 shows the predicted number of "patients" on each form of "treatment". The increase in the "kidney arrival" in the first year from 90 to 110 per year can be seen to have kept not only the size of the "transplant waiting list" stable, but also the total number of "patients" on "dialysis treatment" (following an initial increase in the first six months). Not surprisingly, there is an increase in the number of C.A.P.D. patients but this too levels off after about two and a half years. The increase in the number of "patients" with "functioning grafts", however, shows no sign at all of levelling off.

7.2.2 Haemodialysis as the first choice treatment (Run B)

In this option the majority of "patients" entering the "dialysis/transplant" programme start on "haemodialysis treatment" rather than "C.A.P.D. treatment", as they did prior to February 1983 when the patient data were collected.

Figure 7.2 looks very similar to Figure 7.1. The only difference of any importance is the smaller ratio of "patients" on "C.A.P.D. treatment" compared with "haemodialysis treatment". The different implications for the provision of "unit dialysis" facilities (7.3.1) and "home dialysis machines" (7.3.3) are, however, quite significant.

7.2.3 Increasing the arrival rate of patients (Run C)

The intake of patients to the Portsmouth dialysis/transplant programme was 62 in 1982 compared to an estimated potential demand of 120 per year to provide a service for the whole Wessex Region. In order to attain this figure, I increased the arrival rates of patients from 90 per year to 100 per year in week 44 and to 110 per year in week 88. The proportion of "patients" starting "C.A.P.D. treatment" rather than "haemodialysis treatment" was the same as for Run A.

Table 7.1 shows that the increase in the total number of "patients" at the end of three years over those predicted by Run A was almost equally distributed between "C.A.P.D. treatment" and "haemodialysis treatment", with only 6 additional "patients" with "functioning grafts". The main impact of the increased "patient" arrival rate was on the demand for "beds" (7.3.2).

FIGURE 7.1

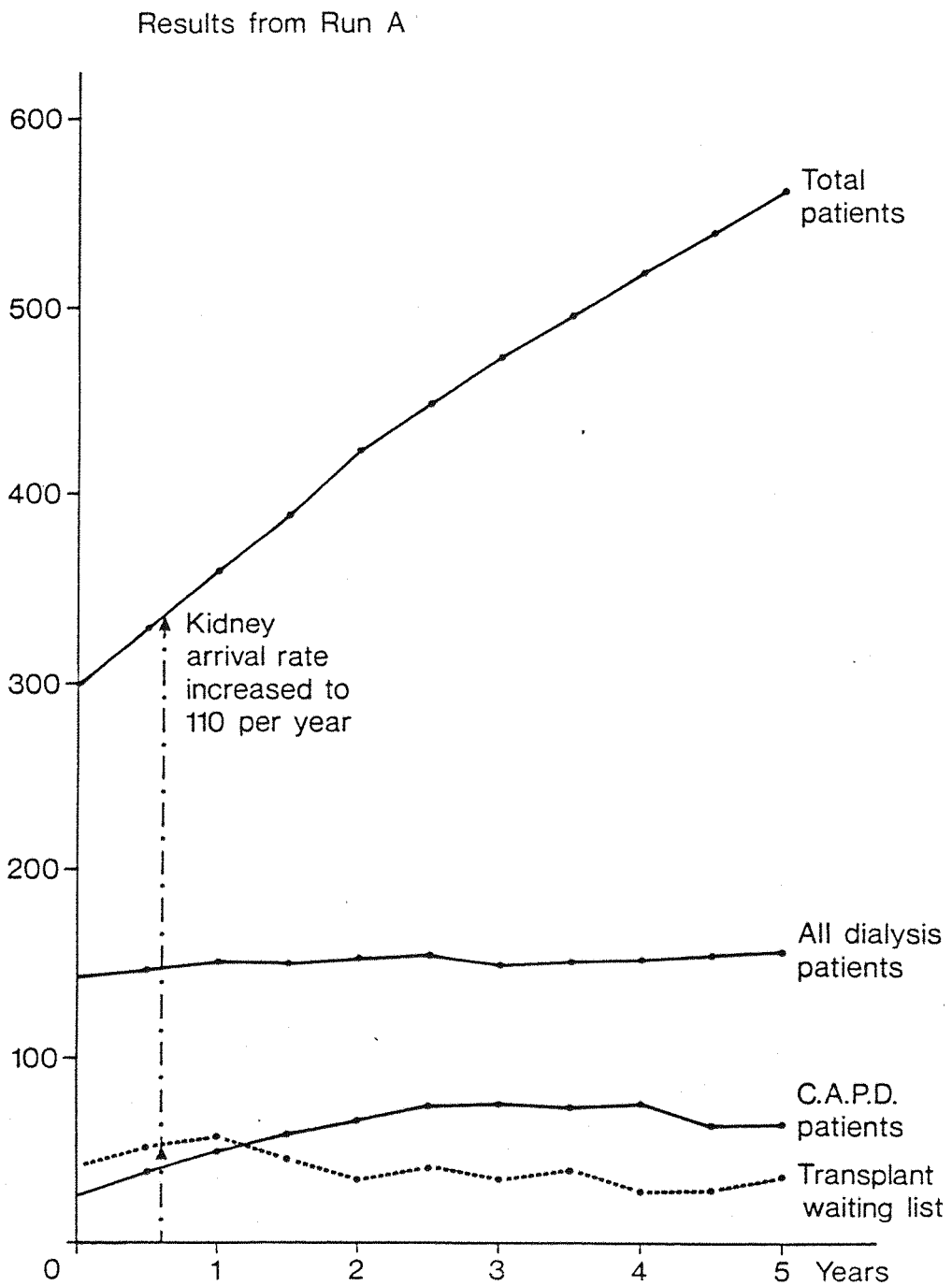

Results from Run A
600
500
400
300
200
100
0
1
2
3
4
5
Years
Total patients
Kidney arrival rate increased to 110 per year
All dialysis patients
C.A.P.D. patients
Transplant waiting list

FIGURE 7.2

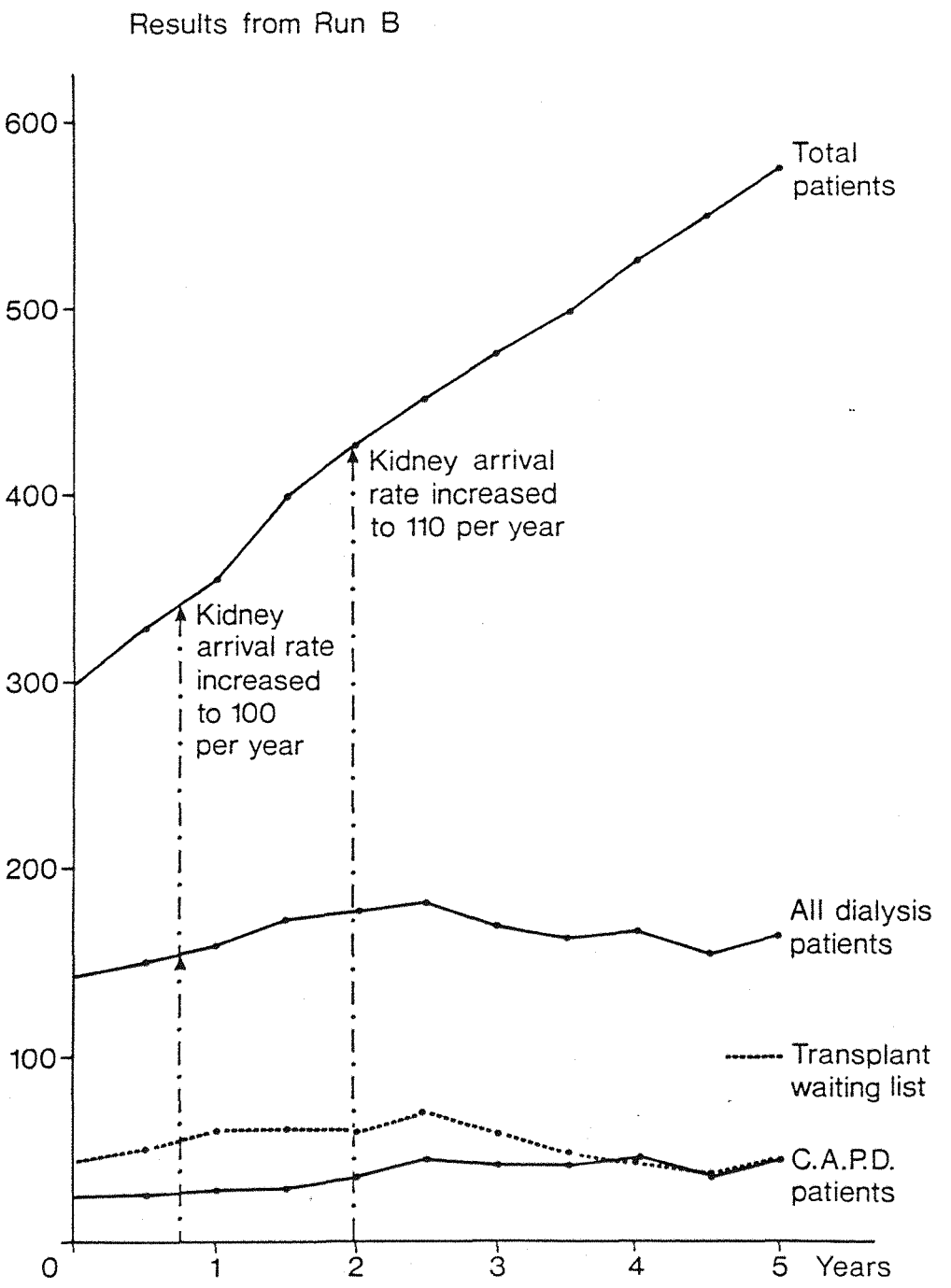

Results from Run B
600
500
400
300
200
100
0
1
2
3
4
5
Years
Total patients
Kidney arrival rate increased to 110 per year
Kidney arrival rate increased to 100 per year
All dialysis patients
Transplant waiting list
C.A.P.D. patients

TABLE 7.1

Number of "patients" on different "treatments" at the end of three "years"

	Unit	Home	C.A.P.D.	Transplant	Other	Total
Starting conditions	14	104	25	156	1	300
Run A	5	66	75	323	3	472
Run B	12	73	88	329	3	505
Run C	24	100	42	307	3	476
Run D	36	48	88	286	3	461

Note: the category "other" includes "new patients" and "patients" who have "failed" a "treatment".

7.2.4 Run down of the home haemodialysis programme (Run D)

The renal physicians in Portsmouth have decided that no further homes are to be provided with home haemodialysis machines after October 1st, 1983. In a few months' time, the District Health Authority will provide minimal care units to which patients trained in the techniques of haemodialysis will travel to use haemodialysis machines (6.5.1). Meanwhile however, all haemodialysis patients who do not have haemodialysis machines at home will have to remain on unit dialysis. In Run D, I reduced the maximum number of "home dialysis" places to zero in "week" 30, thus preventing any "patients" from starting "home dialysis" after that time.

Table 7.1 shows that by the end of three "years" the number of "patients" on "home dialysis" was halved and those on "unit dialysis" more than doubled. The lower number of "patients" with "functioning transplants" at three "years" compared to the other runs, resulted from a lower "transplant rate" (probably due to the high occupancy of the "transplant beds" in the first "two years" because I was less generous with the provision of "beds"!).

7.3 THE NEED FOR RESOURCES

7.3.1 Unit haemodialysis machines and sessions

Figure 7.3 shows that, as a result of the greater use of "C.A.P.D.

