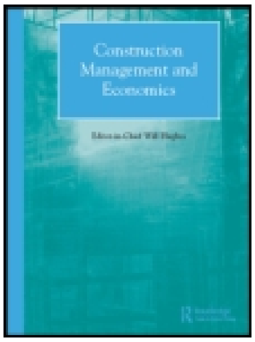

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Life cycle costing and risk management

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Risk and uncertainty is endemic to life cycle costing, and requires that an effective risk management system be an integral part of life cycle cost analysis. Such a system is developed, with emphasis on sensitivity and probability analysis. Its use is demonstrated by means of a case study of building finishes.

Introduction

The term risk management applied to investment appraisal and, more specifically, to life cycle costing in the construction industry refers to the assessment of and reaction to the risk and uncertainty that will inevitably be associated with future forecasting. Life cycle costing, by definition, deals with the future and the future is unknown. Recurrent costs such as maintenance, replacement and cleaning costs are only estimates no matter how precise and reliable the data on which they are based. Similarly, other essential components of life cycle costing, such as the rate of exchange (i.e. the discount rate) between future costs and their present values, replacement cycles of individual components, and the life cycle of the building itself cannot be assessed with certainty.

It is probably fair to claim that one reason, or more properly excuse, for the relatively slow introduction of life cycle costing methods to the building industry has been a feeling that life cycle cost estimates are in some sense inaccurate, or based merely on guess-work. If this view is to be challenged effectively, we must develop simple, practical techniques that address risk and uncertainty explicitly, and give the decision-maker comprehensible information on which to base his judgements.

This paper presents such techniques. We begin from the view that, while risk management has begun to enter into life cycle cost analysis, it remains a relatively peripheral activity. Useful models and techniques can, and have, been applied to the problem of dealing with uncertainty; but these have not, as yet, been translated into definitive decision methods which allow the decision-takers in the building industry to incorporate and react to uncertainty in investment appraisal and life cycle costing.

The paper proceeds as follows. In the next section we outline various risk management systems and discuss methods by which risk management techniques can be incorporated in life cycle costing. We then consider in the following sections two particular techniques – sensitivity and probability analysis – and show how they can be used to enhance a life cycle costing system. Finally, we show how sensitivity analysis works in the context of a practical application.

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Risk management

Fig. 1 illustrates diagramatically how a risk management system could be inter-linked with life cycle costing. One approach to risk management put forward by Perry and Hayes (1985) treats a risk management system as consisting of three main elements each subdivided into a series of sub-systems; see Fig. 2.

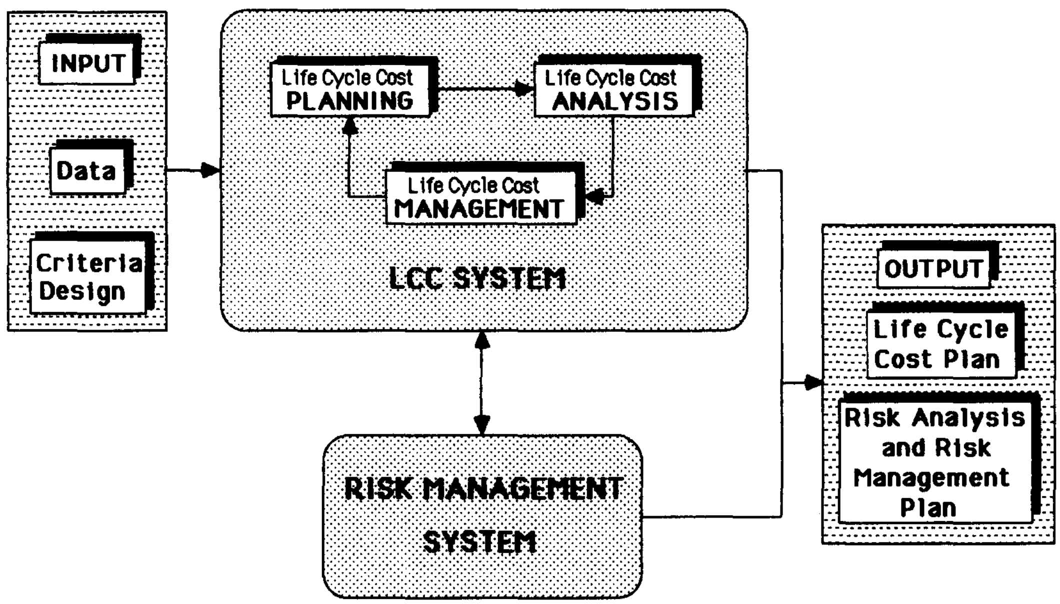


Fig. 1. Life cycle costing and risk management.

Fig. 2. Risk management systems.

Risk identification

Some degree of risk will be present with any form of construction forecasting and it is important to develop an organized approach to identifying those risks associated with each part of the life cycle cost analysis. One such method involves applying a decision tree approach as discussed by Chapman (1979) and Cooper *et al.* (1985). This approach sub-divides the total life cycle cost into its major constituent parts. It is similar in concept to the method developed by Flanagan and Norman (1983) on Levels. Fig. 3 illustrates how maintenance costs might be developed as a decision tree based on levels. As can be seen, maintenance costs are sub-divided in a hierarchical manner, each level in the hierarchy being associated with increasingly detailed cost information.

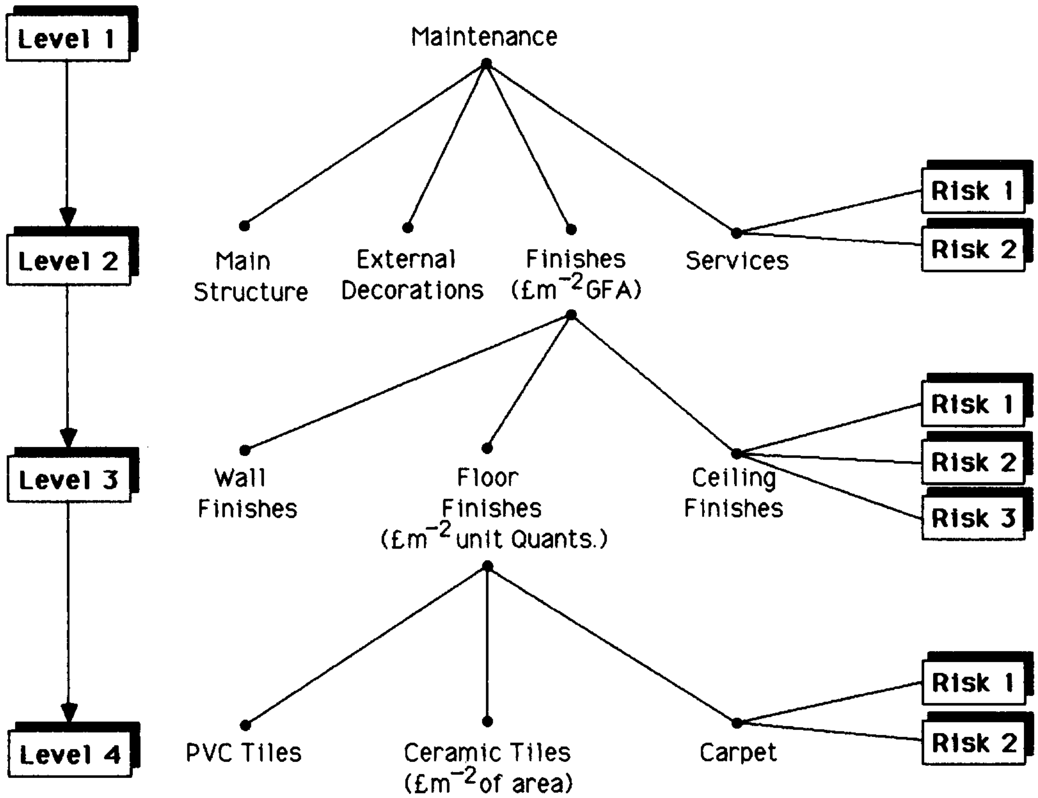


Fig. 3. Decision tree and risk identification.

