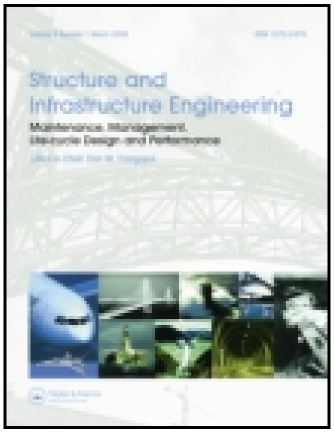

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Monte Carlo simulation approach to life cycle cost management

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Public private partnerships (PPP) and private financial initiative (PFI) projects face the challenge of meeting unforeseen future risks. Life cycle cost estimate is a crucial part of PFI/PPP procurement. The traditional deterministic cost model can not take into consideration the uncertainty of future events let alone determine the contingency allowance for the projects. The large number of cost items in the life cycle cost model of building projects makes cost control difficult. Monte Carlo simulation method is applied to the Quantitative Risk Assessment of life cycle costing risk management. A PFI school project was chosen as a case study to demonstrate a new simulation approach to life cycle cost management. The lives and replacement cost rates of building elements are the inputs for the simulation model, while the cumulative life cycle cost are the outputs of the analysis. The sensitivity analysis revealed the cost significant items, which provides the most efficient way for cost control. The results of the analysis identify the high risk life cycle assumptions and provide a variation reference for the decision-makers to define risk and contingency allowance in PFI/PPP projects. The approach can also be applied to other types of building PFI projects.

Keywords: life cycle costing; cost management; Monte Carlo simulation; risk management; cost significant items

Background

Flanagan *et al.*' s (1983) research showed that the capital costs of a building only represents half the total cost during its whole life, and are only slightly higher than united cleaning and care taking, replacement and maintenance, and routine servicing costs. Recently, there has been a growth in the application of public private partnerships (PPP) and private financial initiative (PFI) projects in the construction industry. As a result, the life cycle cost considerations are playing a more important role in tenders than ever before. The investors of durable buildings realised that an increased amount of money spent on initial cost can considerably reduce future costs of a building. The construction clients began to understand the importance of life cycle cost to their investment, so they require early and accurate life cycle cost advice on their project to help their financial planning and decision-making process. Life cycle costing is also a good assessment tool for sustainable building design (Wang *et al.* 2009).

The construction industry is considered a risk-based industry and strong correlation has been established between project complexity and perceived risks. Although, it can also be argued that the construction industry is no different to other industries in terms of risk exposure (Loosemore *et al.* 2005), the growth in client expectations over the project whole life cycle dictates higher demands on the project team. As 'value for money' was repeatedly recorded as client main interest, it became essential to consider accurate measures and cost control in project life cycle cost analysis. Life cycle costing is one form of appraisal of how well a project meets the clients' performance requirements (ISO 15686-5 2007). Life cycle costing is a valuable technique which is used for predicting and assessing the cost performance of constructed assets. The appropriate time to control the life cycle cost of a building is at the scheme (initial) design stage but little information is available during this stage (Wang and Horner 2007b). Kirk and Dell'Isola (1995) believe that the elemental estimating method, which breaks down building into elemental level for detailed costing, can improve the capability to cope with problems in life cycle costing and then assist earlier design decision-making.

The life cycle costing process includes breaking down building to a measurable and detailed elemental level, to make life cycle assumptions, to calculate replacement cost of each element at each year according to the life cycle assumptions and finally to summarise and generate a life cycle profile over a long period of time (typically 25–50 years for PFI/PPP projects) for the whole building. A typical life cycle

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cost structure of a building comprises of hundreds of different building elements. Each element correlates to several life cycle assumptions such as the replacement cycle, replacement cost and quantity of the element. In order to establish life cycle assumptions the quantity and unit rate of each element have to be estimated according to the design; and the life span for each of the building elements must be predicted. Every assumption is a variable in life cycle costing; therefore assumption making is the most difficult step in life cycle costing due to the complex cost breakdown structure and uncertainties in predicting future events in the long period of time. The combination of these variables can form an excessive number of different scenarios. For example, an estimator may assign 20 year life to PVC windows in a building project, but it only lasts for 16 years due to heavy usage of the building. Either overestimating or underestimating the life cycle assumptions are the risks in life cycle costing which may cause the project to be under funded in future.

