Middle Articles

COMPUTERS IN MEDICINE

Computer Model Simulating Medical Care in Hospital

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Summary: A computer model has been constructed to simulate the activities and events concerned in the care of patients in hospital. After validation of the model it has been used to examine the consequences of certain changes in the mode of working in the hospital, including the scheduling of items of service and a system of progressive care. It is concluded that computer models of this kind are likely to prove of value in the management of hospital resources.

In this communication we describe an attempt to simulate, by the construction of a computer model, the way in which medical care is provided for individual patients in hospital. Simulation techniques have been used effectively in many industrial situations to enable managers to experiment with new policies and to assess their long-term effects. The construction of a model to simulate the care of patients in hospital might make it possible to test alternative management policies without incurring the cost and inconvenience of experimenting in the real situation. It is not possible, however, to transfer the methods of formulating an industrial problem to the hospital situation because of the enormous diversity in the requirements of individual patients. The present approach therefore introduces a new method of formulating complex logic models devised especially for the study of patient care.

The model represents the interaction with their environment of patients admitted to the medical unit. The characteristics of the patients are established in terms of the items of attention they will receive. The environment is defined by a set of logical rules governing the way in which these demands are met. The ward and service facilities have limits on their capacities which are determined from studies of the real situation. These limits may be varied in accordance with changes in management policies.

Each patient is represented in the data input to the model by an "initial patient profile," which defines the pattern of care required and the logical sequence of the investigations and treatment necessary. These initial profiles interact with the environment and are modified according to the logical rules of the model and by the limits placed on the various services. The logical sequences built into the profiles remain unaltered. The output from the model is in terms of modified profiles and statistics on the use of facilities.

Construction of Initial Patient Profiles

Detailed information was obtained by recording daily each item of service received by each patient on two medical wards comprising 58 beds. A total of 94 patients was observed, this being approximately a 10% sample of the patients cared for in a year. Some of the information was obtained by direct observation and the rest from the clinical and nursing notes or the records kept by laboratories and service departments. Nursing dependency was determined daily for each patient according

to the criteria of Barr (1967). Radiological investigations were recorded as simple or complex according to a previously agreed classification.

This information was not in itself sufficient to allow a model to be constructed. The observations have established which items of service were given to each patient and the day on which they were given. They did not indicate the reason for the particular sequence in which they were required. It was not evident, for instance, whether some of the tests recorded were requested because of the results of others. The observed sequence and timing of the items was dependent on both the logic of the pattern of care provided and the availability of resources. The observations on each patient were therefore discussed in detail with the clinician in charge in order to determine the reasons for the sequence observed and the limits within which this might have been allowed to vary. In this way the logic framework of a patient's need for items of service was formulated in terms of an *initial patient profile*, which was used as input to the model. This initial profile not only defines the items of service required but also includes a built-in time structure with, in the present case, a resolution of one day.

The items of service were of more than 200 kinds, each separately coded. The coding system used a four-digit code which allowed for classification of tests and items of service in terms of (a) department, (b) complexity with regard to the tolerance of the patient, and (c) the day of the week on which a particular test is done. Provision was also made for special codes representing the movement of patients in and out of the ward.

The complete set of 94 initial profiles was held on magnetic tape, and these data are known as the "main file." This can be added to or altered at any time if it is necessary to change the population from which admissions are to be drawn. It was found that items of service fell into one of three classes.

Fixed items are defined as those items of service which, by reason of the patient's condition, must occur on a particular day of his stay, and hence are characterized by a day number with respect to his day of admission.

Sequences of items consist of lists of logically related items of service which must occur in a certain sequence. Each sequence has a "start day," which is the earliest possible day the sequence could begin. Sequences include a time element by means of "fixed delays" or "random delays," depending on whether or not the shortest possible time lapse between items in the sequence is known. As an example of a fixed delay it might have been indicated that a particular test should follow after a course of treatment lasting for a specified number of days. Another sequence of tests might be such that one test logically can only follow another, but the time interval would not be fixed and could acceptably range within certain limits, the exact time in any case being determined randomly. Each item in the sequence is characterized by a "priority number," whose value is directly proportional to the greatest permissible delay on the particular item.

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Independent items are those which do not form part of a sequence and whose timing is not critical. These items are characterized by a day number, indicating the earliest possible day for the item to be given, and a priority number, related to the greatest delay permissible for the item.

Description of Model

The model functions in the following way. Admissions are made by random selection of initial patient profiles from the main file to fill empty beds in the ward. Limits are placed on the capacities of the service departments and the availability of the medical staff which restrict the number of procedures or tests to be done on a particular day. A limit was also set to the number and kind of procedures which a patient could tolerate on any one day, this being termed a "patient restriction." All of these limits were determined empirically in the first instance, but if on testing the model was found to be unduly sensitive to any of the restrictions imposed, then a more careful evaluation of the offending restriction was made.

