Flexible engineering designs for urban water management in Lusaka, Zambia

Lucy Tembo, Assela Pathirana, Peter van der Steen and Chris Zevenbergen

ABSTRACT

Urban water systems are often designed using deterministic single values as design parameters. Subsequently the different design alternatives are compared using a discounted cash flow analysis that assumes that all parameters remain as-predicted for the entire project period. In reality the future is unknown and at best a possible range of values for design parameters can be estimated. A Monte Carlo simulation could then be used to calculate the expected Net Present Value of project alternatives, as well as so-called target curves (cumulative frequency distribution of possible Net Present Values). The same analysis could be done after flexibilities were incorporated in the design, either by using decision rules to decide about the moment of capacity increase, or by buying Real Options (in this case land) to cater for potential capacity increases in the future. This procedure was applied to a sanitation and wastewater treatment case in Lusaka, Zambia. It included various combinations of on-site anaerobic baffled reactors and off-site waste stabilisation ponds. For the case study, it was found that the expected net value of wastewater treatment systems can be increased by 35–60% by designing a small flexible system with Real Options, rather than a large inflexible system.

Key words | flexible designs, Monte Carlo simulation, Real Options, sanitation systems

Lucy Tembo
Peter van der Steen (corresponding author)
Department of Environmental Engineering and Water Technology,
UNESCO-IHE Institute for Water Education,
PO Box 3015, 2601 DA,
Delft,
The Netherlands
E-mail: *p.vandersteen@unesco-ihe.org*

Assela Pathirana
Chris Zevenbergen
Department of Water Science and Engineering,
UNESCO-IHE Institute for Water Education,
PO Box 3015, 2601 DA,
Delft,
The Netherlands

INTRODUCTION

Managing urban water systems is increasingly a challenge, especially since at the beginning of the 21st century half of the human population is living in urban areas (United Nations Population Fund 2007). Predicting design parameters for urban systems such as sanitation and wastewater treatment is equally challenging and complex due to multiple relationships that exist between human and natural systems and infrastructure. The need for flexible engineering designs in urban water systems cannot be emphasised enough, given the nature of the environment in which these systems operate. Flexible engineering designs are designed to respond to future uncertain changes in the environment (de Neufville *et al.* 2006; Gersonius 2012). These designs are able to respond to changes and uncertainty due to the embedded flexibility in the design.

Flexible engineering designs (de Neufville & Scholtes 2011) have been in existence for quite some time. However, flexible engineering design is relatively new in urban water systems. This paper discusses how flexible engineering can be applied to urban water systems, specifically sanitation and wastewater treatment systems. The aim of this paper is firstly to demonstrate how a procedure to apply flexibility in an urban water system can be developed starting from existing approaches and secondly to test the developed procedure on proposed sanitation alternatives. It will be shown that by incorporating uncertainties in the design process and by applying Real Options to sanitation systems, the expected net value of projects can be significantly increased.

As in most parts of the world, the sanitation system in Kaunda Square, Lusaka, Zambia was designed using a traditional method where uncertainties were not taken into account during the design. The wastewater treatment plant (WWTP) was designed in the 1970s to cater for a design population of 18,000 persons at the end of the 30-year design period (Government of Zambia 2011). With an increase in population and in economic growth, the sanitation system was unable to treat the increased wastewater generation, affecting the quality of the treated effluent. The water utility responsible for providing water and sanitation

doi: 10.2166/wst.2015.354

services in the city is facing challenges to expand the sanitation system due to non-availability of land. This challenge may have been avoided had the system incorporated flexibilities during the design stage of the system.

FLEXIBILITY IN ENGINEERING AND REAL OPTIONS

For a long time, urban water systems have been designed using traditional methods where deterministic single values are used as design parameters. These design parameters are predicted either through extrapolation, where spatial data of temporal sequence are extended beyond the scope of the observed data, or through interpolation where design data are estimated for locations within the project area with no recorded data (House-Peters & Chang 2011). Traditional designs with deterministic design parameters can only result in optimum project value if the estimated design parameters come out as predicted over the entire design period. In reality, deterministic design parameter values almost never come out as predicted. Flexible design has not widely been addressed in wastewater engineering. Exceptions to this are theoretical comparisons of robust designs, phased expansion and decentralisation, all using Net Present Value (NPV) evaluation techniques for WWTPs (Maurer 2009, 2013; Wang 2014).

