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Uncertainty Analysis by Monte Carlo Simulation in a Life Cycle Assessment of Water-Saving Project in Green Buildings

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Abstract: The complexity of the water-saving project in green buildings when analyzing its Life cycle cost (LLC) renders analytic methods very difficult to be applied. The objective of this study is to conduct a Life Cycle Assessment (LCA) on comprehensive benefit model for water saving in green buildings. Monte Carlo methodology, which substitutes point estimates with random numbers obtained from probability density functions and then builds models of possible results, was applied to calculation in this study. Crystal Ball is utilized to carry out the uncertainty analysis. The most relevant parameters in comprehensive water-saving benefits are identified, which are the annual growth rate in stable phase of water price, discount rate and annual growth rate in transitional period of water price.

Key words: Life cycle assessment, green building, monte carlo, uncertainty analysis, water conservation

INTRODUCTION

The evaluation of green building is based upon Life Cycle Assessment (LCA) which is a technique requires the assessment of the whole period including customer demands, conceptual design, engineering design, manufacturing and service supports (Sterner, 2002a). The international Society of Environmental Toxicology and Chemistry (SETAC) has developed a definition for the LCA methodology since the early 1990s (SETAC, 1993), which leaded to the wide acceptance of the methodology. ISO also endeavored to develop of a formalized system of LCA (ISO 14040, 2006) including four steps: goal definition and scope, inventory analysis, impact assessment and life-cycle interpretation.

The evaluation of green building is a complex issue which requires a life cycle perspective (Horvath, 2004). Tarantini *et al.* (2011) applied LCA to wood windows within procurement procedures and then outlined the assessment features of the environmental performance of building materials and components. Blengini and Di Carlo (2010) carried out an analysis of a detailed LCA of a low-energy family house built in Northern Italy. The initial goal of resource efficiency was achieved by emphasizing the need for encompassing all the life cycle phases. Tarantini and Ferri (2003) employed LCA methodology to estimate the global environmental impact of the existing water treatment systems of Bologna city. The energy, chemicals and materials flows and emissions had been discussed in each technical phases of Bologna water cycle.

There are still some limitations in the practical application of the LCA methodology. The first limitation is the scarce availability of relevant, exact and applicable data (Sterner, 2002b). This made LCA costly because of the need for expert knowledge and professional consultation. The second limitation is a large amount of time required to perform LCA procedure (Udo de Haes *et al.*, 2004). It is quite time-consuming to analyze even a small percentage of the thousands of building materials which are available on the market. Another limitation is the confusion to define boundary settings and decide on which allocation principles to adopt. Borg *et al.* (2001) evidenced that allocation significantly influenced on the results of LCA.

Water saving project of green buildings usually lasts a long life cycle. A large amount of parameters are used when Integrated Benefit Assessment Model (IBAM) is carried out. Thus, the IBAM is of great variation and uncertainty (Huijbregts, 1998) which leads the final results of integrated benefit assessment of life cycle fluctuate annually.

The objective of this study is to analyze the variables and function in the model of comprehensive water saving benefit by Monte Carlo methodology. And the most relevant parameters in life cycle assessment were determined by sensitivity analysis.

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MATERIALS AND METHODS

Monte carlo simulation: Monte Carlo is a method that substitutes point estimates with random numbers obtained from probability density functions and then builds models of possible results (Liu and Zhang, 2012). It recalculates thousands of times, each time applying a different set of random values before it is complete. Monte Carlo produces probability distributions of function, including distribution curve, mathematical expectation and mean square deviation (Marquez *et al*., 2005).

Through series of simulation, Monte Carlo can estimate the total cost by producing the distribution of cost component. Monte Carlo calculates total cost of a project by independent sampling from distribution of cost component. In this process, the optimistic and pessimistic value can be both created. The random value generator can select values for the interval (a, b) and then the frequency of data can be determined based on the distribution (Chen, 2013). The objective of this method is to obtain the distribution of the variables by estimating the probability of input variables (Hung and Ma, 2009).