The life cycle costing should not only perform as a budget estimate tool, but it can also determine the project contingency and review the project cash flow in order to examine project affordability especially for PFI/PPP procurement. However, the input variables are normally given deterministic values in practical models regardless of the risks and uncertainties involved in the estimating process. As a result the deterministic model only produces a single figure as budget estimate of life cycle cost over a long period of time. The cumulative impact of inaccurate information can be drastic and the validity of the life cycle cost model can, therefore, be questioned. It is essential for project coalitions to ensure the application of robust cost estimating methods and tools.

The widely used cost estimate method for life cycle cost estimate is still the deterministic model in practice. However, deterministic models cannot model life cycle costs successfully because the uncertainties of the future events affect the estimate of the life cycle cost of buildings. Mok *et al*. (1997) believe that traditional deterministic (most likely) cost estimation of building services is economically ineffective and reactionary in nature. They suggested implementing risk management process for this estimation. The disadvantages of traditional deterministic single-figure estimating are:

(1) the contingency figure is arbitrarily arrived at, and may not be appropriate for the specific project;
(2) there is a tendency to double-count risks, because some estimators are inclined to include contingencies in their best estimate;
(3) a percentage addition still results in a single-figure prediction of the estimated final cost, implying a degree of certainty that is simply not justified;
(4) it does not highlight any potential for cost reduction, and may reflect the potential for 'downside' risk, and depending on the estimators' attitudes and the sources of original data (Mok 1997).

Loosemore *et al*. (2005) cited that the problem with single point estimate (especially in construction projects) is the potential variability that they hide. Life cycle cost models are normally based on the information provided by cost planner and estimators who include a level of contingency to the estimate. Taking into consideration the number of building elements over the economical life cycle of a PFI project (for instance, the cumulative impeded contingency), can wrongly contribute to the decision-making and inaccurate sums may be allocated to projects. Cost and project information and estimator's experience can also contribute to the outcomes. The basic concepts of risk management of probability and ranging are found useful when dealing with the problem.

Some theoretical non-deterministic models have been developed for estimating life cycle cost of buildings. For example, artificial neural networks (Boussabaine and Kirkham 2004), fuzzy logic approach (Wang and Horner 2007b, Wang 2009), sinking fund method (Bowles *et al*. 1997), coefficient method (Lavy and Shohet 2008). However, those previous researches provide little help on cost control and the determination of contingency allowance for life cycle fund of PFI projects in practice.

A number of factors should be taken into consideration when building life cycle cost model. Technical factors, such as project life span, element life span, and replacement cost rates, affect the total life cycle cost of the building. External factors, such as environment, the age of the building and occupancy condition, also affects the building running costs (Lavy and Shohet 2008). Babalola and Aladegbaiye (2006) identified nine factors that have influence on project contingency. These factors are shown in Table 1. While cost information and estimator's experience are considered technical factors, other factors have an administrative nature which governs the project environment. The analysis and discussion of life cycle cost models should consider the factors identified above.

The determination of time horizon exists in aspects such as the physical, technological and economic life of projects (Dell'Isola and Kerk 1981). It depends on the client's expectations and the characteristics of the

Table 1. Factors affecting project contingency.

Factors affecting project contingency	
Cost information	Contract requirements
Financial requirements	Bidding climate
Project team requirements	Project information
Estimator's experience	Technology requirements
Project complexity	

project (El-Haram and Horner 1998). Dell'Isola and Kerk (1981) believe that 25 to 40 years is long enough to forecast future costs to capture the most important costs for economic purposes. The most commonly used concession periods in PPP/PFI procurements are 25 years and 30 years.

Research methodology

Risk assessment during a building's whole life is an important area, which needs more study due to the uncertainty of the future. Risks in life cycle costing is defined as inaccurately predicting future events, such as estimating the replacement cycles, replacement costs and replacement quantities of building elements and the estimator's experience, which causes the project to be under-funded or over-funded in future. The most used risk analysis technique is the Monte Carlo simulation. The technical factors of cost information and estimator's experience will form an integral part of the model, while non-technical factors are considered in a holistic manner. The concepts of probabilistic risk management are employed to represent different possibilities for the input parameters in the Monte Carlo model. Three-point-estimate and Monte Carlo simulation are applied to find potential realistic scenarios and identify the level of confidence in the life cycle cost result.