Flexible designs and Real Options in capital infrastructure is meaningless unless its value is measured and compared with traditional designs. Real Options analysis has been applied in a variety of settings, including environmental investments (Cortazar *et al.* 1998), infrastructure development, innovative building technologies (Greden *et al.* 2005), building design (de Neufville *et al.* 2006), and nanotechnology (Hemantha & Anteneh 2009). There exists a small body of literature that links Real Options analysis to investments in adaptation to climate change. Gersonius (2012) applied Real Options for investment in urban sewerage systems, and Woodward (2012) used Real Options for optimisation of long-term flood risk planning in the UK. Linquiti (2012) examined application of Real Options for coastal defence improvements in developing countries. There are different methodologies for valuation of Real Options, such as: binomial lattice methods, and (Monte Carlo) simulation methods. One of the most applied formulas for valuing Real Options is the Black-Scholes formula (Black & Scholes 1973), which was originally developed to value financial options. A number of modelling tools exists on how to quantify the value of flexibility. These tools in most cases are too complex and are less appealing to practitioners and decision makers. One of the more accessible tools uses a simple Monte Carlo simulation (MCS) in Microsoft Excel with extra add-ons (Geltner & de Neufville 2012). This tool is more attractive to managers and decision makers of infrastructure developers as it builds on spreadsheet models that are familiar. MCS samples from possible scenarios (uncertainty range) and calculates the values from the outcomes.

The simulation methods usually use the Monte Carlo approach and do not need as many assumptions as the Black-Scholes formula. Simulation methods need sound stochastic models in the form of probability distributions for the underlying uncertain variables in order to generate the functionality between uncertain input variables and output pay-off.

METHODOLOGY

This research compared flexible engineering designs with inflexible systems, based on the procedure outlined by de Neufville & Scholtes (2011). The procedure was applied to various combinations of on-site anaerobic baffled reactors (ABRs) and off-site waste stabilisation ponds (WSPs) in Lusaka, Zambia (Table 1), by redesigning it for the

Table 1 | Design alternatives for the case study for wastewater treatment in Lusaka, Zambia

Sanitation alternatives	Development of designs
Alt 1	Phase I: local sewer + ABR (population 6,841 and flow 600 m^3/day) and on-site disposal Phase II: local sewer + ABR (population 11,144 and flow 1,200 m^3/day) + sewer line + WSP (population 6,841 and flow 1,200 m^3/day) Phase III: local sewer + 2 ABRs (population 18,000 and flow 1,800 m^3/day) + sewer line + 2 WSPs (population 18,000 and flow 1,800 m^3/day)
Alt 2	Phase I: septic tanks (population 6,841) Phase II: septic tanks (population 6,841) + 2 local sewers + ABR (population 6,841 and flow 600 m^3/day) + sewer line + WSPs (population 11,144 and flow 1200 m^3/day) Phase III: septic tanks (population 6,841) + 2 local sewers + 2 ABRs (population 18,000 and flow 1,800 m^3/day) + sewer line + 2 WSPs (population 18,000 and flow 1,800 m^3/day)
Alt 3	Local sewer + ABR (population 18,000 and flow 1,800 m^3/day) + sewer line + WSP (population 18,000 and flow 1,800 m^3/day)
Alt 4	Local sewer + sewer line + WSP (population 18,000 and flow 1,800 m^3/day)

prevailing conditions of the late 1970s and by subsequently comparing it with the inflexible design that was implemented in reality. For the redesign, various alternatives for sanitation were included. Each alternative was evaluated by a standard cost evaluation model, which included a number of uncertain factors. The alternatives included an inflexible (base case) design, as well as flexible designs that used decision rules (DR) or Real Options. The effect of uncertainties on expected value of the project was quantified by an MCS and Real Options analysis.

Four sanitation alternatives were developed (Table 1). Alt 1 and Alt 2 were designs in which the capacity increased in three steps, while Alt 3 and Alt 4 were single phased designs in which the design capacity was installed in one step. The treatment technologies for Alt 1, Alt 2 and Alt 3 were a combination of on-site ABR and an off-site WSP. Alt 4 only had an off-site WSP.

