AN INTEGRATED METHODOLOGY FOR OFFICE BUILDING ELEVATOR DESIGN[1] 8.5

Margaret A. Frederking

Alton J. Penz

School of Urban and Public Affairs
Carnegie-Mellon University

Abstract

The authors have outlined a systematic approach to elevator system design which applies cost-benefit methodology to the design process. This approach relies on a cash flow modeling base for analysis of a total building. It then interprets the effect of elevator operation on the building's value for various traffic conditions. Elevators affect building value via direct and indirect operating costs, the opportunity cost of rentable floor area foregone for shaft space, the rental value derived from user satisfaction, and the cost of lost production time consumed in elevator travel. A computer simulation of elevator operation employing a statistical model of elevator behavior provides the measurement of elevator performance. The traffic patterns simulated reflect, via the use of probability, the nature of traffic generated by floor populations which may vary over time. The resulting methodological approach facilitates evaluation of elevators from the perspective of total building value to the client and to the users of a building.

The Problem

Each participant in the elevator design process of a high-rise office building seeks to have his own particular criteria define which elevator system would be most appropriate. The architect, for instance, concerns himself primarily with coordinating the functional aspects of a building with his aesthetic plans. Such coordination is sometimes achieved, however, only at the expense of efficiency elsewhere--in elevator service, for example. Similarly, the architect's client may consider only system cost, often with little regard for performance criteria. On the other hand, the elevator consultant may favor extreme elevator efficiency. Though this recommendation may stem from a concern for the satisfaction of employees with better than adequate elevator service, it may also be the result of reasoning which suggests that future contracts will be gained or lost on the basis of performance of his currently operating systems. Specifically, he may recommend a system which provides for a morning peak-period maximum lobby waiting time of only twenty-five seconds. The gains from a five-second reduction in waiting time over the generally recognized standard of a thirty-second maximum[2] may not compensate for the additional system costs and lost rentable area which detract from the investor's financial position.

The result of this diversity of inputs into the choice of elevator design may result in a decision in the financial interests of neither the building's future tenants nor the building owner. Of critical importance but often absent from present elevator deliberations is a systematic examination of system costs, both initial and operating; the performance of the system in terms of lobby waiting time and passenger travel time; the opportunity cost of floor space occupied by elevator shafts;[3] and rentability of the building as affected by tenant satisfaction with the quality of elevator service.

Two other factors of importance seem to be missing from the criteria for elevator system design. The first of these concerns the uncertainty with which different levels of service demand are experienced. This demand is affected by population size, the mix of occupations in the population, and the distribution of the population over the floors served by the elevators. Each of these factors affects service quality. The second concern is a quantitative consideration of the amount of time spent in the elevator system by employees. This time represents a cost to the building tenants in terms of foregone productivity. If this cost is excessive, it will represent a source of reduction in the owner's cash flow.[4]

No existing analytical technique would seem single-handedly capable of providing the investor, consultant, or architect with the needed broader perspective. The purpose of this paper is to suggest such a tool: an integration of cost-benefit analysis, principles of cash-flow modeling, and computer simulation of elevator performance to provide improved focus.

Proposed Methodology

The methodology presented here constitutes a first attempt to devise a systematic approach for analyzing a bank of a proposed elevator system via cost-benefit analysis. The procedure, which is implemented as a computer program, essentially simulates a specified elevator system under realistic, random conditions specified by the user. The program then provides means of evaluation focusing on expected performance values to aid the designer in selecting a particular elevator system. The following discussion outlines the structure of the program with the intent of demonstrating its validity for real projects.

Basically the method for analysis involves two types of calculations. (See Figure 1). In the first section, the nominal financial structure of the building and the basic mechanical characteristics of the elevator system are established from specified input data. This information is nominal in the sense that it does not include adjustments for realized elevator performance. For instance, the potential rental rate may differ from the nominal rate to the extent that elevator performance affects rentability. In the second section, performance of the elevators is simulated over the lifetime of the building for varying traffic conditions. This performance is weighted by the probability that the specific conditions arise. The financial characteristics are then altered according to the hypothesized effect imposed by elevator performance. The resulting characteristics are presented in a manner facilitating evaluation of the proposed design.