Using this approach, the appropriate risks for each item at each level can be identified. Note that some of these risks may be common to a number of base-line items, for example, general inflation, labour costs, elemental quantities, etc. and so will set up interdependencies between them.

Decision trees based on levels have the advantage that once the risks at each level have been identified, it is possible to suggest at which level these risks become negligible compared with the cumulative total of the larger risks already considered.

Risk analysis

The construction industry is subject to more risk and uncertainty than perhaps any other industry. Any individual project will involve a complex, generally bespoke and time consuming production process which will involve the coordination of a wide range of disparate, yet interrelated activities. This complexity is further compounded by many external, uncontrollable factors. Effective life cycle cost forecasting must take account of these risks and uncertainties if improvement in current cost performance is to be achieved.

Although the techniques for risk analysis have begun to be incorporated into construction forecasting their practical application has remained a relatively peripheral activity. Of the techniques currently available, two dominant approaches to risk analysis can be suggested: 1. Sensitivity analysis and 2. Probability analysis/Monte Carlo simulation.

Both modelling techniques can be regarded as simulations, as opposed to definitive analyses. The simple distinction between them is that sensitivity analysis does not, in general, require that a probability distribution be associated with each risk element. Sensitivity analysis is a deterministic modelling technique which primarily answers repeated 'what if . . .?' questions. Probability analysis and Monte Carlo simulation techniques, by contrast, treat uncertainty explicitly. All variable factors are modelled as probability distributions, not as single, known values.

In addition, sensitivity analysis is essentially a univariate approach that identifies the impact of a change in a single parameter value within a project with a *ceteris paribus* assumption holding all other parameters constant. The probabilistic approach, however, is a multivariate approach in which all factors subject to risk and uncertainty vary simultaneously.

There are advantages and disadvantages in both techniques. Probability analysis has the obvious advantage that it is multivariate, and so gives an overall assessment of the likely risk-exposure on a particular project. It suffers from two main disadvantages. Firstly it is a more complicated technique requiring sophisticated statistical methods and computer software. Secondly, it is difficult to disentangle the risk impact of any one uncertain factor.

Sensitivity analysis has the obvious disadvantage of being univariate – although we shall discuss, below, a bivariate sensitivity analysis that moderates this disadvantage to at least some extent. It has the clear advantage of being simple to undertake using, for example, standard spreadsheet software on a micro-computer.

Our view is that sensitivity analysis is likely to prove the more easily applicable and comprehensible risk analysis technique, and for this reason have concentrated on sensitivity analysis in the case study.

Risk response

The final element in the risk management system identifies the actions that analyst and decision-maker should take given that they are operating in a risky environment. There are two possible classes of response:

(i) Risk transfer: by, for example, appropriate choice of construction and management contracts;
(ii) Risk control: by design choice and more detailed investigation of risk sources.

Risk transfer is particularly relevant when life cycle costing techniques are being applied to a complete building. There will then be extensive scope for choosing the form of contract most suitable to the identified risk exposure. This will be much less feasible when we apply life cycle cost techniques to individual building components. But even in these circumstances it may be possible to obtain guarantees of performance or cost from particular suppliers, or insure against failure. The risk analysis discussed above will identify those situations in which such guarantees or insurance are most justified.

Risk control is of direct relevance both for complete buildings and individual building components. The discussion of sensitivity analysis and probability analysis systems indicates that it is possible to identify those parameters and environmental variables to which life cycle cost estimates are particularly sensitive. Risk control uses this information to guide attempts to improve the information base, and to reduce risk exposure.

An important point in this respect has been identified by Baker (1985, 1986). There will be a trade-off between the value of information that reduces risk exposure, and the cost of that information. Very simply, information that reduces risk should be collected only if its value (whether objective or subjective) at least equals its cost of collection, storage and analysis. In technical terms, information should be collected only up to the point at which its marginal valuation equals its marginal cost. The risk management system should be designed to guide such value/cost choices.

An illustration might make this clearer. A major objective of life cycle costing is to rank competing projects – whether these be competing designs, or competing finishes to a floor space. Sensitivity analysis of the life cycle cost analysis may indicate that the ranking of the options being considered is unaffected by variation in a particular parameter. There is little value in trying to improve the estimate of that parameter.

Sensitivity analysis

As we have indicated, sensitivity analysis is generally used to identify the impact, on life cycle cost (LCC), of a change in a single risky or uncertain parameter used in the calculation of LCC such as, for example, discount rate, initial capital cost, or running costs. It identifies the sensitivity of LCC to variation in each of these parameters. This has two major uses. Firstly, it indicates for a particular option, the certainty that can be resided in the LCC calculation based on best estimates of all parameters. If the decision-maker is interested in reducing uncertainty or risk exposure, then sensitivity analysis will identify those areas on which his efforts should be concentrated in order to improve the parameter estimates.

Secondly, sensitivity analysis indicates in the comparison of alternatives the conditions under which the ranking of these alternatives will change. Assume that the decision-maker's primary objective is to get the alternatives in the correct order. Then it may not matter that LCC, for these alternatives, is sensitive to a particular parameter if the ranking of the alternatives does not change when the parameter is varied through its expected range – we illustrate one such example in the case study. Effort in this case should be concentrated on improving information with respect to those uncertain parameters that do give rise to a change in ranking.

There are several ways in which the results of a sensitivity analysis can be presented, the simplest of which is to compute a sensitivity table. However, if several variables are changed, a graphical representation of the results is most useful as it quickly indicates the most sensitive or critical variables. In addition, as we shall see in our examples, a graphical representation is useful in identifying relative uncertainty when faced with the choice between competing options and in identifying areas of further risk and uncertainty between those options.

A particularly effective graphical presentation of sensitivity analysis – the spider diagram – has been suggested by Perry and Hayes (1985). This has been developed primarily in the context of civil engineering, but has obvious applicability to the building industry. It is best illustrated by means of a hypothetical project as in Fig. 4. The spider diagram is constructed as follows:

(i) Calculate life cycle cost using best estimates of all parameters;
(ii) Identify the parameters subject to risk and uncertainty using a decision tree approach;
(iii) Select one of the risky parameters and recalculate LCC assuming that this parameter is varied by $\pm X\%$ where X lies in some predefined range. This should be carried out in steps within this range, e.g. recalculate LCC assuming that the discount rate is changed by $+1\% + 2\% + \ldots + 5\%$, and -1%, $-2\% - \ldots - 5\%$;
(iv) Plot the resulting LCC's on the spider diagram, interpolating between each value. This generates the line labelled 'parameter 1' in Fig. 4;
(v) Repeat stages (iii) and (iv) for the remaining parameters that have been identified as risky.

Each line in the spider diagram indicates the impact, on LCC, of a defined proportionate variation in a single parameter that has been identified as having some risk associated with its estimate. The flatter the line the more sensitive LCC will be to variation in that parameter. For instance, it can be seen from Fig. 4 that a variation in the estimate for parameter 3 would have a much greater impact on LCC than an identical variation in parameter 2.