Inventorisation and quantification of uncertain factors

Among the many factors that influence infrastructure expansion strategies, the following were considered to be the major ones: per capita wastewater generation, population growth rate and land price. Per capita wastewater generation was estimated at 80% of the per capita water consumption. The per capita water consumption and population growth rate were estimated using secondary data from reports (Government of Zambia 2012). Land prices were estimated as average deterministic values using Government Valuation Rates for bare land after 1995: €6/m^2 in the period 1970–1979, €18/m^2 from 1980–1989, and €54/m^2 from 1990–2000. A skewed normal distribution was chosen to incorporate uncertainty, since price increases are much more likely than price decreases (Table 2).

Development of standard cost evaluation model for the sanitation alternatives

A standard evaluation model in terms of wastewater to be treated per day as a function of wastewater generation rate and number of years was given by $Q = [P_0(1+r)^n \times q]$, where Q is flow in m^3/d, P_0 is initial population, n is number of years, q is the per capita wastewater generation in lpcd (litres per capita per day) and r is population growth rate. The population in 1970 was 4,200, and assuming a 5% yearly increase (Mulenga 2003) it was 6,800 in 1980, 11,100 in 1990 and 18,100 in 2000. The population growth rate was modelled using an MCS that drew a yearly growth percentage from the specified distribution

Table 2 | Design parameters with uncertainty range for use in the Monte Carlo simulation of design alternatives

Uncertain factors	Estimated deterministic value	Probabilistic representation
Population growth rate (%)	5	Normal, $\mu = 5$, $\sigma = 1.25$ (with cut-off at 2.5 and 7.5)
Per capita wastewater (lpcd)	100	Normal, $\mu = 100$, $\sigma = 25$ (with cut-off at 50 and 150)
Cost of land (euro/m^2) (Phase 1, Phase 2 and Phase 3)	6, 18, 54	Skewed Normal Location $\xi = 6,18,54$, Width $\varpi = 2,6,18$ Shape $\alpha = 5,5,5$ (with cut-off at 5 and 12)

μ = mean; σ = standard deviation.

(Table 2) and used that percentage for each of the 30 years of the planning period (1970–2000). The design flow was 1,800 m^3/d.

The total cost for the sanitation alternatives included the cost of the treatment systems, the main sewer pipe and land. Yearly operation and maintenance (O&M) costs for the ABR and sewer pipe were 2.5% of the construction cost. The evaluation model also included the Discount Cash Flow (DCF) method to calculate NPV. NPV was used to measure how much value is generated by carrying out a certain project, and it is given by: $FV = PV(1+d)^t$; where FV is future value, PV is present value, d is annual interest rates and t is number of years (Libaudiere 2012). The interest rate estimated from prevailing interest rates in most developing countries was assumed to be 6% per annum. Land cost was estimated using the government rate and was assumed to increase by a factor of 3 after each phase (10-year period). Opportunity costs were not considered in the cost estimations.

Land requirement, investment costs and O&M costs for WSPs were estimated using formulae from Thailand, $y = 183.4 \times 10^{0.513}$; where y is land requirements in m^2, $y = 0.00044 \times 10^{1.06}$; where y is construction cost in euros and $y = 10.1x + 40692$; where y is O&M cost in euros and x is design capacity in m^3/d (Singhirunnusom & Stenstrom 2010). The two cost equations had a correction factor applied to them by comparing the costs for WSPs in the 1970s to a case study in India (Arthur 1983). In addition, to apply them to WSPs to treat pre-treated wastewater, a factor was applied. According to Cavalcanti (2003), a WSP to treat pre-treated wastewater to a standard of unrestricted irrigation has a retention time of 10 days, while a traditional

WSP takes 30 days to treat. Based on these ratios, a factor of 0.3 (10/30) was applied.

Investment costs for ABR were collected from a pilot project in Zambia (Wasaza & Borda 2011). O&M costs were estimated to be 2.5% of the construction costs. Therefore, the total cost of each alternative was calculated as Cost of WWTP + Cost of sewer, where Cost of WWTP = construction cost + Land cost + O&M. The sewer construction cost was taken as $L(0.0024D^2 + 2.8788D + 300)$, where: Cost is calculated in rand (South African currency; 1 rand = 0.091 euro), L is length of sewer pipe (m) and D is nominal pipe diameter (mm) (Bester *et al.* 2011).