A powerful feature of the program is the ability to perform sensitivity analyses on various parameters. Since the program analyses proposed systems but does not automatically search for solutions, the ability to quickly obtain the effects of parameter changes guides the user in searching for better systems. In the search for an optimal solution, the building designer may readily explore the merits of elevator systems containing different numbers of cars, car sizes, or numbers of floors served by a bank of cars.

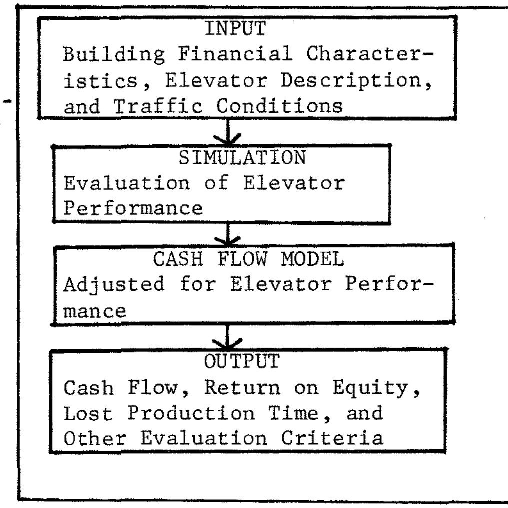

Figure 1

In addition to varying the elevator system, the values for financial characteristics such as the cost of capital and the rent rate may be changed. An analysis of a building project should not rely only on estimates of average values for rent, capital costs, and other indeterminant characteristics but should incorporate evaluation over a range of values, both high, expected, and low, so that the sensitivity of the project values to those parameters can be established.[5]

The financial structure of the model is handled very similarly to standard cash flow models.[6] The anticipated development costs and construction costs exclusive of elevator costs are given by the user. Elevator costs are provided by a detailed cost breakdown of elevators derived from a leading manufacturer's generalized cost data. The anticipated financial flows from operations for the building are initially established from data supplied by the architect's client. The rental income is adjusted to recognize the reductions in net rentable area attributed to elevator shaft space; operating costs are adjusted to include operating costs for specific elevator systems. The debt financing, depreciation, and sale or equity reversion calculations are handled in a customary fashion for cash flow modeling. The process for deriving the cash flows from initial construction through occupancy to sale of the building is illustrated in Figure 2.

The three components of cash flow--initial construction, annual operations, and building sale--are discounted to present value terms using a cost of capital provided by the client. Most importantly, this cash flow value incorporates most of the effects on the viability of the project contributed by elevator performance. The initial elevator costs, the elevator operating costs, and the loss of rentable floor space consumed by shafts are explicitly in the valuation.

