Uncertainties in airport cost analysis

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INTRODUCTION

Uncertainty in View of the History of Decisionmaking

The ultimate goal for all planning is to generate sound alternatives and to supply enough information about their performance for the decisionmakers to be able to make a decision.

In the past, choice among transportation alternatives was made more or less on basis of the alternatives economic performances which were supplied to the decisionmakers by the planners as for example "internal rate of return", "benefit-cost-ratios" or "net-present-worth-values". This can be classified as a one-dimensional information about the alternatives since all information supplied were measured in monetary values.

This technique has later been extended to take into account other attributes such as for example travel-time and traffic accidents, but then transforming the new attribute measurements into monetary values to make them compatible with the other data or information. Thus, the one-dimensional structure is kept.

In recent years the planners and the decisionmakers have acknowledged the loss of information resulting from transforming the data to a common scale and aggregating the information in an early stage of the planning process. As a result, the planners started to supply information about the alternatives as attribute measurements along their original scales, that is, travel time measured in minutes, noise measured in dBA or in number of people or houses inside an area with noise-level above certain dBA-limits etc. As shown, such attributes are not at all measurable along the same common scale without making assumptions about the trade-off values. In the broadest sense one can imagine that information about transportation alternatives is given on different nominal, ordinal, interval and ratio scales. This kind of information requires a multi-attribute or multi-dimensional evaluation and decisionprocess.

While in the earlier work of multi-attribute evaluation, the information given was regarded as being exact, the recent development in this field of decisionmaking [2, 3, 4, 5] is to look upon the multi-attribute measurements only as estimates of random variables. However, so far their probability distributions, or uncertainty distributions as they may be called, are unknown in most cases. This leads up to a fundamental question which is considered to be the main objective for this type or research:

– What is the impact of uncertainties in attribute measurements on the decisions to be made?

However, on basis of this fundamental question, new problems arise:

– What is the nature of the uncertainties and shapes of the uncertainty distributions for different attributes?

– How is it possible to generate probability models to describe these uncertainties?

The Scope of the Research

In order to go into some depth of the problem and in particular to provide some empirical data and results, it is necessary to limit the scope of the work. The first limitation consists of choosing one particular transportation planning problem. In this case, the problem of site selection for a new major airport in an area presently served by airports with capacity- and environmental problems, is chosen.

Although this is, as will be shown later, undoubtedly a multidimensional decision problem, in this research only one attribute, the capital cost incurred by the airport operator, is analysed. However, by doing so, variables having an effect on the cost attribute, such as air transportation demand and capacity of airports will be dealt with to some extent. This represents the second limitation of this work compared to the basic questions already raised.

In order to utilize certain available data, and to apply the results to a realistic problem, it was decided to perform the research with a view towards a specific case study: "Location of a New Major Airport for the Oslo-Region in Norway".

With respect to the basic questions raised in the first section and the limitations of this particular study described in this section, one can rephrase the objective for this particular research:

– What is the nature of the uncertainty distribution for capital costs of a major airport and how can an estimate for this distribution be derived?

Developing a Hypothesis

So far the questions posed do not indicate any specific direction for the research to be performed. Although the historic development of decisionmaking points to the area of uncertainties and uncertainty distributions as academically interesting topics, it is yet to come to establish the need for and the importance of knowing the nature of the uncertainty distributions for capital costs of a major airport and to develop a hypothesis of the possible effect of the uncertainties on the site selection problem.

As a starting point, uncertainty distributions for capital costs of a major airport are assumed to exist. That is, it is possible to describe the uncertainty of capital costs for different airport sites by probability distributions. These distributions, which are still unknown, may have different shapes and both the mean value and the magnitude of the uncertainty expressed for example by the variance of the distributions may vary from one site to another.

However, the need for knowing these probability distributions is not generated by pure academic interest, but these distributions are assumed to be of vital importance when evaluating different airport sites.

So far, cost estimates[1] have been used when evaluating the capital costs of the airport related to alternatives sites, and the differences in costs between the sites have more or less automatically been considered significant. By introducing the concept of uncertainty and analysing the nature of the uncertainty distributions, a statistical treatment of whether or not differences in estimated costs are significant may be possible. Further will knowledge about uncertainty distributions also provide information about confidence limits for the actual costs, and probabilities of exceeding certain cost limits can be calculated. By facing this more complex information, the decisionmakers may come out with decisions different from the ones based on the use of only cost estimates. At least two effects will be of some importance.

First, the use of uncertainty distributions will tend to reduce the significance of the differences in cost estimates, thus also reducing the importance of cost differences in the multi-dimensional evaluation and decision process.

Second, if the dicisionmakers are increasingly averse to high costs (that is "risk averse" in decision theoretic terminology), and capital costs are expressed as probability distributions, alternatives with little uncertainty (small variances in the probability distributions) will come better out compared with high uncertainty alternatives (large variances) than would be the case if only cost estimates were used.

All these statements, although mostly not proven so far, lead up to the hypothesis that information about uncertainties in cost estimates may be of vital importance for the decisionmakers when evaluating different sites for location of the major airport.

STRUCTURING THE RESEARCH

The Case Study: "Location of New Major Airport for the Oslo-Region in Norway"

The Oslo-region in Norway is the most densely populated area in the country with a population of approximately 1 million in the area to be served by the airport. Thus, it is also the single most important origin/destination for both domestic and international flights. Presently the region is served by Fornebu Airport located 8 km (5 miles) south-west of Oslo city center. Due to aircraft noise, night operations are limited by a curfew, and one is also experiencing capacity problems. To relieve the situation, most of the international charter traffic in 1973 was transferred to Gardemoen Airport which is located 35 km (22 miles) north-northeast of Oslo city center.

At Fornebu both runway capacity and passenger- and freight terminal capacities are expected to be exceeded in very near future. Besides, both runways (fig. 1) are, with respect to length (2200 m and 1750 m) considered inadequate for todays air traffic operations. However, there is strong local opposition against extending runways and expanding passenger- and freight-terminal buildings at Fornebu because of the effect of aircraft noise on nearby areas.

The present situation at Gardemoen is that both the strength of the pavement and the runway length are inadequate (fig. 2), thus limiting the aircraft types and the take-off weights. The terminal building is expected to suffice for a few more years.

The airport problem in this area is considered a federal problem thus giving the National Assembly of Norway the decisionmaking power. Several governmental committees, research organisations, and consulting firms have dealt with the problem more of less continuously the last seven years. So far no final decision is reached, but the basic questions appear to be:

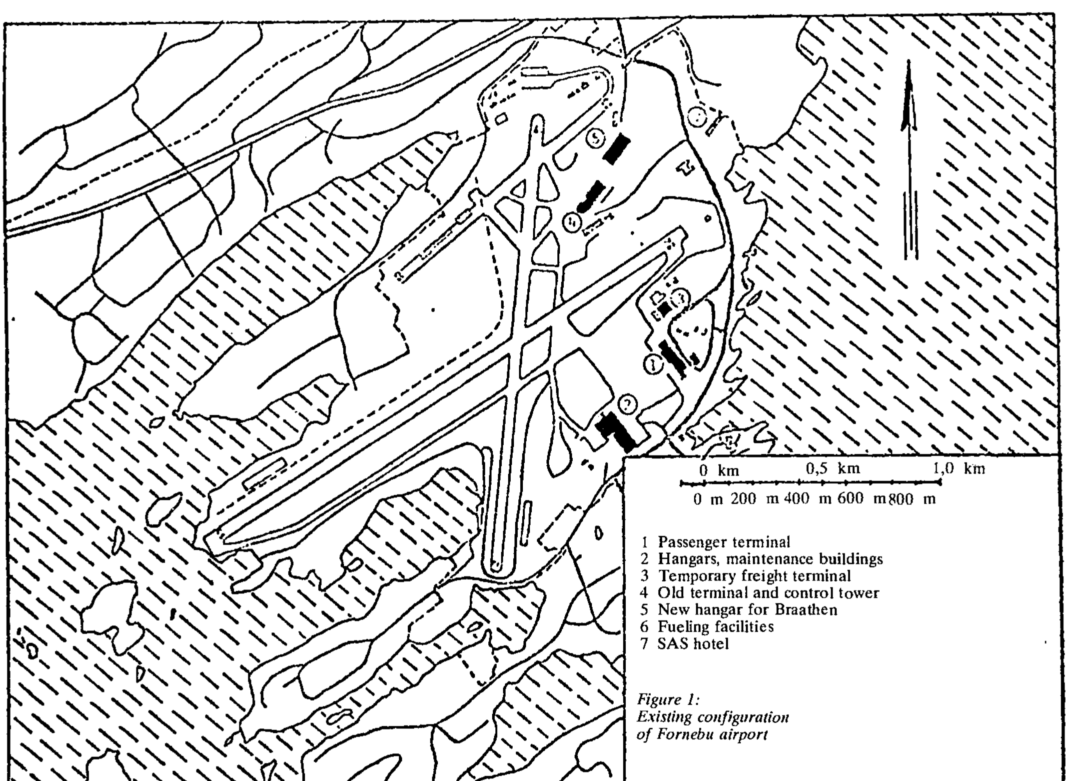

Figure 1: Existing configuration of Fornebu airport

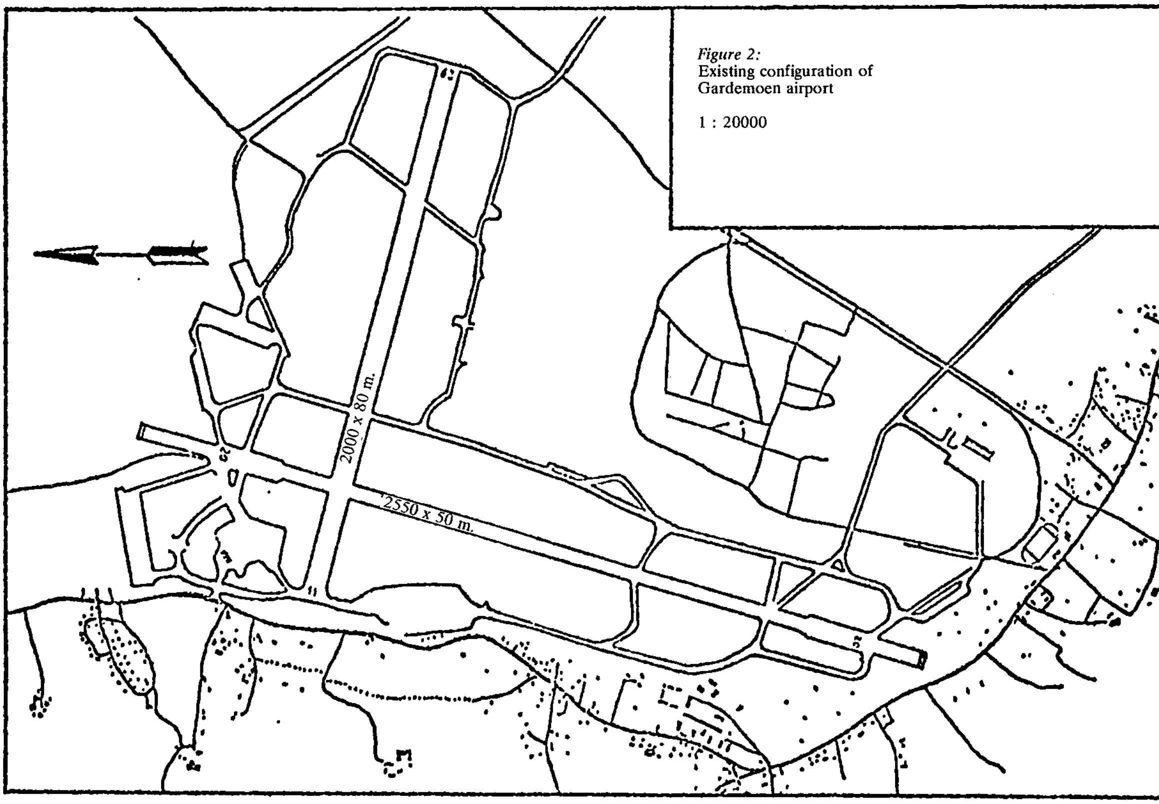

Figure 2:
Existing configuration of Gardemoen airport

1 : 20000

1) Does the Oslo area need a new major airport? In case:

2) When does the new airport have to be ready?

3) What airport size is expected for the horizon year, 2000?

4) Where should the new major airport be located?

5) What will be the consequences of building a new airport with respect to costs and other attributes?

The Airport Planning Process and the Structure of this Research

A simplified description of the airport planning process used in the Oslo-region is shown in figure 3. As already mentioned, this research deals mainly with uncertainties in the cost attribute. The figure, however, indicates the dependency between the cost, of an airport alternative, as one of the resulting consequences, and the demand forecast. Thus uncertainties in the demand forecast may affect the uncertainties in the actual costs.

In order to analyse this problem of uncertainties in actual costs of airports, the problem was restructured according to figure 4.

The basic concept is that the relationship between air transport demand and airport capacity determines the need for airport expansion or a new airport. This is of course a simplification of the problem since other factors such as length and strength of runways, regularity of air traffic or environmental effects may also affect the decision whether or not to expand an existing or build a new airport. However, at least some of these considerations may be transformed to a question of airport capacity.

As shown in figure 3, the demand forecast is used to design an airport model which is able to handle the forecasted number of passengers (terminal capacity). Different alternatives are then generated by implementing this airport model at the alternative sites. However, such alternatives are considered rather static in the sense that they do not allow for an evaluation of more stepwise and flexible development of the airport system for the area. In order to provide for a more flexible and dynamic use of alternatives, the concept of strategies is introduced. In this context a strategy is defined as a list of projects to be implemented at a given site when the need for the projects is determined. This is determined by comparison of the demand for and capacity of the airports serving the area. The complete list of projects may be identical to what earlier is called an alternative, that is the airport model, but one alternative may serve as basis for generating more than one strategy, since operational differences may distinguish one strategy from another. This gives the possibility of analysing not only different sites, but also different operational strategies for the sites under consideration.

When these principles are applied to the case study, different airport projects are put into five groups:

1) Projects that will increase passenger terminal capacity for airline passengers.

2) Projects that will increase runway capacity for air carrier operations.

3) Projects that will increase passenger terminal capacity for charter passengers.

4) Projects that will increase runway capacity for charter operations.

5) Projects that will increase runway capacity for general aviation traffic.

The reason for distinguishing between regular airline traffic and charter traffic is that today Fornebu Airport is mainly used for regular airline traffic while Gardemoen Airport serves as a charter airport.

Within each of these five groups, the projects are

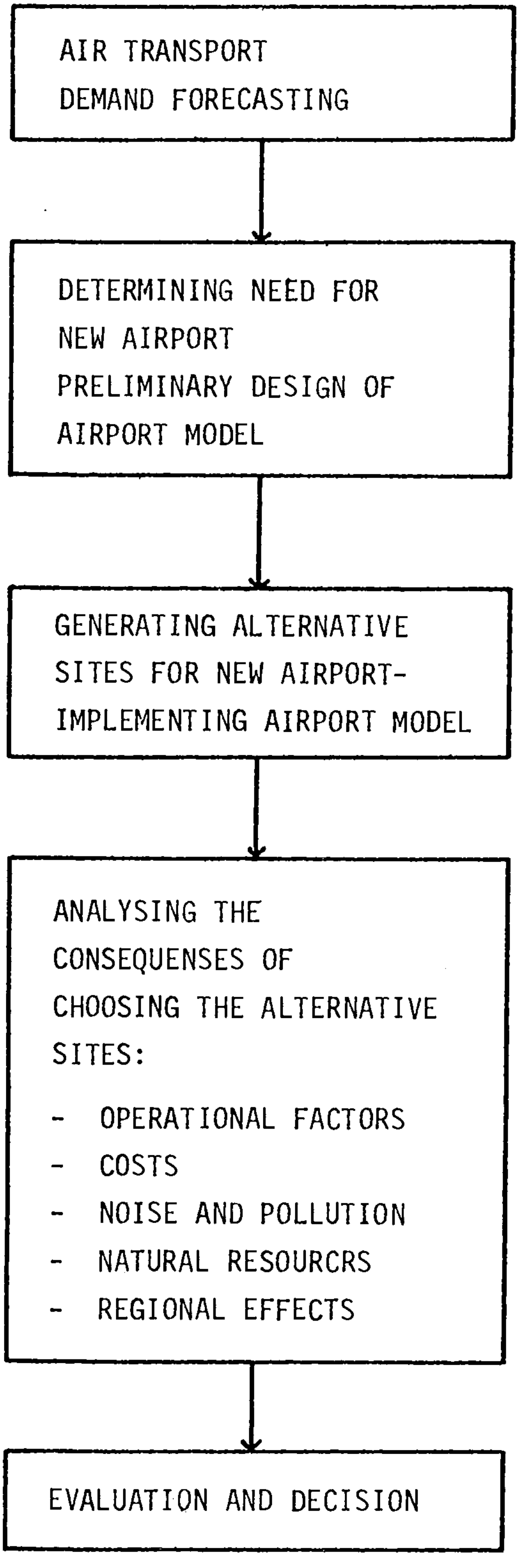

Fig. 3 – Simplified Description of the Airport Planning Process used in the Oslo-Region

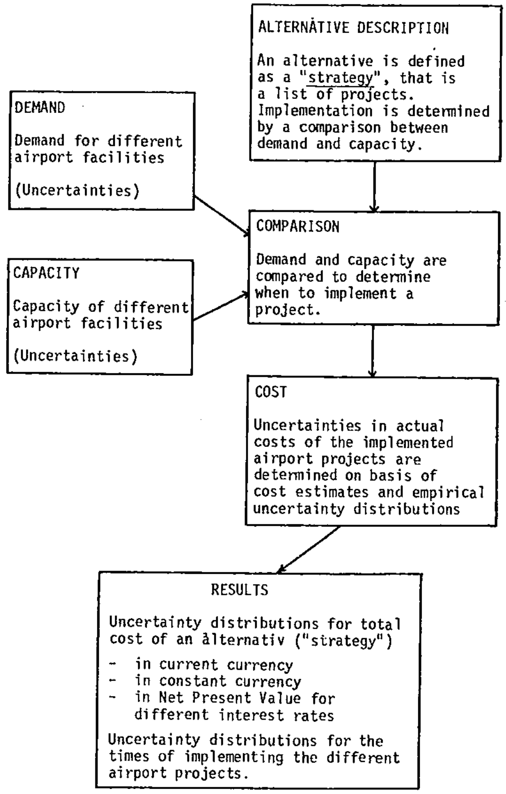

Fig. 4 – Diagram showing how the Problem is structured and expected Results.

ranked according to a specified order of implementation. This feature, together with methods of comparing demand and capacity, give the possibility of analysing both alternative sites and different operational procedures.