In relation to this last point, Fig. 4 does not give any indication of the likely range of variation of each of the risky parameters. This is overcome by incorporating probability contours into the spider diagram. These probability contours are constructed by subjectively identifying the range within which a particular parameter is expected to lie at each level of probability. For example, it might be estimated that there is a 70% probability that the discount rate will lie in the range between +8% and −6% of the best estimate, and a 90% probability that the range is

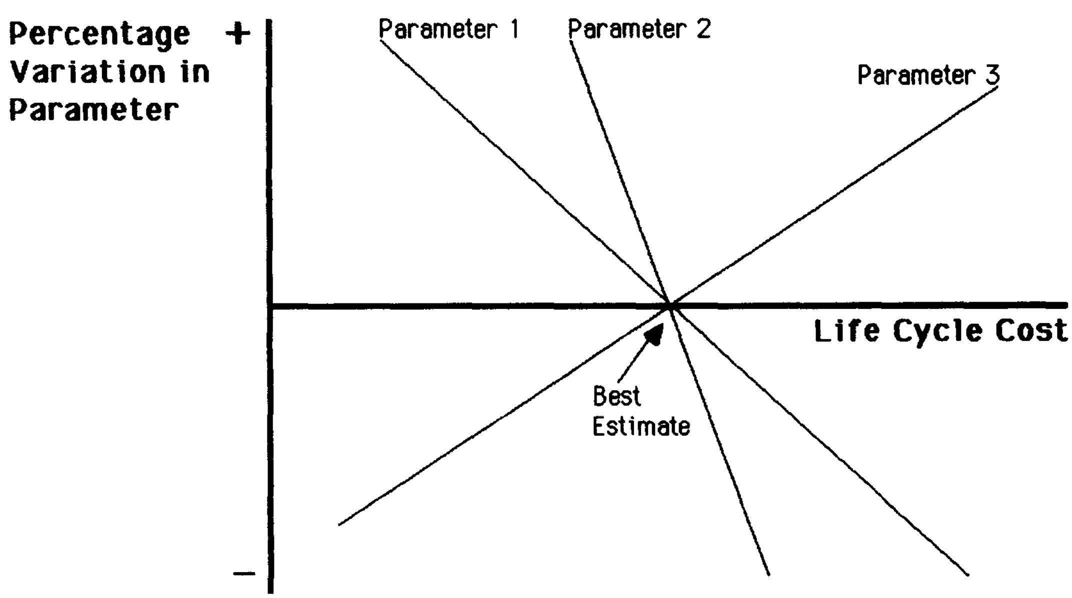


Fig. 4. Sensitivity analysis spider diagram.

between +10% and −8%. Fig. 5 illustrates a spider diagram with 70% and 90% probability contours added.

Criticism can be made of the use of probability contours precisely because they are subjective estimates of the likely range of variation of the relevant parameters. We are not convinced that such criticism has any strong validity. Sensitivity analysis is a management and decision-making tool. Our feeling is that the judgements underlying the placing of the probability contours is precisely the kind of judgement that management can be expected to make.

In addition, the placing of probability contours can be made rather more accurate if additional statistical information is available on the risky and uncertain parameters. In particular, assume that the 'best estimate' of a risky parameter is its mean value, and that an estimate can be made of that parameter's standard deviation. Then if the underlying probability distribution of the parameter is assumed to be the normal distribution, we can take advantage of the statistical properties of the normal distribution. Specifically, it is known that 68% of the possible values of a normally distributed parameter lie within plus and minus one standard deviation of the mean, 95% between plus and minus two standard deviations, and 99% between plus and minus three standard deviations. For moderately skewed distributions these values hold approximately, while for a log-normal distribution (which exhibits the kind of skewness we might expect to find in cost estimates) these values hold in logarithms of the parameter and can easily be transformed into standard values.

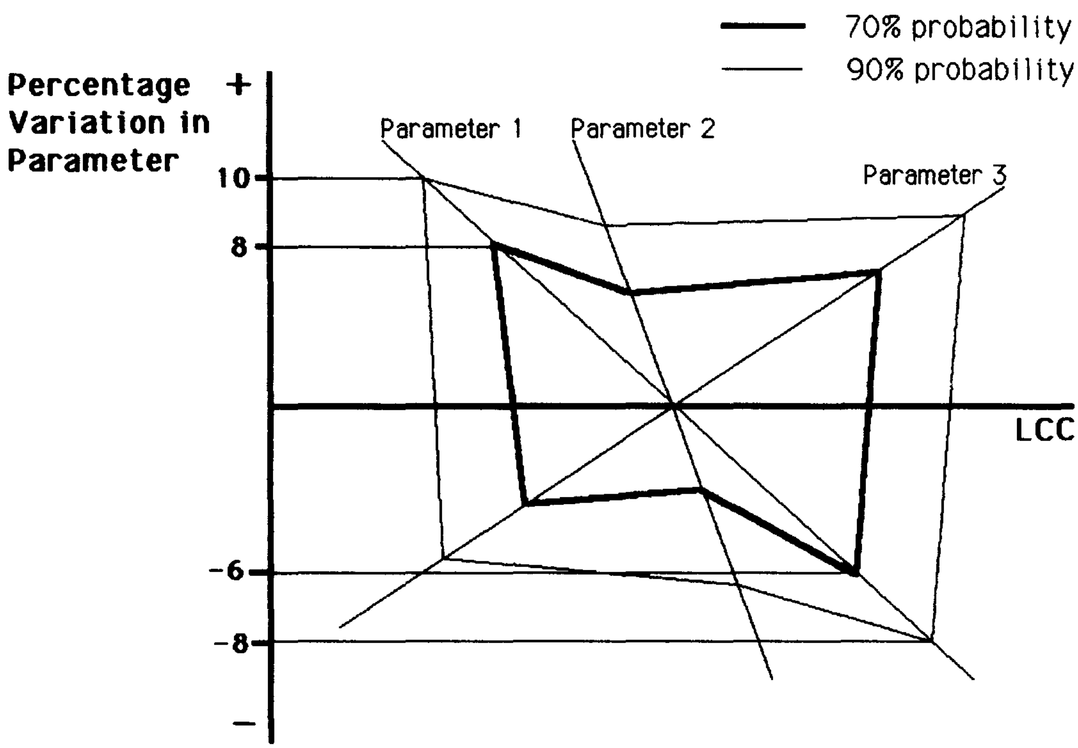


Fig. 5. Probability contours.

Using these properties, it should be clear that probability contours can be placed with some confidence – always provided, of course, that estimates are available of mean and standard deviation.

The discussion thus far has considered sensitivity analysis as it applies to a single option. A prime function of LCC, however, is to compare and rank alternative design solutions – whether this be for a complete building or for a particular component such as the choice of finishes. Sensitivity analysis, using spider diagrams, provides a particularly useful method for guiding such comparisons and rankings.

This is best illustrated by means of the hypothetical example of Fig. 6 which might refer to choice of floor finish to be included in a particular functional space. Best estimates of the relevant parameters lead to Finish A being preferred, having the lower life cycle costs as compared with Finish B – points A and B in Fig. 6. But Finish A is much more sensitive to variation in the uncertain parameters: as can be seen from the degree of sensitivity within the 70% probability contour. If a primary objective of the decision-maker is to 'avoid surprises' then there would be considerable justification in preferring Finish B since it offers much greater cost certainty.

Fig. 7 illustrates a more detailed analysis of sensitivity analysis applied to the rank ordering of the options under consideration. Again, we illustrate an example in which option A has the lower life cycle costs on best estimates. As can be seen, if parameter 1, which in this case represents discount rate, were to vary by anything in excess of 5% above its best estimate, the rank ordering of the two options would change. Similarly, if parameter 3 were to vary by more than 7% of the best estimate value then again the ranking of the two floor finishes changes.