Monte Carlo simulation process

Monte Carlo simulation has been widely used in engineering and science researches. Boyle *et al*. (1997) employed the Monte Carlo simulation to estimate the security pricing, meanwhile Keen and McGreevy (1990) used Monte Carlo simulation on structural modelling of glasses. The method has also been used to model Ising spin systems Bortz *et al*. (1975), Inlayer structure formation in thin liquid films (Chu *et al*. 1994), and to solve option valuation problems in the theory of finance (Boyle 1977).

Monte Carlo simulation uses computing power to explore all of the possible outcomes to a problem given certain bounds of variability expressed in the model. Furthermore the impacts of input variables can be measured by sensitivity analysis. The main advantage of this method over the deterministic models is it allows the uncertainty and risks during the long-term operation stage of buildings to be involved in cost analyses. In the context of life cycle modelling this technique can be used to discover the likely variability in the expected outcome of the model and to identify which areas have the greatest effect on those results. This will in turn enable decision-makers to make smarter, more appropriate decisions regarding investment, and concentrate on the cost significant items that have the greatest impact to the expected costs.

In life cycle costing, risk and contingency allowance is determined by two factors: the probability of any risk to occur and impact of risk if it occurs. The uncertainty as to the input of analysis can be quantified within a range, for example from minimum cost to maximum cost, whilst the impact of risk as the output from the Monte Carlo simulation can be portrayed by a probability distribution. Since risks are unplanned future events, there is a level of uncertainty in identifying impact of risk. The concept of ranging (three-point-estimate) is introduced to identify potential range of input factors. The outcome is determined by the shape of the most likely probability distribution of the minimum and maximum values for each individual risk. Vose (2000) states the advantages of Monte Carlo simulation in risk management can be:

- It does not require sophisticated mathematical knowledge.
- Computer applications are commercially available and can be used to run the analysis.
- Monte Carlo simulation is a parallel process; i.e. iteration results are independent of each other.
- The model elements can be correlated for more reliable and realistic scenarios.

Simulation is a technique used to determine the project contingency where random values are drawn from a full range of individual probability distribution (Loosemore *et al*. 2005). As a result, thousands of scenarios (also called iterations) are produced in a parallel process. However, Monte Carlo simulation as a detailed sensitivity analysis should be cautiously dealt with (Gladwin 2006); the model credibility should be examined and any unrealistic scenario eliminated. In theory, the model credibility is determined by the number of iterations used to generate the outcome. In practice, one to five thousand iterations are sufficient to reach an acceptable answer for most complex models (Gladwin 2006). Once the model is converged, any increase in number of iterations will add to the processing time and will marginally affect the result. Application of the Monte Carlo simulation method in life cycle costing will allow the input factors of the life cycle model using a range of values rather than a deterministic number as in the traditional life cycle models. Therefore the output from the Monte Carlo simulation model takes into consideration various scenarios related to future events, such as the replacement frequencies of the building elements.

Sensitivity analysis to find the cost significant items

The Pareto principle states that 80% of the effects are the results of 20% of the causes; for example, for a given building about 20% cost items contribute to about 80% of total construction cost (Wang 2005). Wang and Horner (2007) stated the theory has been widely implicated in engineering cost control. This principal rings true with risk analysis but the question is how to find the 20%. A sensitivity analysis in the Monte Carlo simulation process identifies the items that have the greatest effect on the total cost. This may be due to their cost, their frequency or both. A change in the top items will have a significant impact on the model; therefore, actions to manage, mitigate and reduce uncertainty on those items will improve the overall certainty significantly. The cost significant item (CSI) method is an efficient way to control overall cost which pays the least effort to achieve maximum effect in cost control (Wang and Horner 2007a). The principle of the CSI method is to identify the cost significant items and pay more attention to those items, because the small amount of CSIs will always represent a huge proportion in the overall cost. The sensitivity analysis in the Monte Carlo simulation method can identify the most sensitive cost items in the life cycle cost structure. These CSIs are the key to control the overall life cycle fund of a project in the most efficient way. Therefore, the objectives of the Monte Carlo simulation approach to life cycle cost management include several aspects:

(1) To establish Trigent distribution to each input variable rather than using a deterministic figure in traditional models.
(2) To simulate the possibilities the input variables change in reality by iterative simulation.
(3) To calculate the probability distribution of the output result – the minimum, maximum and most likely estimates of the overall life cycle cost.
(4) To identify the top sensitive elements and life cycle assumptions.
(5) Suggest the risk and contingency allowance for the project.