Monte Carlo simulation offers many advantages over other analysis:

- **Correlation of input:** Monte Carlo simulation can model interdependent relationships between uncertainty variables. It is an important feature to accurately represent how and when the factors vary
- **Scenarios Analysis:** Deterministic model could hardly figure out the results of truly different scenarios under different combination of values generating from different input. Monte Carlo simulation can easily point out which input with which value leads to a certain result
- **Sensitivity analysis:** It is difficult to find the most relevant parameter in a certain result by deterministic analysis, however, Monte Carlo simulation can easily and accurately seek the variable which affect the result the most

Crystal Ball software: Oracle's Crystal Ball is a powerful but easy-to-use Microsoft Excel add-in component. And it is the leading spreadsheet-based application suite for model prediction, estimation, simulation and optimization (Sonnemann *et al*., 2003). This software can automatically calculates tens of thousands of various "what if" cases, and individual scenarios are created to save the inputs and results of each calculation. Then Crystal Ball produces informative plots such as these to reveal how the system performed in the simulation (Pan *et al*., 2011).

During the whole life-cycle cost management, the customer need not particularly express the distribution of variables when run Crystal Ball; this process is conducted by the software automatically (Wedding and Crawford-Brown, 2007). This software can provide sensitivity analysis, correlation and historical fitting and it can generates clear graphics and reports, thus reasonably quantifies the uncertainty of project cost and simplifies decision-making analysis. This software is often applied to risk assessment of single project, development of uncertainty model, or estimation of combination of value and risk (Charnes, 2007).

Oracle's Crystal Ball as a Microsoft Excel add-in component, could substantially relieve its customers from burdensome calculations, its calculation procedures are as followings:

- Define uncertainty variables as assumption cells
- Select appropriate distribution probability and define forecast cells
- List net present value functions, perform net present value calculation by substituting each forecast cell to life cycle model
- Select iteration times and perform Monte Carlo simulation
- Data analysis

Crystal Ball will provide an appropriate probability distribution after defining uncertainty variables as assumption cells. A series of distribution are presented in distribution gallery by Crystal Ball, including normal distribution, triangular distribution, Poisson distribution, exponential distribution and logarithmic distribution. The distribution Gallery in Crystal Ball is presented in Fig. 1.

Case study

Data collection: The LCA of a water saving project serves as a case study to illustrate the proposed method. In the uncertainty analysis of water saving project, parts of the parameters in Monte Carlo function are constant; parts of the parameters are variable in this study and the variation is in accordance of a probability distribution. The analysis of variable and probability distribution is presented in Table 1.

Construction of monte carlo optimization: Substituting Table 1 into comprehensive benefit model of water saving project (Chai, 2008), the Monte Carlo simulation could be obtained:

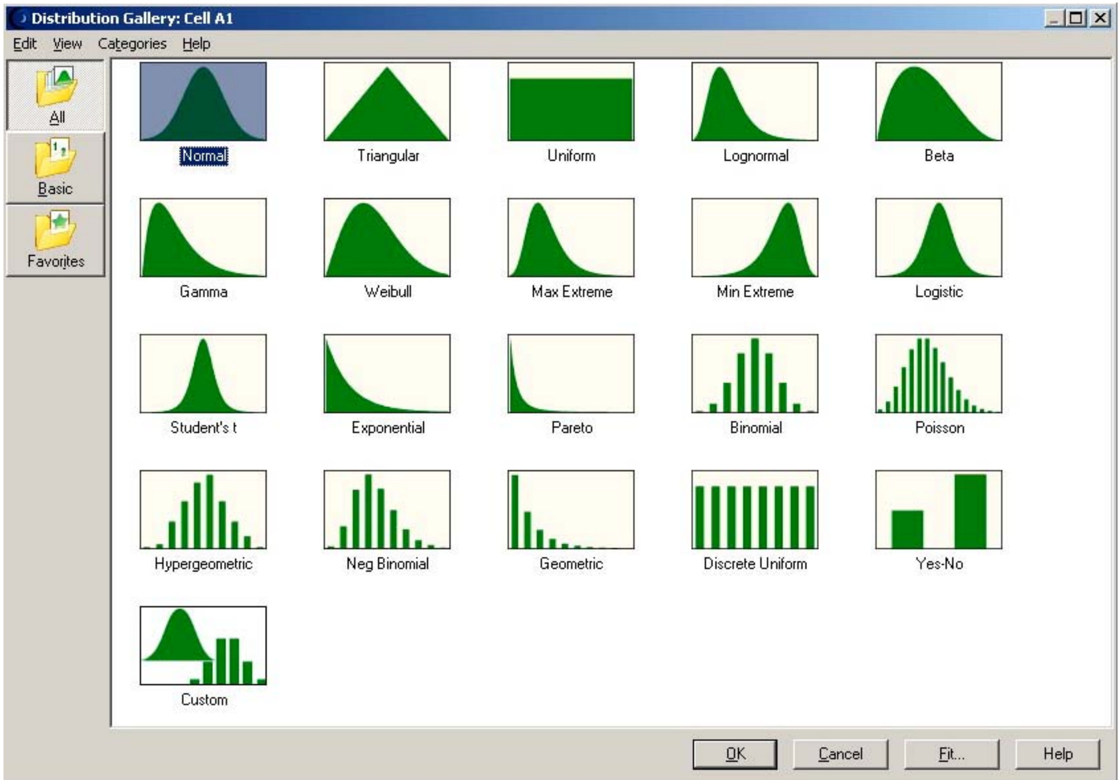

Fig. 1: Probability distribution gallery in crystal ball 7.0

Table 1: The analysis of variable and probability distribution

Constant	Reference value	Probability distribution
Discount rate (r)	7.721%	T, from 4% (wastewater treatment) to 8% (water supply)
Annual growth rate in transitional period of water price (e)	14.10%	T, 9.0-15.1%
Annual growth rate in stable phase of water price (f)	9.90%	T, 9.0-15.1%
Aunual water saved directly (Q_s)	$2.02\times10^5 m^3/a$	N, standard deviation = 5%
Sewage charge (P_s)	0.8 CNY/m^3	T, 0.6-1.0%
Annual utilization of non-traditional water resource (Q_n)	$1.46\times10^5 m^3/a$	N, standard deviation = 5%
Expenditure saved on one cubic water shortage (Q_s)	6.0 $CNY/m^3/a$	T, 5.75-7.67%
Energy and chemical costs of treating one cubic water (P_e)	0.31 CNY/m^3	T, 0.28-0.35%
Annual growth rate of labor cost (g)	9.0%	T, 8-10%
Maintenance costs (O_m)	5.6×10^4CNY/a	T, 4.5×104CNY/a-6.7×10^4CNY/a
Costs of equipment replacement (O_e)	1.694×10^6CNY	T, 1.6×10^6CNY/a-1.8×10^6CNY/a
Major repair cost (O_r)	1.15×10^5CNY	T, 9.5×10^4CNY/a-1.35×10^5CNY/a
Frequency of major repair (n_r)	8	DU, 6-10/a
Residual value (C_r)	2.24×10^5CNY	T, 1.68×10^5CNY/a-2.8×10^5CNY/a,

T: Triangular distribution, N: Normal distribution, DU: discrete uniform distribution

$$
\begin{aligned}
LCC_{\text{Comprehensive benefit}} = {} & \frac{62.62}{1+e}\times\left[F/A,\left(1-\frac{1+e}{1+r}\right),14\right]+\frac{62.62}{1+f}\times\left(F/P,e,14\right)\times\left[F/A,\left(1-\frac{1+f}{1+r}\right),36\right] \\
& \times\left(P/F,r,14\right)+0.6\times10^{-4}\times P_S\times Q_n\times\left(P/A,r,50\right)+\left(0.126\times Q_n+0.1Q_s\right) \\
& \times\frac{1}{365}\times\left[1+\left(P/F,r,25\right)\right]+10^{-4}\times P_c\times Q_s\times\left(P/A,r,50\right)-10^{-4}\times P_e\times Q_S\times\left(P/A,r,50\right) \\
& -\frac{1.44}{1+g}\times\left[F/A,\left(1-\frac{1+g}{1+r}\right),50\right]-5.6\times\left(P/A,r,50\right)-\sum_{i=1}^{k}\frac{11.5}{k}\left(P/A,r,n_r\bullet i\right)-169.4\times \\
& \left(P/F,\left[(1+r)^3-1\right]\right)-623.4+22.4\times\left(P/F,r,50\right)
\end{aligned}
\quad (1)
$$

where, k = ROUND ((n/nr),0).