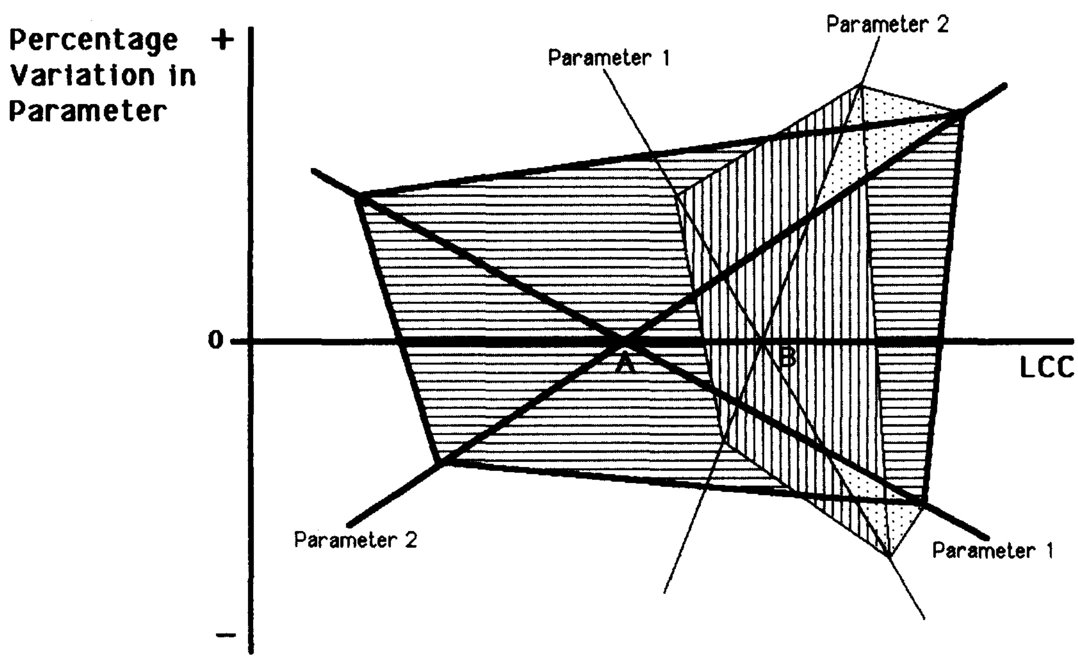


Fig. 6. Comparison of options I.

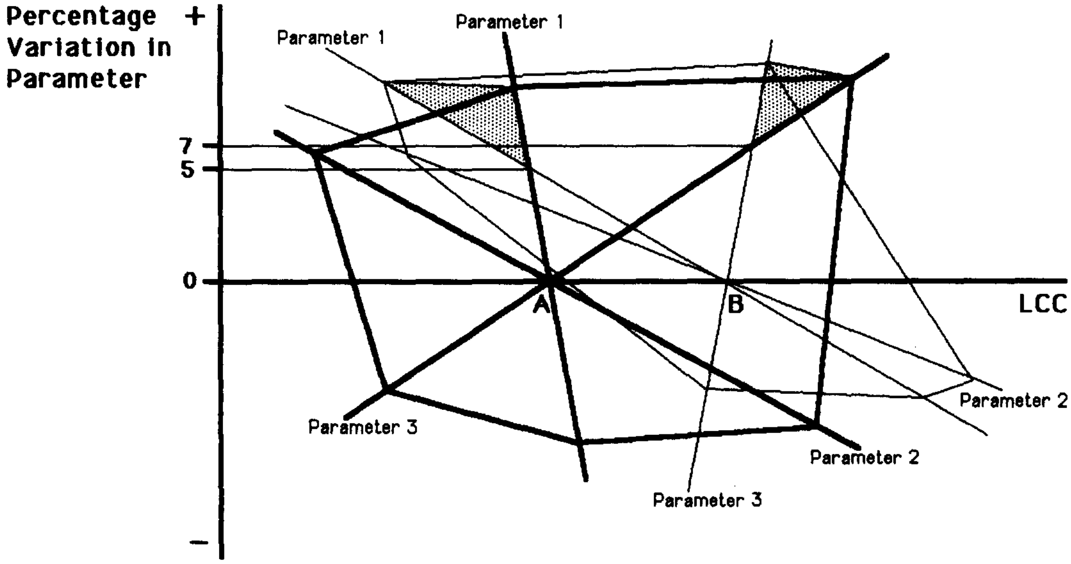


Fig. 7. Comparison of options II.

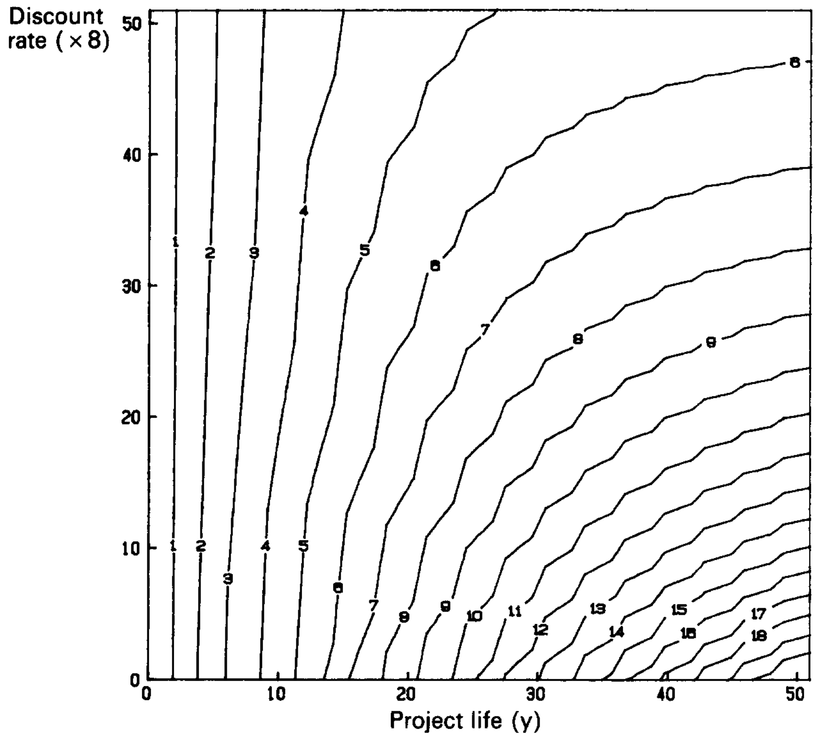
This type of comparison can be repeated for each parameter to indicate those parameters for which the rank ordering of the two options would change. This is indicated by the shaded areas in Fig. 7. The greater the extent to which the rank ordering of the options under consideration would be changed by a parameter variation within the chosen probability contour, the less clear it becomes to reject option B in favour of option A.

It is apparent from our discussion, and in particular the examples given in Figs 6 and 7, that sensitivity analysis does not provide a definitive method of making a choice between the competing options. However, even as currently developed, it is an essential component of managerial decision making. In particular, the use of spider diagrams, together with rank ordering of the options by applying probability contours and analysing the amount of variability necessary in individual parameters to change that rank ordering, provides the decision-maker with a useful decision tool.

One limitation of sensitivity analysis is that, in its current applications, it is univariate – only one parameter is varied at a time. It is possible to overcome this to at least some extent by borrowing contour analysis techniques used, for example, in economics and topography. Assume that two parameters have been identified from 'standard' sensitivity analysis as being particularly important in determining the LCC of a particular option. Further assume that an increase in parameter 1 increases LCC and a decrease in parameter 2 also increases LCC (parameter 1 might be project life and parameter 2 the discount rate). Suppose that best estimates of these two parameters generate LCC of £0.5m.

It will be possible to find other combinations of project life and discount rate that will also generate an LCC of £0.5m: by increasing project life and increasing the discount rate, or decreasing project life and decreasing the discount rate.

This is illustrated in Fig. 8, in which the locus labelled 5 gives all combinations of project life and discount rate (in the relevant range) that generate LCC of £0.5m. Similarly, locus 4 has



Contour	LCC
1	1 000
2	2 000
3	3 000
4	4 000
5	5 000
6	6 000
7	7 000
8	8 000
9	9 000
10	10 000
11	11 000
12	12 000
13	13 000
14	14 000
15	15 000
16	16 000
17	17 000
18	18 000
19	19 000
20	20 000

Fig. 8. Bivariate sensitivity analysis – contour diagram.

LCC of £0.4m and locus 6 has LCC of £0.6m. An alternative, and equivalent illustration of this technique is given by the three-dimensional surface plotted in Fig. 9 (Fig. 8 is, in fact, the contour map of Fig. 9).

Figs 8 and 9 allow the decision-maker to see whether there might be offsetting movements in uncertain parameters. If, for example, it is to be expected that parameters 1 and 2 will move together (either both increase or both decrease), then LCC will be less affected than if they are expected to change in opposite directions. (This presumes, of course, that an increase in parameter 1 moves LCC in a manner opposite to that of an increase in parameter 2. The reader is left to develop a similar diagram when a change in parameters 1 and 2 have the same directional impact on LCC.) Again, no absolute answers can be given, but the quality of decision making will be considerably enhanced by this approach.