Benefits from the sanitation alternatives included the wastewater tariff paid by customers, income from biogas and income from use of sludge as fertiliser. The benefit from the wastewater tariff was estimated to be 30% of the water tariff. Income from biogas was estimated from the volume of methane gas produced per day using the procedure on sizing of ABR (Wafler & Seecon 2008). The volume of methane gas was converted to the amount of firewood that would have been used for cooking (FAO 1996). The cost of firewood was estimated using an online database. Income from the use of sludge as fertiliser was estimated by equating the volume of sludge to the amount of N or urea Vinh & Kien (2010).

Incorporating of uncertainties

Instead of using single deterministic values, a range of values for design parameters was used to incorporate uncertainties (Table 2). Experimental formulae X – aX and X + aX, which assume that the true value lies between the two extremes (cut-off points), was used. X is the deterministic average value. The assumed percentage level of uncertainty, a, was taken as 50%. This method is commonly used where measured data on the variables over longer periods are not available to allow plotting of actual trends for the design parameter and the projected trend over the same period for a realistic estimation of an uncertainty range (Gawasiri 2003). In between the cut-off points the distribution was assumed to be normally distributed (for population growth rates and per capita water consumption) or skewed normally distributed (for land prices) (Table 2).

Monte Carlo simulation and target curves

MCS with 10,000 runs was used as a tool to estimate the expected NPV (ENPV) from the standard evaluation model, given the specified uncertainty. The results (10,000 ENPV values) were plotted as a cumulative frequency distribution, or target curve. A target curve is a graphical presentation of performance metrics to help with decision-making based on the results from MCS. It takes a shape as shown in Figure 1 (de Neufville & Scholtes 2011). Target curves for various design options are helpful to managers as they can graphically show the likelihood of downside losses and the upside opportunities. The curve shows that there is a 10% chance of losing $15 million or more, which is named the value at risk (VAR). There is also a 10% chance of earning more than $9 million, which is named the value at gain (VAG). The graph also shows that the probability of breaking even is about 60%.

Real Options analysis

Flexibility in designs can be achieved in two ways. The first is 'in' system, where flexibility is achieved by making changes in the physical design. The second is 'on' system, where flexibility is achieved through management decisions, also named DR. The DR in this case was to not expand the treatment plant at planned and fixed moments in time, but to expand the treatment plant only when the actual wastewater flow reached 130% of the design capacity. The 'in' system flexibility was the purchase of extra land for expansion already at the start of the project. This is an example of a 'Real Option'. The management could choose to exercise the option to use that reserved land, or not, depending on the increase in wastewater to be treated and the costs of establishing a new plant in a new location. A combination of the two flexibilities was also evaluated by combining a DR and a Real Option.

Although flexibility can bring value to sanitation and treatment systems, it is imperative to compare its value to

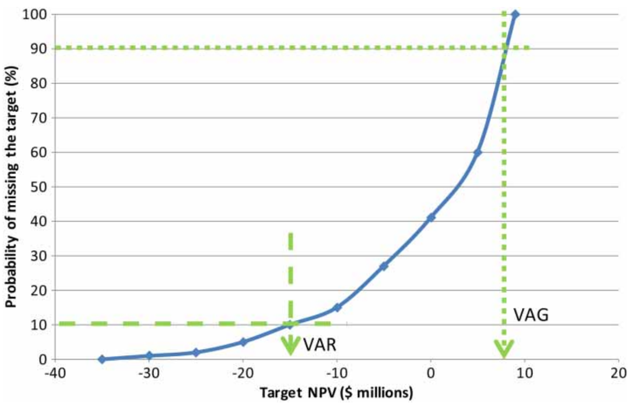

Figure 1 | Target curve for six-storey parking garage case study (de Neufville & Scholtes 2011); 10% value at risk (VAR) and 10% value at gain (VAG) indicated.

the real cost of acquiring it. If the real cost is less than the value of flexibility, it is worth purchasing the Real Option (Cardin *et al.* 2007). The values of flexibility were calculated using the formula $V_{flexibility} = MAX\ [0, ENPV_{flexible\ design} - NPV_{inflexible\ design}]$, where $V_{flexibility}$ is value of flexibility, and MAX is the condition expressing that flexibility can only be implemented if $V_{flexibility}$ is zero or above zero.