FIGURE 7.3

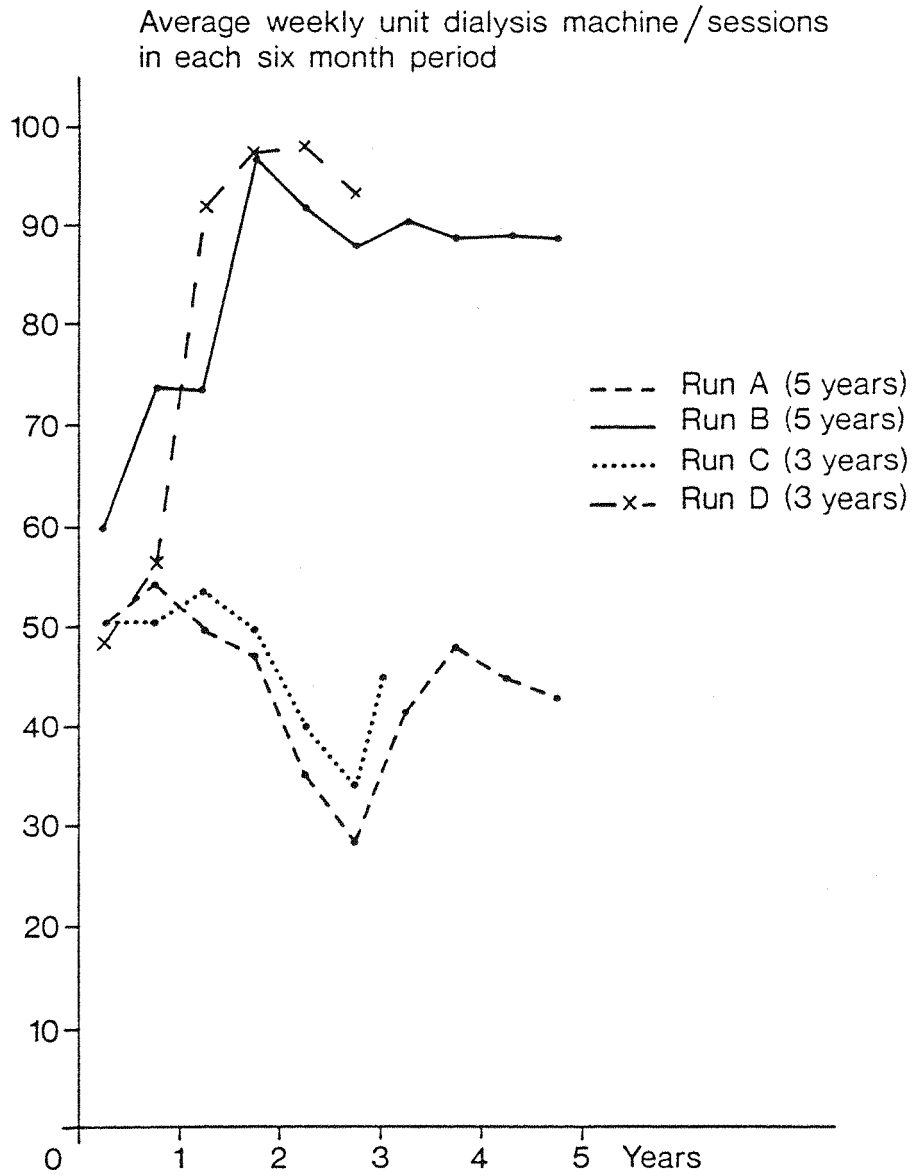
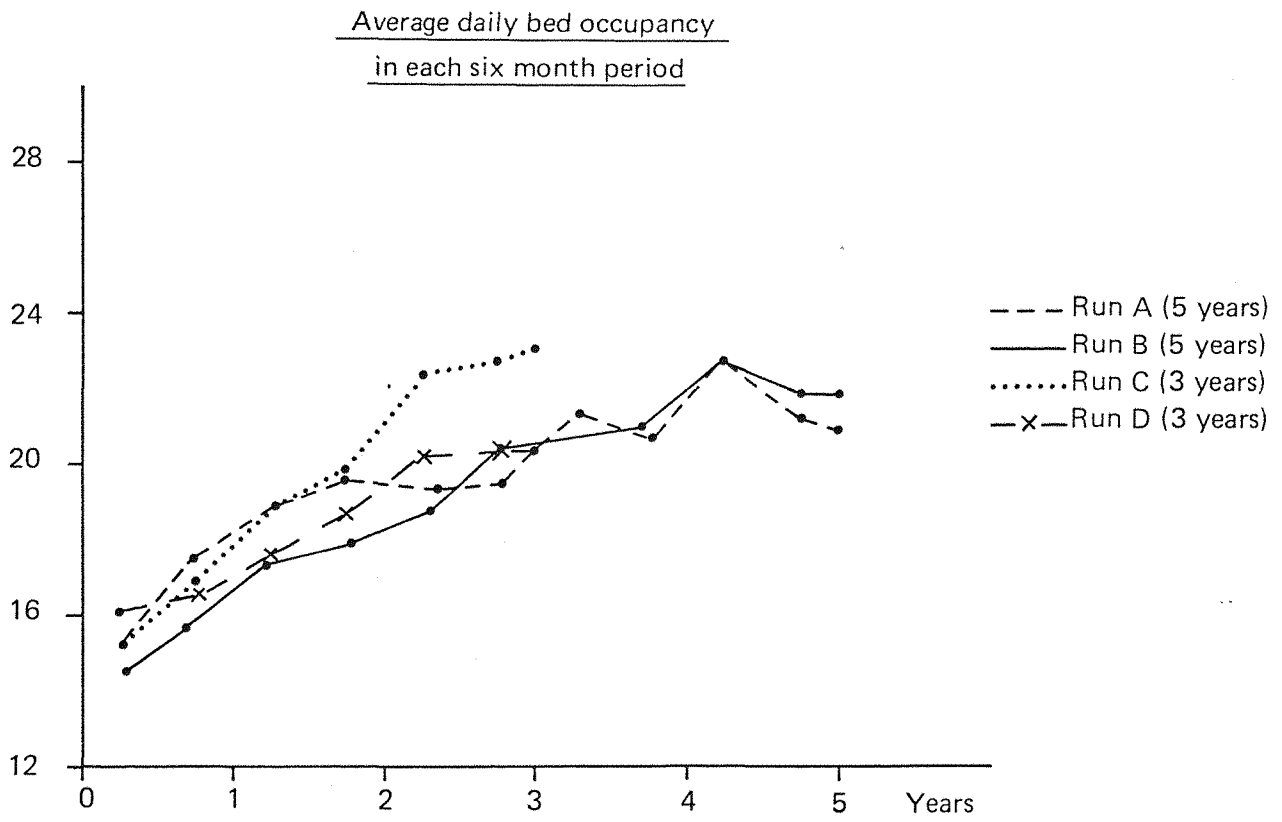

Average weekly unit dialysis machine / sessions in each six month period
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
Years
Run A (5 years)
Run B (5 years)
Run C (3 years)
Run D (3 years)

Figure 7.4


Average daily bed occupancy
in each six month period
28
24
20
16
12
0
1
2
3
4
5
Years
Run A (5 years)
Run B (5 years)
Run C (3 years)
Run D (3 years)

treatment" in Run A, there was a fall in the use of the "unit dialysis facilities" in the first three "years". Following this, however, the demand rose again to almost the previous level. Table 7.2 shows that even with the higher "patient" arrival rates of Run B, the provision of 70 "machine sessions" (the present level of provision) was adequate.

In contrast, additional "unit dialysis sessions" were needed in both Run C and Run D (Table 7.2). I was, however, able to provide these by "opening the unit" on additional "nights" and "Saturday morning" without increasing the number of "machines" (or the size of the "ward"). The difference in the use of "unit dialysis sessions" between Run A and B (Figure 7.3) is an indication of the number of machine sessions that may be needed in the minimal care units.

TABLE 7.2

The "week" number in which "unit dialysis sessions" were added to the original timetable in the space of three "years"

Run	Saturday	Mon. night	Thurs. night	Wed. night
A	-	-	-	-
B	-	-	-	-
C	22	73	73	97*
D	35	58	65	-

* this session was withdrawn again in "week" 143

In summary, the increased emphasis on C.A.P.D. treatment can be expected to lead a stabilisation or even a reduction in the need for unit dialysis places. If, however, trained haemodialysis patients cannot be discharged to home dialysis or minimal care units, it is likely that the Unit will have to be opened for three more sessions within 18 months from February 1983.

7.3.2 Inpatient beds

"Inpatients bed occupancy" fluctuated very considerably from "week" to "week" in all the runs. For a few "days" or even "weeks", "beds" would be occupied for most of the time and *queues* would build up, and then the demand would drop. So although I found that extra "beds" were needed in all the runs, the exact point in "time" at which

I provided them depended on how carefully I was watching the simulation at "times" of peak "bed occupancy".

Runs A, B and D all required an extra 4 "beds" during the first three "years". Run C, however, needed an extra four "beds" during the first "year" and a further four during the third "year". Figure 7.4 shows the difference in the use of "beds" between Runs A and C.

An increasing number of arrivals (Run C), therefore, can be expected to have a considerable impact on the need for beds. There was little difference, however, among the trends in use of "beds" in the other three runs.

7.3.3 Home dialysis machines

Table 7.3 shows that in the runs in which "C.A.P.D." was the first choice "treatment" (Runs A, C and D), more "machines" were removed from "homes" than were put into "homes". In Run B, however, the "installation requirements" exceeded the number of "machines" that were removed from "homes" and could be recycled.

TABLE 7.3

Number of "haemodialysis machines" put into "homes" and removed from "homes" in the first three "years"

Run		WEEKS 0-26	52	78	104	130	156
A	installed	12	17	17	15	13	10
	removed	16	26	20	29	15	17
B	installed	19	24	28	34	39	30
	removed	16	22	24	33	32	28
C	installed	12	18	13	11	15	15
	removed	16	25	17	17	27	16
D	installed	16	0	0	0	0	0
	removed	15	25	14	14	9	3

7.3.4 Kidneys

In all the runs the "kidney" arrival rate was increased from 90 per year to 110 per year in order to maintain between 50 and 70 "patients" on the "transplant waiting list". If the kidneys, in practice, do not prove to be available, the pressures on dialysis facilities in the future can be expected to exceed those predicted by the runs described in this chapter.

7.3.5 Routine operations

In all the runs the twice "weekly" operating sessions appeared well able to cope with the demand for "operations".

7.4 SUMMARY

The simulation runs were easy to perform and demonstrated the following likely shortfalls in resources:

i) inpatient beds whatever the policy,
ii) cadaver kidneys for transplantation and
iii) unit dialysis machine sessions if haemodialysis is the first choice treatment or if the home dialysis programme is run down.

The simulation is thus an extremely useful tool for exploring the implications of proposed policy changes.

Chapter 8

COSTING AND BUDGETING

8.1 BACKGROUND

8.1.1 The need for costs and budgets

The purpose of this chapter is to show how the simulation program can be incorporated within a budgeting system for the Renal Unit.

Each Renal Unit in England and Wales receives an annual allocation of funds from the Regional Health Authority in competition with other health provision (1.1.3). These finances are managed by the District Health Authority in which the unit is located.

In the past, despite the limited allocation of finance from Regional Health Authorities, renal consultants have treated patients without having to pay much regard to the consequent costs. In the absence of specialty costing, overspending could not be measured in detail. The money would, in these circumstances, have already been spent and the costs would have had to be absorbed by the Regional and District Health Authorities, using money intended for other purposes. In Wessex, with the increasing expense of the Renal Unit activities, the Health Authorities have been increasingly unwilling to do this.

It is in the interests of the District staff as well as the Regional and Renal Unit staff to measure, and have a system of monitoring, Renal Unit expenditure to ensure that the allocation is adequate and that the money is well spent. It is not only important to cost the renal services retrospectively and to measure income against expenditure, but also to have a means of predicting and influencing the future resource use and costs. Over the past two years, District staff have been measuring the costs and workload of the renal speciality with the intention of setting up a budget. (In their desire to do this, they have been following a trend towards greater concern for the financial accountability of clinical practices[73]).

8.1.2 Setting up a budget

The purpose of a budget is to plan and control future expenditure and activities. There are many types of budget, the theory of budgeting being detailed and somewhat complex[74]. In brief, however, there are the following stages in budgeting a health system:

i) determining the costs and their relationship to workload,
ii) projecting the numbers of patients who would be on each type of treatment, the resource use and their associated costs,
iii) agreeing with those managing the services (especially the doctors) the numbers of patients who could be treated and the types of treatment that could be offered, within the cost allocations,
iv) monitoring and reviewing patient numbers, treatments, resource use and costs throughout the year and
v) identifying where the projected expenditure is different from the actual expenditure.

For a budget, however, there must be a cost structure (8.1.4) and a means of calculating and monitoring the costs based on that structure. Most important, however, a model based on this structure is needed to project resource use and costs of different policies.

Chapter 7 showed how the simulation program could be used to predict the effects of different policies on patient numbers and resource needs. Because these can be related to the workload, they can be used to estimate costs and therefore the simulation program can be used as integral part of the budget. In this chapter I shall describe:

i) the costs I used, and their relationship to the simulation variables (8.2),
ii) the use of VISICALC[65] to explore the cost implications of the simulation runs discussed in Chapter 7 (8.3) and
iii) the conclusions that may be drawn from the results for the Portsmouth Renal Unit (8.4).

8.1.3 The costs that were included

The purpose of the costing exercise in this chapter was not to develop a definitive model with all possible costs, but to demonstrate the usefulness of the simulation model in the budgeting process. I decided to concentrate on the District Health Authority revenue costs together with the costs of installing, servicing and removing home dialysis machines, because:

i) they were more readily available and
ii) they appeared to have most influence on policies and planning.

The model could in the future, however, be extended to include:

i) local authority costs in providing social work support and in rehousing patients,
ii) ambulance transport costs and
iii) the capital costs of providing hospital buildings for the renal service.

Although patients' quality of life, life expectancy, economic activity and expenditure will inevitably effect decisions too, they do so in an unpredictable way which cannot be easily quantified. Much more work may be needed before these can be included in a costing model.

8.1.4 The cost structure

The cost of producing an item on the production line can be divided into direct material costs, direct personnel costs and overheads[75]. These classifications may also be used for patient care:

i) Direct material costs. These are the consumables, the ingredients for treatment (8.2.2). For patients on the dialysis transplant programme these costs include: drugs, fluids for dialysis, medical and surgical supplies and food for hospital patients.
ii) Direct personnel costs. The people who are employed by the Renal Unit or work exclusively with Renal patients, such as the home dialysis administrator and the ward nurses, are

in this category (8.2.3).

iii) Overheads. These are the costs that are impossible to associate directly with patient care (8.2.4). They include most of the costs of pathology services, maintenance of buildings, portering etc.

Home dialysis machines are difficult to classify because though they can be associated directly with patient care, they last many years and may be used for more than one patient. I shall, therefore, treat them separately (8.2.5).

With appropriate data collection procedures, the direct costs can be measured and accounted for in reasonable detail. In order to use them in a budget, however, projections of the use of the materials and the necessary manpower must be made. In product costing, direct costs are associated with individual products which can be simply scaled up in order to estimate future total direct costs. In the treatment of long term patients, however, there are no identifiable products and therefore future costs have to be estimated from work load projections.