Variables and parameters of the model

The input variables of the simulation analysis are the replacement cycles (expected life span) and replacement cost rates of the building elements. They are the key factors in life cycle assumptions. The replacement cycle, also called life span, life expectancy and replacement frequency is the expected life of the building element. The replacement cost rate is how much it will cost to replace the building element at the end of its life. A triangle probability distribution function (PDF) is defined for each input variable. The PDF is established by three values – minimum, most likely and maximum – which are estimated by the quantity surveyors according to industrial benchmarking and their experiences.

Three-point-estimate is used to define the range of values in the variables. The minimum, most likely, and maximum values define the distribution parameters, but not how these parameters are linked, which is defined by the shape of the distribution. The distribution shape dictates the values generated for each of the iterations. The triangular and Trigent distributions are two commonly used distribution types for three-point-estimate in practice. In the triangular distribution, the most likely cost is used to express a value around which most of the cost possibilities could be expected to occur and the extremes of the minimum and maximum should be unlikely to occur. The Trigent distribution extends the extremes of the triangular distribution by a factor controlled by the modeller. The Trigent distribution is used in the proposed model because (1) it ensures that the extremes are sampled occasionally for the necessary use of integers for event cycles and (2) it allows the experts providing the range estimates to use reasonable extremes rather than wide extremes. The formats of the triangular and Trigent distributions are compared in Figure 1. The Trigent extension of the distribution is an important factor in

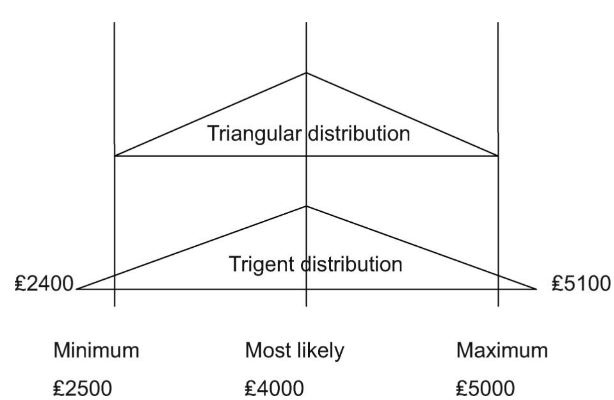

Figure 1. Triangular and Trigent distributions.

the smoothing of cash flow in life cycle cost models, and allows the possibility of events outside the concession period being brought into the concession period in some circumstances. The extent to which the Trigent calculation extends the extremes is defined by the modeller using two numbers which represent the percentiles of the minimum and maximum figures in the distribution. For example (10, 90) describes the stated minimum as being the 10th percentile and the maximum as being the 90th; (5, 95) is the 5th and 95th. 10, 90 extends the extremes more than a 5, 95. Following testing of various parameters to optimise the models together with experts' experience of modelling in other fields, Trigent factors of 5, 95 are chosen in the model to ensure the extremes are included in the model.

In the deterministic model, the input variables are totally independent of one another. However, most of the data has a common source and many external pressures on a project will have an overall effect rather than effecting only one or two building elements. The correlation factor used for the input variables in the proposed model is 0.5 to describe interdependency whilst maintaining a degree of flexibility.

The output variable is the cumulative total life cycle cost profile of the building over 30 years analysis period. In the simplest form, the outputs from the simulation model are the 1000 individual results of the iteration of the model. An inspection of these results will show the lowest possible result and the highest. The average, however, comes in three forms: the mean, median and mode. The use of percentiles provides us with much more data than just averages. They are best interpreted as 'the probability that a given value will not be exceeded'. For example, if the P50 (50th percentile of the results) is £5,000,000, there is a 50% chance that the £5,000,000 will not be exceeded. P50 is chosen as the indicator for the most likely estimate of the output variable. Usually the P20 and P80 are used as guidelines for the lower and upper bounds of the output of the analysis, whereas the P50 is used as the most likely cost.