By comparing the demand forecasts for different years and the capacity of the existing airport(s), the need for additional capacity is determined. However, since both the demand forecast and airport capacity are assumed having uncertainty distributions, the times for implementing the different airport projects will also have its uncertainty distributions. For each project a cost estimate is assumed to exist. However, the actual costs are not known. By deriving uncertainty distributions for cost of airport projects on basis of empirical data, it is possible to utilize these distributions to calculate uncertainty distributions for actual costs of the airport projects to be implemented.

As results from this analysis, one expects to derive uncertainty distributions for total cost of a strategy (sum of all projects which are implemented), where cost is measured in both constant and current currency and where net present values are calculated for different interest rates. In order to derive these distributions, computer simulation was used. However, as it appears in figure 4, necessary inputs to this simulation process are uncertainty distributions for air traffic demand, capacities and costs of airport projects. In this paper the demand and the cost studies are described.

THE COST STUDY

Reasons for Uncertainty in Actual Cost of Airport Projects

Final cost figures from construction projects often reveals that the actual cost of a project does not coincide with the cost estimate from the time it was decided to go on with the project. The difference between the actual and the estimated cost most of the time seems to go in one particular direction, that is cost overruns seems to be the rule. However, complete agreement about how to treat this problem does not exist. On one hand, as Altouney [6] quotes from "The June 1955 Water Resources and Power Report to the Congress by the Commission on Organisation of the Executive Branch of the Government":

"If the cost of a project is underestimated when it is presented to the Congress, obviously the benefits and justifications upon which the Congress made its decision have been misleading."

However, on the other hand, as Zimmerman and Merewitz [7] state:

"Should we seek better cost estimates? Not necessarily. The effort to make more accurate cost estimates may result in higher total costs for projects than would otherwise have been the case. Perhaps an "unrealistic" cost estimate operates as a restraining factor."

These two opinions indicate the nature of the cost estimation problem, that is the "dual purpose" of cost estimates. Cost estimates serve both as basis for decisionmaking and as guidelines or restraining factors during the construction period. This "duality" also explains some of the cost overruns which are observed. In order to get a project accepted, a deliberately low cost estimate is submitted to the decisionmakers. This, however, will of course lead to cost overruns, in spite of the fact that the low cost estimate will work as a restraining factor. The degree of underestimation may vary from project to project and does not consistently imply unrealistically low cost figures from those responsible for the cost estimation.

What is mentioned above may be classified as political or tactical reasons for uncertainty in a specific direction, that is underestimation. Such reasons are believed to exist and to be important, but equally or more important in most cases are other factors which are not tactically motivated and which are to a certain extent characterized by some randomness.

One such factor is "specification completeness". At the estimation stage it is easier to forget to include cost components than it is to include more costs than actually will occur.

Another factor is "quantity and price accuracy". It is difficult to establish the exact quantities of work that has to be done, and materials and equipment needed at a preliminary stage. In addition come uncertainties in unit prices and wages which increase with the length of time until completion of the project.

This again points to yet another factor, "the uncertainty of time". "Time" in this context may be interpreted in two different ways. First, it may mean "construction time", and uncertainty in construction time will again affect the cost of the project. Secound, time may be understood as the time when the whole project is completed. If part of the project, for example one or more sections of the terminal buildings or one or more runways, are intended completed at a later stage, uncertainty in these time estimates will affect the cost, especially combined with other factors mentioned in this section.

"Unpredicted natural causes" is also a factor to be considered. These natural causes often are related to weather conditions or to geotechnical conditions on the construction site. Geotechnical conditions may be either better or worse than expected, but the uncertainty is strongly related to more or less insufficient, preliminary investigations.

A more deterministic cause for what is called uncertainty, is change of design, although the reason for the change may be of random nature. Conceptually, change of design can work to both decrease and increase in actual cost. At an early stage of the project planning, change of design may be used to find cheaper solutions. Later on, however, design changes are mostly made in order to satisfy change in demand and such changes tend to increase the cost of the project.

The last factor to be mentioned is "technological uncertainty". Cost estimates are most of the time based on previous experience, that is "yesterday's technology". In addition one anticipates what kind of new technology will be available before construction starts and what effect it will have on the construction cost. Technology is in this context given a very wide interpretation, since not only construction technology, but also technological development affecting air transportation demand and airport capacity is included. Thus technological uncertainty may result in uncertainty in cost both through construction technology and through change of design or change of time for implementing part of the project due to unpredicted technological development affecting demand and capacity.

The different factors which may give reasons for uncertainty in actual cost of projects are here listed independently. However, as indicated for some of them, they are all strongly interrelated and the resulting uncertainty in actual cost is hard to evaluate. One would expect, however, on basis of this list of factors, both the tactical, political, psychological and the more technical factors, and their most common effects, that cost overruns will be the rule rather than the exception.

Probability Structure for Statistical Treatment of Uncertainties in Actual Costs.

In the preceeding section reasons for uncertainty in actual cost of construction projects were discussed. So far "uncertainty" or "uncertainty distributions" have not been properly defined but uncertainty has implicitly been interpreted as having to do with the relationship between actual and estimated cost. Although there is great uncertainty about the actual cost of an airport project when the cost has not been estimated, in this context the terms "uncertainty" and "uncertainty distributions" refer only to situations when a cost estimate for the project exists. The cost estimate is used as a reference point for measuring the uncertainty. Thus, it is only relevant to talk about an uncertainty distribution during a time period when the cost estimate is known, but the actual cost is unknown. Then, the actual cost can be regarded as a random variable being affected by all the factors mentioned and having a probability density, $f_e(c)$. This probability density shows the distribution of the actual cost. C, given the cost estimate, E. The distribution of C is thus a conditional distribution, it depends on E. Nothing is so far said about the shape of the distribution, $f_c(c)$. It is only assumed to exist, as was also done in the first section. From the conclusions arrived at in the third section it may be assumed that the estimated cost, E, is not equal to the expected value of the actual cost, C. This, however, will be discussed later in the context of the results from the empirical cost study.

In this work, the main objective is to study the uncertainties in actual costs of airport projects. Altouney [6] and Merewitz [8, 9] have studied uncertainties in cost estimates for other types of projects, and they found it useful to study the ratio, R, of actual cost to estimated cost.

$$R = \frac{C}{E}$$

This relationship can also be written:

$$C = E \cdot R$$

It is already stated that the uncertainty is only defined when E is known. In such a case, E can be considered a constant, E = e. This implies that the actual cost, C, will have the same distribution as the ratio, R, but with a different scale factor which is known through the knowledge of e. By studying the variations of R for different airport projects, a measure of the uncertainty in the actual costs can be derived. Mathematically this can be expressed:

$$P(C<c|E = e) = P(R<\frac{c}{e})$$

Thus:

$$f_e(c) = \frac{1}{e}\, g.(\frac{c}{e})$$

or:

$$f_e(c) = \frac{1}{e}\, g(r)$$

where: $f_e(c)$ is the density function of C given E = e expressing the uncertainty in actual cost.
g(r) is the density function of the ratio R, given E = e, where

$$R = \frac{C}{E}$$

When studying the distribution of R and assuming that

$$(C|E = e) \overset{\mathcal{L}}{=} (e \cdot R\,|E = e)$$

one implicity also makes the assumption that the cost estimate, E, is arrived at through the same procedure for each project, that is, the distribution of R represents the uncertainty with respect to this estimation procedure as well as C. This is rather serious assumption, but for this research it was found necessary. However, the possibility exists that when observing r, the variations observed are not only randomness in the actual cost, C, but also include more or less systematic variations in the estimation procedure.

Analysis of Empirical Cost Data

Introduction

The main objective for this study of empirical cost data is to investigate the relationship between actual costs and estimated costs for different airport projects according to the probability structure defined in the preceding section.

This relationship is also considered the single most important component of this research as described through figure 4. The approach is to use historical data for both estimated and actual costs in order to derive the distribution of the ratio:

$$R = \frac{\text{Actual Cost}}{\text{Estimated Cost}}$$

Some additional questions to be answered by the analysis of the empirical data are:

1) Do cost estimates appear to be biased in any direction?
2) Is there any relationship between the size of a project and the uncertainty in actual cost of the project?
3) Is there any relationship between "the completion time"[2] and the uncertainty in actual cost of a project?
4) Are there any differences in the uncertainties for different types of projects within the airport?

One fact should probably be made clear on this initial stage of the cost study. This particular research does not intend to further explain the causal relationship for the uncertainties in cost estimation as for example it is attempted in [7], [9]. Neither will the underlying assumptions for the probability structure as described in the previous section be tested. The purpose of this study is merely to observe historical facts in order to recognize the uncertainties in the relationship between actual and estimated costs. The resulting distribution will both serve as an independent tool for evaluating actual costs of specific airport projects and as input to the simulation model described in figure 4. Finally, the uncertainty distributions will be applied to the case study, both as an independent tool and as part of the simulation model.

Data collection

The district offices of the Federal Aviation Administration (FAA) keep records of estimated costs and final costs for different airport projects. Part of the data for this research are acquired from the FAA Regional Office in Burlingame, California and refers to different airport projects in Northern California. The rest of the data were collected from journals and magazines covering news in the airport and construction field.

In order to derive an uncertainty distribution as described in the preceding sections, the ratios actual costs to estimated costs were calculated. These ratios were named "original ratios". Besides "corrected ratios" were calculated, that is ratios calculated on basis of constant dollars, were the correction is made according to the "Construction Cost Index"[3].

A detailed analysis of these cost data is performed in [1]. In this section a summary of the most interesting results are given.

