COMPUTER SIMULATION OF A HOSPITAL HEALTH-CARE DELIVERY SYSTEM

James W. Kho, Ph.D.
Department of Computer Science
California State University, Sacramento

and

G. Miles Johnson
Technical Consultant, California State
Assembly Office of Research

ABSTRACT

This paper deals with a project undertaken to improve patient services in a health-care delivery system for a state hospital. A computer simulation study is implemented for resource, facility, and patient traffic analyses. This encompasses a set of standardized data collection and analysis techniques, modeling strategies, validation and evaluation tools. A computer model simulates patient flow through a radiology facility. In addition to identifying causes of congestion and low productivity, the model is useful in projecting effects of changes in the system. These changes include planned modifications such as scheduling schemes, increases in resources, and a possible increase in patient load.

INTRODUCTION

This study of hospital health-care system improvement parallels work conducted elsewhere (4) and has several long-term goals. Included are

(1) the design and implementation of a computerized medical data base for efficient record access and updating;
(2) a comprehensive evaluation of existing facilities and resources;
(3) the assessment of congestion as a function of safety, cost-effectiveness, and life-cycle utilization; and
(4) forecasting effects of changes in resources and demand on the system.

A more specific aim of the project is to develop a comprehensive input/output model that provides a description of patient flow for various demand conditions and resource allocation and scheduling schemes. The report here centers on the radiology services provided by the hospital.

SYSTEM DESCRIPTION

The hospital provides adjunct diagnostic and therapeutic radiology services as required for medical examinations and therapeutic treatment procedures. These procedures are classified as

(1) Routine diagnostic procedure--for patients who require X-rays only with no special preparation, e.g., chest X-ray.
(2) Scheduled special diagnostic procedure--for patients requiring special preparation with injections of radio opaque dyes or swallowing a radio opaque solution. I.V.P.'s, barium enemas, or gall bladder examinations fall into this category.
(3) Scheduled surgical procedure--for patients requiring X-ray technicians to assist surgical personnel to perform diagnostic procedures such as angiograms and cystoscopies.
(4) Scheduled therapeutic procedure--this includes teletherapy, i.e., the use of X-ray and other high-energy modalities, radium, cobalt, etc. and bracly therapy, i.e., the surface, intracurvatary or interstitial application of contained radioactive sources.
(5) Non-scheduled emergency--emergency patients have priority over all others in that routine and special procedure patients may be preempted whenever emergency patients enter the system.

Patient flow through the system is shown in the flow diagram in Figure 1. Sources of these patients are listed in Table 1. Patients are routed through the receptionist area unless they are confined to wheeled conveyors. In the latter case, the patient waits in a separate room while reception procedures are completed. A few patients arriving at this point are new or do not have their requisitions available and consequently require a longer processing time to prepare the required records. After reception procedures are completed special patients are seated and wait until the appropriate room becomes available. Routine patients also wait and then are routed to the first available room that has a routine procedure classification.

INVESTIGATIVE PROCEDURE

The simulation study on radiology services is divided into several different phases. These are

(1) data collection and analysis,
(2) problem formulation and experimental design,
(3) model building and programming,
(4) model validation,
(5) output analysis.

A brief description of the procedure follows.

