The design of an efficient elevator operating system

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Received 8 November 1977
Revised 21 June 1978

A method is developed for finding an efficient operating policy for an office building elevator system. The method was applied to a particular eleven story building in which there were four elevator shafts. A queuing model was formulated in which the characteristics of passenger arrivals and destinations were time variable. The objective involved the minimization of the weighted sum of ratios of actual to minimum possible travel time between all pairs of floors. Simulation was used to analyze several logical routing policies for each of two methods in which demand information was used to alter the elevator route. The best policy was found to be almost twice as efficient as most of the other policies which were studied and over 25 times more efficient than another seemingly logical operating policy.

1. Introduction

An investment company, owners of an office building in the Off-Shore area of Cape Town, South Africa, decided to build a similar building on a nearby building site. In order to save the costs of architectural and structural design of a new building as well as to take advantage of the design which had already been approved by the city engineer and planning council, the new building was to be virtually identical to the existing one. There was to be the same number of floors (eleven plus penthouse), a main pedestrian entrance on the ground floor, a parking garage on the second floor, and offices on the other floors.

The planning engineers had intended to investigate the optimal number of elevators to be installed in the building, and the best operating scheme for the elevator bank. However, due to the constraint that there could be no major design changes, the number of elevators in the new building was required to be the same number, four, as in the old building. Thus the planning engineers were required to concentrate their efforts in designing the elevator operating system for the given number of elevators.

Considerable effort in the past has been devoted to the design of elevator systems for tall buildings.

European Journal of Operational Research 3 (1979) 216–221.

Mitric [1] and [2] investigated the optimal size of elevator shaft area for tall buildings including the effects of "banking" or grouping of floors. Powell [3] also studied the effects of "banking" for more efficient transport of passengers in high rise buildings. The use of simulation in studying elevator systems was applied to determining energy requirements for various elevator designs by Sweet and Duket [4].

In this paper, a method is developed for applying a simulation model to finding an efficient *operating policy* for a small or medium size building with a given number and size of elevators with no "banking". The method was applied to the case of the proposed building, and is presented here.

An elevator operating policy was considered to consist of these main elements:

(a) the routing of individual elevators;
(b) the routing mix of the elevators;
(c) the way in which information regarding passenger demand for elevator service is used to effect changes in the elevator route.

2. The objective

In a building with F floors, let t_{ij}, $i = 1, 2, ..., F$ and $j = 1, 2, ..., F$ a random variable, be the total of waiting time and travel time for a passenger travelling from floor i to floor j. (Assume $t_{ii} = 0\ \forall i$.) Denote the expected time as $E(t_{ij})$. The time t_{ij} will be termed the "spent" time.

Now let τ_{ij} be the minimum possible value of t_{ij}, i.e. the value of the spent time when no waiting time for an available elevator is encountered and no intermediate stops are made between floors i and j. The ratio $E\{t_{ij}\}/\tau_{ij}$ will be termed the delay ratio.

A reasonable objective for efficient operation of the elevator system during a particular period of the day, would seem to involve the minimization of the sum of the delay ratio for all pairs of floors $\{i, j\}$, weighted by the expected demand for travel between the pairs $\{i, j\}$, during that period. Denoting $D_{ij}^{(n)}$ as the expected demand from floor i to j during period n, the objective for period n becomes:

$$\min Z = \sum_{i,j=1}^{F} \frac{D_{ij}^{(n)} E(t_{ij})}{\tau_{ij}}.$$

3. Data and assumptions

It seemed reasonable to base the forecasts of passenger demand for elevator service in the new building upon data of elevator usage to be gathered from the identical building already in use.

The daily passenger demands were observed to follow a consistent pattern. Virtually all demand in the early morning hours was to enter the elevators at either floor 1 (entry foyer) or floor 2 (parking garage). Toward the end of the early morning hours a very small demand for elevator service from the upper floors was experienced created mainly by messengers and delivery services. Similarly the late afternoon travel was almost exclusively devoted to destinations of floor 1 and floor 2. The diurnal effect of traffic using the elevators is described in the graph in Fig. 1.