There are different ways of attributing overheads to products (or patients[75]). The method in which an average cost is attributed to patients or other workload measurements (so the costs of pathology staff, for example, would be assumed to increase in proportion to the number of requests for tests) is clearly unsatisfactory for use in projections, because certain equipment and staff have to be available regardless of the workload. Much of the costs of overheads must be regarded as fixed but there are undoubtedly points in time when the increase in workload justifies the investment in new machinery or personnel.

Hospital costs are divided into the categories which are used in Appendix J. Many of these categories relate to departments (e.g. X ray, pharmacy) within the Health Service structure and most categories include some direct costs and some overheads. In order to use the costs for predictive purposes some costs within each category must be regarded as fixed (mainly overheads), and the rest must be related directly to the simulation output or to measures derived from the output. Ideally the proportion of fixed to variable costs in each category should be decided by analysis of retrospective data[75], but this was not possible in the time scale of this project. Since the

purpose of this chapter is simply to demonstrate how the simulation output can be costed, I have taken a short cut to determine the fixed and variable costs and appropriate parameters by "common sense" methods resulting from knowledge of the system and from discussions with finance staff.

8.2 THE COLLECTION AND INTERPRETATION OF COST DATA

8.2.1 Availability of cost data

The cost estimates that were readily available were:

i) those aggregated by hospital into categories used for Health Service accounting and
ii) those of staff appointed to the Renal Unit and of supplies bought specifically for patients on the dialysis/transplant programme (i.e. the direct costs).

In order to relate the costs to the simulation output, I needed, in addition, to know:

i) how much of the consumables (e.g. drugs) and their costs were attributable to Renal Unit patients and how consumption varied with the number and type of patients on the Renal Unit (8.2.2),
ii) the direct staff costs (8.2.3) and overheads (8.2.4) that could be attributed to the Renal Unit and how these could be expected to vary with changes in the numbers of patients on different treatments and
iii) the costs of installing home dialysis machines and removing them from patients's homes (8.2.5).

8.2.2 Direct material costs

In order to estimate the costs of consumables, I needed more information about pathology requests, X ray requests, pharmacy supplies and the use of medical and surgical equipment. I conducted a sample survey of notes of patients on the dialysis/transplant programme (Appendix I) to determine:

i) the type of pathology tests and X rays requested for inpatients, outpatients and day patients and

ii) drug prescriptions for outpatients.

The District Finance staff costed these data and collected information about the use of other consumables.

Table 8.1 shows the way in which I assumed the costs to vary with the simulation output.

TABLE 8.1

The way in which costs vary with resource use

The costs are assumed to vary linearly with those costs marked by an asterisk. The parameters of the equations were based mainly on surveys (Appendix I) and on data collected by the Finance Department.

Cost categories	Inpatient bed days +	Day patients	Out-patients +	Home patients +	New patients +
Consumables:					
pathology tests	*	*	*		
X rays	*	*	*		
medical & surgical equipment	*	*		*	
drugs & fluids	*	*	*	*	
food, laundry linen	*	*			
travel & telephone				*	*
Staff:					
secretarial	*	*	*	*	*
technicians		*		*	

\+ The treatment categories of the patients are also important.

NOTE: Outpatient numbers are not produced by the simulation program but are estimated from it.

8.2.3 Direct staff costs

Table 8.1 show those staffing costs that were regarded as varying with workload. Other direct staffing costs were assumed to vary as follows:

i) a small proportion of nursing staff costs were fixed and regarded as overheads but most staff were related to

numbers of inpatients beds, unit dialysis machine sessions, theatre sessions, outpatient sessions or operating sessions depending on where they worked (Appendix J) and

ii) medical staffing costs were regarded as fixed but with better data the cost model could no doubt be improved by relating the medical staffing to outpatient sessions, inpatients beds and transplant operations.

8.2.4 Overheads

All overheads, which were mainly staff costs (excluding those in (8.2.3), were regarded as fixed costs, with the exception of operating theatre costs which were regarded as varying with routine operating sessions and the number of transplant operations performed in a time period. Appendix J indicates which costs were fixed.

8.2.5 Home Machines

Some new home dialysis patients are given new dialysis machines and others are given recycled machines from patients who have stopped home dialysis (1.4.5). These machines may either be installed in rooms which have been converted at the Health Authority's expense or else in Portakabins. Further expense is incurred when patients stop dialysis and the converted room has to be put to rights or the Portakabin removed. Appendix J shows how the costs are related to following simulation variables:

i) new home dialysis patients with new machines,
ii) new home dialysis patients with recycled machine,
iii) the total number of patients on home dialysis and
iv) the number of patients who leave home dialysis.

8.3 COSTING THE SIMULATION OUTPUT

8.3.1 Use of VISICALC

VISICALC is a well known spread sheet program[65] which is extremely useful for cost applications. If the variables that are to be used in

calculating the costs are entered into the higher rows (or left hand columns) then further useful variables or costs, dependent on those original variables can be calculated in the lower rows (or right hand columns). Any changes in the variables will automatically change the values calculated from them. So if the uppermost (or left hand) variables are from a simulation run and the lower rows (or right hand columns) calculate the costs, the entry of new variables from a different simulation run will immediately produce new costs. Similarly, by applying cost indices (such as the Hospital Prices Index), a table may be recalculated to reflect constant prices. A VISICALC file can be saved on a disk, together with all the formulae used in making the calculations. Thus VISICALC appeared to be ideal for the costing exercise using the results of my simulation.

There was, though, a difficulty. Not only must the data for VISICALC be in specific format (called the DIF format) but the disks on which the data is written must either be in DOS format (APPLE Disk Operating System[76]) or formatted by the VISICALC program itself. The simulation program is in Pascal, however, which uses files which are incompatible with those used by the APPLE DOS. Fortunately Schwartz[77] has written a program called HUFFIN which transfers Pascal files to DOS disks. I, therefore, wrote a program to aggregate output data from the simulation program into appropriate time periods (multiples of one week) and put it in DIF format. I then used HUFFIN to convert the Pascal file to a DOS file so that it could be read by VISICALC.

VISICALC costed Runs A, B, C and D described in Chapter 7. Appendix K shows a printout from the costing of Run A. The left hand column shows data from 1982, the year in which the costs were collected. In the other columns, all the top rows down to and including "unit occupancy" are from the simulation program. The remaining rows including those showing outpatient sessions, pathology requests and the costs, are calculated using the simulation results in the previous rows. The formulae for these calculations are based on the assumptions described in 8.2.

8.3.2 Costing the results from the simulation runs

Costs were based on 1981/82 figures.

Figure 8.1 shows that in the first six months of Run A, the two largest cost categories were nursing and pharmacy. Almost half of the total costs were non-staffing costs including: pharmacy supplies, medical and surgical supplies, chemicals and equipment for pathology tests and the parts and other costs of installing and removing home dialysis machines.

Figure 8.2 shows that the predicted costs from Run B, in which haemodialysis was the first choice treatment, are considerably greater than those predicted from the other runs. This does indicate, therefore, that the change in policy in which C.A.P.D. was made the first choice treatment is likely lead to considerable cost saving of the order of £150,000 per year.

The results from Run C indicate, however, that these savings will be reduced substantially, if admissions to the dialysis/transplant programme increase (which could happen as a direct consequence of C.A.P.D. being the first choice treatment because of the fewer resource constraints limiting entry to the dialysis/transplant programme for patients starting C.A.P.D. treatment (1.4.2)).

There is only a small difference, however, between the predicted costs from Run A (in which suitable "patients" were provided with "home dialysis machines", 7.2.1) and the predicted costs from Run D (in which the "home dialysis programme" was run down, 7.2.4). Although no account was taken, in Run D, of the proposed replacement of unit dialysis sessions by sessions in minimal care units with fewer nursing staff, the consequent decrease in the nurse staffing costs (which would be by no more than £30,000) could be totally offset by the cost of building the units, and the additional overheads of keeping the buildings open and in good repair.

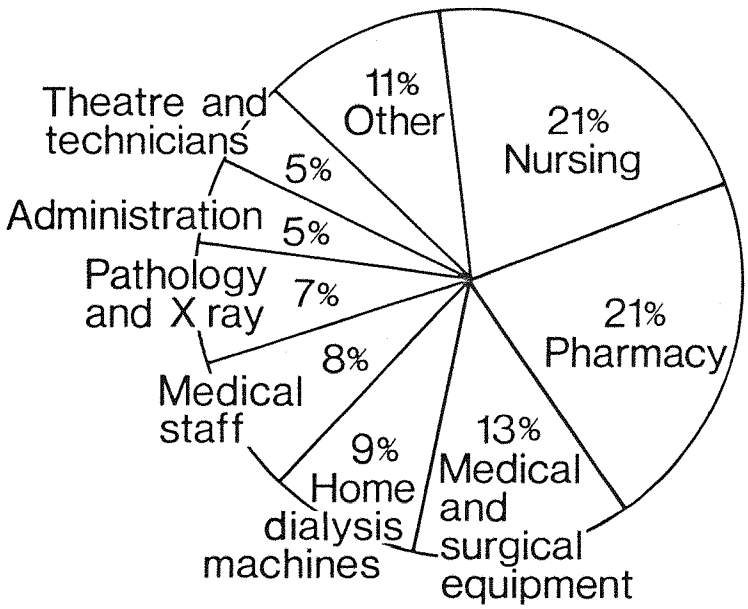
8.3.3 Use of VISICALC as a model

VISICALC can be used to evaluate the effects of different assumptions about costs and to test their sensitivity. For example, the effect of regarding the pathology costs as totally variable instead of mainly fixed, would add approximately £80,000 onto the projected costs at 5 years, a 4% increase.

It is also possible to enter variables into the rows normally

FIGURE 8.1

Costs in the first six months of Run A



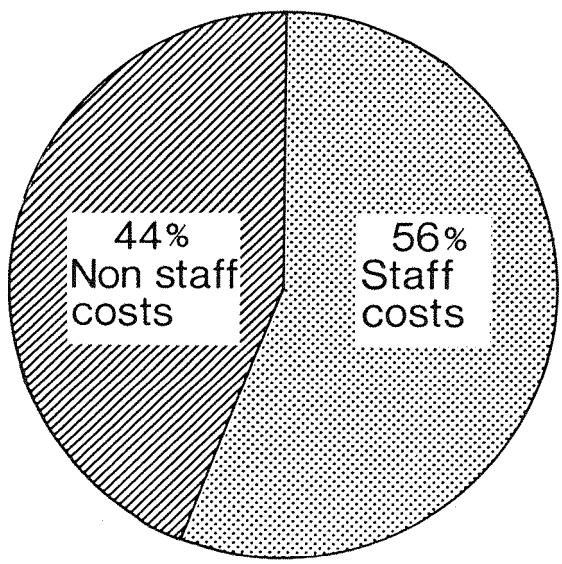
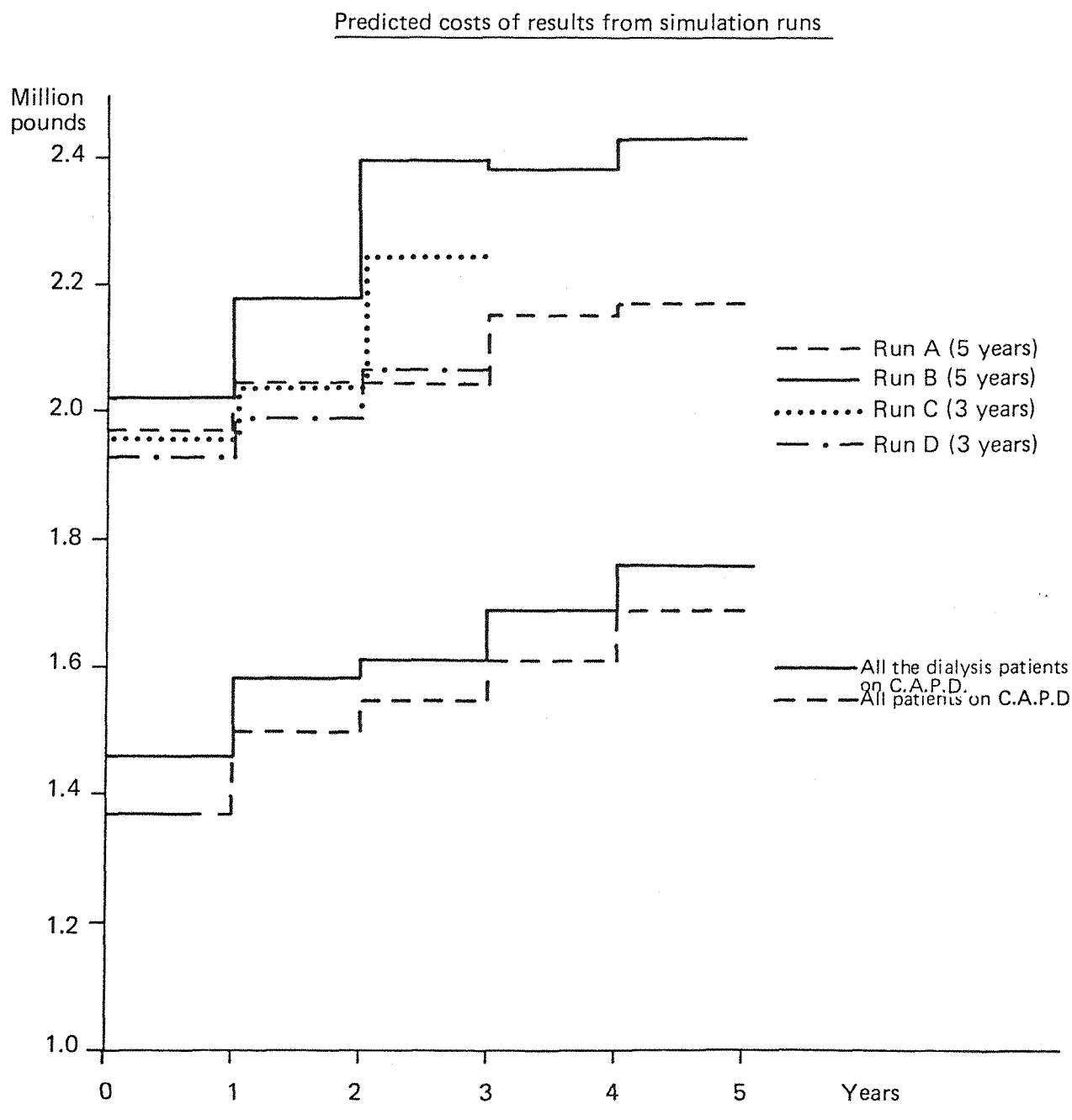


FIGURE 8.2


Predicted costs of results from simulation runs
Million pounds
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
1
2
3
4
5
Years
Run A (5 years)
Run B (5 years)
Run C (3 years)
Run D (3 years)
All the dialysis patients on C.A.P.D.
All patients on C.A.P.D.

used for the results from the simulation program and to perform cost calculations on them. Thus VISICALC can be used quickly to show the effects of different situations that have not been simulated. These must obviously be interpreted with caution because the rough figures entered may violate important assumptions.