FIGURE 1

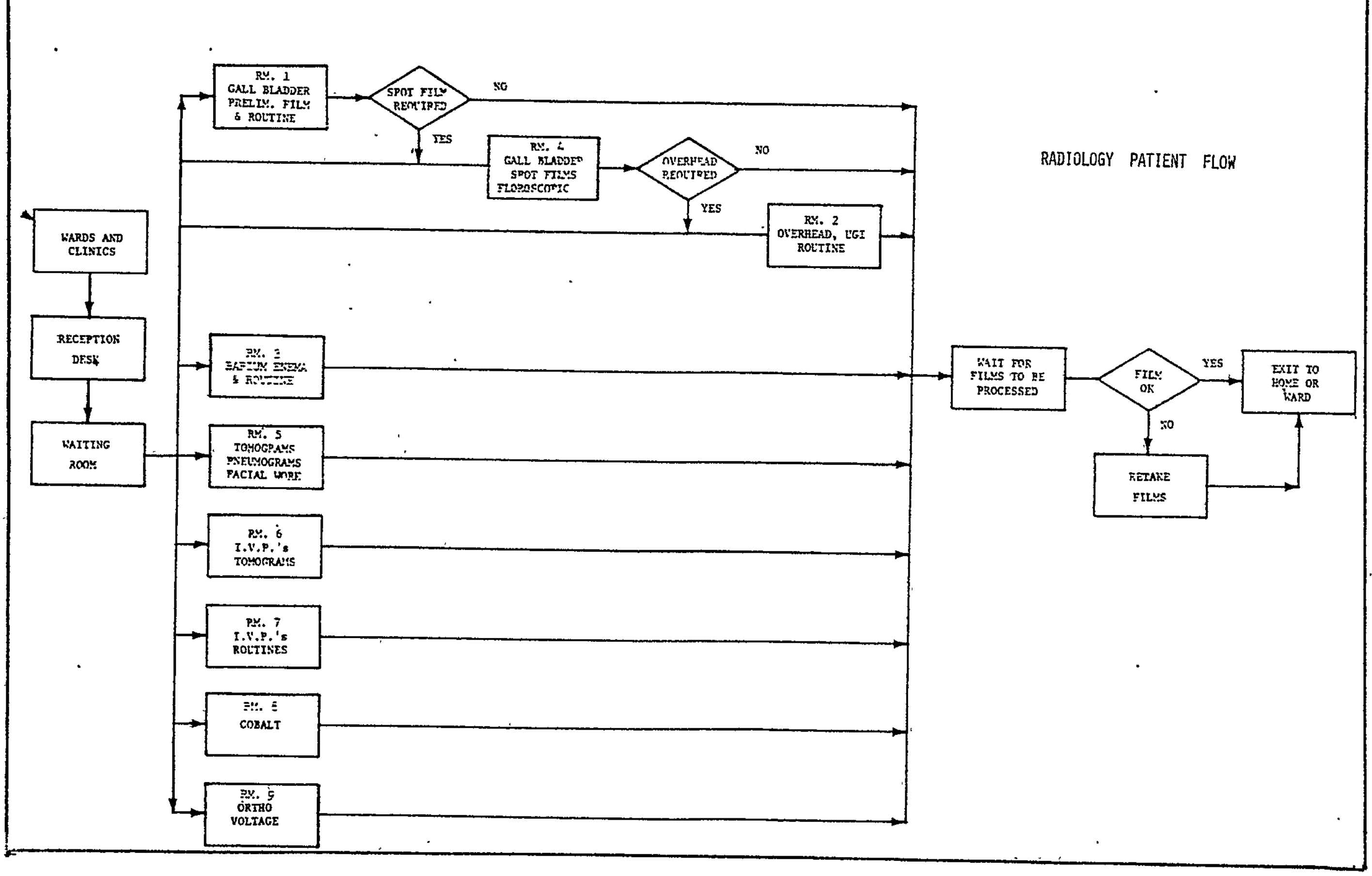


TABLE 1

DEPARTMENTAL INPUT

Gynecology	Orthopedics
Opthamology	Oral Surgery
Plastic Surgery	Ortholate Surgery
Proctology	Urology
Thoracic Surgery	Medicine
Psychiatry	Pediatrics
General Surgery	Outpatient Clinics

Parametric data considered in this study are:

- Patient arrival rates
- Reception service rates
- Examination service rates
- Number of examination rooms
- Probability of using a particular service
- Time to process X-ray films
- Time to proof-read X-ray film
- Number of emergency X-rays
- Number of special procedure patients
- Number of routine procedure patients.