Analysis of the traffic pattern indicated that the major portion of peak traffic could be divided into four 20-minute time periods: period I from about 7.50 to 8.10 A.M. for offices starting work at 8 A.M., period II from 8.20 to 8.40 for offices starting work at 8.30 A.M. Similarly in the afternoon there were two peak periods; period III from 4.50 to 5.10 P.M., and period IV from 5.20 to 5.40 P.M.

Further, it was discovered that the arrival pattern during these periods tended to follow a Poisson distribution with means $\lambda_i^{(n)}$ (arrivals/minute) with $n = 1, 2, 3, 4$, representing the four peak periods and i representing the floor number, as given in Table 1.

Since it was technically almost impossible to observe and record the boarding and destination points of all passengers, it was decided to approximate the peak hours demand by observing only the arrival rates and calculating the inter-floor demand as follows:

(a) For morning peak hours it was noted that virtually all arrivals occur at the first and second floors. It was then assumed that the destinations are distributed in proportion to the pattern of arrivals at the elevators for passengers leaving the building at the corresponding late afternoon hour (i.e. in accordance with an 8 A.M. to 5 P.M. workshift and an 8.30 A.M. to 5.30 P.M. shift).

(b) For the late afternoon peak hours it was assumed that all destinations were either for floor 1 or floor 2 in proportion to the corresponding morning arrival rates.

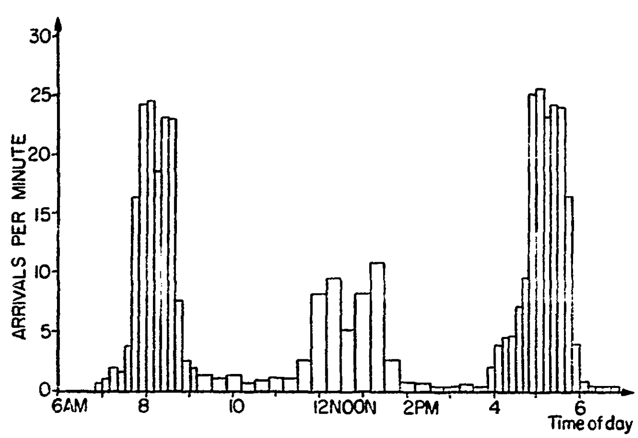

Fig. 1. Diurnal effect of total elevator traffic.

Considering $D_{ij}^{(n)}$ as the mean demand for travel between floors i and j for the nth peak period, the following approximation was made:

$$D_{ij}^{(n)} = \begin{cases} \lambda_i^{(n)}\left[\dfrac{\lambda_j^{(n+2)}}{\sum_{k=3}^{n}\lambda_k^{(n+2)}}\right] & j = 3, 4, 5, \ldots, 11: \; n = 1, 2, i = 1, 2, \\ \lambda_i^{(n)}\left[\dfrac{\lambda_j^{(n-2)}}{\lambda_1^{(n-2)} + \lambda_2^{(n-2)}}\right] & j = 1, 2: \; n = 3, 4, \; i = 3, 4, 5, \ldots, 11, \\ 0 & \text{otherwise.} \end{cases}$$

The variable τ_{ij} (the minimum value of the sum of travel and waiting time t_{ij} was calculated as the time

Table 1
Mean passenger arrivals per minute at elevator

Floor i	Period I (7.50–8.10 A.M.) $\lambda_i^{(1)}$ (arrivals/min)	Period II (8.20–8.40 A.M.) $\lambda_i^{(2)}$ (arrivals/min)
1	23.58	22.77
2	1.86	1.62
3–11	0	0.17
Floor i	**Period III (4.50–5.10 P.M.) $\lambda_i^{(3)}$ (arrivals/min)**	**Period IV (5.20–5.40 P.M.) $\lambda_i^{(4)}$ (arrivals/min)**
1	0.05	0
2	0	0
3	2.75	2.80
4	3.25	1.67
5	2.82	1.96
6	2.63	2.45
7	2.47	3.51
8	2.72	2.41
9	2.73	1.95
10	2.05	3.82
11 and 12 *	3.84	2.77

* Floor 11 includes stair access to floor 12.

between the opening of the doors at floor i to the opening of the doors at floor j. In order to simplify the calculations, it seemed reasonable to assume τ_{ij} to be otherwise independent of the number of passengers in the elevator travelling from i to j and independent of the number of passengers entering and leaving at floor i. Further the variability in the action time of various passengers in pressing the choice-of-floor button was not taken into consideration and a fixed time assumed. Although these assumptions are not entirely accurate in describing the actual situation, the variability introduced by these factors was found to be small.