The results from simulation Runs A, B and C indicate that the increase in the use of C.A.P.D. treatment may be expected to reduce costs. To see how much cheaper the programme might be if C.A.P.D. were used to an even greater extent, I used VISICALC to do the following:

i) turn all the "haemodialysis patients" into "C.A.P.D. patients" and estimate the costs and

ii) turn all the "haemodialysis" and "transplant patients" into "C.A.P.D. patients" (making the number of "transplants" equal to zero) and calculate the costs.

Although these VISICALC models upset assumptions about the different survival and inpatient needs of C.A.P.D. patients, they enabled me to get an indication of the likely costs (much reduced) of a completely different system of treating patients (Figure 8.2).

8.4 IMPLICATIONS OF RESULTS

The results from the simulation run indicate that costs will continue to rise over the next five years unless some radical action is taken to contain them.

Figure 8.2 shows that even if all the patients were to become C.A.P.D. patients overnight with no conversion costs, the predicted costs of treating the patients would still exceed £1.5 million per year by the second year. Nevertheless, the increased use of C.A.P.D. rather than haemodialysis can be expected to save considerable sums of money, provided admission criteria remain constant.

The run-down of the home dialysis programme, to be replaced by minimal care units, on the other hand, appears to have very little financial benefit.

The vigorous transplant programme has in the past, no doubt, played an important role in keeping haemodialysis costs down. Figure 8.2 indicates that, in taking into account the high inpatient

costs of transplant patients, transplant treatment appears to be no cheaper than C.A.P.D. treatment, and maybe even more expensive. This should be explored further because it runs counter to the conclusions arrived at by the South East and South West Regional Health Authorities[2], with their simple deterministic model (2.3.1). This model, however, takes no account of inpatient stays.

Costs could be cut by reducing services to patients (for example, by cutting down the number of pathology tests requested). The scope for this is limited, however, and the pie charts on Figure 8.1 indicate that the saving would be comparatively small. More savings might accrue from substantially cutting the drug bill (one of the biggest slices of the pie). The prospect of doing this is small too unless perhaps, by increasing the proportion of drugs prescribed by the patients' general practitioners, more of the costs could be absorbed by the Family Practitioner Committees. These savings would be seen by District Health Authority, however, rather than the tax payer.

If the Health Authorities wish to cut costs, further simulation runs should be done to investigate other options. The results from this chapter indicate that the avenues to explore might be:

i) the gradual transfer of all dialysis patients to C.A.P.D. (including patients returning to dialysis after a failed transplant),
ii) the policy in (i) together with a reduction in the transplant programme and
iii) a rationing of the number of places on the dialysis/transplant programme.

The financial effects of such options, which may seem unattractive to patients (and perhaps to medical staff too) can be explored in the simulation without any cost or risk to human life, health or happiness.

8.5 CONCLUSION

Costing the simulation results thus not only gives extremely useful information for planning purposes but also can be used to indicate appropriate simulation runs for the investigation of different and possibly cheaper policy options.

The simulation program is an invaluable tool for budgeting the dialysis/transplant programme because it can give forecasts, in some detail, of the costs of different policies and provides the necessary information with which to monitor activities within the Unit.

Chapter 9

ASSESSMENT AND FUTURE USE OF THE MODEL

The discrete event simulation model of Portsmouth Renal Unit was developed in response to a need for planning information. The model not only gives information about resource use and needs (Chapter 7) but can also play an important role in budgeting renal services (Chapter 8). This chapter will:

i) assess the properties of the model against the criteria established in Chapter 2 (9.1) and
ii) show how the modelling techniques, developed in this dissertation, have more general applications, both for other Renal Units and in different Health and Social Services areas (9.2).

9.1 ASSESSMENT OF THE MODEL

9.1.1 All relevant parts of the system

The modelled system includes not only the patients and their transfer from one treatment to another but also constraints on the numbers of inpatient and day patient beds, routine operations, C.A.P.D. places, kidneys for transplantation and haemodialysis machines (3.4.3). The use of kidneys is further constrained by the matching criteria for transplantation between donor kidneys and recipient patients (3.5.6). The wider system boundaries (System B), when compared with those of System A used in previous models (2.1), enables the model:

i) to reflect, by altering the constraints, many different circumstances and policies (7.2) and
ii) to provide information on resource use which is not only valuable information in its own right (7.3) but also enables the results from the model to be costed (8.3).

In other words, the described simulation faithfully models System A, (not just System B (2.1)).

9.1.2 Reflection of the system properties

The model was developed in close consultation with the staff of the Renal Unit and validation of the model established its good reflection of system properties (6.5).

i) Survival distributions. Most of the survival distributions are derived empirically from data from the Renal Unit and can be adapted readily to any change in Renal Unit policy or activities (4.6). The model could be amended, with ease, to use parametric distributions if appropriate distributions were found to fit the data.

ii) Constraints. The user may set a range of constraints affecting the passage of "patients" through the simulation. The inclusion of constraints enables the model to be more realistic and adaptable (see 9.1.1).

iii) Patient characteristics. One of the major advantages of using a discrete event simulation is that patients can be given characteristics rather than having to be members of a homogeneous group (2.4.2). This has enabled matching between patients and donated kidneys to be modelled much more realistically and patients' characteristics to influence their choice of treatments, their survival on the treatments and the time they spend using the different resources.

iv) Time units. A day, the time unit of my simulation, is short enough for measuring all the important events in the model.

9.1.3 Variability

The use of constant rather than random, arrival rates for "patients" and "kidneys" (6.3.3) considerably reduces the range of the total number of patients in the system and thus, of the resources they use. Since the main purpose of the simulation is to identify the limitations of existing resource provision and the need for additional

resources, one run with constant arrival rates will serve the same purpose as several runs, (using different random number streams) with random arrival rates.

If estimates of the variances were to be needed they could be made from several runs using independent random number streams and random arrivals.

Unwanted random fluctuations causing differences between comparison runs, (with, say, one or more changed parameter) are kept to a minimum by giving different groups of distributions different random number streams, each of which always start from the same seed (6.3.5).

The simulation can thus be used with confidence for comparing different policy options.

9.1.4 Credibility

The model is extremely credible because it has a good reflection of system properties (9.1.2). In addition, because the structure of the simulation model imitates, as far as possible, the activities of the real system, it is reasonably easy for those familiar with the modelled system to understand and criticise it. This is greatly helped by the model's visual interactive facilities (6.5.2).

9.1.5 Robustness

Only a few assumptions are fundamental to the model (6.4.1). The model can be made to behave differently by changing:

i) the constraints and parameters while the simulation is running,
ii) the distributions and decision criteria using the DISTRIBUTION INPUT program and
iii) the flow of "patients" through the system by small alterations to the program coding.

In validating the model, I showed the model to be robust even to extreme policy changes (6.5.1).

9.1.6 Ease of Use

The use of a microcomputer has made it possible for the simulation program to be interactive, thus giving the user much more control over simulation runs (4.4). The supporting programs for the entry of patient and distribution data are also interactive and have facilities to ensure the entry of valid data into the simulation program. The system has been designed to be extremely easy to use so that it could, in the future, be "handed over" to Health Service staff.

9.2 FUTURE USE OF THE MODEL

The model thus fulfils the criteria outlined in Chapter 2. Chapters 7 and 8 showed that the model could be used to provide information which is very pertinent to planning services. With detailed system documentation, it will be ready for immediate use by the Health Authorities to plan and budget the Renal Services in Wessex.

9.2.1 The hardware

The model could be made more flexible and interactive (4.8) but the size of the Apple II computer's memory is a major limitation on introducing further improvements. The slow speed of the running program (4.9) is also frustrating. As very little of the simulation program and its supporting units are machine dependent, a transfer of the program to a larger faster machine that supports UCSD Pascal, such as the Sage II[58] should be quite easy.

9.2.2 Use for other Renal Units

All Renal Units have to cope with increasing numbers of patients and the consequent increase in expenditure (1.1.2). They all have a need, therefore, for a tool to help them in planning and budgeting.

The simulation model was designed for Portsmouth Renal Unit with the intention of extending it to other Renal Units. In adapting the model to a new Renal Unit, different distributions could be accommodated using the DISTRIBUTION INPUT program, and appropriate

patient data would be entered using the PATIENT INPUT program. It would, in addition, almost certainly be necessary to change the scheduling of "unit dialysis machine" sessions and the organisation of "haemodialysis training". Some further work may need to be done to make this part of the simulation program more generally applicable.

9.2.3 Inpatient episodes in other health care specialties

The subsystem describing the use of inpatient beds (3.5.1) could usefully be embedded in other simulations, either in another model of the treatment of long term patients (9.2.4) or to describe the activity of a hospital ward or speciality. I should, for example, have found it a very helpful tool in exploring the potential costs and benefits of five day wards[78].

9.2.4 Treatment of maternity and chronic patients

The techniques of using *shadow entities* which I have developed to model patients on a dialysis/transplant programme can be used in a similar way for other groups of patients in order to *hold* their survival time in the system while the main "patient" *entities engage* in "treatment" *activities* and use *resources*. With an adequate data base, a simulation could be used to explore their use of resources together with the measurable benefits and costs of alternative treatments.

There are many groups of patients who make either expensive and continuous (or intermittent) demands on Health Service resources over a period of time. For chronically ill patients, that period of time (survival time) may be their remaining life time and for maternity patients it will be the duration of the pregnancy.

Chronic patients who make expensive demands on Health Service resources include those:

i) fitted with cardiac pacemakers,

ii) with certain types of cancer (e.g. bladder cancer).

9.2.5 Other applications

The use of *shadow activities* which is a concept developed in this simulation may be extended to other systems, for example:

i) the planning of services for Social Service clients such as Homes, foster parent services and other accommodation for children in Care (where, for example, the *shadow entities* could *hold* the *time* children spent in care) and

ii) manpower planning in any organisation (where the *shadow entities* would *hold* the *time* the employees worked in the organisation).

9.3 SUMMARY

The simulation model of Portsmouth Renal Unit which I have developed is a valuable planning tool. The model, which gives a good reflection of wider system properties and is robust, can with little additional work be adapted to model other Renal Units. These characteristics mean that the model is a great improvement on all previous models for which published work exists.

The use of a microcomputer has both speeded development time and enabled an interactive system, which greatly enhances the credility and improves the robustness of the model, to be developed. The model, which is easy to use and portable, should enable Renal Units to plan and control their own services. It is a straightforward matter to use simulation output for costing or budgeting purposes.

The simulation techniques which I have developed have many other applications. The facility to model the treatment of patients with long term or chronic problems, in particular, could become an important aid to planning future Health Services on a much wider basis.

APPENDIX A

THE SIMULATION PROGRAM - a brief description of its contents

This appendix describes briefly the role of each of the library units shown in Figure 4.1, Chapter 4.

A.1 THE PACKAGE UNITS

This section includes all those units that are of general application to any simulation program. The authors' names are written in brackets.

i) SIMULATE and INITIALISE (mainly John Crookes with additions by myself),

ii) SAMPLING (John Crookes, myself and Robert O'Keefe),

iii) INPUTPROGS (mainly myself but based on a demonstration Apple program) and

iv) SCREENS (Robert O'Keefe).

A.1.1 SIMULATE and INITIAL

The two units contain the procedures and functions for the manipulation of *entities* and *queues*.

INITIALISE has those which are only needed during the initialisation phase of a simulation run and

SIMULATE has those which are needed while the simulation is running.

The units can thus be overlaid to save space in the computer memory at run time.

A.1.2 SAMPLING

The functions of this unit are to:

- load the cumulative distributions (or identify their locations if they are to be loaded from the disk files while the simulation is running),

- set the random number streams,

- find the next random number from a specified stream,

- sample a number from a normal or negative exponential distribution or a distribution derived from raw distribution data,

- sample a number from a conditional distribution derived from raw distribution data.