Mechanics of the Elevator Simulation

The criteria for good elevator system design primarily focus on acceptable

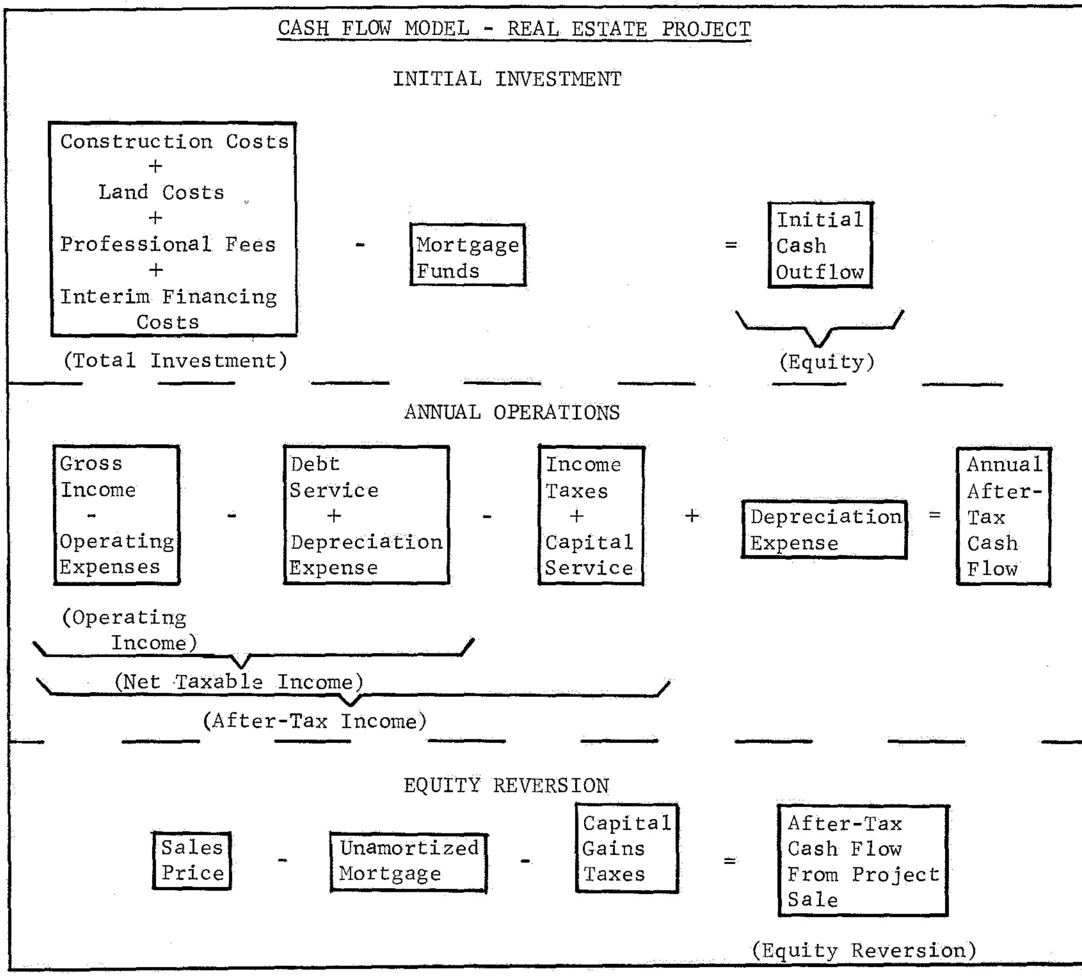

Figure 2

system performance under the heaviest traffic conditions. If service is satisfactory under the heaviest or worst conditions, then it should be satisfactory at all other times. Usually the heaviest conditions occur during periods of traffic peaks. At this time, if elevator system capacity is not greater than traffic demand, lobby areas quickly fill with dissatisfied people.

In office buildings peak demand occurs during the morning arrival period, the noon lunch hours, and the evening departure period.[7] Of these three periods, the morning period is usually studied for determining the capacity of a proposed elevator system. This traffic places strenuous demand on the elevator system and includes direct implications for lost production time as a result of lobby waiting and time spent in the elevator cars.

A further justification for analysis of the morning peak period is no efficient means currently exists for accurately studying the more complicated elevator performance during the noon and evening traffic periods. Only the morning period is included in the methodology presented here. To the extent that the effect of performance at other times can be inferred from morning elevator performance, then it can be included in the evaluation.

Although consideration of traffic demand is restricted to the morning arrival period, the analysis problem remains a complex one in that there are an infinite variety of possible morning arrival patterns. Two of these possibilities are pictured in Figure 3. The pattern on the left portrays

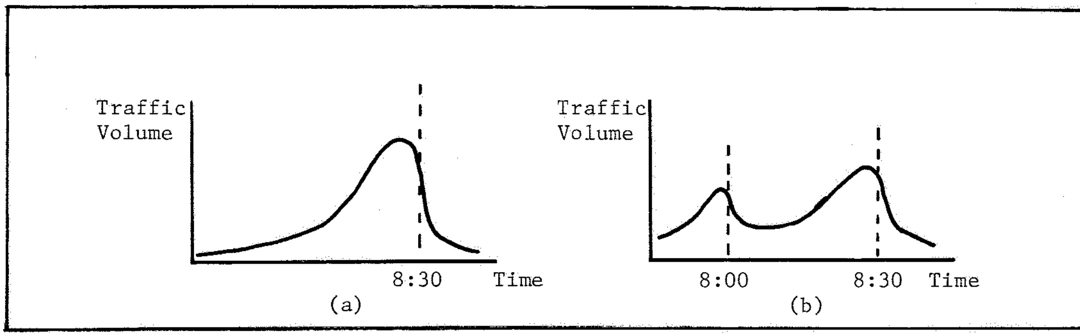

Figure 3

a morning arrival distribution which, by virtue of its higher peak, will place a greater demand on the service capabilities of the elevator system than will arrivals in the bimodal pattern of Figure 3b. As it will generally be true that any multi-modal arrival distribution will be less exacting of an elevator system than a unimodal, attention will be restricted to the unimodal case.