Probability analysis

Even the bivariate sensitivity analysis of Figs 8 and 9 is limited, of course. We now turn to an approach to risk and uncertainty that takes explicit account of the fact that all risky and uncertain parameters can be expected to vary simultaneously.

Probability analysis is a powerful tool in investigating problems which do not have a single

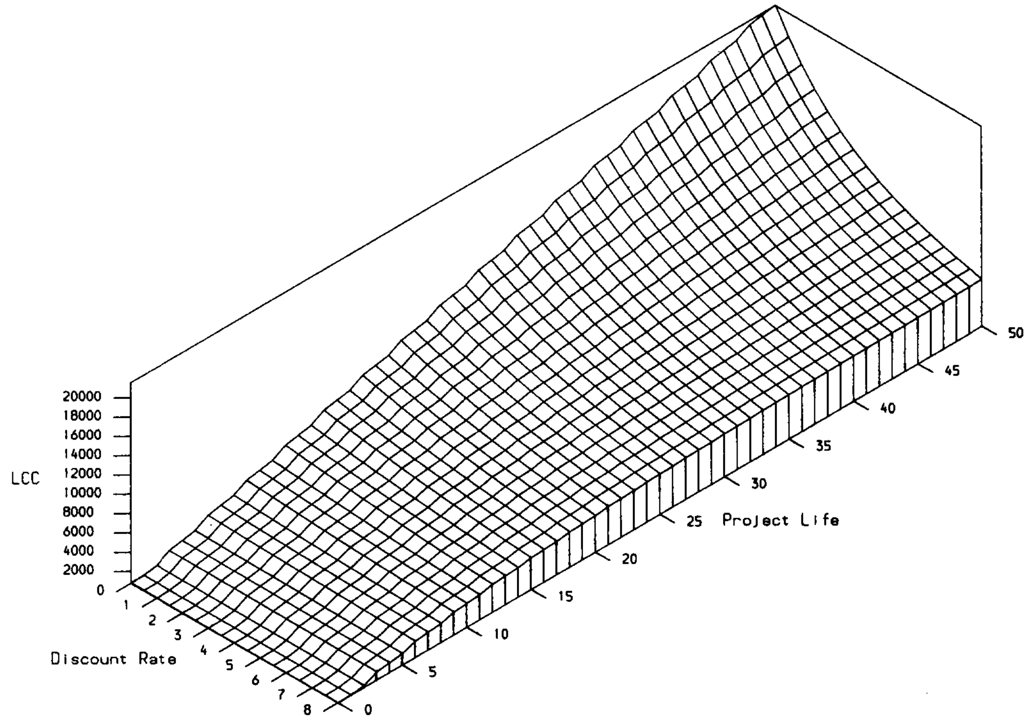


Fig. 9. Bivariate sensitivity analysis – surface diagram.

value solution. Stochastic simulation in the form of Monte Carlo simulation is perhaps the most easily used form of probability analysis. It makes the assumption that parameters subject to risk and uncertainty can be described by probability distributions. The Monte Carlo technique makes use of these probability distributions to generate a number of simulations of the desired overall cost estimate. Simply put, in each simulation (or iteration), the relevant risky or uncertain parameter is replaced by a random number drawn from the probability distribution associated with that parameter: this is described in more detail below. The number of iterations is critical to the final accuracy of the process. No hard and fast guidelines can be given, but we would suggest that the number of iterations necessary for the resulting choices to be representative of the original data is 100. This will produce an accuracy of $\pm 2\%$ (Bennett and Ormerod, 1984). Further increases in the number of iterations will result in improved accuracies but also will increase computing costs.

The results from the simulation process are best presented as a frequency distribution, which will show the expected pattern of outcomes, and a cumulative frequency curve in which the decision-maker can read off risk levels or the probability of a particular range of life cycle costs occurring. The simulation process proceeds through a number of stages as follows and illustrated in Fig. 10.

(i) Identify the basic cost items for analysis using a hierarchical decision tree and levels approach as previously discussed;

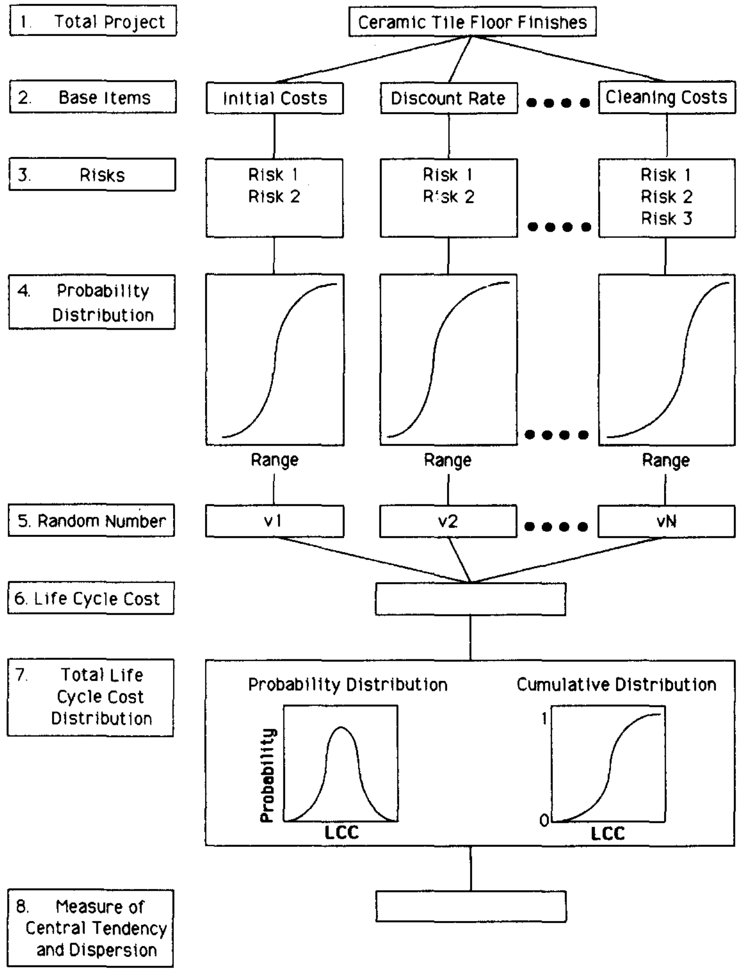


Fig. 10. Probability analysis system.

(ii) Identify the risks associated with each of these costs and, where necessary, express them in the form of a probability distribution;
(iii) Using a random number generator select a random value from the probability distribution for each of the parameters in Stage (ii);
(iv) Use the random values selected to calculate a life cycle cost and store this cost;
(v) Repeat Stages (iii) and (iv) between 100 and 1000 iterations depending upon the number of risky parameters;
(vi) Plot the stored values in (iv) as a frequency distribution and cumulative frequency curve and calculate measures of central tendency and dispersion.

Given the Central Limit Theorem, the overall probability distribution of life cycle costs will approximate to the normal distribution. The normal distribution is useful in the sense that firstly, the measures of central tendency – mean, median and mode – will be approximately identical: this gives an indication of the most likely life cycle cost. Also, the measure of dispersion gives a measure of the confidence associated with the most likely life cycle cost.

As a hypothetical example, the resulting probability distributions in Fig. 11 will identify to the decision-maker what the probabilities associated with particular life cycle costs are. Suppose, for example, that the probability analysis generated the values:

Mean LCC	£32 120
Standard Deviation	£ 1 080

Given the properties of the normal distribution there is a 95% probability that the life cycle cost lies within the range £29 960 to £34 280, and a 68% probability that it lies within the range £31 040 to £33 200.