The time τ_{ij} used in the model was based upon the mean of a sample of observations and found to be fairly accurately approximated by the function (in seconds)

$$\tau_{ij} = 2(j - i) + 11 \text{ (seconds)} .$$

The queue discipline observed in the building was found to be somewhat varied; loosely it could be described as an approximate first-come, first-served queue with priorities to female and sometimes elderly passengers. In the model this situation was represented by a simple first-come, first-served discipline.

4. Operating policies

At any time an elevator containing passengers (a "loaded" elevator) can be described as being in an "up" mode or a "down" mode or a "wait" mode. Having reached the first floor, the elevator is automatically in an "up" mode and similarly, having reached the top floor it is considered to be in a "down" mode. An elevator which has discharged all its passengers at an intermediate floor can be considered in a "wait" mode. Each intermediate floor has two external call indicators ("up" and "down"). The extreme floors of course have only one such indicator. Within the elevator are the internal (destination) indicators. A loaded elevator reaching floor i ($i \neq 1$, $i \neq 11$) will continue to the next closest floor in its direction of travel mode for which an internal button or external indicator (in the proper direction) has been activated.

It becomes necessary, however, to determine an operating policy for elevators which have off-loaded all their passengers at a particular floor i. To which floor should it proceed? A search must be made to determine whether there are any external calls or not and if there are any external calls of what type they are.

External calls may be of four different types:

(I) Calls from floors further along the last direction of travel of the elevator (prior to the discharge of its last passenger), and for travel in the same direction.

(II) Calls from floors that are further *back* in the last direction of travel of the elevator (i.e. floors which may have already been passed while the elevator was traveling in its last direction of travel prior to reaching its present location), and for travel in a direction opposite to the last direction of travel of the elevator.

(III) Calls from floors further along the last direction of travel of the elevator, and for travel in a direction opposite to that of the last direction of travel of the elevator.

(IV) Calls from floors that are further back in the last direction of travel and for travel in the same direction as the elevator was proceeding before reaching its present location.

If there are any calls of type I (regardless of the existence of any other type of calls) the elevator will continue to proceed along the direction of previous travel picking-up and dropping off passengers.

If there are *no* calls of type I but there exist calls of type II, the elevator will move in a direction opposite to its previous direction of travel and will proceed along picking-up and dropping off passengers.

If there are no calls of either type I or type II but there are calls of either type III or type IV or both, there are basically two rules for determining the movement of the elevator. These rules are termed "search policies" and consist of "forward search" and "backward search". In a forward search, the elevator will proceed to the closest floor with an activated indicator and there change its direction of travel in accordance with the instruction of the caller. In a "backward search" the elevator will proceed immediately (i.e., without stopping on route at other floors with an activated indicator) to the most distant floor with an activated indicator and there change its direction in accordance with the instructions of the caller.

In both search procedures a tie may exist, wherein the distance (in terms of the number of floors above or below) of a type III and a type IV caller from the position of the elevator when it discharged its last passenger is equal. In such cases the type III has precedence.