THE SIMULATION STUDY

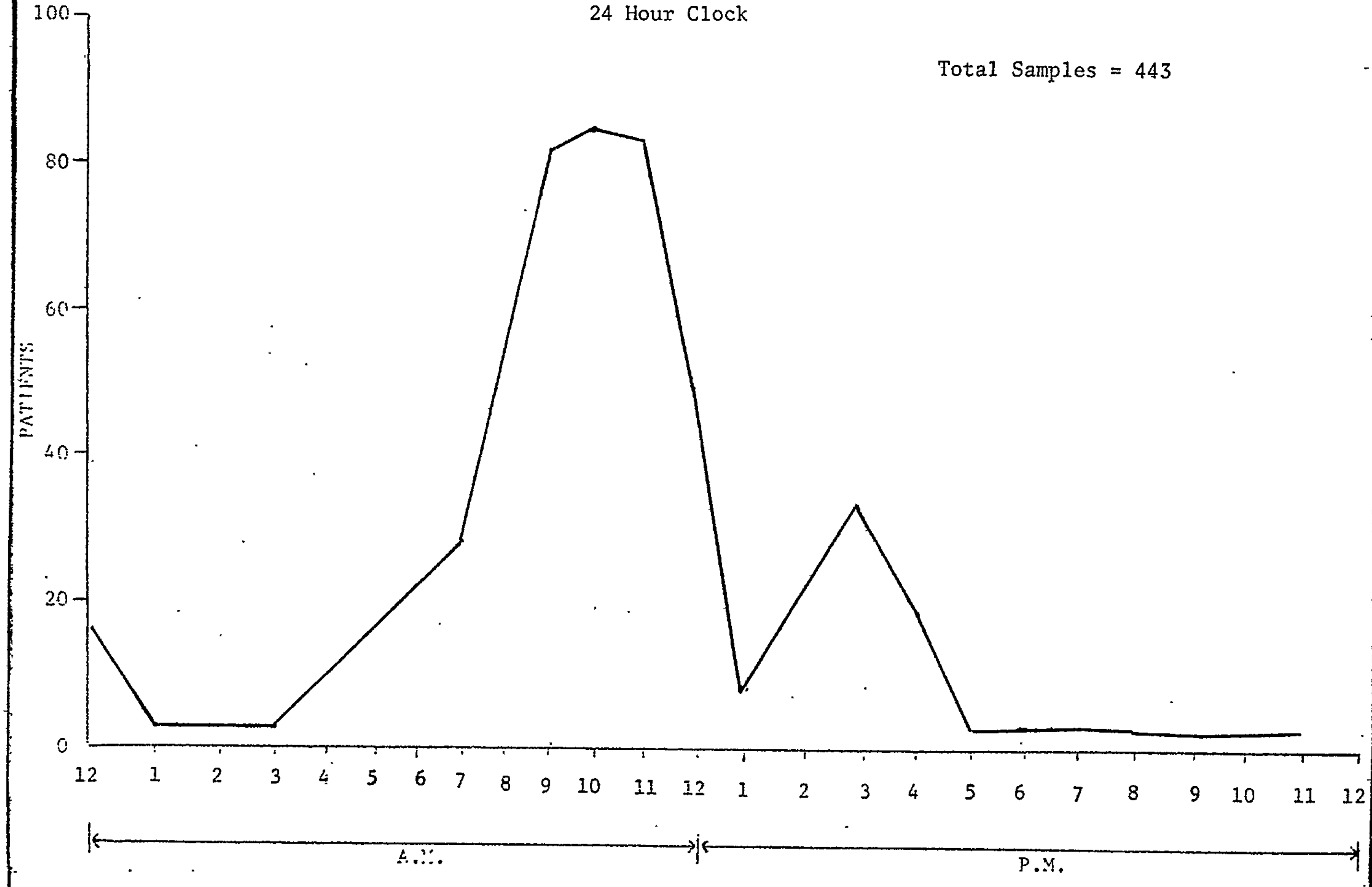
DATA ACQUISITION

Data collection consists of two methods. First, daily monitoring of patient flows and queue times is carried out through the aid of hospital technicians. Information is registered on special forms