A.1.3 INPUTPROGS

This unit validates data entered from the keyboard and allows errors to be corrected immediately. The facilities of the program include:

- clear screens, clear lines on screens and cursor control,

- read in a string value of a certain maximum length from the keyboard,

- read in an integer value from the keyboard between maximum and minimum values,

- read a real value from the keyboard,

- read in a date from the keyboard,

- interpret a yes, "Y", or no, "N", entered by the user.

The program reads and validates character by character, sounding a bell when it encounters an invalid entry. The program also allows the user

to backspace in order to delete and overwrite characters, should he wish to do so.

This main simulation program, the INPUT DISTRIBUTION program and the PATIENT DISTRIBUTION program all use this unit for interactive data entry.

A.1.4 SCREENS

This is a unit from Robert O'Keefe's AIMS simulation package. The Renal Unit simulation uses the following facilities to :

- interrupt a running program by pressing a key on the keyboard

- save a screen of text as a file on a disk and recall it when required.

A.2 THE BACKGROUND UNITS

I wrote three background units:

i) RENSTART which has procedures and functions used only during the initialisation phase or when the user changes the simulation *resources* after interrupting the running simulation program,

ii) RENAL.1 which has procedures and functions used frequently throughout a simulation run and relates to the manipulation of *shadow entities* and the *resources* needed for "inpatient treatment" and

iii) RENAL.2 which has procedures and functions that are used throughout a simulation run, but less frequently than those in RENAL.1.

A.2.1 RENSTART

This unit sets:

- the days of the week,

- the *resource* values,

- the timetables,

- the tabular layout of the screen shown during the simulation run.

A.2.2 RENAL.1

The facilities in this unit include:

- finding the record of a particular "patient",

- changing the record of a "patient",

- finding the "patient" *entity* relating to a particular *shadow entity*,

- finding a *shadow entity* for a particular "patient" *entity*,

- finding an unused "patient" *entity* for a new "patient",

- removing a *shadow entity* from a "patient",

- reserving an "inpatient bed",

- releasing an "inpatient bed",

- booking an "operation".

A.2.3 RENAL.2

The facilities of this unit include:

- finding, booking and cancelling "dialysis sessions",

- giving characteristics to a new "patient",

- stopping the *activities* of a "patient" and his *shadows*,

- removing him from *queues* when, for example, he fails a "treatment" or receives a "cadaver transplant",

- freeing a "patient" *entity* after a "patient" death,

- testing whether a "patient" and "kidney" have compatible "blood groups" and "HLA antigens",

- changing the "patient" record and setting the *shadow entities* when a "patient" changes "treatment",

- testing whether a "patient" is waiting for, or receiving "inpatient treatment",

- writing figures to the monitor screen at the end of each day.

A.3 INITIALISATION

The unit called SETUP includes procedures and functions which:

- control the screens described in Appendix B, accept data from the keyboard and use it to set the *resource* values etc.,

- identifies and, where necessary, loads the cumulative distributions,

- sets *entity* and *queue* names,

- sets variable values (used to count "patient" numbers etc.,) to zero.

A.4 SETTING THE STARTING CONDITIONS

The unit called PATPROG is described in more detail in Chapter 4. In summary, it:

- reads "patient" data record by record from the PATIENT file,
- *engages* the appropriate *entities* and *shadow entities*,
- puts "patients" in *queues*, *books* *resources*,
- transcribes the records to another file to be accessed, augmented and amended by the simulation program.

A.5 THE ACTIVITIES

The simulation *activities* are divided between three library units:

i) CAPDIAL has the *activities* relating to "patient" arrival, "C.A.P.D. treatment" and "inpatient admissions" and "discharges",

ii) HAEMDIAL has the "unit" and "home haemodialysis" *activities*,

iii) TRANSPL has the "transplant" *activities* and those relating to "treatment failure" and "death".

The *activities* and their relationship to each other are described in detail in Chapter 3.

A.6 THE MAIN PROGRAM

The main program has three main parts:

i) control of the interactive facilities (Appendix B),

ii) the EXECUTIVE which controls the initialisation, the time advance, the *B* and *C* *activities* and screen updating and

iii) opening and closing the disk files needed during a run of the simulation program.

APPENDIX B

SETTING THE PARAMETERS OF THE SIMULATION PROGRAM

Chapter 4 explains how the user may set simulation parameters both during the initialisation phase of the simulation and also after interrupting the running simulation program (by striking any key on the keyboard, followed by "A" for alter). The program shows the following screens:

Screen 1. This screen (Figure B.1) is for setting *resource* values. If the user types "N" in response to the question, "DO YOU WANT TO CHANGE RESOURCE PROVISION?", the program displays screen 2. If, on the other hand, he types "Y", the cursor moves to each number in turn so that the user may enter a new value or press (RETURN) to retain the original value.

Figure B.1

```
DO YOU WANT TO CHANGE RESOURCE
PROVISION?  Y
PRESS (RETURN) FOR NO CHANGE

NEPHROLOGY BEDS                          =    11
TRANSPLANT BEDS                          =     6
HAEMODIALYSIS MACHINES IN UNIT           =    10
HAEMODIALYSIS TRAINING PLACES            =     2
MAX. OPERATIONS PER SESSION              =     6
MAX. TRANSPLANTS PER DAY                 =     2
MAX. HOME MACHINES                       =   500
MAX. C.A.P.D. PATIENTS                   =   500
```

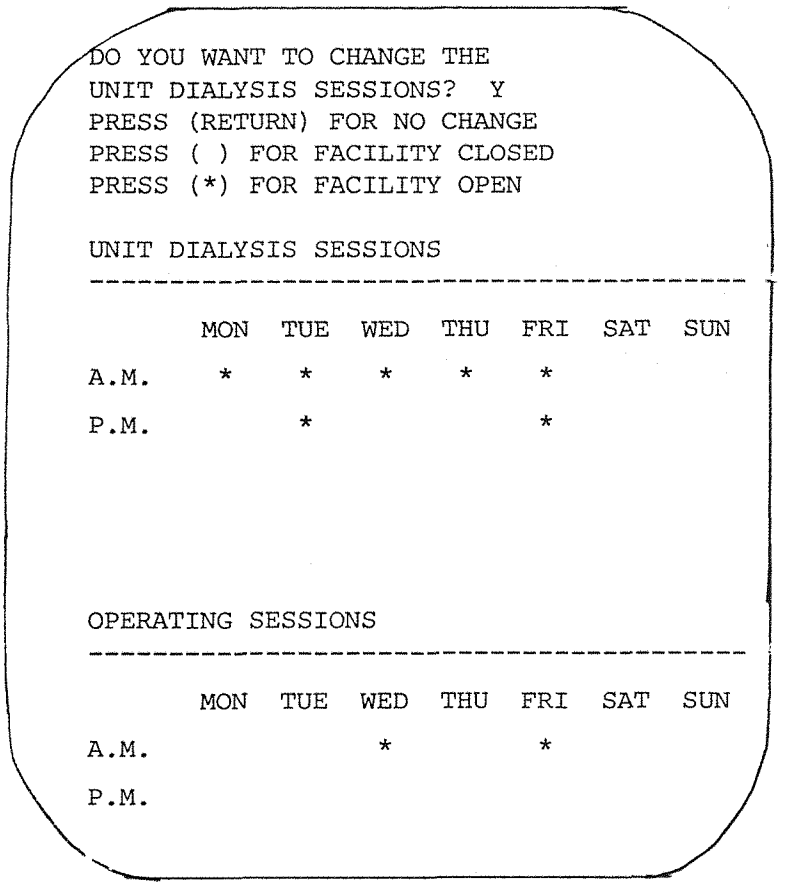
Screen 2. This screen (Figure B.2) is for scheduling unit dialysis and theatre sessions. For each of the two timetables on the screen, the user must respond a similar question. The first is "DO YOU WANT TO CHANGE THE UNIT DIALYSIS SESSIONS?". If he types "Y" he may:

- allocate sessions by typing a "*",

- withdraw sessions by typing a " " or

- leave them as they were by typing (RETURN).

Figure B.2

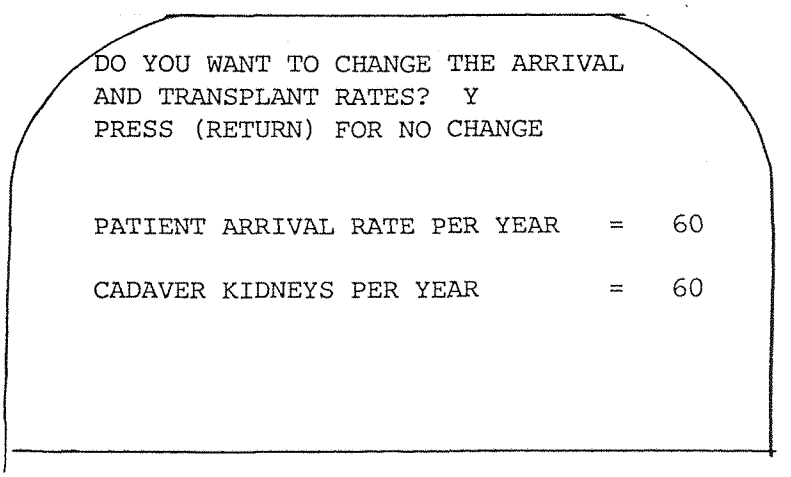


He is then asked "DO YOU WANT TO CHANGE THE THEATRE SESSIONS?" and may alter these sessions in exactly the same way as the unit dialysis sessions.

Screen 3. This screen (Figure B.3) is for setting patient and kidney arrival rates and is operated in exactly the same way as screen 1.

When the user has finished screen 3, the simulation program proceeds.

Figure B.3



APPENDIX C

THE DISTRIBUTION INPUT PROGRAM

C.1 OPENING A FILE

When the program starts running it first displays a question asking the user for a filename. This may be either a file of distributions created on a previous occasion, or a new file name. If the program cannot find an existing file, it first checks that the user wants a new file opened and then asks how many records should be reserved. If there is insufficient space for those records, the user must change his requirements. The program initialises all new records.

C.2 THE MENU

Once the program has opened an existing file, or a new file with an appropriate number of records, it displays a menu to give the user a choice of activities:

SEE - view a record (C.3),
CHANGE - change a record (C.4),
NEXT - repeat the last activity (either viewing or changing) on the next record in the file,
DUPLICATE - duplicate a record,
MAKECUM - create a file of cumulative distributions from the file of distributions (C.5),
FILE - close the existing file of distributions and start a new one (C.1),
QUIT - quit the program.

The menu remains on the screen throughout the viewing and changing activities (Figures C.1, C.2, C.3) and may be used on the completion of each activity.

C.3 VIEWING A RECORD

Once the user has pressed "S" for see, the program asks which record the user wants to view (Figure C.1). When user has responded by typing a record number, the program displays the distribution showing the distribution title, type, number of points and the values at each point.

The distribution type may either be:

- a discrete distribution,

- a survival distribution,

- a histogram.

Figures C.1, C.2 and C.3 show the different formats of each distribution type.

Figure C.1

A discrete distribution displayed by the DISTRIBUTION INPUT program, after the user has typed "S" for see.

```
S(EE, C(HANGE, N(EXT, F(ILE, D(UPLIC, M(AKECUM, Q(UIT

VIEW WHICH RECORD ? 45
BLOODGRPS,0=0,1=A,2=B,3=AB
DISTRIBUTION TYPE: DISCRETE
NUMBER OF POINTS:  4

X        0.0   1.0   2.0   3.0
FREQ    45.0  40.0  10.0   5.0
```

BLOODGRPS = Blood groups,

FREQ = frequency

Figure C.2

A histogram displayed by the DISTRIBUTION INPUT program, after the user has typed "N" for next, following a viewing activity.

```
S(EE, C(HANGE, N(EXT, F(ILE, D(UPLIC, M(AKECUM, Q(UIT

RECORD NUMBER 40
I.P.STAY HAEM.DIAL PATIENTS
DISTRIBUTION TYPE: HISTOGRAM
NUMBER OF POINTS:  11

DAYS     0.0   0.5   1.5   2.5   3.5
FREQ       5.0  79.0  25.0  18.0   8.0

DAYS     4.5   5.5   6.5  13.5  20.5
FREQ       6.0  10.0  21.0  11.0  14.0

DAYS    27.5
FREQ       0.0
```

I.P.STAY HAEM.DIAL PATIENTS = inpatient stay of haemodialysis patients

FREQ = frequency

Figure C.3

A discrete distribution displayed by the DISTRIBUTION INPUT program, after the user has typed "C" for change.

```
S(EE, C(HANGE, N(EXT, F(ILE, D(UPLIC, M(AKECUM, Q(UIT

CHANGE WHICH RECORD ? 0
HAEMDIAL SURVIVAL,<35YRS,NO TRANSPL
DISTRIBUTION TYPE:SURVIVAL
NUMBER OF POINTS: 19

MTHS     0.0   6.0  12.0  18.0  24.0
PERC   100.0  95.0  92.0  87.0  82.0

MTHS    30.0  36.0  42.0  48.0  60.0
PERC    77.0  77.0  75.0  73.0  71.0

MTHS    72.0  84.0  96.0 108.0 120.0
PERC    69.0  67.0  66.0  64.0  62.0

MTHS   132.0 144.0 288.0 576.0
PERC    61.0  59.0  44.0   0.0

(PRESS RETURN FOR NO CHANGE)

WHICH POINT DO YOU WANT TO CHANGE?  5
```

HAEMDIAL SURVIVAL = survival on haemodialysis treatment

MTHS = months, PERC = percentage

C.4 CHANGING A RECORD

When the user has identified which record he wants to change, the program displays the distribution and asks questions at the bottom of the screen (Figure C.3). The questions relate to the changes that the user may make. These are:

- the title,
- the distribution type,
- the number of points,
- the time units (if if is a time dependent distribution),
- the values of each point.