For each airport project the following information existed:

i) Estimated cost
ii) Actual cost in current dollars
iii) Actual cost in constant dollars (corrected by construction cost index)
iv) Original cost ratio
v) Corrected cost ratio
vi) Completion time
vii) Type of project.

The projects are classified in three groups:

I: Runway projects
II; Terminal building projects
III: Land acquisition

Based on this information some of the most interesting relationships are analysed.

Results from the Cost Study

Relationship between the Cost Ratio and the Size of a Project

Altouney [6] investigated the relationship between the size of a project expressed as final cost and the cost ratio, but he did not find any such relationship. Merewitz [8] postulates: "One hypothesis arising from earlier work is that the ratio of actual to estimated cost, R, is larger on bigger projects". However, Merewitz did not test this hypothesis.

In figure 5 corrected cost ratios and actual cost data

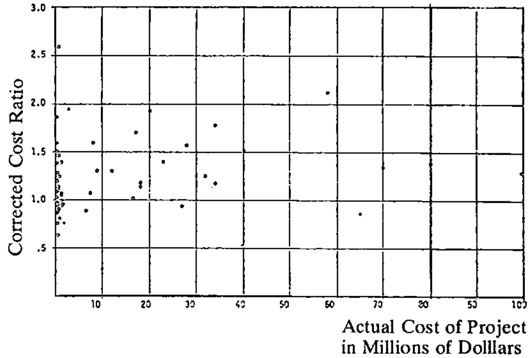

Figure 5 – Plot of the relationship between actual cost and corrected cost ratios.

are plotted for different airport projects. The figure does not reveal any relationship between the two variables investigated.

Relationship between the Cost Ratio and the Completion Time

From the beginning of this study, the completion time, that is the time from when a cost estimate is made and until the project is finished, has been assumed to affect the cost ratio. In figure 6 the corrected cost ratios are plotted against the completion times. The figure does not reveal any relationship between the two variables investigated.

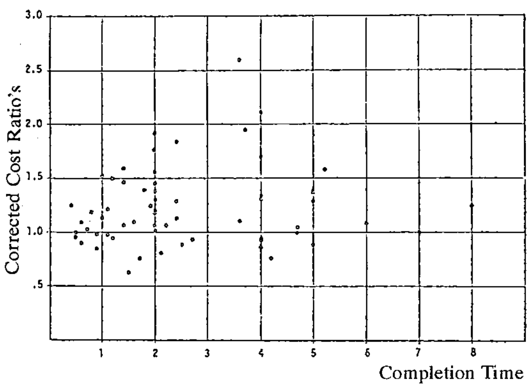

Figure 6 – Corrected Cost Ratios Plotted Against Completion Time

Comparison Between Different Types of Projects

Although the number of observations in the data set is rather small and the possibility for errors is large, it is tempting to look at the data separately for two of the project-types (for land acquisition, type III, the number of observations is definitely insufficient). In this case only projects exclusively classified in one group are included. Tables 1a and b show the most important properties for the two project types. The difference of the mean values of the original ratios is considered less important in this case since it can be explained by the difference in completion times. (A t-test shows that the means are significantly different on the 99% confidence level). More important is the observed difference in the corrected ratios. A t-test performed on the mean values yields a t-value of only 0.8883, which is below any reasonable critical t-value [10]. However, a difference in the mean values is observed although the statistical proof is lacking.

Another feature which seems to be different for the two project types is the skewness. However, the coefficient of skewness, calculated as a function of the second and third central moments, is very sensitive to small variations in the data, especially the occurence of a few rather extreme values. In order to test if the observed difference in the coefficient of skewness also indicates a significant difference in the shape of the two distributions, the hypothesis that the two distribution functions are equal is tested:

$H_0 : F_I(x) = F_{II}(x)$

The Smirnov Test [11] was used and the conclusion was that the hypothesis of the two distributions being equal cannot be rejected at any reasonable significance level. The results from both these tests show that although differences are observed in the distributional properties of the two types of projects, the differences are not significant from a statistical point of view. However, in spite of the lack of statistical proof of the possible differences, additional support can be found by comparing these results with similar results from other areas. Merewitz [8] presents several tables of raw data comparable to those used in this research for different types of projects. Since these data are what here is called original ratios, that is ratios based on actual costs which are not corrected for price increase, they will be compared with similar data from this study.

Table 1 a) and b) – Properties of cost ratios for type I and type II projects

Projects type I	Original Ratios	Corrected Ratios
Mean value	1.3295	1.2224
Standard error or the mean	.0762	.0721
Standard deviation	.3492	.3304
Coefficient of Variation	.2627	.2703
Coefficient of Skewness	.5663	.7538
Average completion time	2.1905	2.1905
Number of observations	21	21

Projects type II	Original Ratios	Corrected Ratios
Mean value	1.6705	1.3220
Standard error or the mean	.1219	.0864
Standard deviation	.5453	.3866
Coefficient of Variation	.3264	.2924
Coefficient of Skewness	1.5199	1.6857
Average completion time	3.300	3.300
Number of observations	20	20

In table 2 the different project types are arranged in order of increasing mean values.

Table 2 – Cost Ratios for Different Types of Projects

Project Type	Original Ratios Mean Values	Average Completion Time
Highway Projects	1.2633	4.6541
Airport Projects Type I	1.3295	2.1905
Water Resource Projects	1.3774	10.0200
Urban Rapid Transit	1.5447	6.1679
Buildings	1.6272	3.0833
Airport Projects Type II	1.6705	3.3000
Ad Hoc Public Works	2.1447	4.9333

Conceptually, this ordering makes sense with highly experienced, state or federal agencies on the top of the list. However, that such an argument is not consistent is documented by Altouney's [6] results.

He found average, uncorrected ratio for water resource projects to be 2.63, far above all the results reported by Merewitz and the airport data collected for this study.

If the results from the airport projects are compared with other types of projects, the runway projects (type I) came out very close to the highway projects. The other type (type II) consisting mainly of terminal buildings and internal transit systems came close to "Urban Rapid Transit" and "Building"-projects. Without being able to prove statistically the difference between the different project types within the airport by use the airport data, this comparison is another indication that such a difference may exist.

Properties of the Complete Data set and the Resulting Uncertainty Distribution

The main reason for collecting these data and deriving their distributional properties, was to get information about the size and shape of the uncertainty distribution associated with cost estimation of airport projects. With this objective in mind, it was decided to gather all the collected data in one data set and analyse its distributional properties. The results of the numerical calculations are shown in table 3.

Table 3 – Major properties of the complete dataset

Project Type	Original Ratios	Corrected Ratios
Mean value	1.4351	1.2330
Standard error of the mean	.0605	.0464
Standard deviation	.4724	.3623
Coefficient of Variation	.3292	.2938
Coefficient of Skewness	1.4622	1.2689
Average completion time	2.6328	2.6328
Number of observations	61	61

In the further analysis the corrected ratios are chosen as data base for deriving the uncertainty distribution.

In order to derive the density function for the corrected cost ratios, the observations can be plotted as a histogram. However, here is used a modified density estimate (e.g. Bickel and Doksum [12] which is continuous and consistent at every point. An existing computer program which utilizes this technique was modified and used to produce a plotter output of the resulting density function, figure 7. As a comparison, a gamma- and a log-normal distribution calibrated by the method of moments are plotted.

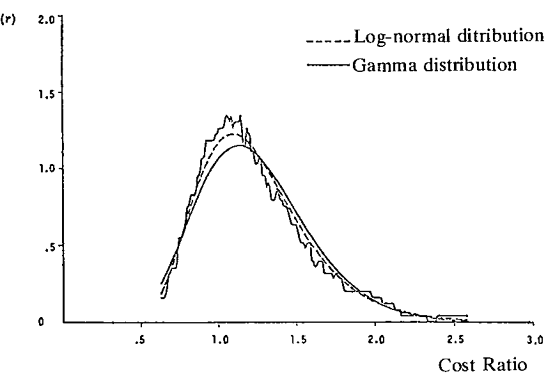

Figure 7 – Density Function for Corrected Cost Ratios

This distribution is accepted as an uncertainty distribution for the fatio R for airport projects and it will be used according to the probability structure described to calculate the uncertainty in actual costs for airport projects of some interest for the case study. This will be shown in a further section.

THE DEMAND STUDY

Introduction

When analysing air traffic demand, the airport facilities are grouped in following two groups:

1) *Passenger facilities* such as terminal buildings with their ticketing, baggage handling and internal transportation systems, parking areas and ground transportation.

2) *Aircraft facilities* such as runways, taxiways, apron, gate positions, fuel supply and maintenance facilities, landing instrumentation and airport and air-traffic control.

Less aggregation is of course possible, but for this project, the grouping above is considered sufficiently detailed. Besides, it corresponds to the aggregation of projects made in the cost study. It is also necessary to stratify demand according to type of operations, that is air carrier, charter, and general aviation to mention the most important categories. In this case the annual number of passengers is chosen to represent the demand for passenger facilities while peak hour aircraft operations represent the demand for aircraft facilities. Since the underlying case in this research is an airport which mainly will serve commercial air transportation, it was decided to limit the studies of uncertainties in demand to "annual number of airline passengers" and "peak hour air carrier movements". In order to perform this analysis, it was necessary to recognize the dependency between these two demands and identify their relationship. In this case, the annual number of airline passengers is considered the basic demand for air transportation. From this basic demand, first the annual number of air carrier movements, and then the peak hour movements are derived.