The cumulative frequency curve can also be used to indicate the chances that the life cycle cost will not exceed a particular value. For example, Fig. 11 shows that there would be an 84% probability that life cycle cost will be less than £33 200. Again, consideration must be given to how simulation can be used in making choices between competing options, whether these choices are between two or more different refurbishment schemes or simply selecting a floor finish. For instance, how can the decision-maker choose between the two options illustrated in Fig. 12? Although option A has the lower expected LCC, it is a much more risky option to choose. This can be seen by the much wider dispersion in relation to option B and by the much flatter cumulative distribution curve.

As with sensitivity analysis there is no definitive answer. The decision-maker must take

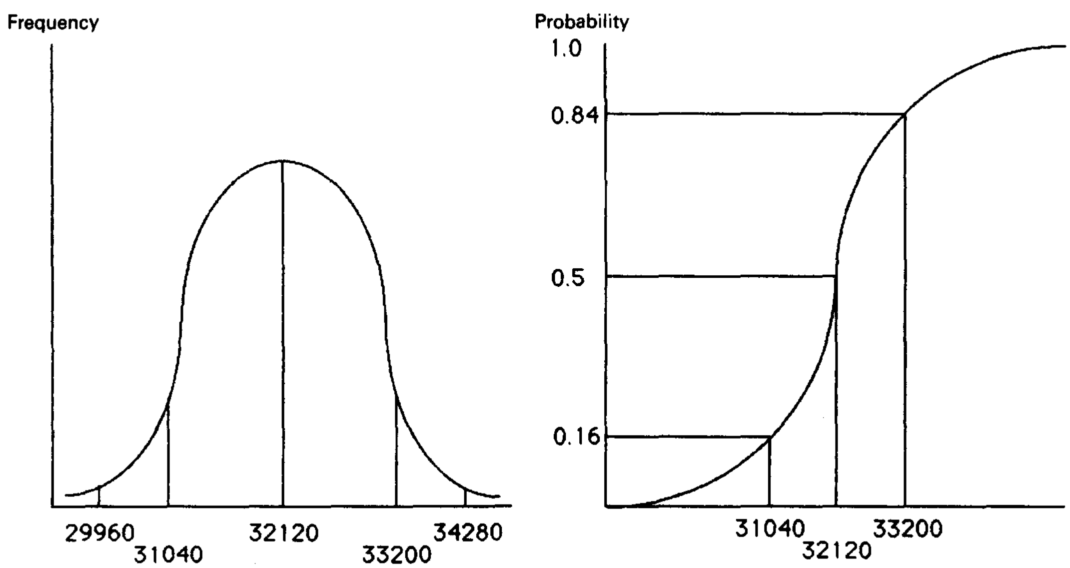


Fig. 11. Frequency distributions.

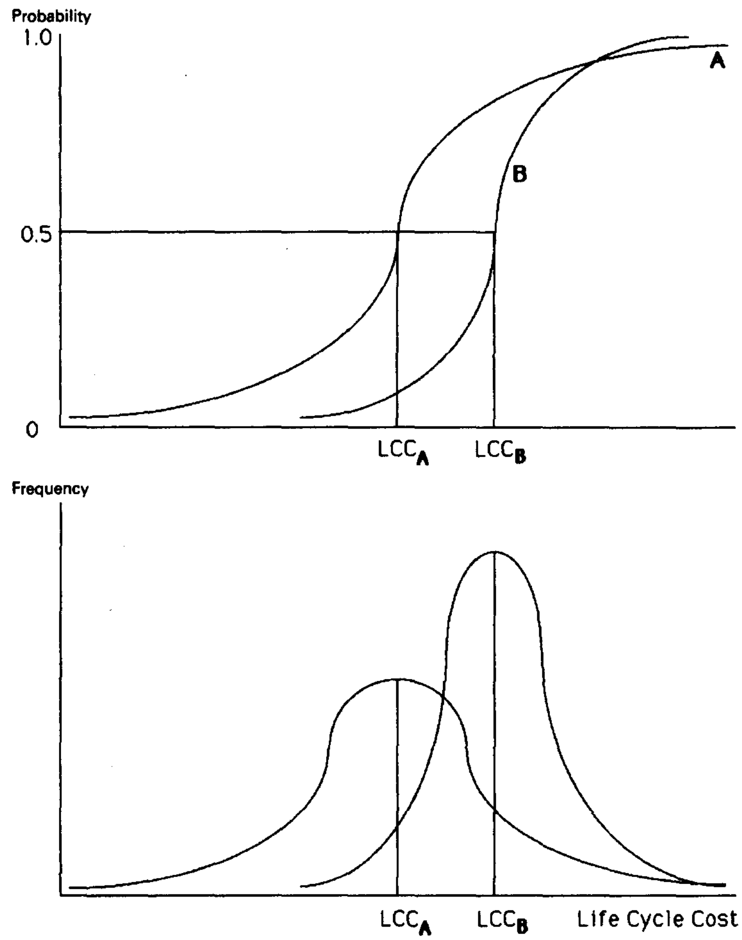


Fig. 12. Probability analysis comparisons.

account of the implied trade-off between the lower expected life cycle costs of option A and its relatively higher risk. But the information provided by carrying out this form of risk analysis presents invaluable information to the decision-maker when faced with risk and uncertainty.

An illustrative case study

The primary objective of this paper is to extend the existing methodology of life cycle costing. Nevertheless, we recognize that theoretical arguments acquire more meaning when illustrated by practical examples. In this section we present, in brief form, one such example.

Fig. 13 illustrates the result of a case study of the use of ceramic tiles in a passenger departure lounge of an air terminal, assuming a gross floor area of 100 m^2, a discount rate of 4%, and