The mean number of people arriving per unit of time is given by the expression

$$N(p,t) = L(p,t)\ p,$$

where L(p,t) is the mean arrival rate of a Poisson process [8] and p is the population of the set of floors served by the elevators. Usually, L(p,t) is expressed as the percentage of the population p arriving per five minute interval. L(p,t) is a function of p as well as of t because of the dependence of arrival rates on population composition by occupation. Arrival patterns for bank clerks and secretaries differ from those of executives, for example.[9] Thus, we represent L(p,t) as

$$L(p,t) = A_i(p)\ L_i(t)$$

where $L_i(t)$ is the arrival rate for occupation set i at time t and $A_i(p)$ is the percent of total elevator bank population p consisting of occupation set i. That is, L(p,t) is a weighted sum of all arrival rates characteristic of the occupations represented. The area under the curve L(p,t) multiplied by p is the total number of building occupants likely to arrive during the morning rush period.[10]

We have presented this concept via a continuous function; typically, empirical data, based on five minute intervals, is used to establish a discrete representation of arrival patterns.

Performance of a specific elevator system is evaluated from a simulation of the elevators under various traffic conditions specified by N(p,t). The simulation is constructed by calculating elevator performance at specific time intervals over the range for t and for different values of p. In each time interval the number of people to arrive is generated by a Poisson process, assuming a uniform arrival rate for the people generated and a constant mean arrival rate for the interval. At the end of the interval, the number of people in queues is compared with the capacity of the elevators. If the capacity is exceeded, the excess people are left in the queue and are assumed to wait an additional time interval. The performance of the elevators for a particular load of people is determined by statistical approximations of elevator operation.[11] From these calculations, values for average waiting time and average travel time are derived for each one minute interval of a traffic distribution. The calculations of waiting time and travel time for all passengers form the basis for estimating the value of production time lost in elevators.

The use of simulation in the model facilitates the calculation of a satisfaction value (provided a satisfaction function can be established). Two systems with the same average waiting time can have different distributions of waiting time (e.g., the number of people to wait x seconds). Only by simulating the elevator operation for realistic arrival conditions in which system capacity may be exceeded can one hypothesize the degree of satisfaction or dissatisfaction arising from elevator performance.

In addition, a simulation approach avoids a source of error in the statistical method of Gaver and Powell. As shown in Figure 4, mean waiting time remains relatively constant over large ranges of traffic volume below approximately 95 percent of elevator system capacity. Traffic levels within 5 percent of capacity cause service to deteriorate, however, because of difficulties associated with scheduling elevators to coincide with random passenger arrivals at the lobby.[12]

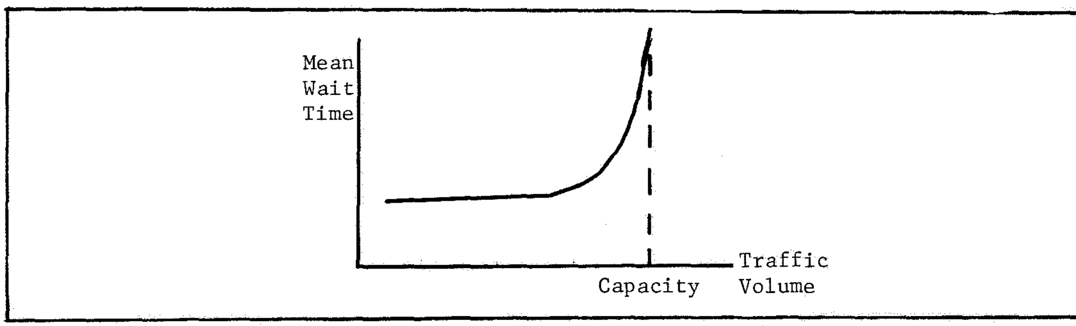

Figure 4

Implementation of the Methodology

Summarizing briefly, the proposed methodology contains three components: a statistical simulation of elevator performance, cash-flow modeling to represent the financial position of the building owner given varying expenditures for purchase and operation of an elevator system, and cost-benefit analysis to weigh changes in performance against changes in the owner's financial position.