C.5 MAKING THE CUMULATIVE DISTRIBUTIONS

After asking the user for a filename for the cumulative distributions and opening the file, the program validates each distribution before calculating the cumulative values and entering them in the file. If any errors are found, the program returns to the main menu (C.2) so that the user can correct them.

APPENDIX D

THE PATIENT INPUT PROGRAM

D.1 OPENING A FILE

When the program starts running, it first displays a question asking the user for a filename. This may either be a file of patient records created on a previous occasion (either one in which all the data had been entered by the user or one which has been altered and augmented by the simulation program), or a new file name. If the program cannot find an existing file, the program first checks that the user wants a new file opened and then asks how many records should be reserved. If there is insufficient space for those records, the user must change his requirements or leave the program. The program initialises all new records.

D.2 THE MENU

Once the program has opened an existing file, or a new file with an appropriate number of records, it displays a menu to give the user a choise of activities:

SEE - view a record (D.3),
CHANGE - change a record (D.4),
NEXT - repeat the last activity (either viewing or changing) on the next record in the file,
VALIDATE - validate all the records and print out the errors (D.5),
REMOVEVAL - remove the validation markers on the records so that they can be changed (D.5),
PRINTALL - print all the patient records,
FILE - close the existing file of distributions and start a new one (D.1),
QUIT - quit the program.

The menu reappears on the screen following each activity.

D.3 VIEWING A RECORD

Once the user has pressed "S" for see, the program asks the user which record he wants to view. The user responds by typing a record number and the program then displays the patient record (Figure D.1). If the record has previously been validated and found to be error free (i.e. it has a validation marker) the program displays an asterisk beside the patient's name.

Figure D.1

A patient record displayed by the PATIENT INPUT program, after the user has typed "C" for change.

```
PRESS (RETURN) FOR NO CHANGE

PATIENT NAME IS  JOSEPH BLOGGS
E.D.T.A. NUMBER IS        987654
DATE OF BIRTH:            19/3/46
BLOOD GROUP:              AB
PRESENT ACTIVITY:         HAEM-UNIT
 (I,U,H,C,L,G)
STARTED THIS TREATM. ON: 12/2/83
NUMBER OF TRANSPLANTS     0
ANTIBOD INDEX:            66
ON TRANSPLANT W.L ?       Y
TRAINED FOR HAEMODIAL.?   N
MACHINE AT HOME ?         N
SUITABLE FOR TRANSPLANT?  Y
PREF. DIALYSIS:   HAEMO?  Y
                  C.A.P.D.? N
SUITABLE FOR HOME HAEMO?  Y
MAY HAVE L.R.TRANSPL?     N
IN HOSPITAL BED?          Y
```

D.4 CHANGING A RECORD

When the user has typed "C" for change and has identified which record he wants to change, the program displays patient record. If the record has a validation marker, a message appears on the screen to say that the record cannot be changed. Otherwise the cursor moves to each value on the screen in turn, whereupon the user may either replace the value or type (RETURN) to retain it. Data on new patients may be entered directly from the patient data form (Figure D.2).

D.5 VALIDATION

When the user types "V", the program validates each record and if it is found to be error free, gives it a validation marker in order to:

- prevent the user from inadvertently changing it

- prevent invalid records from entering the simulation program.

If a record is invalid, the program prints out a description of the error so that the record can be changed.

If the user wants to change validated records, he must remove the validation markers on all the records by entering the activity REMOVEVAL from the menu (D.2).

Figure D.2

Patient data for the Renal Unit Simulation

Patient name: .....↕

E.D.T.A. Number: .....↕

Date of birth: ...../...../....↕

Blood group (O,A, B, AB): ....↕

Present treatment: (circle one activity only and enter the date of starting the most recent treatment)

imminent patient	I	
unit haemodialysis	U)	
	)	
home haemodialysis	H)	
C.A.P.D.	C	
live related graft	L	
cadaver graft	G	...../...../....↕

How many transplants has the patient received? .....↕

Cytotoxic antibodies:
Percentage of mismatches with reference panel (if known) .....↕

Is the patient waiting for a transplant? Y/N .....

Has the patient (and companion) at any time been successfully trained for home haemodialysis? Y/N .....

Has the patient got a haemodialysis machine at home? Y/N .....

Will this patient be suitable, at some time, for having a transplant? Y/N .....

Which dialysis treatment will the patient receive if he/she needs it:

haemodialysis? Y/N .....

or CAPD? Y/N .....

Note: if the patient is already receiving the treatment, write "Y" against it.

If the patient were successfully trained would he/she be suitable for home haemodialysis? Y/N .....

Is there any prospect of this patient receiving a live related transplant? Y/N .....

Is the patient occupying a hospital bed? Y/N .....

APPENDIX E

PRINTOUT OF RESULTS FROM A SIX WEEK SIMULATION RUN

Renal Unit Simulation Date: 20/2/83

Weekly Treatment Totals

Week	Arrivals per year: Patients	Arrivals per year: Kidneys	Patients: New	Home	Unit	CAPD	Trans-plant	Fail	TOTAL	DEATHS	Trans-plant W.L.
0	70	75	1	104	14	25	156	0	300	0	42
1	70	75	1	104	15	24	156	1	301	0	41
2	70	75	2	103	15	24	157	1	302	0	40
3	70	75	2	100	17	24	158	3	304	0	37
4	70	75	2	101	18	22	157	3	303	2	36
5	70	75	3	100	18	22	159	1	303	4	34
6	70	75	2	98	19	22	160	0	301	7	32

Use and Demand for Unit Dialysis Machines and Home Dialysis Machines

Week	Unit Machines: Available	Occupied	Unit dialysis waiting list	Home Machines: Installed New	Installed Recycled	Removed
0	70		2			
1	70	40	2	0	0	0
2	70	51	1	0	0	0
3	70	44	1	0	0	1
4	70	49	4	0	1	0
5	70	47	1	0	1	0
6	70	48	1	1	0	2

Use and Demand for In-patient Beds

Week	Available	Occupied	Waiting list	Transplants performed: live related	cadaver	Routine Operations
0	20	13	0			
1	20	9.7	0	0	1	2
2	20	12.3	0	0	1	4
3	20	15.6	0	0	2	1
4	20	15.3	0	1	1	1
5	20	17.3	1	0	2	3
6	20	19.0	1	0	1	3

Note: The lengths of the queues are those recorded at the end of the week.
Occupied beds are the average occupied bed days.
Unit machines = unit machine sessions per week.

APPENDIX F

DATA USED IN THE SIMULATION PROGRAM

F.1 THE DISTRIBUTION DATA

F.1.1 Haemodialysis survival

The figures below show survival of patients on haemodialysis to the time of treatment failure or death (transplants were not included in the "failures"). The data were obtained from John Chambers' study of Portsmouth Renal Unit, augmented by figures from the UK Transplant Review 1981. The tails of the distributions, for which no published figures were available, were assumed to be geometric.

1. HAEMODIALYSIS SURVIVAL, AGE 0-34 YEARS

MONTHS	0	6	12	18	24	30	36	42	48	60	72	84
PERCENTAGE	100	95	92	87	82	77	77	75	73	71	69	67

MONTHS	96	108	120	132	144	288	576
PERCENTAGE	66	64	62	61	59	44	0

2. HAEMODIALYSIS SURVIVAL, AGE 35-44 YEARS

MONTHS	0	6	12	18	24	30	36	42	48	60	72	84
PERCENTAGE	100	93	90	89	89	89	79	79	62	56	50	44

MONTHS	96	108	120	132	144	288	576
PERCENTAGE	39	35	31	28	25	22	0

3. HAEMODIALYSIS SURVIVAL, AGE 45-54 YEARS

MONTHS	0	6	12	18	24	30	36	42	48	60	72	84
PERCENTAGE	100	92	85	78	72	66	61	56	52	44	38	32

MONTHS	96	108	120	132	144	188	576
PERCENTAGE	27	23	20	17	14	12	0

4. HAEMODIALYSIS SURVIVAL, AGE 54-80 YEARS

MONTHS	0	12	24	36	48	60	72	84	96	144	288
PERCENTAGE	100	72	61	50	43	36	30	26	21	10	0

F.1.2 C.A.P.D. survival

The figures below show survival of patients on C.A.P.D. to the time of treatment failure or death (transplants were not included in the "failures"). The source of these data were the European Dialysis and Transplant Association Annual Report, 1981. The tail was assumed to have a geometric distribution. There were insufficient data available to estimate survival by age group.

5. C.A.P.D. SURVIVAL

MONTHS	0	3	6	12	24	36	48	60	72	240
PERCENTAGE	100	88	75	57	32	17	10	6	3	0

F.1.3 Transplant survival

I used two mutually exclusive survival distributions for patients with transplants:

survival to transplant failure, excluding deaths and

survival to death.

Patients were divided into those having cadaver transplants and those having live related transplants. Where sufficient data were available these were divided into age groups and into those having a first transplant and those having second or further transplants. The distributions below were based on figures from the UK Transplant Report 1981. The tails of the distributions were assumed to be geometric.

6. LIVE RELATED GRAFT SURVIVAL EXCLUDING DEATHS

MONTHS	0	3	6	12	24	48	60	72	84	144	576
PERCENTAGE	100	83	79	77	75	74	73	72	71	66	0

7. CADAVER GRAFT SURVIVAL EXCLUDING DEATHS

MONTHS	0	3	6	12	24	48	60	72	84	144	576
PERCENTAGE	100	83	79	77	75	74	73	72	71	66	0

8. LIVE RELATED GRAFT, PATIENT SURVIVAL

MONTHS	0	12	24	36	48	60	72	84	180	288	576
PERCENTAGE	100	92.4	87.5	85.2	83.4	81.6	79.0	78.0	66.0	53.0	0

9. CADAVER GRAFT, PATIENT SURVIVAL, 0-34 YRS, 1ST TRANSPLANT

MONTHS	0	1	3	6	12	24	36	48	60	72	84	180	288	576
PERCENTAGE	100	90	86	84	82	80	79	76	75	73	71	57	47	0

10. CADAVER GRAFT, PATIENT SURVIVAL, 35-44 YRS, 1ST TRANSPLANT

MONTHS	0	1	3	6	12	24	36	48	60	72	84	180	288	576
PERCENTAGE	100	88	82	76	71	66	63	62	61	59	57	45	34	0

11. CADAVER GRAFT, PATIENT SURVIVAL, 45-54, 55+ YEARS, 1ST TRANSPLANT

MONTHS	0	1	3	6	12	24	36	48	60	72	84	180	288	576
PERCENTAGE	100	81	74	67	60	53	50	47	47	46	45	35	27	0

12. CADAVER GRAFT, PATIENT SURVIVAL, 0-34 YEARS, 2+ TRANSPLANTS

MONTHS	0	1	3	6	12	24	36	48	60	72	84	180	288	576
PERCENTAGE	100	88	82	76	71	66	63	62	61	59	57	45	34	0

13. CADAVER GRAFT, PATIENT SURVIVAL, 35-44 YEARS, 2+ TRANSPLANTS

MONTHS	0	1	3	6	12	24	36	48	60	72	84	180	288	576
PERCENTAGE	100	88	82	76	71	66	63	62	61	59	57	45	34	0

14. CADAVER GRAFT, PATIENT SURVIVAL, 45-54, 55+ YEARS, 2+ TRANSPLANTS

MONTHS	0	1	3	6	12	24	36	48	60	72	84	180	288	576
PERCENTAGE	100	81	74	67	60	53	50	47	47	46	45	35	27	0

F.1.4 Suitability for transplantation

Although data on the number of patients thought unsuitable for transplantation, at a particular point in time, were available from Portsmouth Renal Unit. It was difficult to obtain data about the proportion of patients thought unsuitable for transplantation in each age group, at the time of their arrival into the system. The data below were based both on figures from UK Transplant Annual Report 1980 and 1981, and also on information gleaned from talking to staff in the Renal Unit.

15. SUITABILITY FOR TRANSPLANT

AGE GROUP	NOT SUITABLE	CADAVER TRANSPLANT	LIVE RELATED TRANSPLANT
0 - 34	0	80	20
35 - 44	10	90	0
45 - 54	20	80	0
55 +	95	5	0

F.1.5 Time spent on unit dialysis

Data, shown below, on the two largest groups of patients using unit dialysis facilities (those patients starting haemodialysis and those returning to haemodialysis after a failed transplant) were obtained from the European Dialysis and Transplant Association (E.D.T.A.) computer files for Portsmouth. The lengths of stay for other groups of patients were obtained from Portsmouth Renal Unit.