The simulation proceeds by first scanning the "ward file"—that is, the collection of the profiles of patients in the ward—and completing all fixed items for the day. The sequences are then scanned and top priority items are completed, unless there is a patient restriction forbidding this. Top priority items are completed even if the capacities of the service departments or the medical staff are exceeded, in which case an "overflow" is recorded.

Sequence items which do not have top priority are formed into a queue in order of priority. The independent items are then scanned and those with top priority are completed, unless there is a patient restriction. Again, as for the sequences, if the limits on capacities of service departments or the availability of the medical and nursing staff are exceeded, then an overflow is recorded. Lower priority items are queued in order of precedence following the sequence items in their respective priority queues.

Each time an item is completed a record is made in an output table. After all the top priority items have been completed the queues are scanned and items with lower priorities are completed until the various limits on capacities are reached. Any items which cannot be completed remain in the queues but have their priorities raised by one. The ward file, the profiles of patients in the ward, and the output table are updated. Profiles of patients leaving the ward this day are printed out and removed from the ward file. This is equivalent to releasing a bed for a further admission. The total nursing dependency index for the ward is printed out and also the average dependency index per patient. An output table is printed which indicates, under 30 headings, the items of service that have been given to the entire ward during the day and any overflows that have occurred.

The operating rules for the model and the use of service facilities and the interpretation of the logic of the initial patient profiles, are written in a number of computer subroutines called by the main computer programme. This provides considerable flexibility for future development of the model. The programme is written in FORTRAN to be run under the EGDON III system on a KDF 9 computer. The present suite of programmes comprises seven subroutines and two main programme segments. The running-time is of the order of 90 minutes for 60 simulated days.

Validation of Model

In order to establish the validity of the model it is necessary to show that the predictions contained in the output closely resemble the real situation. In the present model this has been examined from three aspects.

Comparison of Various Statistics.—The model was run to simulate 100 days and the frequency distributions of various criteria were compared with the distributions observed in the real situation. The values for the length of stay, nursing dependency index, and daily number of biochemical tests are shown in Table I. In no instance was there any significant difference between the simulated and observed mean values or frequency distributions.

Comparison of Output Profiles with Input Profiles.—Altogether 189 output profiles were examined and compared with the corresponding initial patient profiles. In each instance the two were compatible within the limits set by the logic sequence and the delays allowed in the input profile. Individual lengths of stay in the ward were compared and in 38% of cases the output and input profiles agreed exactly. In 62% of patients they differed by no more than ± 2 days and in 81% they were within ± 4 days.

Effects of Alterations in Limits.—Further evidence of the general validity of the model was obtained when the limits on the number of items of service per day allowed for certain departments were permitted to vary. If the model were unstable then small changes in these limits would be expected to cause substantial alterations in the number of patients leaving hospital and in the mean length of stay. When this was tested the contrary was found, considerable variation in the limits producing little effect on length of stay.

Though the validity of the model could be examined more exhaustively, it is felt that these findings justify confidence in the model when used to study the criteria described.

Some Applications of Model

The model may be used for a range of purposes to determine the consequences of particular changes in the hospital environment or ways in which resources are used. The examples which follow are some of those so far examined.

TABLE I.—Comparison of Long-term Statistics

	Simulated Values		Observed Values		% Patients Lying Within Stated Ranges		
	Mean	Range	Mean	Range		Simulation	Observed
Length of stay (days)	14.4	1-76	14.7	1-168	Stay in days:		
					3	10	9
					8	38	39
					8-21	41	40
					21	21	22
Nursing dependency index	49.0	39-61	48.7	31-71	30	10	10
					Values for index:		
					40	6	9
					41-50	58	53
					51-60	35	33
Daily number of requests for biochemical tests	12.2	3-27	12.7	0-47	60	1	5
					No. of tests per day:		
					10	42	40
					11-15	35	40
					16-20	16	18
					21-25	4	6
					25	3	6

Values for nursing dependency indices and daily number of biochemical tests have been normalized for 30 occupied beds.

They are chosen to illustrate the possible applications of the model rather than for their individual relevance.

"Ideal" Situation

This is defined as the situation in which there is no limit on the availability of any resource and there are no delays. The patient will receive any item of service as soon as it is decided he requires it and without it being necessary to book or schedule the procedure. In order to simulate this situation all limits were removed and all random delays were reduced to zero. A period of 100 days was simulated and the results were compared with those from a similar period of simulation under normal conditions.

Under normal conditions 189 patients were discharged in the period, while under the "ideal" conditions 235 patients left hospital, an increase of 24%. Values for selected criteria are given in Table II, and it will be seen that the mean values in the two situations differed to a variable extent. The number of days on which the limits were exceeded is also shown, and this provides some indication of the overload on the particular service.