RESULTS AND DISCUSSION

Developing sanitation alternatives

The NPV for Alt 1, Alt 2, Alt 3 and Alt 4 was, respectively, €1,215,000, €145,000, €815,000 and −€297,000. Alt 1 had a higher NPV because in Phase I only a 10-year capacity ABR was constructed to cater for an initially smaller population and only later expanded as population increased. On the other hand, Alt 4 had a negative NPV, which means that the project is not worth taking. The negative NPV was attributed to the implementation of a large WSP from the start of the project, even though in the initial stages the population did not require that large capacity. This resulted in underutilisation of the design in the initial stages and cost inefficiencies.

Incorporating uncertainties in the developed sanitation alternatives and Real Options analysis

Uncertainties were incorporated in population growth, wastewater generation and land price for the sanitation alternatives (Table 2). MCS was run and the resulting target curves (Figure 2) show that Alt 1 gives a higher expected project value. Therefore Alt 1 was selected as the sanitation alternative where flexibilities were incorporated. The flexibility was created by the 130% flow DR, by purchasing extra land at the start of the project and by the combination of the two. The results show that in each case the target curve for the flexible system is to the right of the target curve for the inflexible system, meaning that the flexible systems perform better. Figure 3 shows the target curve for the combination of DR and Real Option. The values of flexibility for the three flexible designs were €929,000 (43%), €122,000 (10%) and €668,000 (35%), respectively. For all the performance metrics (Table 3), the alternative based on DR flexibility had better values compared to the other two. However, the combination of DR and the land option was selected due to additional benefits of keeping land as an option and the possibility of reselling

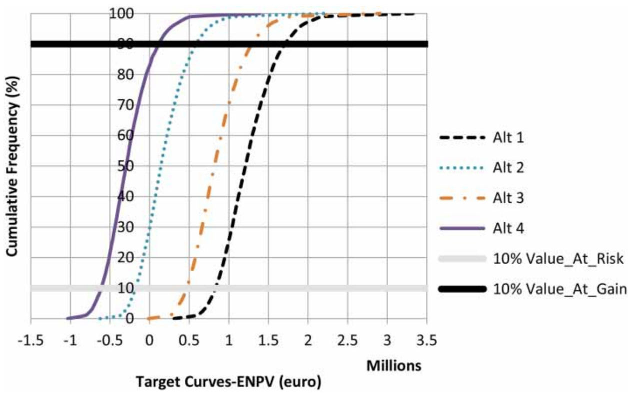

Figure 2 | Target curves for the four sanitation alternatives, without incorporating flexibility, but taking into account uncertainty in land prices, wastewater production and population growth.

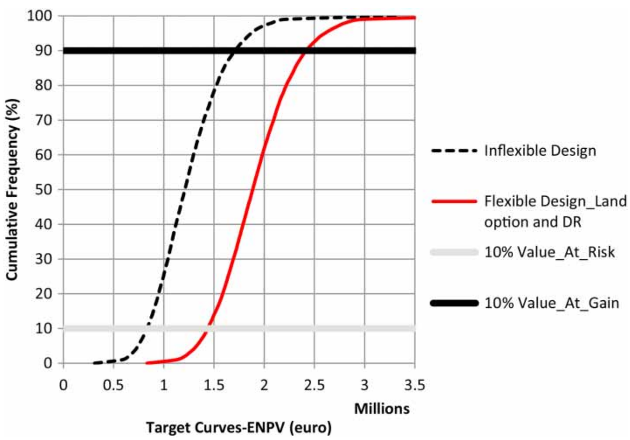

Figure 3 | Target curve for Alt1Flex with both the application of the decision rule of surpassing 130% load before the capacity is enlarged and the purchase of extra land as Real Option at the start of the project.

land at the end of the design period if expansion is not required.