The software tools

Since there are a great number of variables involved in the simulation analysis, the software @RISK has been employed to carry out the calculations. It can help Monte Carlo simulation to be used in the project with a large number of variables.

Case studies

The simulation process

The building project in the case study is an 18,000 square metre PFI secondary school building in the UK. The building project includes a three-storey concrete building with flat roof, double glazed aluminium windows, external sports pitch and car parks. The concession period is 30 years which is also the analysis period of the life cycle cost model. A deterministic model was set up by professional quantity surveyors who made life cycle assumptions based on their experience and industrial price books. The input factors of the model are the life cycle assumptions on the replacement costs and replacement cycles of the building elements. The profile of the life cycle cost over 30 years generated by the deterministic model is shown in Figure 2. The life cycle cost of this building project over 30 years was estimated at £8,267,564 by deterministic model. The deterministic model produces a sharp life cycle profile (Figure 2) with high peaks at years 10, 15, 20, 29 and 30. That is because some large building elements, such as floor finishes, some mechanical and electrical equipment, and fittings, are expected to be replaced in these years according to the estimator's life cycle assumptions.

The Monte Carlo simulation was built upon the deterministic model. Some senior quantity surveyors have been asked to estimate the minimum, maximum and most likely values for the input variables in order to build the Trigend distribution for the variables. For example, the Trigent distribution of the replacement cycle of carpet floor finishing is (11, 15, 18).

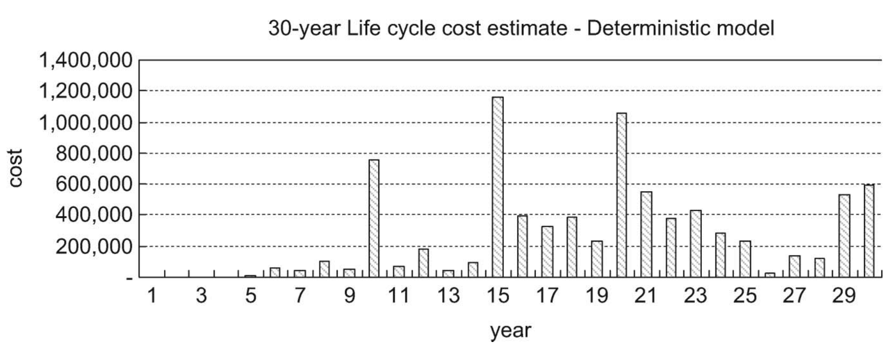

Figure 2. 30-year life cycle cost profile by deterministic model.

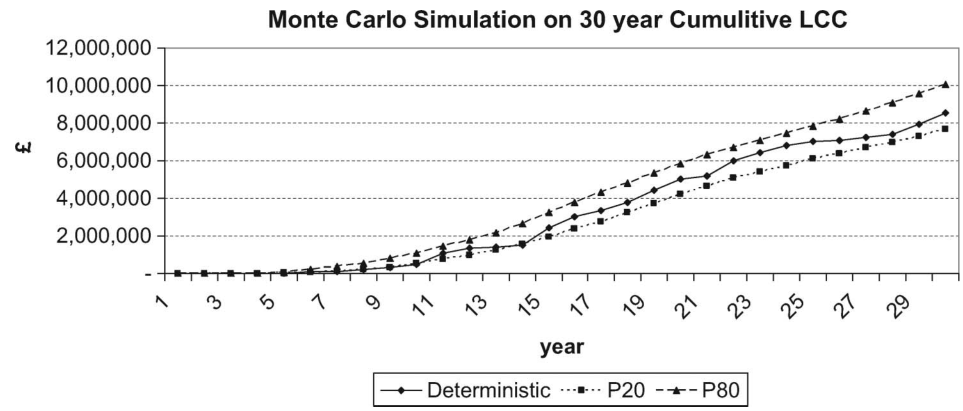

Figure 3. Monte Carlo simulation on 30-year cumulative LCC.