FIGURE 2

PATIENT ARRIVALS

24 Hour Clock



The above graph illustrates the composite arrival rate over one week plotted by hour of the day in which the patient arrived. The arrival time was rounded to the nearest hour (on the horizontal scale). The vertical scale represents the weekly number of patients. The daily patient interarrival distributions have close to the same proportions as this weekly composite.

containing items such as arrival time, department, procedure to be performed, room, and service time. Second, hospital records provide aggregate data such as number of patients served at a particular station, or number of examinations of a specific type carried out per month. Tables and distributions are then compiled from the empirical data, and where statistical "goodness-of-fit" tests confirm, appropriate standard distributions are used.

During the last 6 years, the number of examinations per month show little fluctuation from month to month, as shown in Table 2. There is also little variation from week to week. The average daily patient interarrival distributions are shown in Figure 2 and Table 3. Results of data analysis on a daily basis demonstrate significant variation in demand (1) between "Orthopedics" days* (Tuesdays and Thursdays) and other days, (2) between weekdays and weekends, and (3) between mornings and afternoons.

*An "Orthopedics" day is one in which orthopedics patients are sent as a group to radiology for examination of previously set broken bones.

Various service rates and examination delay times are tabulated. At the reception desk, the hospital employs two receptionists who process requisitions and locate records for each patient. This takes an average of 9 minutes for patients whose requisitions are available and 15 minutes if the requisition is not available. The distribution of waiting times preceding the examination is shown in Table 4.

Examination delay times are uniformly distributed from day to day (see Table 5) indicating a "state dependent" service rate. That is, the technicians relinquish allocated break times to attenuate long patient waiting lines on busy days. Some statistics on examination service times are shown in Tables 6 and 7. Data analysis is aided by computer programs written in FORTRAN and the use of canned statistical analysis programs.

TABLE 2

TOTAL EXAMS

	1970	1971	1972	1973	1974	1975
January	4,570	4,742	5,303	4,472	4,881	4,708
February	3,613	4,276	4,324	3,912	4,106	3,985
March	4,519	4,581	4,783	4,618	4,065	4,619
April	4,132	4,594	4,672	4,470	4,023	4,851
May	4,182	4,298	4,885	4,929	4,272	4,317
June	3,859	4,941	4,798	4,335	4,639	3,788
July	4,473	4,408	4,612	4,796	4,170	5,899
August	4,552	5,029	4,635	4,157	4,328	5,165
September	4,636	4,714	4,326	4,101	4,294	4,832
October	4,619	3,991	4,089	4,524	4,492	4,721
November	4,343	4,306	4,052	4,059	4,530	4,389
December	4,427	3,949	4,227	4,098	4,247	4,519

TABLE 3

DISTRIBUTION OF AVERAGE PATIENT INTER-ARRIVAL TIMES

MINUTES	NUMBER OF PATIENTS	PROBABILITY OF OCCURRENCE
1-5	195	.440
6-10	104	.234
11-15	43	.097
16-20	32	.072
21-25	22	.050
26-30	8	.018
31-35	18	.040
36-40	4	.009
41-45	5	.011
46-50	0	.000
51-55	2	.006
56-60	3	.007
61-65	4	.009
66-70	2	.005
71-75	0	.000
76-80	0	.000
81-85	0	.000
86-90	0	.000
91-95	0	.000
96-100	1	.002
TOTAL PATIENTS	443	1.000

TABLE 4

DISTRIBUTION OF EXAMINATION WAITING TIMES

MINUTES	NUMBER OF PATIENTS	PROBABILITY OF OCCURRENCE
1-5	108	.244
6-10	82	.185
11-15	75	.169
16-20	61	.138
21-25	36	.081
26-30	21	.047
31-35	11	.025
36-40	10	.023
41-45	11	.025
46-50	8	.018
51-55	5	.011
56-60	6	.014
61-65	1	.002
66-70	0	.000
71-75	1	.002
76-80	3	.007
81-85	0	.000
86-90	2	.005
91-95	0	.000
196-100	0	.000
101-105	1	.002
106-110	0	
111-115	1	
TOTAL PATIENTS	443	1.000