Probability distributions of variables are input to Crystal Ball as basic data, Eq. 1 does not indicate the probability distributions of each variable.

RESULTS AND DISCUSSION

Determination desirable number of simulations: Number of simulation could strongly affect the accuracy of the

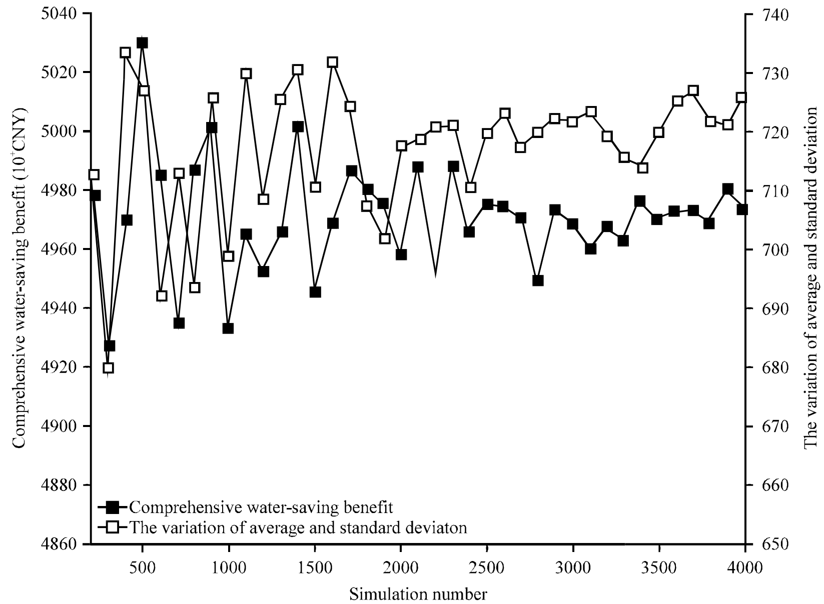

Fig. 2: The variation of NPV, average and standard deviation with the increasing of simulation number

results. Monte Carlo and Crystal Ball were adopted to determine an appropriate number of simulations. Sample average and standard deviation were calculated cumulatively. Two hundred samples were added in each simulation until the 2000th simulation finished. Figure 2 presented the variation of comprehensive water-saving benefit (NPV), average and standard deviation with the increasing of simulations number (Yi, 2012). In Fig. 2, the average and standard deviation tended to be stable with the increasing of simulation number. When fewer simulations (less than 2,500) were performed, there was strong fluctuation in the results; while more than 2,500 simulations brought the results closer to stabilization. Thus more than 2,000 simulations should be performed to achieve stable data. In this study, 10,000 simulations were carried out (Luo *et al*., 2012).

Results of simulation: Ten thousand NPV data was obtained by iterating of Crystal Ball and a 95% confidence level is used for evaluation of the data. Histogram and cumulative probability of the 10,000 NPV data were presented in Fig. 3a and b, respectively.

From Fig. 3a and b, 49,706,000 CNY is the sample mean of the comprehensive water-saving benefit. A high standard deviation (14.5% of sample mean) is due to 10 uncertainty variables were included in the calculation and the effect of each uncertainty variable caused a high deviation. This also indicated the complexity of water-saving and effect of uncertainty variables on water resource utilization.

Excluded costs of small probability (probability less than 5%, i.e., NPV>62,150,000 CNY and NPV<38,280,000 CNY), then the interval with a relative high probability of the NPV would be determined. The interval of 40,000,000-60,000,000 NPV is with a relative high probability of 83.16%.

Sensitivity analysis: Uncertainty of estimation is attributed to the uncertainty of assumption and the equation in the models. An assumption of high uncertainty but low weight could hardly affect the estimation. On the contrary, an assumption in low uncertainty but high weight strongly affected the results. Sensitivity analysis by Crystal Ball can provide the effect of each assumption cell on the forecast cells (i.e., NPV of life cycle cost). Sensitivity analysis was presented in Fig. 4.