As was done when analysing uncertainties in cost of airport projects, historical data will be analysed. However, in the cost study, engineering reasons for bias and uncertainties could be found and it was assumed that the knowledge acquired could be used to make better estimates in the future. In demand forecasting this is not exactly the situation. Bias observed in old forecasts cannot be utilized to a large extent when dealing with future years since there is no a priori reason to believe that the forecasts are biased in any particular direction. But in spite of this limitation in the use of historical data when dealing with forecasting, it still may be possible to learn something about the uncertainties of forecasting by comparing old forecasts with what actually happened.

When dealing with demand, expressed as "annual number of airline passengers", one would expect to get a fairly accurate statistical material for different airport for past years. However, when informations from two different sources covering the same airport are compared, one discovers small and large differences, some of them impossible to explain although some sources of possible errors are known. Transit passengers, for example, are not counted identically all the time. Sometimes they are counted twice, other times once, and in some statistics transit passengers are not included at all. Another problem occurs when an airport also accommodates international and domestic charter, airtaxi, commuter traffic and helicopter routes. Treatment of the passengers on these types of flights obviously varies and gives reasons for uncertainty with respect to what kind of traffic is reported in a particular statistic. The last source of uncertainty in the data-material to be mentioned here, is the treatment of general aviation passengers for types of flights not mentioned above, which also obviously varies.

Uncertainties of these and similar types, make it to a certain extent difficult to compare demand forecasts with actual traffic data. An old set of forecasts for 107 US airports made in 1953 by "Air Transport Association" and which appeared in "American Aviation" in November 1953, could not be evaluated because the base year data (1953 F.Y.) could not be verified by available statistical data. FAA's 1953 data for those airports were not at all similar to the data used as basis for the forecast. The general impression of these forecasts was that annual number of passengers and movements for year 1970 were underestimated by a factor of 2 – 8, that is actual traffic was 2 – 8 times estimated traffic volumes.

Probability Structure for Statistical Treatmant of Uncertainties in Demand

As was the case in the cost problem, uncertainty in demand is connected to the relationship between actual and forecasted values. That is, in this case the relationship between actual demand, T, and forecasted demand, F. Further, uncertainty is only defined when a demand forecast is known. Thus, actual demand, T, is considered a random variable, and the distribution of T is considered conditional on the forecast, F.

Again the ratio: $M = \frac{T}{F}$

is of considerable interest. It is already stated that the uncertainty is only defined when the forecast F is known. In such a case, F can be considered a constant, F = f. This implies that the actual demand, T, where

$T = f \cdot M$

will have the same distribution as the ratio, M, but with a scale factor given by the value of F = f. By studying the variations of M for different airtraffic forecasts, a measure of the uncertainty in the actual demand, given a forecast, can be derived. This is very similar to the probability structure for the cost study and thus the resulting mathematical expression will be

$$f_f(t) = \frac{1}{f}\, h(m)$$

where $f_f(t)$ is the density function of T given F = f expressing the uncertainty in actual demand

h(m) is the density function of the ratio M given F = f, where $M = \frac{T}{F}$ f is the known demand forecast

As in the cost study, one should, also when dealing with demand, be aware of the fact that by assuming:

$$(T|F = f) \overset{\mathcal{L}}{=} (f \cdot M|F = f)$$

one implicitly also make the assumption that the forecast, F = f, is arrived at through approximately the same forecasting procedure and with the same a priori accuracy for each forecast. This, is a rather serious assumption, but necessary in order to make some progress toward realizing the nature of uncertainty in demand.

Observed Uncertainties in Annual Number of Passengers

Uncertainties in annual number of passengers will be analysed according to the probability structure described in the previous section, that is by studying the ratio, M, of actual to forecasted demand for different airports.

In 1968 FAA made forecasts for all airports in the United States classified as medium hubs [13] both for annual number of passengers and annual number of aircarrier movements. Actual traffic data were found in [14, 15, 16]. In figures 8 and 9 are shown the distribution of the ratios: actual traffic/forecasted traffic for both categories and for different ages of the forecasts. Although the distributions are based on 33 observations, these cannot be regarded as independent since they all probably are subordinated in a national forecast. For both passengers and air carrier movements an almost consistent overestimation seems to exist. This implies that the distribution of ratios is biased. In order to measure the uncertainty, the following two measurements are used.

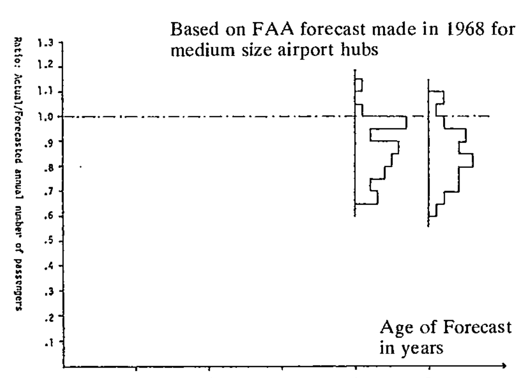

Figure 8 – Distribution of ratios: Actual/Forecasted number of passengers.

Based on FAA forecast made in 1968 for medium size airport hubs

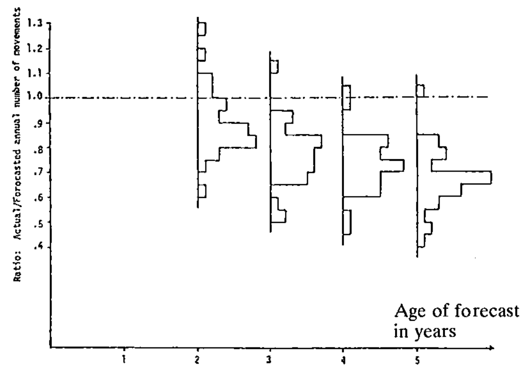

Figure 9 – Distribution of ratios: Actual/Forecasted annual number of movements.

1) The variance (and standard deviation) of the observed distribution, s_r^2 (and s_r) around the distribution mean, $\bar{r}$.

2) The mean square error (M.S.E.) (and its square root, the root mean square error, R.M.S.E.) around the value, $\bar{r}$ = 1,0, (unbiased mean) s_b^2) and s_b).

It can easily be shown that:

$s_b^2 = s_r^2 + (\text{bias})^2 = s_r^2 + (\bar{r} - 1.0)^2$

and thus:

$s_b = s_r^2 + (\bar{r} - 1.0)^2$

Numerical results from this study are given in table 4 and show a considerable bias for both passengers and aircarrier movements, .1574 and .2960 after five years respectively. Compared to figures 8 and 9, the root mean square error, s_b, seems to reflect the increasing uncertainty over time in a satisfactory manner, increasing from .1639 for two years old forecasts of aircarrier movements to .3159 for five years old forecasts.

The Washington D.C. airports, two of them owned and operated by the Federal authorities, have been given special attention by the FAA. Forecasts for these airports were made by the FAA in 1962, 1968, 1969 and 1971 [17, 18, 19, 20], and the forecasts were compared with actual data. In figures 10 and 11 are shown how the different forecasts compare with the actual development. For the Washington D.C. area forecasts were also made for each of the two federal airports. Figure 12 shows the comparison with actual data.

For San Francisco International Airport there also exist forecasts made at different points in time, but contrary to the data for the Washington D.C. airports, these forecasts are made by different agencies and research organizations. FAA District Office in Oakland, 1957, Stanford Research Institute, 1965, and Association of Bay Area Governments, 1969 and revised in 1970 - 71, have made the forecasts which are compared with actual data, both absolutely in figure 13 and relatively, figure 14.

At this point it is time to look back and consider what kind of conclusions can be drawn on basis of the knowledge acquired through the analysis of these data.

Most planners probably have to admit that uncertainties in forecasting as they appear in figures 8-14 and table 4 are greater than what has so far been realized. From the results it seems reasonable to assume RMSE around unbiased mean, $\bar{r}$ = 1.0, that is s_b of the magnitude, s_b = .20 for 5 years old forecasts, s_b = .30 – .40 after 10 years, and probably s_b > .50 for 20 years old forecasts.

Table 4 – Numerical results from the statistical analysis of the FAA forecasts made in 1968

	Passengers		Movements			
Age of forecast in years	– 4 –	– 5 –	– 2 –	– 3 –	– 4 –	– 5 –
Mean ($\bar{r}$)	.8655	.8426	.9020	.7708	.7303	.7040
Standard error of the mean	.0199	.0208	.0229	.0209	.0174	.0192
Uncertainty measurements:						
Standard deviation (s_r)	.1107	.1158	.1314	.1198	.1074	.1104
RMSE around $\bar{r}$ = 1.0 (s_b)	.1742	.1954	.1639	.2590	.2903	.3159
Coefficient of Variation	.1279	.1374	.1457	.1554	.1470	.1568
Coefficient of Skewness	.0882	.0549	.7341	.4391	.5508	.6243
Number of observations	31	31	33	33	33	33

It is also apparent from the Washington D.C. data that when an area is served by two or more airports the uncertainties of the individual forecasts, figure 12, are larger than the uncertainties of the aggregated forecast for all airports, figure 10 and 11. But in this case the individual forecasts seem to improve over time.

With respect to the shape of the uncertainty distribution, there are at least two indications that we may expect a positively skewed distribution.