TABLE 5

DAILY EXAMINATION DELAY TIMES IN MINUTES

DAY	AVERAGE DELAY
MONDAY	15
TUESDAY	13
WEDNESDAY	20
THURSDAY	21
FRIDAY	18
SATURDAY	15

TABLE 6

EMERGENCY X-RAY UTILIZATION

FACILITY	ARRIVAL RATE PATIENTS/HR.	AVERAGE TIME BETWEEN ARRIVALS	SERVICE RATE PATIENTS/HR.	AVERAGE SERVICE RATE (MINUTES)	PROBABILITY OF USE
EMERGENCY X-RAY	1.090	55 MIN.	4.285	14	.980
EMERGENCY PATIENTS SENT TO CENTRAL X-RAY	.125	8 HR.	3.333	18	.020

TABLE 7

CENTRAL RADIOLOGY UTILIZATION

EXAMINATION ROOM	SERVICE RATE PATIENTS/HR.	AVERAGE SERVICE RATE (MINUTES)	PROB. OF USE
1	3.333	18	.361
2	3.529	17	.164
3	1.500	40	.057
4	1.428	42	.044
5	1.428	42	.020
6	.983	61	.037
7	2.222	27	.212
Co^{60}	3.750	16	.089
ORTHO VOLTAGE	4.000	15	.016

SIMULATION MODEL

The program model is written in GPSS. Part of the flow diagram representing the basic model is shown in Figure 3. Patients, represented by transactions flowing through the system, are divided into two groups--emergency and routine. Facilities and storages represent servers, while queues and tables are used for tabulating results. Both empirical and standard statistical distributions are used to represent arrival rates, transfer rates, and service distributions. The model is used to simulate the system during different time periods where arrival rates differ.

SENSITIVITY ANALYSIS

Incremental manipulation of parameters to forecast performance under varying conditions allows for

(1) Simulation of patient flow under current existing conditions,

(2) Simulation of hypothetical 30% increase in patient flow representing a projected demand for services by the presentation of new patient case types,

(3) Simulation of improved patient scheduling to more evenly distribute patient demand throughout the day,

(4) Simulation with additional personnel and physical resources.

MODEL VALIDATION

An important part of the simulation study is the validation phase. Confidence in the model is developed through various means. First, input distributions used are fairly accurate. Where standard statistical distributions, rather than empirical distributions, are used, statistical tests are applied to ensure goodness of fit. Second, since real data are readily available, input-output analyses provide for direct comparison of the simulation model with that of the real world. Finally and perhaps most importantly, hospital personnel views the simulation results with satisfaction as to its accuracy.

OUTPUT ANALYSIS

This section lists some results of 320 simulation runs of patient flow through the system, and their comparisons with real data where applicable:

(1) Patient arrival rates (Tables 8 and 9),

(2) Patient reception delay times (Table 10),

(3) Average patient waiting times for examination (Tables 11 and 12),

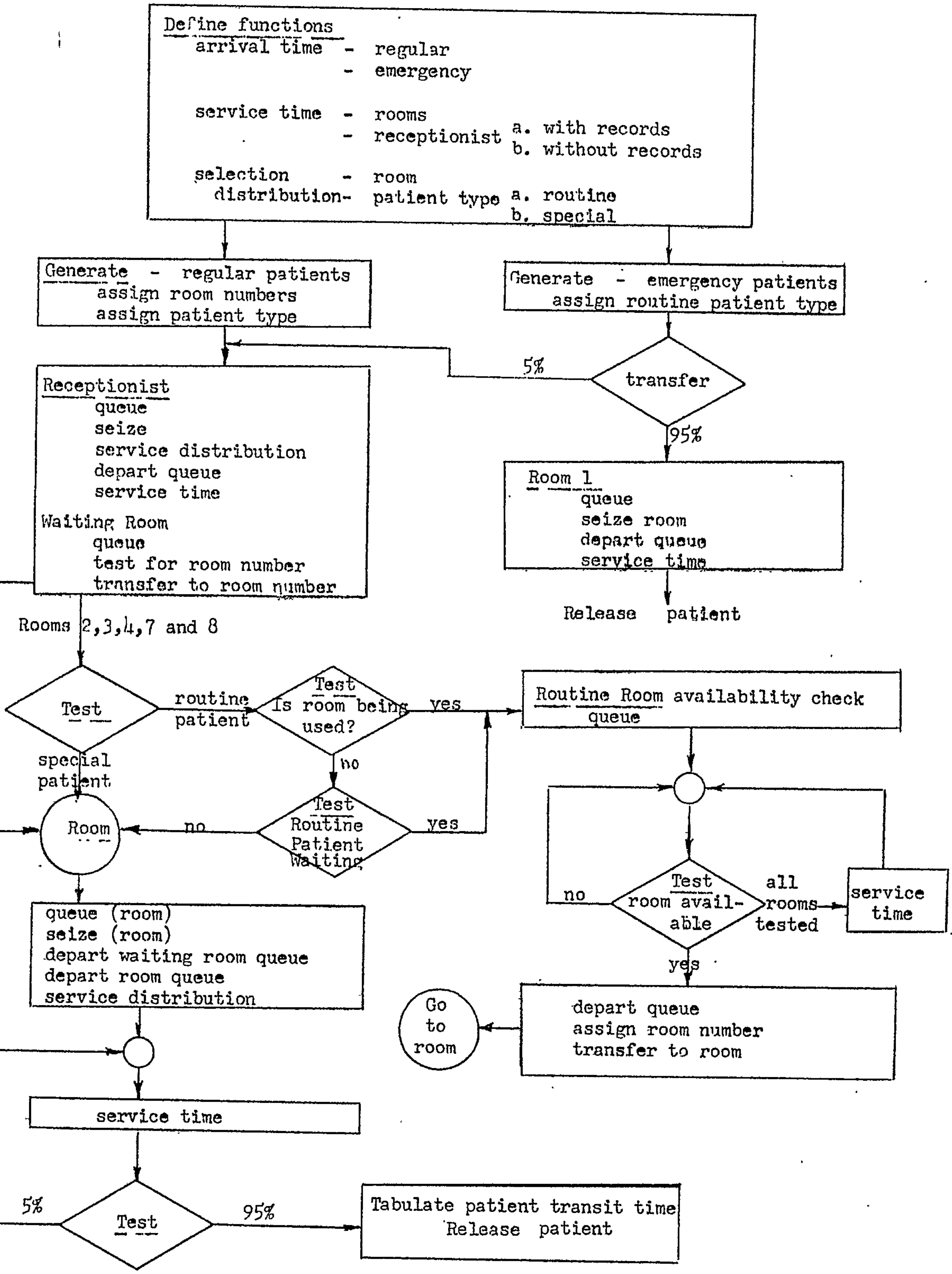
(4) Patient queue in main waiting room (Table 13),

(5) Examination service times (Table 14),

(6) Total patient transit times (Tables 15 and 16),

(7) Patient queue in main waiting room when the patient arrival rate is more evenly distributed throughout the day (Table 17).