The authors have investigated the implications of this methodology by employing it in the context of an existing thirteen floor office building of conventional structure. The building costs approximately $25 per square foot to construct in a recent year. It contains 21,500 gross square feet per floor and is served by five 3,000-pound elevators. The maximum estimated demand per five minute interval is 13 percent of the building population, and the system was estimated by its designers to provide service within a maximum wait interval of 30 seconds. Table 1 shows the values obtained for the actual system as well as for other alternative elevator systems.

As a first example of tradeoffs, let us consider the question of an elevator system with a twenty-five second maximum lobby waiting time as opposed to one with a thirty second maximum. A priori such a change is of questionable value for two reasons. First, the ability of passengers to discriminate between a maximum waiting time of twenty-five seconds versus thirty seconds is uncertain, particularly since the average waiting time is approximately fifteen seconds. Furthermore, any advertising advantage which might accrue to the building owner by virtue of exceptional elevator service may be of limited time duration. That is, should such a criterion become widely accepted, the novelty of the building's offering will cease to be a drawing card as more buildings with similar service are constructed.

In the immediate context of the example presented, however, Table 1 reveals that a system with a twenty-five second maximum waiting time (either six 2,500-pound cars or six 3,000-pound cars) increases initial system cost substantially without decreasing the value of passenger time consumed in the system by a corresponding amount. The difference must be made up in additional rent associated with increased passenger satisfaction to justify the faster system.

As yet no method has been delineated for explicitly recognizing the passenger satisfaction (or dissatisfaction) associated with lobby waiting time. To account for this aspect of elevator service, we have introduced the notion of satisfaction $S=f(WT,WT^*)$, a function of the realized waiting time WT and some criterion waiting time WT^*. Though no actual experimentation has been done concerning this concept, presumably some positive satisfaction occurs when an elevator arrives after only a brief wait, but dissatisfaction is experienced with a wait beyond some criterion time limit. In such a case, it may be that satisfaction can be represented as shown in Figure 5. If this view is appropriate, it may be possible to mathematically represent satisfaction by the following equation:

$$S=2.0-e^{-B(1.0-WT/WT^*)}$$

where the constant coefficient B, $0<B<1$, adjusts the slope of the curve. A

TABLE 1

Elevator Systems for a Thirteen Floor Office Building

Number of Cars	4	5	5	6	6
Car Capacity (lbs.)	4000	3000	3500	2500	3000
System Capacity (% of pop/5 min)	12.2	13.0	14.3	13.6	15.8
System Cost (000)	$334.2	$384.0	$394.0	$450.0	$460.8
Max. Wait Time (sec)	42.2	29.0	31.6	21.0	24.1
Net Rent. Area (000)	222.0	221.6	220.7	220.3	219.6
Syst. Oper. Cost (000)	4.05	4.87	4.75	5.66	5.27
Project Value[1] (000)	$123.1	$ 75.5	$ 53.3	$ 0.4	$-17.7
Value Lost Time[2] (000)	$176.2	$132.4	$140.0	$111.5	$119.4

1. Net Present Value of after tax cash flows, based on $7.00 rsf, unadjusted for satisfaction, discounted at 5%.

2. Present Value of all future lost production time, valued at $5.00 per hour.

larger B generates greater satisfaction or dissatisfaction depending upon the value of WT. Again, there is no proof that satisfaction behaves in the manner described or even that 30 seconds, that point at which people waiting for elevators have been observed to become fidgety, should be the criterion time used. However, such a representation appears plausible and permits use of the performance measure WT in calculation of a satisfaction coefficient. One may verify that the coefficient equals 1.0 when WT equals WT*.

The mean value of S multiplied by the nominal net rental income represents the expected value for rental income. This value may be interpreted as a change in the level of rent which may be levied as a result of the quality of elevator service. The value for revenue as adjusted by the satisfaction coefficient is

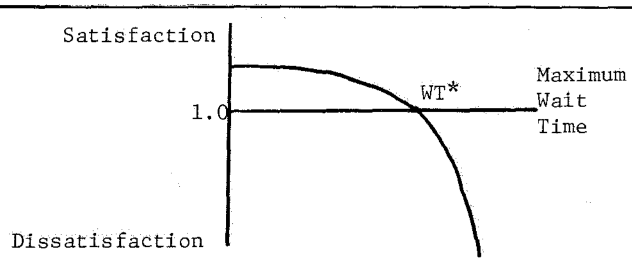

Figure 5

employed in the cash flow model and thus affects the financial evaluation of the project.