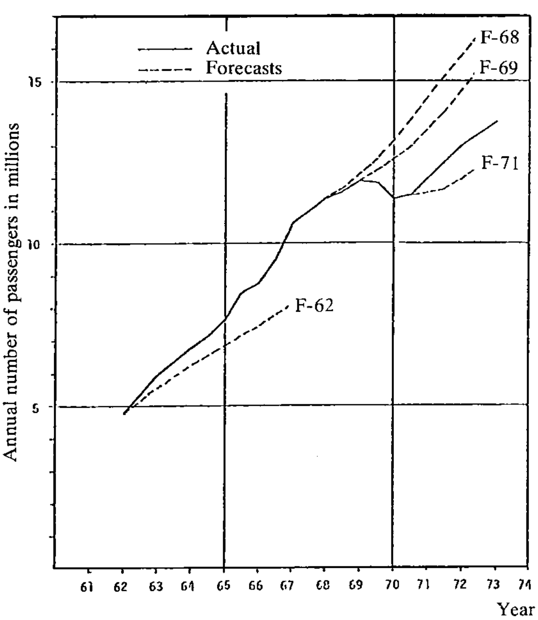

Figure 10: – 1962, 1968, 1969 and 1971 forecasts compared to actual annual number of airline passengers for Dulles and Washington National Airports.

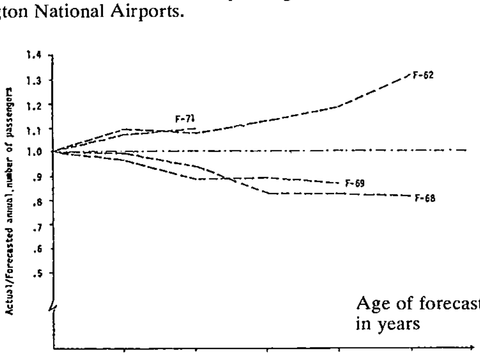

Figure 11 – Comparison of ratios: Actual/Forecasted number of annual passengers for 1962, 1968, 1969 and 1971 forecasts for Dulles and Washington National Airports.

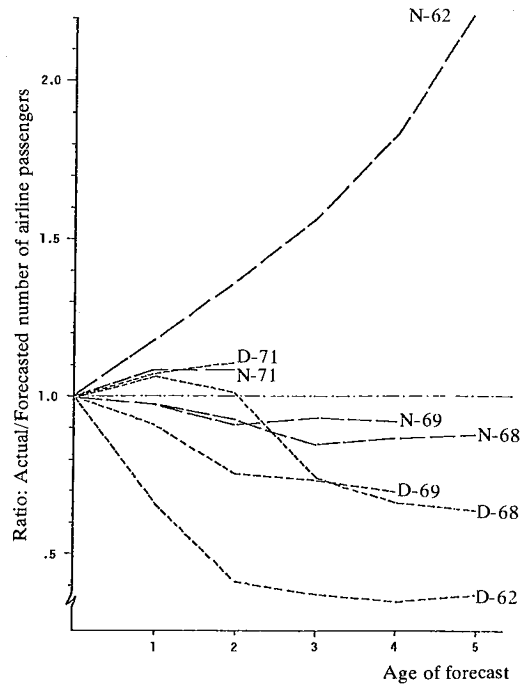

Figure 12 – Comparison of different forecasts for Dulles and Washington National Airports.

Ratios arrived at by dividing two positive variables, always have a lower limit equal to zero, but not necessarily any upper limit, thus indicating a density function skewed to the right.

The development of annual number of passengers over time can be described by the following model:

$$T_{an} = T_0 \prod_{t=1}^{n} (1 + a(t))$$

where T_{an} – actual demand in year n
T_0 – base year demand
$a(t)$ – actual growth factors for each year t
n – horizon (number of years)

However, at the forecasting stage, the actual growth factors, a(t), are not known, but estimated (forecasted) values, $\bar{a}$ (t), are used.

The forecasting model will then be:

$$T_{en} = T_0 \prod_{t} (1 + \bar{a}(t))$$

where T_{en} is estimated (forecasted) demand in year n

Once the $\bar{a}$(t)-values are determined, the estimated demand, T_{en}, is calculated and can from then on be regarded as a constant. The uncertainty is now tied to what actually will happen, that is a(t). At the forecasting

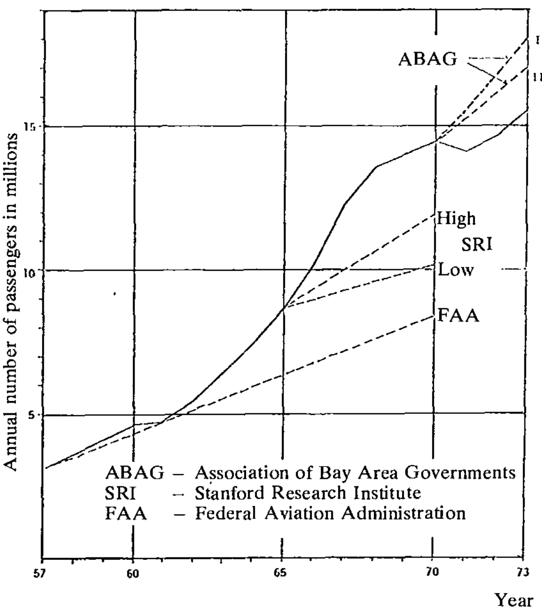

Figure 13 – 1957, 1965 and 1970 forecasts compared to actual number of airline passengers for San Francisco International Airport

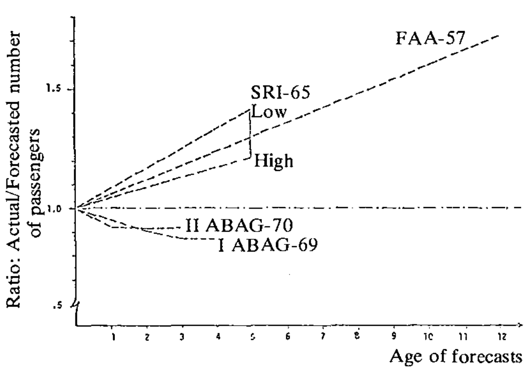

Figure 14 – Comparison of ratios: Actual/Forecasted number of annual passengers for different forecasts for San Francisco International Airport.

stage growth factors are expected to be chosen such that the RMSEs are minimized which again lead to unbiased $\bar{a}(t)$-values. The a(t)'s can then be considered random variables coming from distributions with $\bar{a}(t)$ as expected values. In [1] is shown that when multiplying two variables, X and Y, each having symmetrical or positively skewed distribution, the resulting variable, Z, will be positively skewed.

$Z = X \cdot Y$

Applying this result to the demand model described above, one would expect the distribution of T_{an} to be positively skewed because of the multiplicative model.

Based on these theoretical considerations and the analysis of the historical data, the conclusion is that when dealing with demand forecasting for air transportation, uncertainties can be expressed as the density function of the variable M, where:

$$M = \frac{T_{an}}{T_{en}}$$

Based on the assumption that the actual growth factors are random variables having density functions with non-negative skewness, the density function for M will be skewed to the right, for example similar to a gamma-, log-normal- or an F-distribution. Its standard deviation (RMSE) increased with the age of the forecast. In figure 15 are shown examples of likely distributions of M for $s_b = 0.2$ (5 years old forecasts) $s_b = 0.4$ (10 years old forecasts), $s_b = 0.5$ (20 years old forecasts) and $s_b = 0.6$ (30 years old forecasts). It should be evident that these distributions represent a very crude estimate of the nature of the uncertainty connected to demand forecasting. However, if true, they do imply some interesting consequences:

– Due to the assumption made and the resulting skewness, actual demand is more likely to be less than the forecasted demand, that is, overestimation is more likely than underestimation.

– The 95% confidence interval for a 5 years forecast given an estimated demand of T_{en} = 5 million is approximately:
3.4 mill. $< T_{an} <$ 7.2 mill.

– The 95% confidence interval for a 10 years forecast given an estimated demand of T_{en} = 5 million is approximately:
2.6 mill. $< T_{an} <$ 9.7 mill.

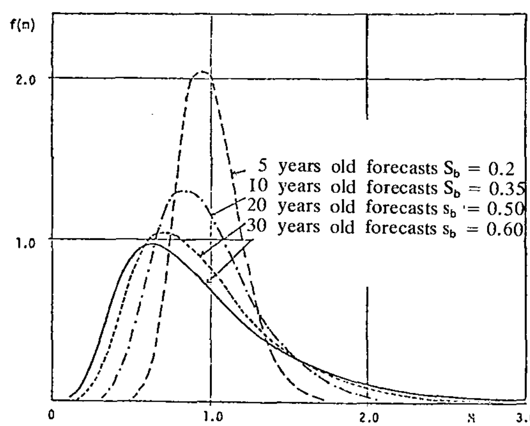

Figure 15 – Uncertainty in the variable M as a function of the age of the forecasts

Uncertainty Distributions for Different Types of Demand for the Airports in the Oslo-region

"Annual number of passengers" was considered to express the basic demand for air transportation. However, in this case this figure only expresses the demand for passenger facilities while "peak hour aircarrier movements" was chosen to express the demand for runway facilities. The relationships between "annual number of passengers", "annual number of aircarrier movements" and "peak hour air carrier movements" are analysed with respect to uncertainties by study of actual airport data for a number of airports [1] and all these results are implemented in the simulation model which again is applied to the case: "Location at a New Major Airport for the Oslo-region". The resulting simulated uncertainty distributions for demand are given in figures 16, 17 and 18.