Rank correlation coefficient was used to sensitive analysis by Crystal Ball. The negative value of rank correlation coefficient indicated that in an X element increased, the corresponding Y element decreased and vice versa. The larger absolute value of the rank correlation coefficient improved its ability to predict one variable from another. From Fig. 4, the annual growth rate in stable phase of water price (f) had the strongest influence on comprehensive water-saving benefit, with 32.9% contribution to variance; followed by discount rate (r), with 23.3% contribution to variance; the next is annual growth rate in transitional period of water price (e), with

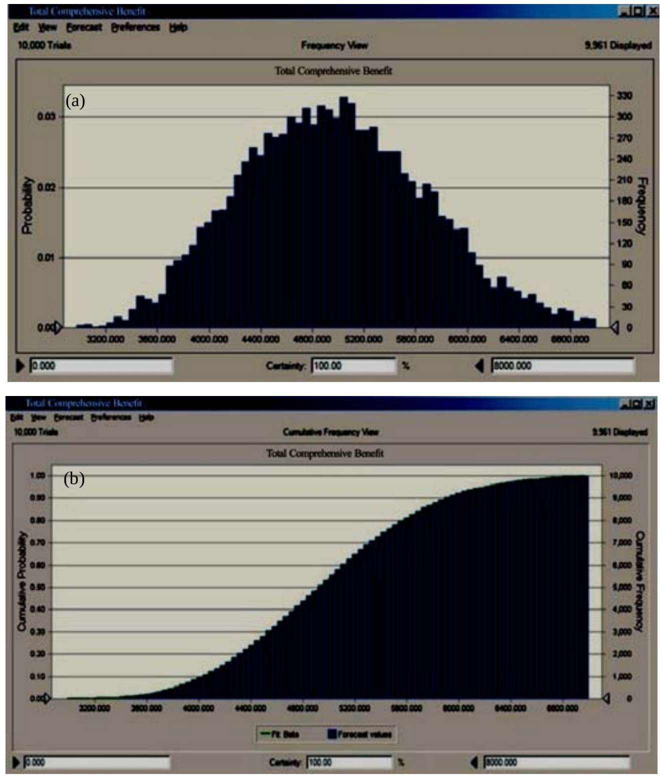

Fig. 3(a-b): (a) Histogram and (b) Cumulative probability of the 10,000 NPV data

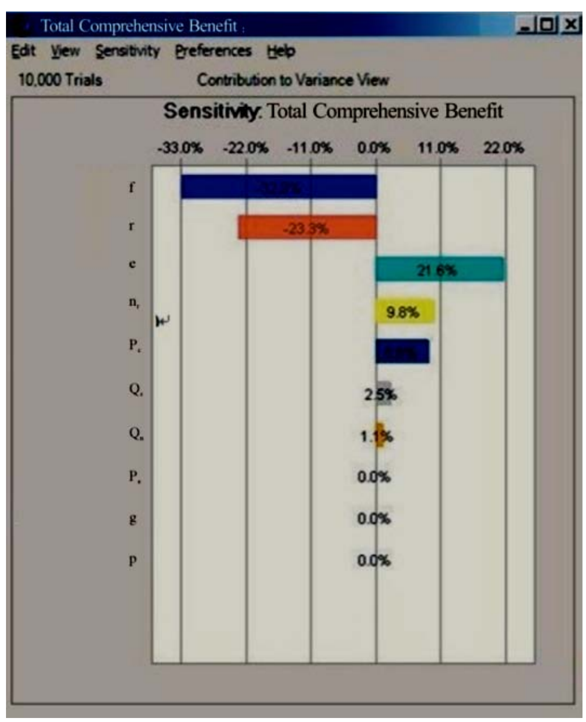

Fig. 4: Sensitivity analysis of life cycle cost in net present value

21.6% contribution to variance. The results sensitivity analysis provided a better understanding of water-saving comprehensive benefit.

CONCLUSION

Based on life cycle conception, a LCA comprehensive benefit model for water saving in green buildings was proposed. Monte Carlo simulation was adopted to analyze and reduce the uncertainty in life cycle. Cost function and parameter system were developed on the basis of Monte Carlo simulation. Crystal Ball analyzed the uncertainty of the model and identified most relevant parameters in comprehensive water-saving benefits: the annual growth rate in stable phase of water price, discount rate and annual growth rate in transitional period of water price.

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