The financial evaluation and the value of lost production time derived from the simulation of specific traffic conditions are multiplied by the probabilities of occurrence associated with the traffic conditions to obtain weighted values. When these values are summed for all traffic conditions, the expected value of lost production and the expected financial value for the project are obtained. Both the expected value of lost production and the expected financial value of the project derived from cash flow modeling and adjusted for satisfaction should be used in the design process of a building project. For all other factors held constant, the best proposed design in a cost-benefit sense would be that system resulting in the greatest

$$V = f(W,P)$$

where W is the value of lost production and P is the satisfaction-adjusted project value exclusive of production time. Use of V as a criterion avoids the possibility of a decision on the basis of P alone or any component of P or W without regard for the total system. A sensitivity analysis should, of course, be performed on V to examine the effect of changes in market, financial and economic conditions on the project.[13]

The complete model has now been presented. A schematic diagram of its structure is illustrated in Figure 6. The value of V represents the expected value of a project when tenant satisfaction, employee performance, rentable floor area, and elevator costs are calculated for a specific elevator system operating under stochastic traffic conditions.

Several difficulties prevent the use of the methodology presented in an analytic context, i.e., to calculate THE value of an elevator system. Initial indications are that the interaction of satisfaction criterion, the value of lost time, and the market rental rate predominate the decision process. Unfortunately, no means currently exist for establishing the validity of a quantitative formulation of passenger satisfaction with elevator service. In addition, the passenger time saved by a more efficient elevator system may not have much value. Some studies suggest that the value of marginal time gains is negligible.[14] Finally, the authors have found no research indicating how market rental rates reflect the benefit of efficient elevators, either via improved satisfaction *per se* or via reductions in lost time.

As a result of these observations the methodology proposed here is for a decision process rather than an analytic process. In this context, alternative solutions are evaluated on the basis of known parameters, and then decisions are made according to the range of values for unknown parameters implied by each alternative. If all parameters except satisfaction are known, for example, boundary conditions can be calculated for satisfaction. A client can then choose between alternatives associated with different ranges of satisfaction according to his own judgment. In Figure 7, either solution 1, 2, or 3 is selected, depending upon whether the satisfaction parameter is judged to be less than a, greater than b, or between a and b.