In order to choose effective number of iteration, the model was tested by different iteration number from 500 to 5000. It was found the output factors, for example P50, remains unchanged after the number of iteration increased to 1000. Therefore the number of iteration in the simulation analysis was 1000 times, which is sufficient to deliver stable outputs.

The Monte Carlo simulation process calculated the life cycle cost of the building at each year in iteration by choosing a random value between the minimum and maximum for each input variable. The statistic analysis after the one thousand iterations gave the cumulative life cycle cost of the building at P20, P50, and P80. The cumulative life cycle cost of the building in the case study from year 1 to 30 years after iterations is shown in Figure 3.

The Monte Carlo simulation model outputs a range of results for the output variable – the 30-year life cycle cost of the building rather than a single figure. Given the variability inherent in the model, there is a 20% chance that the cumulative 30-year spends will not exceed £7,676,378(P20) and there is an 80% chance that the cumulative 30-year spend will not exceed £10,069,858 (P80). The expected total life cycle cost could be taken as the P50, in this case £8,803,029.

The final output variable discussed here is the total life cycle cost of the school over 30 years. The P50 from the simulation are the most likely costs which is 6% more than the estimate by the original deterministic model. P50 is recommended as the best fit (the most likely) estimate that takes into consideration the uncertainties in various life cycle assumptions. The PDF of the output factor is shown in Figure 4. The P20 is the estimated minimum value of the output factor – the 30-year total life cycle cost, which represents the best scenario. The P80 is the estimated maximum of the output variable, which can be explained as the worst scenario. The difference from the maximum life cycle cost, P80, to the most likely, P50 is 14% more. The difference covers possible early failures of building elements and the unexpected costs in future operation stage of the building therefore it should be the base of project risk and contingency allowance.

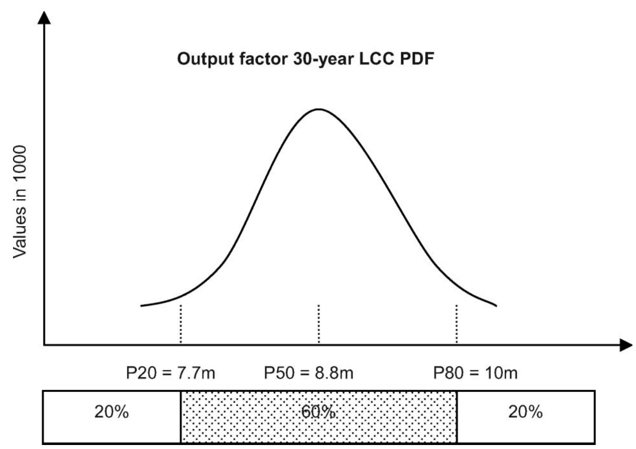

Figure 4. PDF of the output factor.

The cost significant life cycle cost items

There is a great benefit in carrying out sensitivity analysis for those funding the project as it allows revision to affordability and prioritisation of expenditure making the project more predicable and better value. The Monte Carlo simulation model also identified the top sensitive items from a large number of building elements – the most influential items during iterations. The most sensitive building items and life cycle assumptions to the total life cycle cost costs are showing in Table 2. The Tornado chart in Figure 5 shows their influence degrees on the total life cycle cost.

These building elements in Table 2 are the CSIs which contribute much more to the total than the rest

Table 2. The top 20 sensitive life cycle assumptions.