The results suggest that the increased number of patients passing through the hospital would not greatly increase the nursing-load, in so far as this is measured by the dependency index. The demands on the diagnostic service departments would be substantially increased and, depending on the limits applied, these additional demands could be met to a varying degree.

System for Scheduling Services

This situation would exist if the need for each item of service normally associated with a random delay could be foreseen and if, by means of a system of scheduling, all such delays were eliminated. In order to examine this situation all random delays were reduced to zero, but the limits were left unaltered. A period of 100 days was simulated and the results were compared with the normal and ideal situations.

The number of patients leaving hospital in the period was 228, an increase of 21% over the normal situation. Selected values are again given in Table II. Comparison of these values shows that the additional loads to which individual departments were subjected are similar to those in the ideal situation.

It may be concluded that under the conditions of this model an increase in the number of patients leaving hospital could be achieved by an effective scheduling system, and that there would be little further improvement if the specific

departmental and other limits were removed. No firm conclusion is possible, since these limits are at present imprecise, but the findings indicate the kind of conclusions that might be obtained with a model representing a whole hospital, for which the constraints would be more accurately known.

Full Seven-Day Working Week

In the model representing normal conditions allowance was made for most items of medical care to be provided on Sundays, but only emergency surgery and no laboratory investigations unless these were indicated as being required for urgent reasons. In order to test the effects of working a full seven-day week the model was set to operate with all days of the week exactly alike.

In the test period of 100 days 196 patients were discharged from hospital, representing a 4% increase over the normal condition. The effect on the number of requests to the service departments was predictably to even out the demands, with flattening of the usual peaks on Mondays.

System of Progressive Patient Care

The purpose of this application was to determine the effects on nursing requirements if a unit comprising 100 beds were reorganized into three sections providing intensive care, normal care, and minimal care. Patients suitable for the intensive care section were defined as those with the highest index of nursing dependency according to the criteria of Barr (1967). In brief, these criteria include unconsciousness, pronounced confusion, or a requirement for a number of technical nursing procedures. Patients classified as fit for the minimal care section had a low index of nursing dependency, were ambulant, needed no assistance with feeding or toilet, and were not undergoing technical procedures or complicated investigations.

It was considered that to be effective the intensive care section must not contain fewer than four beds. For the purpose of the study we have assumed from the observations of Barr (1967) that patients in the low, intermediate, and high categories of nursing dependency require nursing attention in the ratio of 1:2:5. We have assumed that when a patient with high nursing dependency is transferred to the intensive care section the requirement would fall from 5 to 4 units of nursing attention. From other published data (Meredith *et al.*, 1968) we have calculated that a patient in the minimal care section would require only 0.3 unit of nursing attention instead of 1 unit. All of these assumptions can be seriously

TABLE II.—Comparison of Results from Simulation of System for Existing Normal Conditions, Ideal Conditions, and Conditions Involving Elimination of All Unnecessary Delays

	Mean and Range			Upper Limit	No. of Days When Limit Exceeded		
	Normal	Ideal	No Delay		Normal	Ideal	No Delay
Nursing dependency index	49.0 (39-61)	50.2 (40-62)	50.14 (41-66)				
I.V. drips in progress	2.2 (0-7)	2.8 (0-6)	2.49 (0-8)	5	3	5	4
Dressings	3.45 (0-7)	4.45 (1-10)	4.39 (1-9)	20	0	0	0
Bedfast patients	8.95 (2-13)	10.4 (5-17)	11.1 (5-17)	30	0	0	0
Patients requiring extensive medical care	1.59 (0-7)	2.11 (0-5)	2.17 (0-7)	5	1	0	4
Consultants' visits	2.05 (0-5)	2.63 (0-7)	2.62 (0-7)	3	4	29	6
Biochemical tests	12.2 (3-27)	17.2 (5-35)	14.72 (4-31)	47	0	0	0
Haematology tests	9.58 (1-17)	11.01 (0-26)	10.29 (2-17)	17	0	10	0
Simple radiology	3.49 (0-8)	3.48 (0-13)	3.7 (0-8)	8	0	3	0
More complicated radiological procedures	0.9 (0-3)	1.08 (0-5)	1.14 (0-5)	2	2	8	6
Bacteriology tests	4.42 (0-9)	4.09 (0-16)	4.57 (0-6)	6	2	12	0
Surgical operations	0.49 (0-3)	0.56 (0-3)	0.47 (0-3)	3	0	0	0

Nursing dependency is for 30 beds.