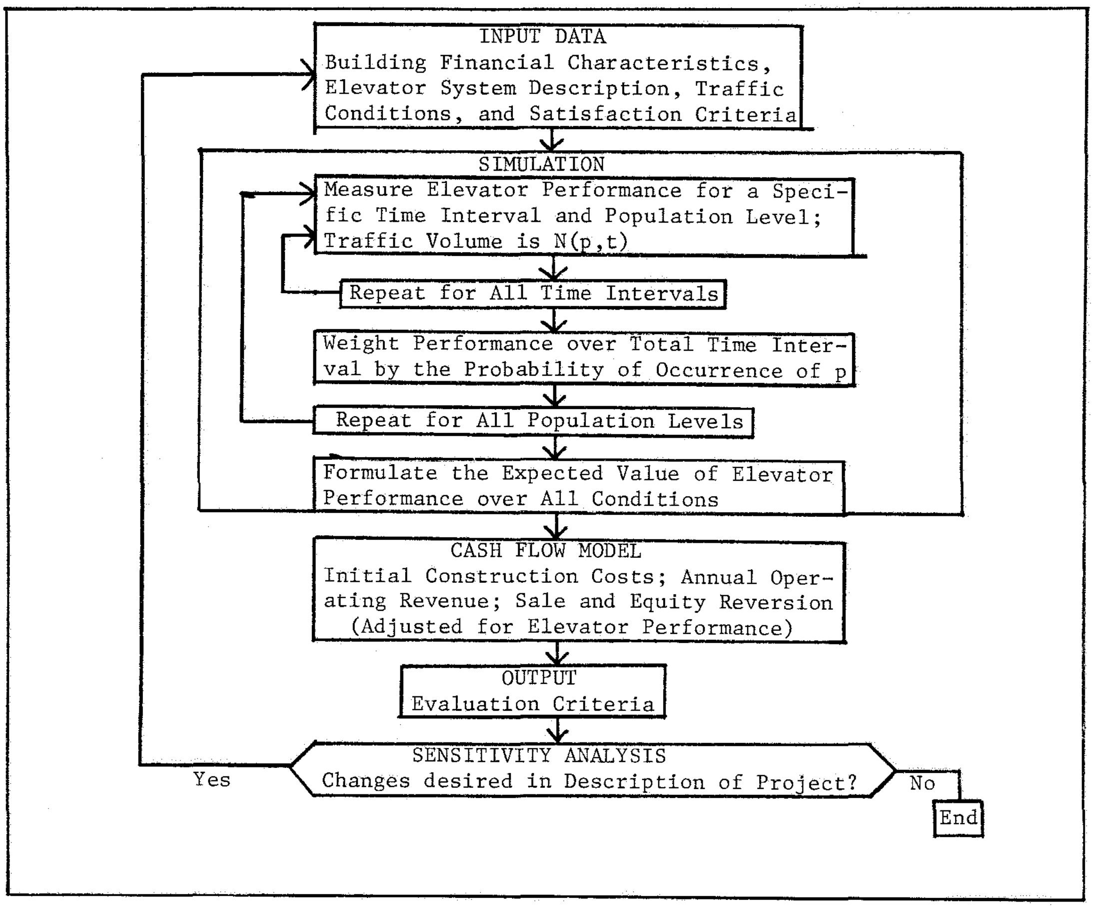

Figure 6

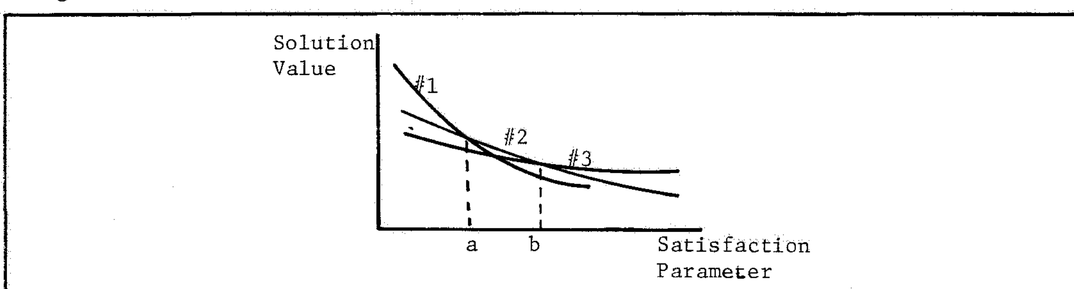

Figure 7

Application

The methodology suggested here represents a powerful tool for examining the performance of a system which operates in the context of a larger system. This combination of statistical simulation, cash-flow modeling, and cost-benefit analysis enables multiple objectives to be evaluated in the context of the more universal objectives of the client and users.

The proposed approach emphasizes the need for additional research to provide appropriate data for quality decision-making. As mentioned above, no appropriate procedures exist for representing the behavior of elevators during the noon and evening peaks. The noon hours are particularly difficult because demand is in both directions as opposed to only up traffic in the morning. In addition, traffic during the noon and evening periods is clustered as people travel in groups. Improved capabilities for analysis during these two periods would expand the situations of peak demand under which elevator performance could be observed.

As the quality of elevator service is so dependent on parameters of the building population, much uncertainty would be eliminated if studies were conducted of buildings near the proposed location to determine:

(1) arrival patterns characteristic of various occupations,[15]

(2) expected population densities and trends,[16] and

(3) a relationship between population or population density and the mix of occupations represented.

Other important data concern anticipated changes external to the building which may seriously affect the rates of arrival of employees. An example is the installation of a subway station within a very short distance of the office building. Though individual walking rates may disperse the crowd, dispersal will naturally be reduced as distance is shortened. It is under situations such as this that considerations of the duration of the demand peak and evaluation of satisfaction become particularly important.

Extensions

The model described in this paper was designed with computer implementation in mind. The approximations made and the assumptions contained in the model are believed to be reasonable ones with respect to actual implementation. Subsequent research should resolve these questions when a fully validated model is implemented with empirical data to support the traffic behavior. At that time its full potential can be examined by comparing the actual decisions made on projects to the recommended decisions based on V.