16. UNIT DIALYSIS TIME, RETURN FROM FAILED GRAFT

DAYS	0-49	50-99	100-149	150-199	200-399	400-699	700-3600
FREQUENCY	54	14	7	3	10	1	1

17. UNIT DIALYSIS TIME, INITIAL PRE-TRAINING

DAYS	15-19	20-39	40-119	120-139	140-169	170-199	200-319	320-3600
FREQUENCY	4	8	84	15	18	5	9	1

18. UNIT DIALYSIS TIME, TRAINING

DAYS	6.9-7.0	7.1-13.8	13.9-14.0
FREQUENCY	50	0	50

19. UNIT DIALYSIS TIME, AFTER TRAINING

DAYS	0-6	7-13
FREQUENCY	50	50

20. UNIT DIALYSIS TIME, HOME PATIENTS RETURN FOR UNIT DIALYSIS

WEEKS	0	1-2	3-4	5-8
FREQUENCY	24	3	4	5

21. TIME WAITING TO GO ON THE TRANSPLANT LIST
(for C.A.P.D. patients as well as haemodialysis patients)

MONTHS	0-2	3-5	6-8	9-17	17-48
FREQUENCY	0	30	100	2	1

F.1.6 Decision data

The proportion of patients starting C.A.P.D. rather than haemodialysis, was estimated from data collected from Portsmouth Renal Unit in 1981. The proportion of patients expected to start on a different type of dialysis (rather than to die) after treatment failure was estimated from the E.D.T.A. Annual Report 1981, and from talking to staff at Portsmouth. Data on the hospital episodes of home dialysis patients were from Portsmouth Renal Unit.

22. INITIAL DIALYSIS TREATMENT

AGE GROUP	CAPD	HAEMODIALYSIS
0-54	15	85
55+	75	25

23. OUTCOME AFTER HAEMODIALYSIS FAILURE

	TO DEATH	TO CAPD
FREQUENCY	90	10

24. OUTCOME AFTER CAPD FAILURE

	TO DEATH	TO HAEMODIALYSIS
FREQUENCY	50	50

25. HOSPITAL TREATMENT FOR HOME PATIENTS;
0=ACCESS OPERATION, 1=EMERGENCY ADMISSION, 2=PERIOD OF UNIT DIALYSIS, 3=ONE OFF UNIT DIALYSIS

	0	1	2	3
FREQUENCY	31	69	0	200

F.1.7 Inpatient data

The inpatient data below were based on figures collected over a period of eight months in 1981 Portsmouth Renal Unit. Additional data were available from John Chambers' study.

26. INPATIENT STAY AFTER ACCESS OPERATION

DAYS	0	1	2
FREQUENCY	5	48	0

27. INPATIENT STAY AFTER TENKOFF CATHETER INSERTION

DAYS	0	1	2
FREQUENCY	95	5	0

28. INPATIENT STAY AFTER TRANSPLANT OPERATION

DAYS	12-14	15-17	18-20	21-23	24-26	26-29	29-32	32-35	35-38	38-41	41-45
FREQUENCY	5	18	12	12	12	7	6	5	1	1	1

29. INPATIENT STAY AFTER NEPHRECTOMY

DAYS	7-14
FREQUENCY	100

30. INPATIENT STAY OF NEW PATIENTS PRIOR TO SURGERY (SURVIVAL DISTRIBUTION)

DAYS	0	1	2	3	4	5	6	7	8	9	10	11	12	50
FREQUENCY	100	80	64	51	40	32	26	20	16	13	10	8	7	0

31. INPATIENT STAY OF HAEMODIALYSIS DIALYSIS PATIENTS

DAYS	0	1	2	3	4	5	6	7-13	14-20	21-27
FREQUENCY	5	79	25	18	8	6	10	21	11	14

32. INPATIENT STAY OF C.A.P.D. PATIENTS

DAYS	0	1	2	3	4	5	6	7	8-14	15-21	22-28	29-35	36-60
FREQUENCY	1	17	27	15	18	13	7	3	27	8	3	1	3

33. INPATIENT STAY OF PATIENTS WITH TRANSPLANTS

DAYS	0	1	2	3	4	5	6	7	8-14	15-21	22-70
FREQUENCY	2	13	12	9	20	14	6	6	16	1	3

34. INPATIENT STAY OF PATIENTS AFTER FAILING TREATMENT

DAYS	0	1	2	3	4	5	6	7	8-14	15-21	22-28
FREQUENCY	5	48	31	25	18	8	6	10	21	11	14

35. AVERAGE TIME BETWEEN HOSPITAL EPISODES

TREATMENT	NEW HOME	UNIT	CAPD	TRANSPLANT(1)	TRANSPLANT (2)
DAYS	110 100*	170	35	110	500

(1) first six months
(2) after six months

* The hospital episodes included the return of home patients for unit dialysis as well as for inpatient treatment.

F.1.6 Patient Characteristics

These data were obtained or estimated from the UK Transplant Annual Review and Report 1981.

36. BLOOD GROUPS

	O	A	B	AB
FREQUENCY	45	40	10	5

37. AGE GROUPS

	15-34	35-44	45-54	55-64
FREQUENCY	29	24	24	25

38. CYTOTOXIC ANTIBODY INDEX

INDEX	0.0-0.4	0.4-39.0	40.0-59.0	60.0-99.0
FREQUENCY	2134	394	394	115

F.2 CHANGES TO THE DATA AFTER VALIDATION OF THE SIMULATION PROGRAM

F.2.1 Haemodialysis survival

In validating the simulation program, the survival rates were found to have improved in recent months and therefore the survival distributions were changed for use in the runs described in Chapter 7. Distribution 1 was used for patients up to the age of 44 years old, and distribution 2 for the older patients.

F.2.2 C.A.P.D. survival

Following validation of the simulation program, when survival rates were found to have improved, distribution 5 was replaced by distribution 4.

F.2.3 Transplant survival

The cadaver graft patient survival rates were increased for the simulation runs in Chapter 7. Distribution 9 was used for all patients with ages less than 45 years old and for patients having a first transplant less than 55 years old. Distribution 10 was used for first transplant patients over 55 years old and for other patients between the ages of 45 and 54 years old. Distribution 11 was used for patients who were both having a second or further transplant and were over the age of 54 years old.

F.2.4 Suitability for transplantation

Validation of the simulation program showed that the criteria for patient suitability for transplantation have been relaxed in recent months and the following data were, therefore, used in the Chapter 7 runs:

SUITABILITY FOR TRANSPLANT

AGE GROUP	NOT	CADAVER	LIVE RELATED
0-34	0	80	20
35-44	3	97	0
45-54	10	90	0
55+	30	70	0

F.2.5 Time spent on unit dialysis

In the Chapter 7 runs of the simulation program, I reduced the waiting time distribution of patients going onto the transplant list to the following:

TIME WAITING TO GO ON THE TRANSPLANT LIST
(for C.A.P.D. patients as well as haemodialysis patients)

MONTHS	0-2	3-5	6-8	9-12
FREQUENCY	5	75	19	1

F.2.6 Decision data

Following a change in Renal Unit policy in 1983 to making C.A.P.D. the first choice treatment rather than haemodialysis, the proportion of patients starting C.A.P.D. rather than haemodialysis (in the Chapter 7

runs) was made 80% for all age groups. I also assumed that as there were many younger patients starting this treatment, a higher proportion (80%) os those failing C.A.P.D. would receive haemodialysis treatment rather than die.

F.2.7 Inpatient data

During 1982 and 1983 the length of stay and number of admissions of C.A.P.D. patients was reduced. In the data for the runs in Chapter 7, therefore, the average time between the hospital episodes of C.A.P.D. patients was increased to 100 and the length of stay distribution was changed so that the average stay was reduced by one day.

F.2.8 Patient Characteristics

These were not changed after validation of the simulation program.

F.3 ARRIVAL RATES

The arrival rates to Portsmouth Renal Unit, over the past few years, have been as follows:

ARRIVAL RATES

	Patient arrivals	Cadaver kidneys available *	Cadaver transplants
1979	39	40	32
1980	41	51	45
1981	71	66	44
1982	62	71	63
1983	(68 per year)	(80 per year)	(76 per year)
	50 until 26.9.83	28 until 31.5.83	56 until 26.9.83

* this includes kidneys from UK Transplant.

On the basis of 1982 data, the patient arrival rates were assumed to be 70 per year and the kidney arrival rates 75 per year. From the more recent data, however, it is clear that the kidney arrival rate has now been exceeded. The patient arrival rate has also been increasing, and between the beginning of June and the end of September averaged 8.5 a month, which was a rate of over 100 arrivals a year. This increase in arrivals may be due to the increased availability of haemodialysis facilities following the increased transplant rate and the increasing use of C.A.P.D. as the first choice haemodialysis treatment. I therefore

used arrival rates of 90 patients per month and 90 kidneys per month at the start of the runs described in Chapter 7.

Note: The data in this Appendix was used in the DISTRIBUTION INPUT program. The frequencies quoted may be either numbers from surveys or percentages. The program will accept either.

APPENDIX G

CONSTRAINTS AND PARAMETERS USED IN THE SIMULATION RUNS

The simulation runs

1. To show the range of results with constraints relaxed (6.3.1, 6.3.3).

2. To show the range of results with constrained unit dialysis sessions (6.3.2).

3. The validation of the simulation using the original data (6.5.1).

4. The validation of the simulation using the updated data (6.5.2), and the exploration of different Renal Unit policies (7.1).

5. The factorial design sensitivity analysis (6.6.1).

6. The sensitivity of the simulation to kidney arrival rates (6.6.2).

TABLE G.1

The constraints and variables entered at the start of the simulation runs

Variables	Simulation run					
	1	2	3	4*	5	6
Nephrology beds	50	50	11	11	11	11
Transplant beds	50	50	9	9	6,15 +	9
Haemodialysis machines	50	10	10	10	10	10
Haemodialysis training places	10	2	2	2	2	2
Maximum home machines	200	120	120	120	120	120
Maximum C.A.P.D. places	200	30	200	200	200	200
Unit dialysis sessions	12	7	7	7	5,12 +	7
Patient arrival rate	60	70	70	90	70	70
Kidney arrival rate	60	60	75	90	40,100 +	0-120!

* This run used updated distribution data (Appendix F.2).

\+ These runs were performed at each of these two levels.

! These runs were performed at kidney arrival rates of: 0, 20, 40, 60, 80, 100 and 120 per year.

APPENDIX H

RESULTS FROM THE FACTORIAL DESIGN SENSITIVITY ANALYSIS

Table H.1

Results from factorial analysis averaged over two runs

Averaged over unit machine sessions: 50 and 120

Kidney arrival rate	Total patients				Transplant patients			
	6 months		1 year		6 months		1 year	
	Inpatient beds							
	17	26	17	26	17	26	17	26
40	303.0	302.0	315.0	314.0	159.0	159.0	165.5	166.0
100	300.5	297.5	310.5	310.5	164.5	173.0	178.0	185.5

Averaged over beds: 17 and 26

Unit machine sessions	Total patients				Transplant patients			
	6 months		1 year		6 months		1 year	
	Kidney arrival rate							
	40	100	40	100	40	100	40	100
50	292.5	289.0	298.5	296.0	158.5	168.0	164.5	180.0
120	312.5	309.0	330.5	325.0	159.5	169.5	167.0	183.5

Averaged over kidney arrival rates: 40 and 100

Beds	Total patients				Transplant patients			
	6 months		1 year		6 months		1 year	
	Unit machine sessions							
	50	120	50	120	50	120	50	120
17	290.5	313.0	296.0	329.5	162.0	161.5	172.0	171.5
26	291.0	308.5	298.5	326.0	164.5	167.5	172.5	179.0

Table H.2

Sums of squares for the main effects and interactions in the three factor sensitivity analysis, described in Chapter 6.

The method of calculating the main effects and interactions is described in Davies,[71] . Because each of the simulation runs used the same random number streams, the results were not independent of each other. The F test could not, therefore, be used to test the significance of the interactions. The magnitudesof the sums of squares, however, summarise the relative importance of the various effects. The large sums of squares are underlined.

	Total patients		Transplant patients	
	6 months	One year	6 months	One year
Main effects:				
1. Unit machine sessions (U)	800.0	1860.5	3.1	18.0
2. Inpatient beds (B)	8.0	0.5	36.1	32.0
3. Kidney arrival rate (K)	24.5	32.0	190.1	512.0
Interactions:				
4. UB	12.5	18.0	6.1	24.5
5. UK	0.0	4.5	0.1	0.5
6. BK	8.0	0.5	36.1	32.0
7. UBK	12.5	18.0	6.1	24.5

APPENDIX I

SAMPLE SURVEY OF PATIENT NOTES TO DETERMINE NUMBERS AND TYPES OF PATHOLOGY XRAY REQUESTS AND DRUG PRESCRIPTIONS.

I.1 THE PURPOSE OF THE SURVEY

Costing renal unit activities require estimates of the total workloads generated by the Renal Unit in each major hospital department. In order to use the simulation program to its full potential to project the future costs, however, the estimates must be related to the numbers of patients on the different treatments and taking part in different activities (such as inpatient treatment and outpatient and day patient visits). There was very little information, in Portsmouth District, about the workload imposed by the Renal Unit, on the pathology laboratories, Xray department and the pharmacy department.

Two possible sources of these data were:

i) the departments themselves and

ii) the patient notes.

I chose to survey the patient notes so that I could more easily relate the workload to the type of treatment each patient was receiving. I conducted a pilot study of 16 sets of patient notes in order to design the main survey.

I.2 A PILOT SURVEY OF 16 PATIENT CASE NOTES

The case notes were carefully read and the following data were collected:

i) the dates of inpatient stays, outpatient visits, operations and treatment charges,

ii) the date of each pathology request and its type (i.e. chemical pathology, microbiology, haemotology or histology),

iii) the date and type of each Xray request and

iv) the details and dates of drug prescriptions.