In this study it was decided to examine nine sys-

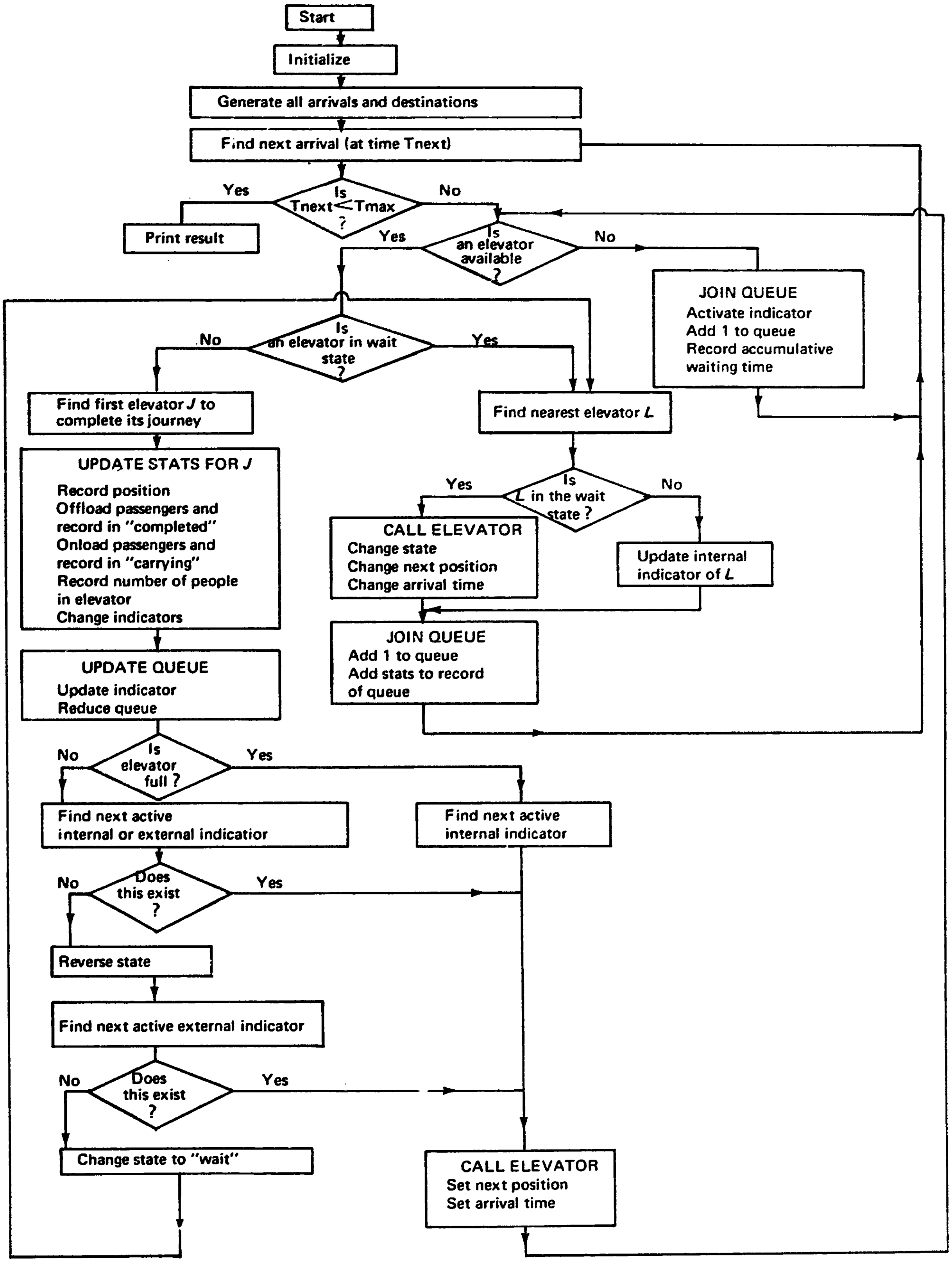

Fig. 2. Simulation flow chart.

Table 2
Proposed routing policies

System	Elevator 1	Elevator 2	Elevator 3	Elevator 3
1	All floors	All floors	All floors	All floors
2	All floors	All floors	1,3–11	1,3–11
3	All floors	All floors	1–6	1,2,7–11
4	All floors	1,3–11	1–6	1,2,7–11
5	All floors	All floors	1–5	1,2,6–11
6	All floors	1,3–11	1–5	1,2,6–11
7	All floors	All floors	1–7	1,2,8–11
8	All floors	1,3–11	1–7	1,2,8–11
9	All floors	1–5	1,2,6–8	1,2,9–11

tems of routing policy mixes. The policies refer to the bank of four elevators and are described in Table 2. Each policy was examined for both a forward search technique and a backward search.