TABLE III.—Effect on Requirement for Nursing Staff of Alternative Allocations of Beds within a System of Progressive Care

Total No. of Beds in Unit	No. of Beds in Each Section			% Days When Extra Beds Needed in Normal Care Section								Total No. of Nurses Required
	Intensive Care Section	Normal Care Section	Minimal Care Section	No Extra Beds	1 Extra Bed	2 Extra Beds	3 Extra Beds	4 Extra Beds	5 Extra Beds	6-10 Extra Beds	>10 Extra Beds	
100	4	60	36	2	0	1	1	3	4	37	52	37
100	4	70	26	41	12	11	10	9	5	12	0	37
100	4	80	16	80	8	8	4	0	0	0	0	39
100	6	78	16	44	19	17	8	8	4	0	0	39
100	2	82	16	95	5	0	0	0	0	0	0	39
100	1	83	16	100	0	0	0	0	0	0	0	39

questioned, and before any numerical conclusions were drawn they would need to be supported or modified by the results of suitable work studies. The values are used in order to show the possibilities of the particular application.

The simulation allocates a fixed number of beds to the intensive and minimal care sections, the remaining number of beds in the general section making up a total of 100. Patients meeting the criteria specified are transferred from the general ward, and subsequently back again should their requirements change. Vacant beds in the general ward are filled by newly admitted patients. In consequence a variable number of extra beds are required in the general ward.

Some results are shown in Table III, and it will be seen that of those tested a distribution of beds in the ratio intensive:general:minimal care of 4:80:16 provides optimum conditions. Other distributions result in a much greater need for extra beds in the general ward. Using the data of Meredith *et al.* (1968) there would be a need for 44 nurses to serve 100 beds, working normally. From the simulation it is found that for the distribution of beds mentioned above the number of nurses required falls to 39. Under these conditions of working the percentage occupancy of the beds in the intensive, general, and minimal care sections was 89, 96, and 100 respectively.

Discussion

We believe that the approach we have described provides a model which simulates activities within a hospital faithfully enough to make it a potentially useful device for studying the consequences of a variety of operational policies. Since we were primarily concerned with the development of a method, we decided to collect data from only a limited section of the hospital initially, though it should be noted that the wards concerned accommodate patients having a wide range of illnesses, about a fifth of whom are treated surgically. It would, however, be unrealistic to base any conclusions on the results of the particular applications we have described, since the patient profiles used for data input were not fully representative of all patients admitted. Furthermore, the limits applied to the various elements of service were difficult to determine for a small portion of the hospital, but could be more realistically stated for the hospital as a whole. For these reasons more meaningful results are likely to be obtained when the model is extended to simulate the work of the whole hospital, with input data composed of profiles of patients selected from each ward in proportion to the number of patients treated in a specified time.

It will be evident that, using a model as detailed as the one described, it will be possible to test the consequences of a large range of policy decisions. It will of course be essential to examine critically all predictions made by the model. For example, if a particular simulation were to reveal that the limits for a particular service facility were often exceeded a detailed examination would be necessary. This might show that the limits had been set at an unrealistically low level or that the limited availability of the service represented a true restriction to the care of patients and caused important delays. In the latter case the model could be used to deter-

mine the extent to which the facility needed to be augmented. Furthermore, the effects of such an increased service facility could be examined with particular attention to the possibility that restrictions from other sources might then become evident, so limiting the benefits to be expected.

Many other examples could be mentioned extending over different activities of the hospital. The functional consequences of a full system for scheduling procedures have already been indicated in terms which have a qualitative significance for the whole hospital. It would be of interest to study the effects of admitting patients in different proportions according to clinical classifications and of distributing these patients between individual wards in an altered manner. The possible application of the model to predict the number of nurses needed to work under different patterns of patient care has been illustrated. The example given is a relatively crude one, but with experience it may prove possible to reach more accurate predictions. It is possible that the precision might eventually be such that the predictions could be used with confidence in day-to-day management.

It has often been suggested that a high proportion of the costs of running a modern hospital result from delays due to the slow transmission of clinical data. To reduce such delays is one of the principal objectives of real-time computer systems for hospitals. It may prove possible to forecast, by use of the present model, the benefits likely to result from the elimination of these delays. This might help to provide justification for the further development of the necessarily expensive computer systems themselves.

The outcome of any simulation with this model is to a large extent dependent on the form taken by the patient profiles used for the data input. In particular the logic underlying the time sequences, acceptable time limits, and order of individual items of service is most important. The present profiles were established by observation and the logic was agreed after discussion of individual patients by two doctors involved in their medical care. This procedure is time-consuming, especially so when large numbers of criteria are included in the patient profile. A simpler but less satisfactory procedure would be to construct idealized patient profiles with a logic based on what the doctor believed to happen or considered should occur. Finally, it would be possible to reduce the number of criteria under consideration and in this way substantially reduce the task of constructing the patient profiles. This would make the output of the simulation less comprehensive and reduce the range of questions open to consideration—an approach which might nevertheless be acceptable for limited applications.

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