Number	Building element	Sensitivity
1	3C – Ceiling finish – bulkheads cost per replacement	0.455
2	3C – Ceiling finish – bulkheads replacement cycle	−0.410
3	5E – Heat source – split type heat pump system – event cycles	−0.100
4	5H – Electrical installations – lighting distribution wiring – replacement cycle	−0.073
5	4A – Fittings and furnishings – equipment – selected equipment total based on room titles – event cycles	−0.060
6	3B – Floor finishes – 2.5mm thick vinyl sheeting – replacement cycle	−0.052
7	5M – Specialist installation – passive ICT installations – replacement cycle	−0.036
8	3B – Floor finishes – 2.5mm thick vinyl sheeting – event cycles	−0.032
9	5E – Heat source – split type heat pump system – replacement cycle	−0.032
10	5A – Sanitary appliances – wash hand basins – replacement cycle	−0.031
11	5H – Electrical installations – luminaires – replacement cycle	−0.031
12	6A – Site works – 80 mm thick dense bitumen macadam base course, car park areas – replacement cycle	−0.031
13	6A – Site works – 80 mm thick dense bitumen macadam base course, 50 mm thick dense macadam binder course, 40 mm thick rolled asphalt to surface course; roads – replacement cycle	−0.030
14	2C – Roof – mild steel balustrades, welded and bolted fabrication, polyester coated finish, 1100 mm high – replacement cycle	−0.028
15	5E – Heat source – gas fired boiler(s), pressure jet burner(s), pressurisation unit, expansion vessel(s) – replacement cycle	−0.027
16	3C – Ceiling finish – suspended linings, Rockfon grid system, 600 × 600 × 12 thick Rockfon Deckor tiles with white painted micro textured matt surface, various suspension, including trims, upstands – replacement cycle	−0.027
17	5E – Heat source – biomass – burners – replacement cycle	−0.025
18	4A1 – Fittings and furnishings – fixed – overall fixed FFE total – replacement cycle	−0.025
19	3B – Floor finishes – quarry tiling skirting – replacement cycle	−0.024
20	6A – Site works – nets and similar associated sport equipment; to hard surface games court – replacement cycle	−0.024

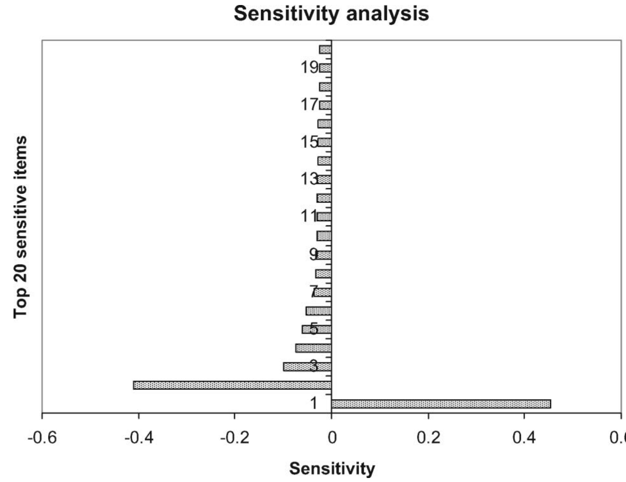

Figure 5. Tornado chart of the sensitive items.

of the building elements. As the key for cost control, they should be where the value engineering is concentrated. The list shows the CSIs for this school project lie in ceiling and floor finishes, M&E, FFE and external surfacing. In order to control the overall life cycle cost of the building in the most efficient way, value engineering should be carried out on these items. The different design alternatives for these building elements should be carefully studied in detail. It may be found the high quality alternatives with higher replacement cost actually less over a long-term than low quality and cheap ones because the former needs less replacements over the concession period than the later.

Conclusion

The Monte Carlo simulation method has been applied to life cycle cost analysis with the help of @RISK software. The case study on a PFI building project revealed the advantages of the simulation method over the traditional deterministic modelling method. Instead of using a definite number for each life cycle assumption, the Monte Carlo simulation model allows life cycle assumptions using a range of values for input variables so that the simulation process took into consideration uncertainties of the assumptions of future events related to the life cycle cost of the building.

The P50 was recommended as the most likely estimate for the output variable – the overall life cycle cost of the building over 30 years. It is about 6% more than the result of the deterministic model, which shows the life cycle cost has been under estimated by the deterministic model. That is because the deterministic input variables did not take into consideration the early failure of building elements. The difference between P80 and P50 is recommended as the risk and contingency allowance for building life cycle cost analyses. The sensitivity analysis identified the CSIs for the life cycle cost of the building which provides an efficient way to cost control in life cycle analysis. In comparison to previous published life cycle cost models the Monte Carlo model was tested by real data of a live PFI project. It allows probabilistic input variables; and it can identify CSIs for cost control. The Monte Carlo simulation model for life cycle cost analysis can also apply to other types of buildings such as health, residential and offices.

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