The pilot survey indicated that:

i) the notes, though disorganised, reliably contained copies of the majority of pathology and Xray reports performed, letters to general practitioners specifying the drugs patients were to take at home, dates of inpatient stays, outpatients visits, operations and dates of treatment changes,

ii) the notes did not contain all the drug charts of hospital inpatients,

iii) the vast majority of pathology and Xray requests were made while patients were inpatients, outpatients or day patients and could, therefore, be related to these activities,

iv) patients in different treatment categories (i.e. new, haemodialysis, C.A.P.D. or transplant) made noticeably different demands for pathology services and

v) the analysis of one set of case notes took about one hour and the aggregation of the collected data took a further hour.

I.3 ORGANISATION OF THE MAIN SURVEY

A sample of 25% of the patients (64 patients) on the dialysis/ transplant programme on 30 June 1981 were chosen for the survey. Portsmouth Renal Unit funded the payment of a former employee of the Renal Unit, who was experienced with patients' notes, to collect the data.

I designed two forms for the collection of data relating to patient activities between the dates 1.7.80 and 31.12.81. These were:

i) a computer coding form to collect pathology, Xray, operation patient treatment category information and dates for each patient activity (i.e. inpatient episode, outpatient visit or visit for unit dialysis) and

ii) a form giving more information about operations, reasons for inpatient admissions and drug prescription information from letters to general practitioners.

Inpatient drug information was omitted from the survey and was collected from the pharmacy department by the District Finance staff.

I wrote programs for the Apple II computer to analyse the data from the computer form. The District Finance staff costed the drug information.

I.4 RESULTS OF THE SURVEY

Table I.1 shows the pathology requests, by type and total Xray requests made during the survey period. The transplant patients can be seen to make particularly heavy demands on pathology services when they attend hospital.

Table I.1

Pathology requests between 1.7.80 and 31.12.81 from a sample of 62 patients on the dialysis/transplant programme

Units	Bed days			Visits			
Activity	Inpatient			Unit	Outpatient		
Treatment	Haemo-dialysis	CAPD	Trans-plant	dialysis	Haemo-dialysis	CAPD	Trans-plant
Total units in survey	274	72	406	1334	715	497	1145
Tests per unit:							
Chemical pathology	0.65	0.45	0.84	0.29	1.09	0.85	1.79
Histology	0.01	0.00	0.10	0.00	0.01	0.00	0.00
Bacteriology	0.28	0.40	0.93	0.05	0.16	0.28	0.43
Virology	0.17	0.11	0.21	0.11	0.70	0.33	0.09
Immunology	0.08	0.05	0.14	0.10	0.59	0.54	0.97
Haematology	0.69	0.42	1.02	0.33	1.16	0.83	1.03
Total pathology	1.90	1.44	3.24	0.88	3.71	2.83	4.32
Total Xray	0.28	0.70	0.35	0.02	0.05	0.01	0.05

I.5 USE OF THE SURVEY RESULTS

Chapter 8 describes how the survey results were used in VISICALC (Appendix K) together with cost data (Appendix J) and the results from the simulation runs, to predict future costs of pathology tests, Xrays and drugs for Renal Unit patients.

APPENDIX J

Form designed to collect Costs information from Portsmouth and South East Hampshire Health Authority.

Note : M4 is the nephrology ward

M3 is the transplant ward

and M5 is the unit haemodialysis ward

Renal Unit Costs

Description of costs required within each category		Assumed independent variable (or * if fixed cost)
Nurse Staffing	Annual Costs	
Day nurses		
Nursing Officer		*
M3 Sisters/Charge nurses		)
M3 Staff nurses/SENs		)
M3 Other nurses		) Available inpatient beds
M4 Sisters/Charge nurses		)
M4 Staff nurses/SENs		)
M4 Other nurses		)
M5 Sisters		)
M5 Staff nurses/SENs		) Available machine/sessions
Night nurses		
Sisters/Charge nurses		)
Staff nurses/SENs		) Available inpatient beds
Other nurses		)
Other nurses		
Home dialysis nurse		*
Outpatient nurses - renal unit		Outpatient sessions for renal patients
	Other costs	
Theatre nurses per theatre session		Routine theatre sessions and transplants
Medical Staff	Annual Costs	
(sessions spent on Renal Unit patients)		
Consultants (costs to District)		*
Senior Registrars & Registrars		*
Clinical Assistants		*
Junior Medical Staff		*

Annual Costs	Assumed independent variable (or * if fixed cost)
Transport	
Medical staff transport	*
Pharmacy	
Apportionment to the renal unit of staff costs	*
Drugs and fluids consumed by:	
a) M3	Occupied beds by dialysis patients.
b) M4	Occupied beds by transplant patients.
c) M5	Occupied machine/sessions
Supplies to:	
a) home haemodialysis patients	Home haemodialysis patients
b) CAPD patients	CAPD patients
Outpatient subscriptions to:	
a) haemodialysis	Home haemodialysis patients
b) CAPD	CAPD patients
c) transplant patients	Transplant patients
Medical and Surgical Equipment	
Equipment used by:	
a) M3	Occupied beds by dialysis patients.
b) M4	Occupied beds by transplant patients.
c) M5	Occupied machine/sessions.
d) Home haemodialysis patients	Home haemodialysis patients
e) CAPD patients	CAPD patients

		Assumed independent variable (or * if fixed cost)
	Annual Costs	
Pathology		
An apportionment to the renal unit of the fixed costs		
Costs (excluding fixed costs) of the following requests:	Costs per request	
chemical pathology		)
histology		) Occupied beds by new,) haemodialysis, CAPD) and transplant patients.
blood transfusions		) Home haemodialysis, unit) dialysis, CAPD and
other haematology (including immun- ology)		) transplant outpatient) visits or day patient) visits.
microbiology		))
Average cost per request		
Miscellaneous Direct Treatment	Other costs	
a) Operating Theatre		
cost of a theatre session		Routine theatre sessions and transplants
b) Technicians	Annual costs	
Renal technicians		*
Immunology technicians		*
Artificial kidneys Assts.		Machine/sessions on M5.
Dialysis technicians		New haemodialysis patients and home haemodialysis patients.
Administration		
An apportionment to the renal unit of the general hospital costs		*
Home dialysis administrator		*
Transplant co-ordinator		*
Store keeper		*

Administration cont.	Annual Costs	Assumed independent variable (or * if fixed cost)
Secretaries to:		
a) Renal consultants		)
b) Home dialysis administrator		) Total patients
c) Transplant co-ordinator		)
d) General renal		)
Telephones		)
Medical records -		
Ward clerk		*
Renal Outpatients		Outpatient sessions
Other administrative costs:		
Transport		Home dialysis patients
Costs related to size of Buildings		
Domestic staffing		*
Portering		*
Buildings & maintenance		*
Energy & utility		*
Estate management		*
Radiology	**Costs per request**	
X-Ray requests		Requests estimated from inpatient occupancy and outpatient visits.
Catering		
An apportionment to the renal unit of the staff costs.		*
Staff of metabolic kitchen		)
Provisions, hardware and kitchen equipment		) Occupied beds in M3 and M4 and day attendances on M5
Extra cost of provisions for patients on diets		)

Annual Costs	Assumed independent variable (or * if fixed cost)
Laundry	
An apportionment to the renal unit of the staff costs	*
Linen services	Occupied beds in M3 and M4 and day attendances on M5.
Paramedical	
E.C.G.	*
Physiotherapy	*
Medical photography	*
Dietician	*
Post mortem technicians	*
Other	
Training and education	*
Miscellaneous	*
Machines and Portakabins	
Cost of a machine	New home haemodialysis patient (excluding those using recycled machines).
Cost of installing a machine in a house	New home haemodialysis patients (50%).
Cost of replacement parts (annually)	Home haemodialysis patients.
Cost of a portakabin	)
Cost of installing a portakabin	) New home haemodialysis) patients (50%).)
Cost of moving a portakabin	)
Cost of putting home to rights	) Patients leaving home) haemodialysis))

APPENDIX K

VISICALC PRINTOUT SHOWING ESTIMATES OF COSTS USING RUN A

Notes

1. The values are rounded to the nearest integer.
2. The first column is based on data available in 1982 and the other columns are based on simulation results, in six month time periods.
3. The first block (down to the second dotted line) shows resource levels at the end of the six month time periods, from the simulation.
4. The second block shows patient activities (e.g. arrivals and transplants) during each six month period and patient numbers at the end of each six months period, all from the simulation.
5. The third block shows average weekly bed days by treatment from the simulation, average weekly machine sessions from the simulation and weekly outpatient attendances estimated from the patient numbers in the previous block.
6. The fourth block shows the pathology requests, estimated from the previous block.
7. The other blocks show costs, estimated using the figures in the previous blocks and data collected on the form shown in Appendix J.

	DATA 81/82		PREDICTED FROM SIMULATION RESULTS			
WEEKS	2PER YEAR	I	26	52	78	104
I.P.BEDS AV	17	I	20	24	24	24
UNIT M/SESS	70	I	70	70	70	70
THEATRE SES	2	I	2	2	2	2
O.P.SESSION	4	I	4	4	4	4
ARRIVALS	25	I	45	46	45	46
RECYCLE MAC	5	I	7	10	7	11
START HOME	18	I	5	7	10	4
STOP HOME D	15	I	16	26	20	29
TRANSPLANTS	30	I	40	49	55	52
TRANSPL. W.		I	51	56	45	35
PATIENTS:		I				
NEW	0	I	2	2	3	4
UNIT	14	I	17	16	13	13
HOME	80	I	87	83	72	71
C.A.P.D.	15	I	42	50	57	66
NEW GRAFT	25	I	33	37	47	35
FN. GRAFT	100	I	148	171	197	234
TOTAL	234	I	329	359	389	423
I.P.-HAEMOD	9	I	6	6	5	5
I.P.-C.A.P.		I	2	2	2	3
I.P.-TRANSP	5	I	8	9	10	11
I.P.- TOTAL		I	15	18	19	20
UNIT OCCUPA	48	I	51	53	50	47
O.P.-HAEM	22	I	24	23	20	20
O.P.-C.A.P.	7	I	19	23	26	30
O.P.-TRANSP	36	I	52	59	70	74
		I				
		I				
PATH.TESTS	13833	I	17688	19823	21451	22475
COSTS		I				
NURS.FIXED	6434	I				
I.P.VARIABL	132649	I	156057	187268	187268	187268
UNIT VARIAB	23055	I	23055	23055	23055	23055
HOME DIALYS	4393	I	4393	4393	4393	4393
RENAL O.P.	5832	I	5832	5832	5832	5832
ROUT.THEATR	7064	I	7064	7064	7064	7064
EMERG.THEAT	4076	I	5434	6657	7472	7064
NURSES TOTA	183501	I	208268	240702	241517	241110
NSULTANTS	39506	I				
REGISTRARS	23205	I				
JUNIOR	6910	I				
TRANSPORT	200	I				
MED.STAFF T	69821	I	69821	69821	69821	69821
PHSTAFF	5387	I				
I.P.DIALYSI	25036	I	20001	22032	21281	23534
I.P.TRANSPA	61244	I	96521	114894	127632	131430
UNIT DIALYS	10324	I	10877	11439	10728	10110
HOME DIALYS	70611	I	76789	73259	63550	62667
C.A.P.D.	5973	I	16723	19908	22695	26279
TRANSPLANT	4752	I	6881	7907	9276	10226
PHARM.TOTAL	183326	I	233178	254826	260549	269632
MED+SURG EQ		I				
I.P.DIALYSI	15210	I	12151	13385	12929	14297
I.P.TRANSPL	11323	I	17844	21241	23596	24298
UNIT DIALYS	16193	I	170	17942	16827	15857
HOME DIALYS	67355	I	73248	69880	60619	59777
C.A.P.D.	891	I	2493	2968	3384	3918
EQUIP.TOTAL	110970	I	122796	125416	117354	118148
PATH FIXED	49994	I				
TESTS	5379	I	6878	7708	8341	8740
PATH.TOTAL	55374	I	56872	57703	58336	58734
MISC.DIR.TR		I				
ROUT THEATR	6365	I	6365	6365	6365	6365
EMERG THEAT	3263	I	4350	5329	5982	5656
REN TECHNIC	5418	I				
A.K.ASSISTA	19920	I	19920	19920	19920	19920
DIAL.TECHNI	12873	I	19598	18964	16219	16223
MDT TOTAL	47838	I	55652	55996	53904	53581
ADMIN.FIXED	16108	I				
SECRETARIES	18825	I	26468	28881	31295	34030
MED.RECORDS	4848	I	4848	4848	4848	4848
TRANSPORT	3961	I	4308	4110	3565	3515
ADMIN.TOTAL	43742	I	51731	53946	55815	58501
X RAY	4174	I	4493	5158	5387	5721
OTHER FIXED	93225	I				
FOOD+LINEN	6146	I	6506	6986	6735	6561
OTHER TOTAL	99370	I	99731	100211	99959	99785
REVENUE TOT	798115	I	902541	963778	962643	975032
RECYCLE MAC	7560	I	10584	15120	10584	16632
NEW MACHINE	64960	I	18560	25984	37120	14848
RUNNING COS	4000	I	4350	4150	3600	3550
REMOVE MACH	7350	I	7840	12740	9800	14210
CAPITAL TOT	83870	I	41334	57994	61104	49240
GRAND TOTAL	881985	I	943875	1021772	1023747	1024272

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