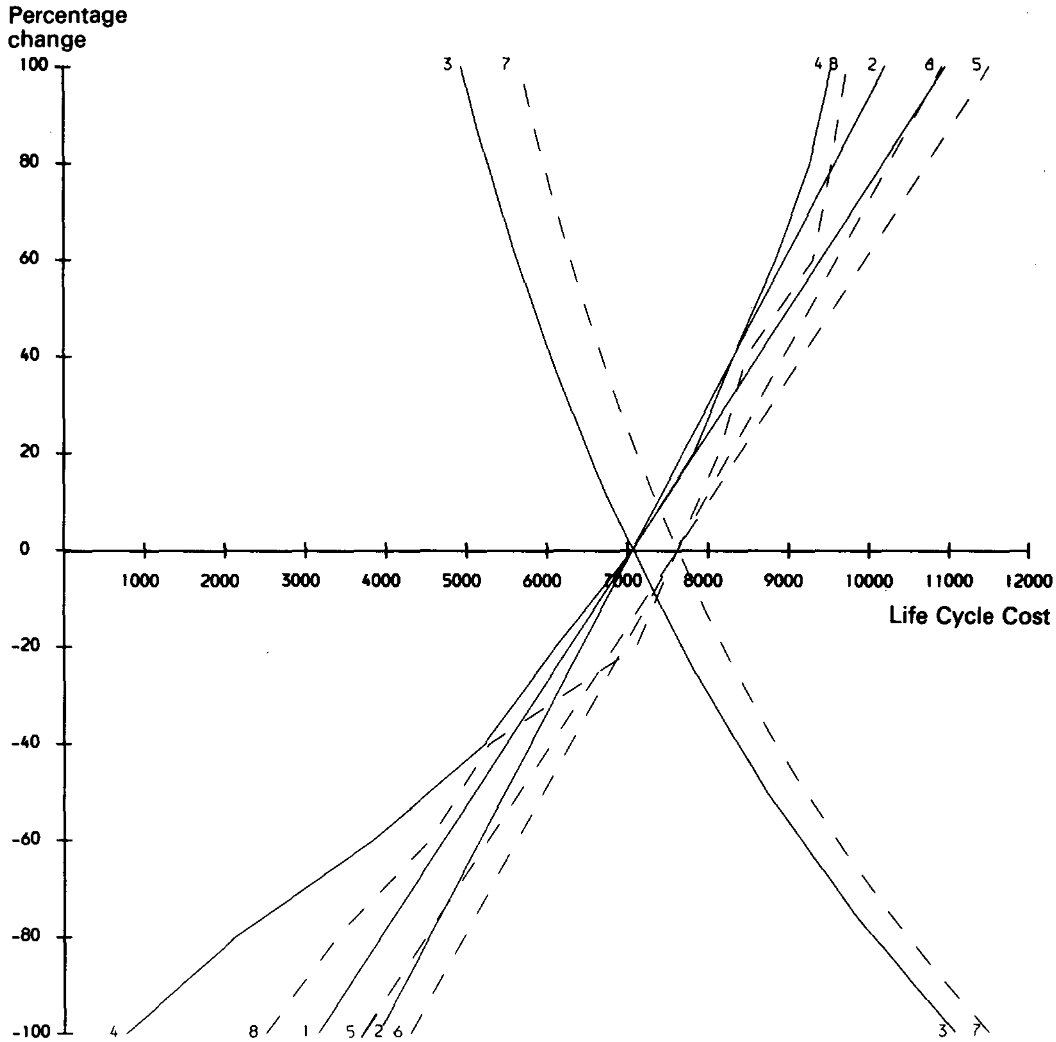


Fig. 13. Comparative finishes spider diagram – case study 1. Solid lines represent PVC tiles: 1. cleaning costs; 2. capital costs; 3. discount rate; 4. project life. Broken lines represent ceramic tiles: 5. cleaning costs; 6. capital costs; 7. discount rate; 8. project life.

project life (study period) of 25 years. (For more details of the examples discussed here, see Flanagan *et al.*, 1987.) This figure compares ceramic tiles (the broken lines) with PVC tiles. As might be expected, life cycle costs for both options are affected by assumptions regarding costs, discount rate and assumed finish life. It turns out in this example, however, that the ranking of the two options does not vary even with a $\pm 100\%$ variation in these parameters (assuming, of course, that this variation is common to both options).

This is an extreme example of a relatively common occurrence. The ranking of two options is unlikely to be affected by every risky parameter. Rather, this ranking can be expected to be robust to variation in most parameters, leaving the decision-maker free to concentrate his attention on the few parameters that do affect the final choice.

Figs 14–16 illustrate a second case study, in this case wall finishes in a similar environment, using the same initial discount rate and study period. Ceramic tiles are the low cost option on best estimates, but this judgement would be reversed if the study period were reduced by anything in excess of 25% (i.e. to less than 20 years), or if the discount rate were increased by

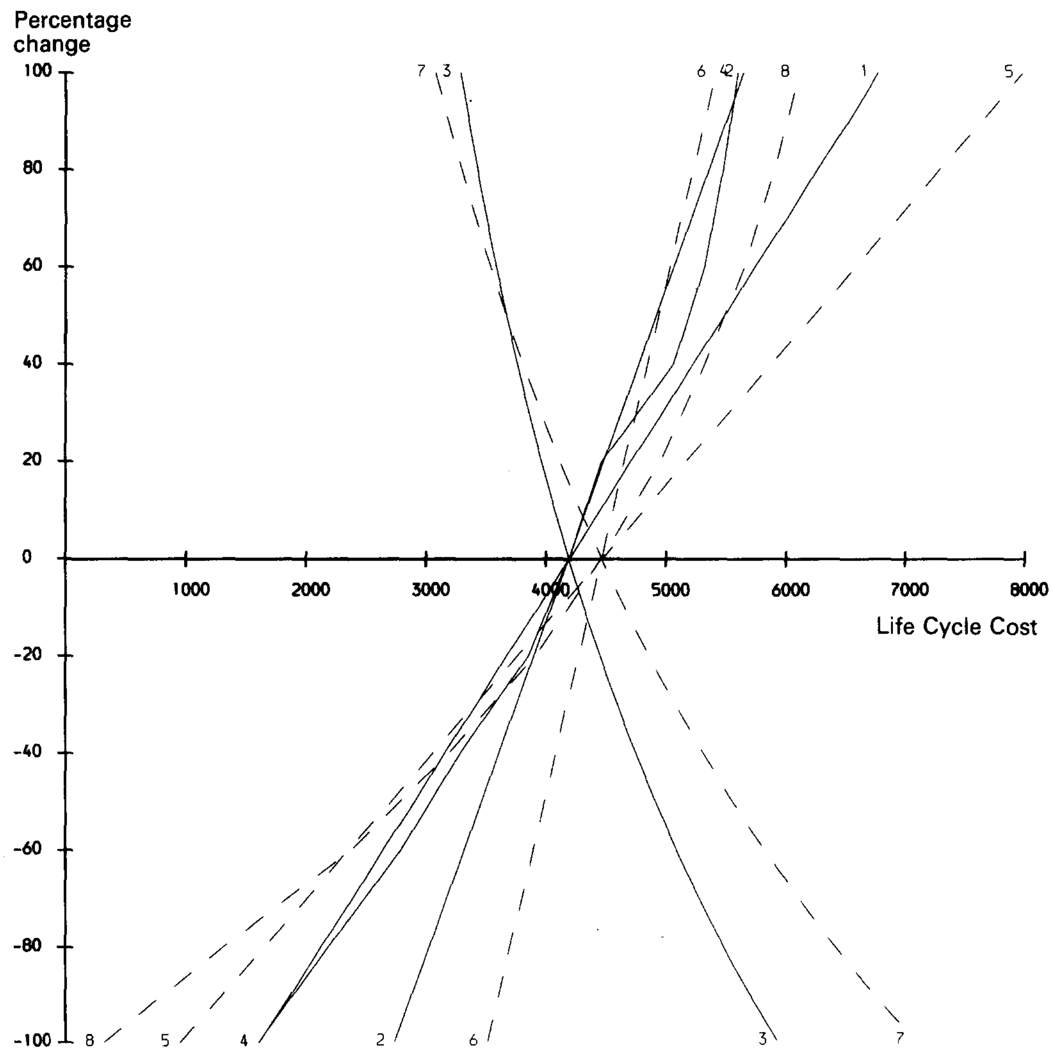
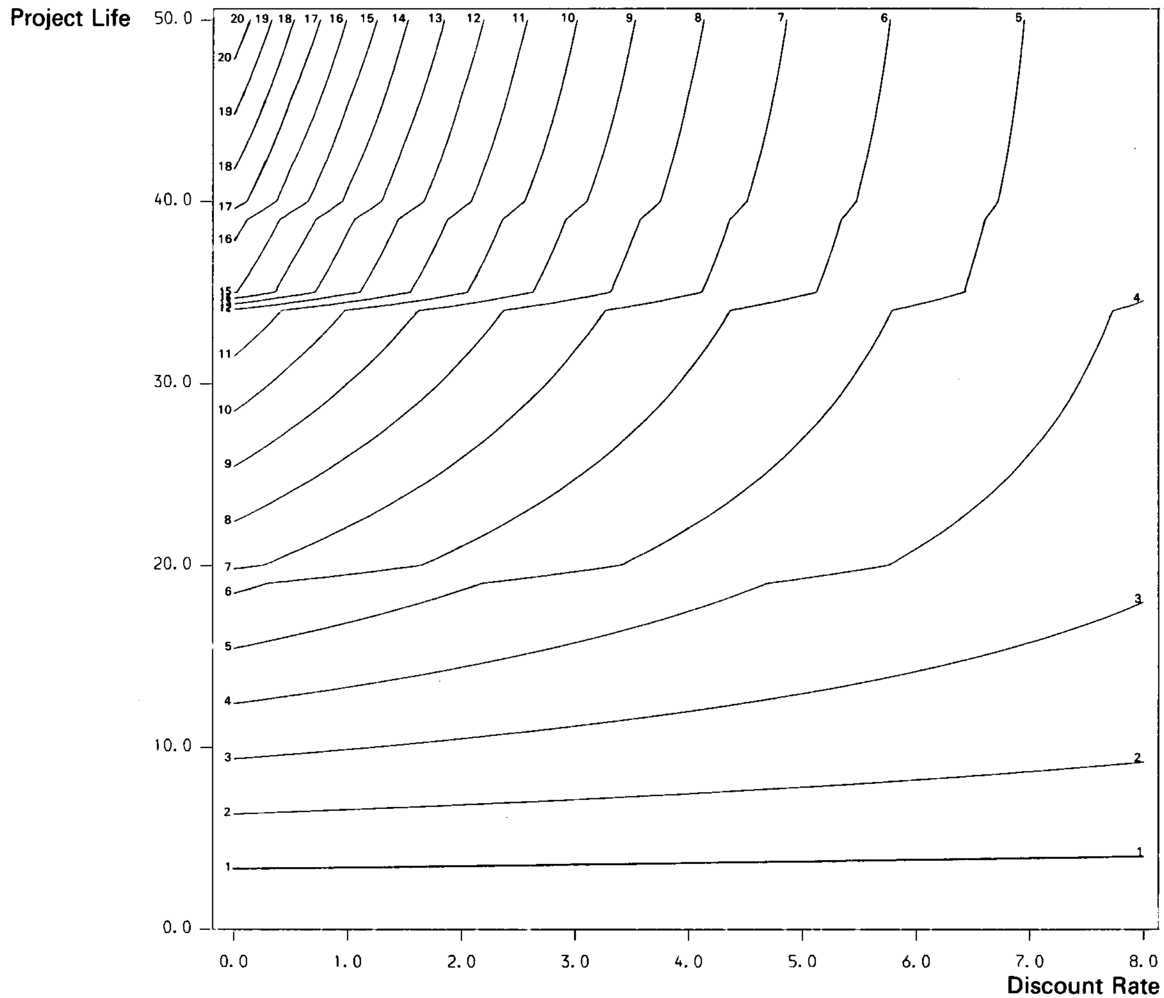