FIGURE 3



Define functions
arrival time - regular
- emergency
service time - rooms
- receptionist a. with records
b. without records
selection - room
distribution- patient type a. routine
b. special
Generate - regular patients
assign room numbers
assign patient type
Generate - emergency patients
assign routine patient type
5%
transfer
95%
Receptionist
queue
seize
service distribution
depart queue
service time
Waiting Room
queue
test for room number
transfer to room number
Room 1
queue
seize room
depart queue
service time
Release patient
Rooms 2,3,4,7 and 8
Rooms 5,6 and 9
Test
routine patient
Test
Is room being used?
yes
Routine Room availability check
queue
no
special patient
Room
no
Test
Routine
Patient
Waiting
yes
Test
room available
no
all rooms tested
service time
yes
queue (room)
seize (room)
depart waiting room queue
depart room queue
service distribution
Go to room
depart queue
assign room number
transfer to room
service time
5%
Test
95%
Tabulate patient transit time
Release patient

TABLE 8

COMPARISON OF ACTUAL AND SIMULATED PATIENT ARRIVALS FOR ORTHOPEDICS DAYS IN PATIENTS/HOUR

PERIOD	ACTUAL ARRIVAL RATE	SIMULATED ARRIVAL RATE	SIMULATED 30% INCREASE
7 A.M. to 12 P.M.	15	14	18
12 P.M. to 6 P.M.	5	6	8

TABLE 9

COMPARISON OF ACTUAL AND SIMULATED PATIENT ARRIVALS FOR ALL OTHER DAYS IN PATIENTS/HOUR

PERIOD	ACTUAL ARRIVAL RATE	SIMULATED ARRIVAL RATE	SIMULATED 30% INCREASE
7 A.M. to 12 P.M.	9	8	13
12 P.M. to 7 A.M.	4	4	6

TABLE 10

COMPARISON OF ACTUAL AND SIMULATED RECEPTION DELAY TIMES IN MINUTES

PATIENT TYPE	ACTUAL RECEPTION DELAY	SIMULATED RECEPTION DELAY
RECORDS AVAILABLE	9	10
RECORDS NOT AVAILABLE	15	14

TABLE 11

COMPARISON OF ACTUAL AND SIMULATED AVERAGE WAITING TIMES FOR EXAMINATION ON ORTHOPEDICS DAYS

IN MINUTES

PERIOD	ACTUAL DELAY	SIMULATED DELAY
7 A.M. to 12 P.M.	17	16
12 P.M. to 6 A.M.	13	14

TABLE 12

COMPARISON OF ACTUAL AND SIMULATED EXAMINATION WAITING TIMES FOR ALL OTHER DAYS

PERIOD	ACTUAL DELAY	SIMULATED DELAY
7 A.M. to 12 P.M.	15	16
12 P.M. to 6 A.M.	19	18

RECOMMENDATIONS

As patient demand approaches operating capacity, waiting lines develop in the main reception area. Empirical and simulation data (Table 13) indicates that congestion in patient flow is at maximum for two periods each day: between 7:00 A.M. and 12:00 Noon, Monday through Friday, and between 1:00 P.M. and 3:00 P.M., Monday through Friday. Patient congestion in the afternoon, however, is substantially smaller relative to the 7:00 A.M. to 12:00 Noon period. Consequently, facility idle time is increased in the afternoon, which is neither productive nor cost effective. This dichotomy of patient demand becomes even more critical on orthopedics days when patient arrival rates double.

The effective utilization of X-ray facilities is constrained by a few factors concerned primarily with patient scheduling practices. These include:

(1) Physicians requesting examinations in the morning when an afternoon examination would be as effective.

(2) High frequency of short-term routine procedures performed on orthopedics days, particularly in the mornings.

(3) Uneven dispersion of orthopedics days throughout the week.

(4) Scheduling many routine examinations when the demand for more time-consuming "special procedure" examinations is expected.

(5) Uncoordinated patient scheduling by outpatient clinics.

Alternative patient scheduling routines can be employed to more evenly distribute the demand for radiology services. These include:

(1) Scheduling orthopedics examinations daily rather than 2 or 3 days per week.

(2) Scheduling orthopedic examinations for the relatively slack afternoon hours between 1:00 P.M. and 5:00 P.M.

(3) Securing the cooperation of physicians to request examinations in the afternoon unless more expedient results are required.

Simulation results demonstrate that the average number of patients waiting for service becomes more evenly distributed when patients are rescheduled for the slack afternoon period (Table 17).