The flexibilities identified in this paper are quite similar to those identified in the parking garage example by de Neufville & Scholtes (2011). In the parking garage example, the combination of 'on' and 'in' system flexibilities was applied and the DR was to expand the three-floor garage with an extra floor when demand exceeded capacity consecutively for 2 years. To implement this flexibility, the foundation and the columns were designed with adequate capacity to carry the extra load that would come with the increase in demand. There is a difference though, between the flexibility of enhancing the columns and foundation in the parking garage example and the flexibility of purchasing

Table 3 | Performance metrics for inflexible and flexible designs for Alt1Flex

		Flexible design		
Valuation metrics	**Inflexible design**	**Decision rule**	**Land option**	**Both**
ENPV (euro)	1,245,000	2,174,000	1,368,000	1,913,000
Probability of at least breaking even (%)	100	100	100	100
10% value at risk (euro)	832,000	1,639,000	960,000	1,438,000
10% value at gain (euro)	1,709,000	2,745,000	1,828,000	2,415,000
Value of flexibility (euro)	NA	928,000	122,000	668,000
Real cost of acquiring flexibility (euro)	NA	No cost	90,140	90,140

NA = not applicable.

extra land in this paper. Enhancing the columns and foundation are fixed physical features in the design. Where demand does not increase, the option cannot be traded for. On the other hand, the flexibility of purchasing land as an option can easily be sold off where the need for expansion does not arise. Reselling the land at the end of the design period where the need for expansion does not arise can increase the gain to about 60%. This makes flexible engineering designs in sanitation systems even more valuable because in either situation the flexibility brings value to the system.

Limitations

Non-availability of reliable local data was the major limitation in this study. Records on real investment and O&M cost for the WSP in Kaunda Square could not be found. Cost functions developed for Thailand were used to calculate the investment and O&M costs. Wastewater flow data for the study area were not available. Again interpolation of flow data was performed to establish the trend so as to determine the level of uncertainty in the input over the 30-year period. In this case, a ± 50% uncertainty range was assumed for the input factors, which might not be a true representative of the case study. All these limitations could have affected the values obtained from the analysis. Therefore, the results are primarily an illustration of the procedure to apply flexible designs to sanitation and wastewater treatment.

CONCLUSIONS

The value of wastewater treatment systems can be increased if uncertainties are considered during the planning and designing of these systems. By designing small, a flexible system is able to reduce losses in case of poor performance (in this case low wastewater generation). By incorporating flexibility, the system is also able to increase project value through expanding the system. Therefore, designing small in combination with Real Options may be a better alternative in similar cases as described in this paper than designing large. It is recommended that both designers and project funders consider this phenomenon in their project designs.

A number of input factors can be included in the analysis with the use of MCS. The type of flexibility that can be identified in a sanitation system includes DR and the extra land option. A combination of DR and extra land option gives an increase in expected value of 35% to the project. The possibility of reselling the land at the end of the design period where the need for expansion does not arise can increase the gain to about 60%.

Therefore, it can be concluded that applying both DR and land option as a form of flexibility in the case of Kaunda Square could have increased the value of the sanitation system by about 35%. Currently, managers of the WSP in Kaunda Square have challenges to take advantage of the increased wastewater flow by expanding the WSP due to non-availability of land. This could have been avoided had the system been designed with land as a Real Option.

REFERENCES

Arthur, J. P. 1983 World Bank Technical Paper Number 7: Notes on the Design and Operation of Waste Stabilization Ponds in Warm Climates of Developing Countries, p. 54.

Bester, A. J., Jacobs, H. E., Van der Merwe, J. & Fuamba, M. 2011 Unit cost functions for value estimation of waterborne sewer infrastructure. Article, Stellenbosch University.

Black, F. & Scholes, M. 1973 The pricing of options and corporate liabilities. *The Journal of Political Economy* **81**, 637–654.

Cardin, M. A., Nuttall, W. J., de Neufville, R. & Dahlgren, J. 2007 Extracting value from uncertainty: A methodology for engineering systems design. In: *17th Annual International Symposium of the International Council on Systems Engineering (INCOSE)*, San Diego, CA, Citeseer.

Cavalcanti, P. F. F. 2003 Integrated Application of the UASB Reactor and Ponds for Domestic Sewage Treatment in Tropical Regions. Doctoral thesis, Wageningen University, pp. 45–60.