Fig. 14. Comparative finishes spider diagram – case study 2. Solid lines represent emulsion paint: 1. cleaning costs; 2. capital costs; 3. discount rate; 4. project life. Broken lines represent ceramic tiles: 5. cleaning costs; 6. capital costs; 7. discount rate; 8. project life.



Contour	LCC
1	2 000
2	2 500
3	3 000
4	3 500
5	4 000
6	4 500
7	5 000
8	5 500
9	6 000
10	6 500
11	7 000
12	7 500
13	8 000
14	8 500
15	9 000
16	9 500
17	10 000
18	10 500
19	11 000
20	11 500

Fig. 15. Ceramic tile contour diagram – case study 2.

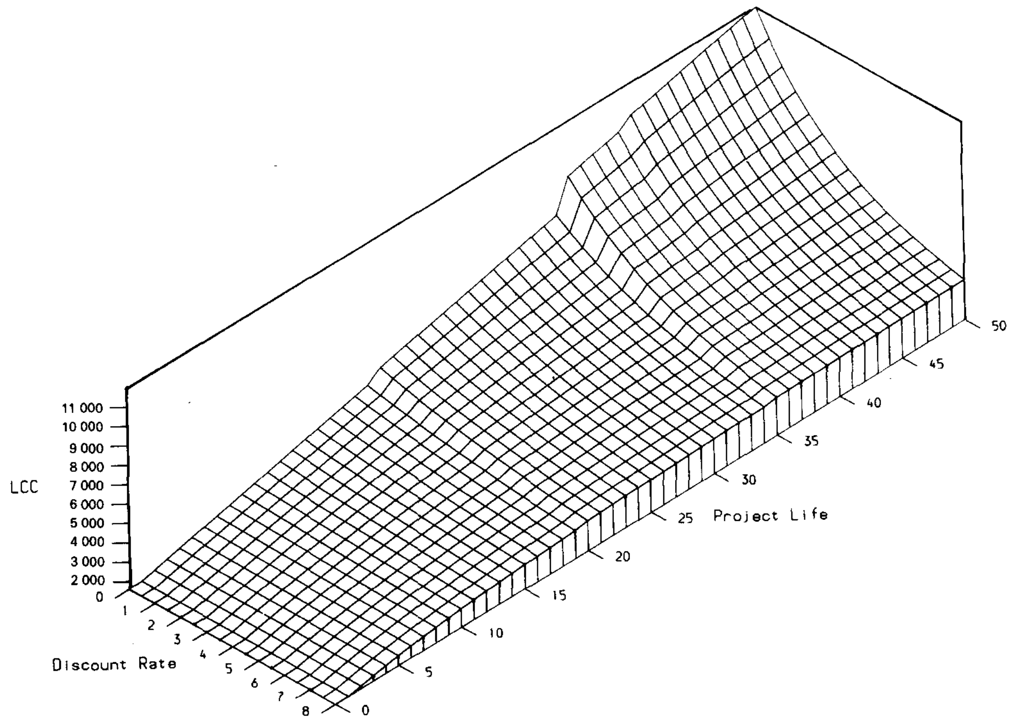


Fig. 16. Ceramic tile LCC surface diagram – case study 2.

more than 43% (i.e. to anything above 5.7%). The emulsion paint finish is more sensitive to both these parameters. Indeed, this example illustrates the opposite extreme, in which the ranking of the two options is sensitive to variation in all four risky parameters. Such sensitivity leaves final choice to the (informed) judgement of the decision-maker.

Figs 15 and 16 illustrate a bivariate sensitivity analysis of ceramic tiles, taking discount rate and project life as the two risky parameters. This highlights the fact that sensitivity with respect to one parameter can be affected by the value of another parameter. It is clear, for example, that the longer the project life (e.g. more than 10 years), the more sensitive are life cycle costs to the discount rate. Similarly, the lower the discount rate the more sensitive are life cycle costs to the project life.

Conclusions

Life cycle costing by definition makes predictions about the future. The outcome of any life cycle costing exercise is, therefore, only as good as the assumptions upon which these predictions are based.

This has led some critics to reject life cycle costing as inherently unreliable. Our view is that this criticism is misguided. There is no doubt that life cycle costing is subject to risk and uncertainty. But risk cannot be ignored. Indeed, we would argue that decision advice based on initial capital costs is likely to be more susceptible to risk than advice based on life cycle costs precisely because the former criterion ignores risk.

Effective life cycle costing needs an equally effective risk management system in order to use the risk and uncertainty to improve decision making. This paper has presented the outlines of such a system. Using this, risk identification, analysis and response can be achieved in a systematic manner. Sensitivity and probability analysis will indicate, in quantitative terms, the impact of the various assumptions underlying a particular life cycle costing exercise.

These analyses will guide follow-up work, should this be necessary, in an efficient manner: there is little value in expending effort on improving the estimate of an uncertain parameter to which life cycle cost is insensitive.

There will remain occasions, of course, when the decision advice is ambiguous. But a risk management system of the type advocated in this paper will identify the source of the ambiguity, and so better inform the decision making process.

References

Baker, A.J. (1985) 'Information about Risks and Uncertainties under a Weak Ordering of Preferences', University of Leicester Discussion Paper No. 43.

Baker, A.J. (1986) 'Valuing Information about Risks', University of Leicester Discussion Paper No. 51.

Bennett, J. and Ormerod, R.N. (1984) 'Simulation Applied to Construction Projects', *Construction Management and Economics*, **2,** 225–263.

Chapman, C.B. (1979) 'Large Engineering Project Analysis', *IEEE Trans. Eng. Management*, **EM-26,** 78–86.

Cooper, D.F., MacDonald, D.H. and Chapman, C.B. (1985) 'Risk Analysis of a Construction Cost Estimate', *Project Management*, **3,** 141–149.

Flanagan, R., Meadows, J., Norman, G. and Robinson, G. (1987) Life Cycle Costing: an application to building finishings, Surveyors Publications, London (forthcoming).

Flanagan, R. and Norman, G. (1983) Life Cycle Costing for Construction, Surveyors Publications Ltd, London.

Perry, J.G. and Hayes, R.W. (1985) 'Risk and its Management in Construction Projects', *Proc. Instr. CW. Engrs.*, **78** 499–521.