A crucial point in the presentation of this model is that all building design factors are either constant, maintain constant rates of change, or are influenced only by elevator design. Realistically, this situation does not hold; structure, mechanical requirements, legal codes, site and market conditions may very well affect the design more strongly. Nevertheless the conceptual approach remains the same. In the continual give and take of a design process when elevators and all other aspects of design are evaluated, changed, re-evaluated, and changed again, the form of evaluation should always be in the context of the total problem. Hopefully, as more of the evaluation process is systematized, the interaction between project components can be more effectively integrated and evaluated.

The model for evaluation has been presented for analysis of one bank of elevator cars at a time. In high rise buildings, a major problem involves the allocation of floors to several elevator banks so as to provide the best overall elevator service. In this case a dynamic allocation program as currently developed[17] could be used, with evaluation of each state handled as suggested here. This approach may very well be expensive to operate, however.

Some Broader Implications

The concepts contained in the approach delineated here are not restricted to elevator design. Many other components of an architectural project may incorporate the same considerations of human satisfaction, employee performance, and system costs (both indirect and direct) which are tied to system capacity and randomly occurring system operating conditions.

Methodology similar to that proposed here may also be applied to the design of interior environments. An example is the design of office building furnishings where concern must be given to rates of change of operating procedures and organizational structure, deterioration of the equipment, and employee efficiency and comfort.[18]

Recent work has indicated the value of adaptive capabilities for a building. The more readily a space can be transformed to satisfy changing use requirements over time, the more desirable it will be to prospective tenants. On the other hand, flexibility often requires additional expenditures. Thus the costs associated with varying degrees of flexibility must be related to the expected gains from the flexibility.

Notes

1. The authors acknowledge receiving numerous suggestions on the substance and form of this paper from Dr. Alfred Blumstein, Professor Charles Eastman, and Robert Carbone, Carnegie-Mellon University.

2. Adler, Rodney. Vertical Transportation for Buildings. (New York: American Elsevier Publishing Company, 1970), p.15.

3. Swartz, W.W. "Optimizing Space Requirements for Elevators", Architectural Record (March, 1970), pp. 133-136.

4. Strakosch, G.R. Vertical Transportation. (New York: John Wiley and Sons, Inc. 1967), p.353.

5. Penz, Alton J. "Financial Analysis in Architectural Design". Carnegie-Mellon University (1971). Submitted for publication.

6. Farrell, Paul B., Jr. "Financial Analysis of Real Estate." AIA Journal (August, 1968), pp.74-81.

7. For a discussion of traffic periods, see G.R. Strakosch, Vertical Transportation (New York: John Wiley and Sons, Inc., 1967),p.53.

8. Morning arrivals are assumed to obey a Poisson distribution.

9. Brown, J.J. and Kelly, J.J. "Simulation of Elevator System for World's Tallest Buildings." Transportation Science, 2:1 (February, 1968), p.35-36.

10. See G.R. Strakosch, Vertical Transportation (New York: John Wiley and Sons, Inc., 1967), Chapter 4, for characteristics of morning arrivals.

11. The work of Gaver and Powell was used for equations of expected round trip time and system capacity. See D.P. Gaver and B.A. Powell, "Variability in Round Trip Times for an Elevator Car During Up-Peak", Transportation Science, 5:2 (May, 1971), pp.169-179.

12. In queuing theory, as the mean arrival rate approaches the mean processing rate (from below), the length of the queue increases.

13. Byrne, E.J. and Landry, R.A. "RAM-30: A Computer Model for Real Estate Investment Analysis." The Arthur Young Journal (Summer, 1971).

14. Nelson, J.R. "The Value of Travel Time." Problems in Public Expenditure Analysis. Edited by Samuel Chase (Washington, D.C.: The Brookings Institution, 1968).

Beesley, M.E. "The Value of Time Spent in Travelling: Some New Evidence." Economica (May, 1965).

15. Brown, J.J. and Kelly, J.J. "Simulation of Elevator System for World's Tallest Buildings." Transportation Science, 2:1 (February, 1968), pp.35-36.

16. For a study of office building population density, see R. Fisher, The Boom in Office Buildings (Washington, D.C.: Urban Land Institute, 1967).

17. Powell, B.A. "Optimal Elevator Banking Under Heavy Up-Traffic." Transportation Science, 5:2 (May, 1971), pp.109-121.

18. Eastman, C.M. and Penz, A.J. "Decision Making in Adaptive Environments", IPP Report 32, Carnegie-Mellon University (November, 1972).