Payoffs will accrue from effective patient scheduling in terms of:

(1) Timely patient service,

(2) Enhanced technician efficiency as a result of reduced pressure to attenuate long patient waiting lines, and

(3) More effective utilization of personnel by allowing radiology managers to perform administrative duties without constant interruption by less relevant tasks.

TABLE 13

COMPARISON OF EXPECTED AND SIMULATED NUMBER OF PATIENTS WAITING FOR EXAMINATION

CATEGORY	EXPECTED	SIMULATED CURRENT CONDITIONS	SIMULATED 30% INCREASE IN DEMAND
ORTHO. 7-12	10	9.6	15.6
ORTHO. 12-6	8	7.4	13.3
NONORTHO. 7-12	8	9.1	10.2
NONORTHO. 12-6	4	3.4	5.1

TABLE 14

COMPARISON OF ACTUAL AND SIMULATED EXAMINATION TIMES

ROOMS	REAL	SIMULATED	SIMULATED 30% INCREASE
EMERGENCY	14.0	13.9	14.1
1	18.8	18.6	19.4
2	17.2	18.0	18.6
3	40.7	43.0	42.5
4	42.3	45.0	48.5
5	42.1	42.0	43.1
6	61.7	62.0	63.2
7	27.4	27.5	27.4
CO^{60}	16.4	16.2	27.4
ORTHO VOLTAGE	15.0	15.1	26.0

TABLE 15

COMPARISON OF ACTUAL AND SIMULATED

PATIENT TRANSIT TIMES FOR ORTHOPEDICS DAYS

IN MINUTES

PERIOD	ACTUAL TIME IN SYSTEM	SIMULATED TIME IN SYSTEM
7 A.M. to 12 P.M.	37	33
12 P.M. to 6 P.M.	23	28

TABLE 16

COMPARISON OF ACTUAL AND SIMULATED

PATIENT TRANSIT TIMES FOR ALL OTHER DAYS

IN MINUTES

PERIOD	ACTUAL TIME IN SYSTEM	SIMULATED TIME IN SYSTEM
7 A.M. to 12 P.M.	32	32
12 P.M. to 6 P.M.	28	30

TABLE 17

COMPARISON OF ACTUAL AND SIMULATED PATIENT

WAITING LINES WHEN PATIENT SCHEDULING IS EVENLY DISTRIBUTED

THROUGHOUT THE DAY

CATEGORY	EXPECTED	SIMULATED NEW SCHEDULING
ORTHO 7-12	10	7.9
ORTHO 12-6	8	8.0
OTHER 7-12	8	6.4
OTHER 12-6	4	6.4

REFERENCES

1. Bobillier, R. A., Kahan, B. C., and Probst, A. R., Simulation with GPSS and GPSS V, Prentice-Hall, Englewood Cliffs, N. J., 1976.

2. Hamilton, W. F., "Systems Analysis in Emergency Care Planning," Med. Care, Vol. 12, No. 2, February, 1974, 152-162.

3. International Business Machines, General Purpose Simulation System/360, IBM Corporation Technical Publications, White Plains, N.Y., 1970.

4. Johnson, G. M., "Modeling and Simulation for Testing Resource Allocation Alternatives in a Hospital Radiology Facility," Interim Report to the California State Assembly Office of Research, June, 1976.

5. Pike, R. W. and Durby, R. D., "Diagnostic Radiology Replacement Model," Proceedings of Systems Engineering Conference, Las Vegas, Nevada, November, 1975.

6. Rao, D. R., "Applications of Operations Research Techniques in Health Administration - Simulation," Indian J. Public Health, Vol. 18, No. 2, April-June, 1974, 636-671.

7. Sanuzano, P. J., "Health Services Research and Development," J. Med. Education, No. 45, 1975, 725-730.

8. Taylor, W. R., "System Engineering in Small Hospitals," Proceedings of System Engineering Conference, Las Vegas, Nevada, November, 1975.