5. Solution method

Evaluation of the expected spent time, $E(t_{ij})$ for each pair of floors for the various parts of the day was made using a digital simulation. The appropriate analytical queuing model was found to be too difficult to solve inasmuch as it involved the interaction, in a complex manner, of several simultaneous queues. On the other hand, it was felt that simulation was ideally suited to handle a problem of this nature.

The state of each elevator could be described by the following attributes:

(i) mode: down, up, or wait;
(ii) the current position of the elevator;
(iii) the next scheduled stop;
(iv) the time of arrival at this stop;
(v) the number of people in the elevator;
(vi) the number of people in the "up" queue for each floor;
(vii) the number of people in the "down" queue for each floor.

The simulation model is based on the following procedure:

An arrival at time T_i is generated according to the appropriate distribution. If no elevators are available, then that arrival is added to the appropriate queue. An elevator may be "available" if either it is in the "wait" state (provided that the system allows it to visit the appropriate floors involved in the latest arrival's journey), or if an elevator completes a journey between times T_{m-1} and T_m. If an elevator is available, then the following procedures are carried out: passengers are onloaded and/or offloaded as required and the relevant queues updated; the arrivals and destinations and times of journey of these passengers are recorded; the next destination of the elevator is selected, and its time of arrival is set.

A flow chart of the basic simulation model is shown in Fig. 2.

6. Results of simulation trials

The nine proposed routing policies described in Table 2 were tested using a simulation of 48 hours simulated time. Convergence to steady state was found to occur after approximately 3 hours of simulated time. Mean values of the objective, Z, were determined for all nine proposed systems for the various periods of the day. Since the daytime period was found, during the preliminary runs, to be long enough for the system to converge to steady state, the means and variances of the simulation for the nine proposed routing policies tested were steady state results as presented in Table 3.

Inasmuch as the morning and afternoon peak periods were found to be too short for achieving steady state operation, 144 repeated trials of twenty minute duration were performed, each under transient conditions and the means and variances calculated.

As can be noted in Table 3, System 1 (all elevators visiting all floors) appears to be optimal for the daytime period. Preliminary runs for the morning and evening peak periods (Period I and Period III) indicated that systems 3–9 resulted in much higher

Table 3
Results of simulation runs – daytime period

System	Forward search		Backward search	
	$E(Z)$	Var(Z)	$E(Z)$	Var(Z)
1	2.266	0.0064	3.541	0.0077
2	2.645	0.0072	3.451	0.0130
3	4.266	0.0570	4.659	0.0331
4	4.241	0.0440	4.731	0.0437
5	4.309	0.0595	4.554	0.0400
6	4.264	0.0468	4.470	0.0679
7	4.391	0.0513	4.711	0.0512
8	4.292	0.0402	4.767	0.0633
9	51.669	1.776	38.122	1.382

Table 4
Results of simulation runs – peak periods

	Forward search		Backward search	
	$E(Z)$	Var(Z)	$E(Z)$	Var(Z)
Peak period I (A.M. period)				
System 1	7.180	0.0120	4.785	0.0071
System 2	7.361	0.0301	4.763	0.0108
Peak period III (P.M. period)				
System 1	6.944	0.0117	4.306	0.0099
System 2	5.810	0.0181	4.310	0.0131

delays than system 1 or 2, and therefore were eliminated from consideration. The results for Systems 1 and 2 are tabulated in Table 4.

As can be seen in Table 4, Systems 1 and 2 resulted in approximately equal values of the objective. In this case it was recommended to use System 1 so that users of the parking garage on floor 2 could benefit from the use of all four elevators.

7. Conclusion

A technique was developed for evaluating the effectiveness of various elevator operating schemes. In the case where the method was applied, serious consideration had been given to an elevator operation scheme whereby some elevators would operate as "express elevators" serving only some of the floors. Application of the technique in this case however led to the recommendation of employing an "all-floor" visiting system, for all elevators, with a backward search for peak hours, and a forward search during the daytime period. Although only nine possible operating systems were investigated here, in a larger, more complex application the technique could be applied to determine the relative effectiveness of a larger number of operational possibilities.

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