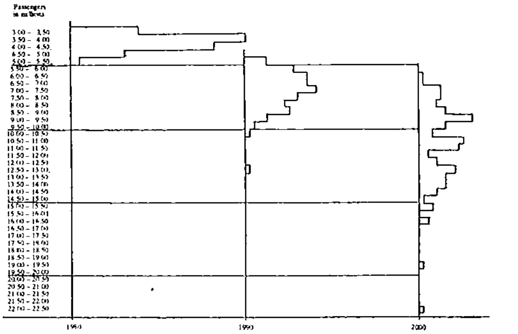

Figure 16 – Uncertainty distributions for annual number of passengers for 1980, 1990 and 2000

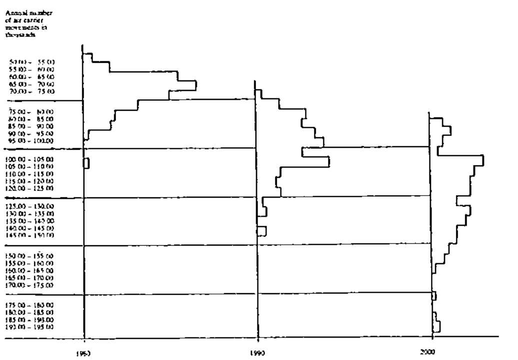

Figure 17 – Uncertainty distributions for annual number of air carrier movements for 1980, 1990 and 2000

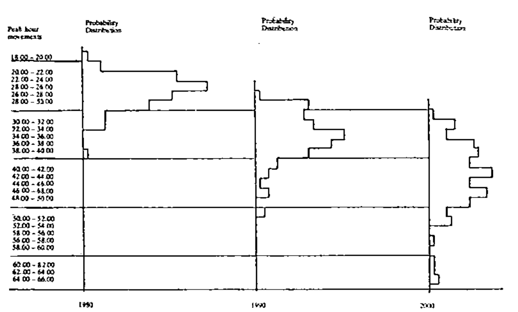

Figure 18 – Uncertainty distributions for peak hour air carrier movements for 1980, 1990 and 2000

The calculations are based on existing forecasts for the demand for air transportation in the Oslo-region and the figures are drawn on basis of 100 simulation runs. Keeping in mind the importance of the demand forecast when designing the airport model (figure 3), the knowledge of these rather large uncertainties may have a significant effect on the decisions to be made. This problem, however, is not analysed in detail in this work, but should be given considerable attention in the future.

APPLICATIONS AND CONCLUSIONS

Introduction

The purpose of this final chapter is to demonstrate the effect of the uncertainty distributions developed in the third and fourth sections. This is done by applying the results to the case study described briefly in the second section. In order to minimize the computations and to make the presentation more clear, only two of the alternative sites for a new airport are considered. The two sites chosen are Gardemoen and Hobøl which represent the low and the high values for the estimates of construction costs. The cost estimates for two-stage development of the two alternatives are given in table 5.

Uncertainties in Actual Costs Based Only on Uncertainty Distribution for the Cost Ratio

As a first application of the research results the uncertainty distribution for the cost ratios is applied to the cost estimates for the alternatives, table 5. Recalling the basic model:

$$R = \frac{C}{E}$$

or:

$$C = E \cdot R$$

where

R – the ratio of actual to estimated cost
C – the actual cost
E – the estimated cost

When E is known, that is E = e, the expression can be written: $C = e \cdot R$

The cost ratio, R, which is considered a random variable, was found to have an approximate log-normal distribution. Better fit to the observed data was however obtained by considering the variable $R^1 = R - 0.3$ which was approximately log-normal distributed with parameters

u = 0.1385
o = 0.3719

This yields the following properties for the distribution of R.

Mean	1.2330
Standard of deviation	0.3623
Coefficient of variation	0.2938
Coefficient of skewness	1.2125

Table 6 – Properties for the distribution of R

	Gardemoen		Hobøl	
	1. stage	2. stage	1. stage	2. stage
Runway costs (includes land acquisition)	1062	383	1141	403
Terminal costs	515	350	515	350
Ground transportation costs	44	—	129	—
Sub-total	1621	733	1785	753
Total airport cost	2354		2538	
Cost of general aviation facilities	90		127	

All costs in mill. N. Kr. (1970)

Table 5 – Cost Estimates for two-stage development of new airport at Gardemoen and Hobøl

Confidence limits for the actual cost, C, will then be:
95% level: $.72 \cdot e < C < 2.10 \cdot e$
90% level: $.77 \cdot e < C < 1.91 \cdot e$
50% level: $.98 \cdot e < C < 1.42 \cdot e$

When these results are applied to the cost estimates for Gardemoen and Hobøl, they yield the following confidence limits:

	Gardemoen		Hobøl	
	Stage one	Whole Airport	Stage one	Whole Airport
95% level	1167 – 3405	1695 – 4943	1285 – 3749	1827 – 5330
90% level	1248 – 3096	1813 – 4496	1374 – 3409	1954 – 4848
50% level	1589 – 2302	2307 – 3343	1749 – 2535	2487 – 3604

Cost in mill. N. Kr. (1970)
General Aviation facilities not included

Table 7 – Confidence intervals for actual costs for Gardemoen and Hobøl

The resulting distributions are shown in figure 19.

As it appears when applied to the case study, this method has its limitations. The method cannot be used to analyse the effect of a two or multiple stage development of the airport, and it is not possible to assign different uncertainties to different groups of projects. Finally, this approach does not reflect the uncertainties in demand and capacity, and the method cannot be used for analyzing different operational strategies. However, such analysis does provide some useful information about the uncertainties in actual costs of airport projects and represents an "easy to use" tool for both planners and decisionmakers.

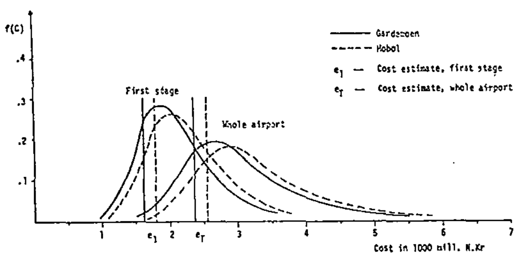

Figure 19 – Uncertainty distributions for Gardemoen and Hobøl derived by use of the empirical uncertainty distribution for the cost ratio, R

Uncertainties in Actual Cost Based on Uncertainties in Costs, Capacity and Demand

Application of the Research Results to the Alternatives Gardemoen and Hobøl

The two alternatives, Gardemoen and Hobøl, are both described as two-stage developments. The first stage, that is the first main runway and terminal facilities to accomodate up to 9 million passengers, is to be implemented when air carrier demand exceeds either the terminal or runway capacity of the existing Fornebu Airport. By use of a simulation model, demand and capacity values are simulated for each year up to year 2000 while uncertainties in actual costs are calculated according to their uncertainty distribution. The resulting uncertainty distributions based on 100 simulation runs are shown in figures 20 (Gardemoen) and 21 (Hobøl).

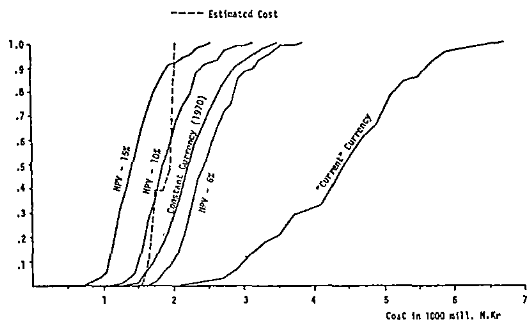

Figure 20 – Uncertainty distributions for Gardemoen derived by the simulation model

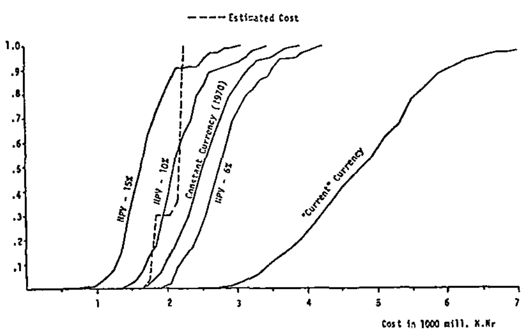

Figure 21 – Uncertainty distributions for Hobøl derived by the simulation model

Table 8 – Some of the properties of the different cost distributions for Gardemoen and Hobøl

	Net Present Values			Actual Cost	
GARDEMOEN	6%	10%	15%	Constant Currency	Current Currency
Mean	2564 mill	1981 mill	1526 mill	2380 mill	4473 mill
Standard deviation	449 mill	379 mill	358 mill	449 mill	960 mill
Coeff. of variation	0.175	0.191	0.234	0.189	0.210
Coeff. of skewness	0.516	0.692	0.728	0.428	–0.108
HOBØL					
Mean	2860 mill	2235 mill	1743 mill	2652 mill	4882 mill
Standard deviation	501 mill	456 mill	439 mill	462 mill	923 mill
Coeff. of variation	0.175	0.204	0.252	0.174	0.189
Coeff. of skewness	0.486	0.774	0.866	0.332	–0.064

The fact that even the estimated cost has a distribution indicates that the number of projects to be implemented before the horizon, year 2000, is not the same in all simulation runs.

The simulation results also include numerical information about some of the properties of the different distributions. These are given in table 8.

As information to the decisionmakers, all these distributions and their properties may turn out to be rather confusing, but as basis for a discussion of the properties of the different cost distributions and their use in the decision process, such information is considered valuable.

Cost information in terms of net present values are commonly used in economic evaluation of construction projects. The interest rate is usually determined on basis of economic considerations in the country where the project is to be realized. However, it is worth noticing that higher interest rates, in this case exemplified by 15%, tend to decrease the absolute uncertainty expressed as the standard deviation, while the relative uncertainty, that is the coefficient of variation, and the skewness are increased.