Cortazar, G., Schwartz, E. S. & Salinas, M. 1998 Evaluating environmental investments: a real options approach. *Management Science* **44** (8), 1059–1070.

de Neufville, R. & Scholtes, S. 2011 *Flexibility in Engineering Design*. Massachusetts Institute of Technology, Cambridge, USA, MIT Press, p. 312.

de Neufville, D., Scholtes & Wang 2006 Real options by spreadsheet: parking garage case example. *Journal of Infrastructure Systems* **12**, 107–111.

FAO 1996 Biogas technology: Training manual for extension: Consolidated management services for Nepal, FAO/TCP/NEP/4415-T, 11 pp.

Gawasiri, C. B. 2003 Modern Design of Waste Stabilisation Ponds in Warm Climates: Comparison with Traditional Design Method. MSc thesis, Sch. of Eng., Univ. of Leeds.

Geltner, D. & de Neufville, R. 2012 *Uncertainty, Flexibility, Valuation & Design: How 21st Century Information & Knowledge Can Improve 21st Century Urban Development*. ESD Working paper series, MIT.

Gersonius, B. 2012 *The Resilience Approach to Climate Adaptation Applied for Flood Risk*. Delft University of Technology and UNESCO-IHE Institute for Water Education.

Government of Zambia 2011 Lusaka Master Plan, pp. 2–13.

Government of Zambia 2012 *Preparation of Feasibility Studies and Preliminary Design for Water Supply and Sanitation Projects*. Lusaka, Zambia, pp. 2–12.

Greden, L., Neufville, R. D. & Glicksman, L. 2005 Management of technology investment risk with real options-based design: A case study of an innovative building technology. In: *9th Annual Real Options Conference*, Paris, France.

Hemantha, H. & Anteneh, A. 2009 *Real Options in Nanotechnology R&D. Real Options in Engineering Design, Operations, and Management*. CRC Press.

House-Peters, L. A. & Chang, H. 2011 Water modeling: review of concepts, methods, and organizing principles. *Water Resources Research* **47** (5), W05401.

Libaudiere, P. 2012 Estimating project feasibility. Unpublished lecture notes, UNESCO-IHE, Delft, The Netherlands.

Linquiti, P. D. 2012 Application of Finance Theory and Real Option Techniques to Public Sector Investments Made Under Uncertainty: Research & Development and Climate Change. PhD thesis, University of California at Berkeley.

Maurer, M. 2009 Specific net present value: an improved method for assessing modularisation costs in water services with growing demand. *Water Res.* **43**, 2121–2130.

Maurer, M. 2013 Full costs, (dis-)economies of scale and the price of uncertainty. In: *Source Separation and Decentralization for Wastewater Management* (T. A. Larsen, K. M. Udert & J. Lienert, eds). IWA Publishing, London, pp. 85–100.

Mulenga, C. L. 2003 Understanding Slums: Case Studies for the Global Report on Human Settlements. The Case of Lusaka. http://www.ucl.ac.uk/dpu-projects/Global_Report/pdfs/Lusaka.pdf (accessed April 2015).

Singhirunnusom, W. & Stenstrom, M. K. 2010 A critical analysis of economic factors for diverse wastewater treatment processes: Case studies in Thailand. *Journal of Environmental Engineering and Management* **20** (4), 263–268.

United Nations Population Fund 2007 *State of the World Population 2007: Unleashing the Potential of Urban Growth Report*, New York, UNFPA.

Vinh, N. Q. & Kien, T. C. 2010 *Utilisation of Liquid Bio-Slurry as Fertiliser for Green Mustards and Lettuces in Dong Nai Province*. Final report, Dept of Agronomy, Ho Chi Minh City, pp. 29–30.

Wafler, M. & Seecon Gmbh 2008 Training material on anaerobic wastewater treatment: Capacity building for ecological sanitation in Bhutan, pp. 23–33.

Wang, S. 2014 Values of decentralized systems that avoid investments in idle capacity within the wastewater sector: a theoretical justification. *J. Environ. Manage.* **136**, 68–75.

Wasaza & Borda 2011 On-site treatment of community wastewater: P-locSan-WASAZA, ZM-PL-ND.

Woodward, M. 2012 The use of Real Options and Multi-Objective Optimisation in Flood Risk Management. PhD thesis, University of Exeter, Exeter, UK.

First received 2 February 2015; accepted in revised form 29 June 2015. Available online 14 July 2015