The simulation program also gives information about what projects are implemented in each simulation run (table 9).

Table 9 – Projects implemented in each simulation run; excerpt from computer output

PROJECTS IMPLEMENTED

1RUN	11	21	51	12
2RUN	11	21	51	12
3RUN	11	21	51	12
4RUN	11	21	51	12
5RUN	11	21	51	
6RUN	11	21	12	51
7RUN	11	21	51	
8RUN	11	21	12	
9RUN	11	21	51	12
10RUN	11	21	51	12
11RUN	11	21	12	51
12RUN	11	21	12	51
13RUN	11	21	51	12
14RUN	11	21		
15RUN	11	21	51	12
16RUN	11	21	51	12
17RUN	11	21	51	
18RUN	11	21	51	
19RUN	11	21	51	12
20RUN	11	21	51	12
21RUN	11	21	12	51
22RUN	11	21	12	51
23RUN	11	21	51	12
24RUN	11	21	51	
25RUN	11	21	51	12

Projects: 11 – Terminal facilities at new airport
1. stage – Capacity: 9 mill. passengers
21 – First main runway at new airport
51 – General aviation runway at new airport
12 – Terminal facilities at new airport
2. stage – Capacity: 18 mill. passengers

The sequence 11-21 indicates that new airport is needed because of demand for terminal facilities.

Based on this information the probabilities of the different projects being implemented before year 2000 can be calculated. These results are shown in table 10.

Additional information about when the first stage of the new airport is needed is also given by the simulation program.

Figure 22 shows the resulting distribution of years when stage 1 of the new airport has to be completed.

Table 10 – Probabilities of Inplementation of Different Projects Before Year 2000

Project Description	Probability of Implementation Before Year 2000
Terminal facilities at new airport 1. stage – Capacity: 9 mill pass.	1.00
First main runway at new airport	1.00
General aviation runway at new airport	0.86
Terminal facilities at new airport 2. stage – Capacity: 18 mill. pass.	0.66
Second main runway at new airport	0.00

As shown in table 9, the project sequence 11 - 21 indicates that the critical facility at the existing airport is the passenger terminal. This conclusion is not at all surprising since the terminal facilities at Fornebu are now being improved.

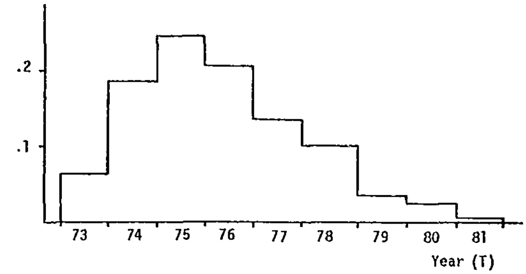

Figure 22 – Distribution of years when stage 1 of new airport has to be completed

Extensions in the Use of the Simulation Model

The results discussed in the preceding section were based on the use of the simulation model on two of the alternative sites for a new airport. However, the use of the model can be extended in several ways.

The simulation model gives, in addition to the results already discussed, information to the planner about forecasted demand, stratified according to air carrier demand for terminal facilities and runways, charter traffic demand for terminal facilities and runway, and general aviation demand for runways. This information also includes uncertainty measurements for the forecasts as already shown. Based on this information the planner can discover the most critical parts of the airport system with respect to capacities, and thus generate new solutions for these particular problems. For example, as shown in table 9, two of the most important problems for the airport system in the Oslo region, seem to be:

1) Capacity of the terminal facilities for air carrier traffic

2) General aviation runway capacity

Although the quality of the existing runways at Forneby Airport may represent a problem (figure 1), there is no immediate runway capacity problem if the general aviation demand for runway capacity can be taken care of.

However, the noise problem has resulted in severe constraints on the operational procedures. Due to these constraints, no plans or cost estimates for major improvements of Forneby have been made public. If adequate cost and capacity data were available for such major improvements of Fornebu Airport, the economic impacts of the operational constraints could be analysed by the simulation model. This points to another possible use of this approach, that is; analysing different operational procedures for the airport system.

General Conclusions and Suggestions for Further Research

Based on empirical data, uncertainty distributions are estimated for actual cost of airport projects and for air transportation demand. The magnitude of the uncertainties is likely to be considerably larger than most planners and decisionmakers expect. The shape of the uncertainty distributions is found to be approximately log-normal for the actual cost of airport projects. For air transportation demand, reasons are given for expecting a distribution slightly skewed to the right (positive coefficient of skewness).

The effect of uncertainties in actual costs on decisionmaking is hard to analyse since cost is only one factor in a multidimensional evaluation and decision process. The importance of cost of projects as basis for decisions has decreased in recent years due to the introduction of a number of other attributes into the decision process.

By realizing the rather large uncertainties in actual costs, differences in cost estimates between different projects may be even less important in years to come.

Since this research represents one of the first attempts to gather and analyse information about uncertainties in the attribute measurements for transportation facilities which planners supply to the decisionmakers, the whole area is open for research. Within the field of air transportation, the most urgent projects seem to be to analyse the nature of the uncertainties in other attribute measurements. Since noise obviously is of major importance, uncertainty analysis of noise measurements should be given high priority, but also attributes such as operating costs, ground transportation costs and regional effects should be dealt with.

Within the specific areas treated in this work, additional research should be performed both with respect to costs and to demand. As for the uncertainties in actual cost of projects, a crucial point is the assumptions of complete independence or dependence between projects within one airport and between alternative airport sites. These problems seem to be of great importance in order to extend the statistical treatment of the uncertainty distributions. However, additional research is also needed in order to verify or adjust the distributions as they were found in this work.

As for the uncertainties in air carrier demand forecasts, the problem should also be analysed by going more deeply into the individual forecasting models and deriving uncertainties on basis of the structure of the models and the uncertainties in the input to the models.

So far only airport problems are considered. Of course, other modes of transportation and their transportation facilities can be analysed in similar ways.

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REFERENCES

[1] Knudsen, T. **Uncertainties in Airport Cost Analysis and Their Effect on Site Selection.** Ph. D. Dissertation University of California, Berkeley 1976.

[2] Hutchinson, B.G. Stucturing Urban Transportation Planning Decisions: The Use of Statistical Decision Theory. **Environmental Planning,** Vol. 1. 1969.

[3] Khan, Ata M. Transport Policy Decision Analysis: A Decision-Theoretic Framework. **Socio-Economic Planning Sciences, Vol. 5,** No. 2, April 1971.

[4] Mac Crimmon, K.R. **Decisionmaking among Multiple-Attribute Alternatives: A Survey and Consolidated Approach.** The Rand Corporation, RM-4823-ARPA, December 1968.

[5] Manheim, Marvin, L. Decision Theories in Transportation Planning. **HRB-Special Report 108,** Highway Research Board, Washington D.C., 1970.

[6] Altouney, Edward A. **The Role of Uncertainties in the Economic Evaluation of Water Resources Projects.** Institute of Engineering – Economic Systems. Stanford University, 1963.

[7] Zimmerman, J. and Merewitz, L. **The Effects of Uncertainty and Conscious Underbidding on Cost Overruns: The BART Experience.** University of California, Berkeley, 1974. Unpublished.

[8] Merewitz, Leonard. How Do Urban Rapid Transit Projects Compare in Cost Estimating Experience? **Proceedings of the International Conference on Transportation Research First Conference, Bruges, Belgium.**

[9] Merewitz, Leonard. Cost Overruns in Public Works. Niskanen, W. (ed) **Benefit Cost and Policy Analysis.** Chicago, Aldine, 1973.

[10] Selby, S.M. (ed) **Standard Mathematical Tables Fourteenth Edition.** The Chemical Co. Ohio, 1965.

[11] Conover, W. **Practical Nonparametric Statistics.** John Wiley & Sons, New York, 1971.

[12] Bickel, P.J. and Doksum, K. A. **A Course in Mathematical Statistics.** Holden Day, San Francisco, 1976.

[13] Federal Aviation Administration. **Aviation Demand and Airport Facility Requirement Forecast for Medium Air Transportation Hubs Through 1980.** Washington D.C., 1968.

[14] U S Federal Aviation Administration. **Air Traffic Activity.** 1965 - 1972.

[15] U S Federal Aviation Administration. **FAA Statistical Handbook of Aviation.** 1965 - 1973.

[16] U S Civil Aeoronautes Board. U S Federal Aviation Administration. **Airport Activity Statistics of Certificated Route Air Carriers.** 1971 - 1974.

[17] Federal Aviation Agency. **Aviation Forecasts for Dulles International Airport and Washington National Airport.** Calendar years 1963 - 1967. Washington D.C., 1962.

[18] Federal Aviation Administration. **Washington National and Dulles International Airport Forecasts.** Fiscal Years 1969 - 1980. Washington D.C., 1969.

[19] U S Federal Aviation Administration. **Washington National and Dulles International Airport Forecasts.** Fiscal Years 1970 - 1981. Washington D.C., 1969.

[20] U S Federal Aviation Administration. **Washington National and Dulles International Airport Forecasts.** Fiscal Years 1972 - 1983. Washington D.C., 1971.

FOOTNOTES

1. The term "estimate" is in this context not used according to its statistical interpretation, but as a synonym to "forecast" which is the way it is used in the references dealing with cost-oriented problems.
2. Completion time is here defined as the length of time from when a cost estimate is made and till the project is completed.
3. Construction Cost Index is published monthly in Engineering News Record and annual averages are calculated and published annually.