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# Uncertainty, Flexibility And Design: Real-Options-Based Assessment Of Urban Blue Green Infrastructure

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# UNCERTAINTY, FLEXIBILITY AND DESIGN: REAL-OPTIONS-BASED ASSESSMENT OF URBAN BLUE GREEN INFRASTRUCTURE

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Climate change and rapid urbanization requires decision-makers to develop a long-term forward assessment on sustainable urban water management projects. This is further complicated by the difficulties of assessing sustainable design and various design scenarios or technical alternatives from an economic standpoint. A conventional valuation approach for urban water management projects, like Discounted Cash Flow (DCF) analysis, fails to incorporate uncertainties such as amount of rainfall, unit cost of water, and technological uncertainties associated with future changes in scientific domain. Such approach also fails to include the value of flexibility, which enables managers to adapt and reconfigure a system over time as uncertainty unfolds.

This work describes an integrated framework to value investments in urban water management systems under uncertainty. It extends conventional DCF analysis through explicit considerations of flexibility in systems design and management. The approach incorporates flexibility as intelligent decision-making mechanisms that enable the system to avoid future downside risks (e.g. cutting potential losses by reducing initial investment in case rainfall amounts are lower than expected), and increasing opportunities for upside gains (e.g. novel water catchment technology efficiency better than expected) over a range of possible futures. The approach builds upon real options analysis technique to value flexibility, and adapts the technique to address practical considerations for the system at hand.

*Keywords*: Urban water management systems; Real options analysis; Engineering system design and evaluation

## 1. Introduction

Traditional water resources planning and analysis methods are based on requirements that are unrealistically deterministic [6]. Under such considerations, the most common practice consists of three phases. First, after collecting and analyzing relevant data, the most likely scenarios are identified, which include projections of major exogenous drivers of the system, such as markets, operational environment, government policy, climate change, etc. Then, according to those predictions, system designers generate design concepts and select design parameters that enable the system to perform optimally under the predictions. Economic evaluation of the design is then conducted, of which standard methodology, like discounted cash flow (DCF) analysis, optimization, sensitivity analysis, scenario planning, etc., is applied. The result achieved through the above practice is usually to be a "point optimal" design.

Flexibility in engineering design is one avenue to deal with uncertainty pro-actively. In this case, flexibility-also referred as real options-is defined as the "right, but not the obligation to change a project in the face of uncertainties" [14]. According to studies, a different perspective on system design and evaluation is characterized by considering a large number of possible future scenarios and taking pro-active actions to mitigate critical uncertainty sources. Number of applications of this methodology on large-scale infrastructure systems [2][1] have demonstrated that incorporating flexibility considerably improves life cycle performance of systems.

## 2. Motivation

Sustainable water systems are defined as "systems that are managed to satisfy changing demands placed on them (both human and environmental) now and into the future, whilst maintaining ecological and environmental integrity of water" [15]. However, for such emerging sustainable urban water management systems, we lack knowledge of how sustainable development should be attained and how sustainability of various technical systems should be assessed [5]. Traditional water resources planning and analysis methods based on fixed requirements may lead to an inaccurate picture of systems' performance and underestimate systems' ability to deal with uncertainties. Integrated Water Resource Management (IWRM) is proposed to support the management of alternative water resources from multiple perspectives [13]. However, IWRM does not explicitly accounts for the various sources of uncertainties, like instability of technical efficiency or fluctuation in rainfall that can impact the results. Some of the recent studies have taken one step further to recognize the exogenous and endogenous uncertainties faced by water systems, and even explicitly take those uncertainties into account when doing evaluation analysis. For example, Morimoto and Hope [9] [10] applied probabilistic techniques to the cost-benefit analysis of hydroelectric projects in Sri Lanka, Malaysia, Nepal, and Turkey, where they generate Net Present Value (NPV) distribution for design alternatives. However, their analysis did not incorporate pro-active actions to handle situations that might go beyond designers' predictions.

In light of the situation explained above, this study considers applying the different approaches from flexibility in engineering design to planning and assessment of urban water management systems. It has been indicated that incorporating flexibility into systems can bring about performance improvements ranging between 10% and 30% compared to standard design and evaluation approaches. These improvements are achieved because flexible designs enable systems to hedge against downside scenarios (e.g. by reducing the scale of initial capital expenditure) and prepare for the unexpected favorable conditions (e.g. by allowing for future expansion of the system). Indeed, there are some recent studies already moving towards this direction by using the real option approach to analyze water supply systems. For example, Zhang and Babovic [18] have conducted real option analysis to identify optimal water supply strategies, and Deng et al [22] applied the approach to optimize the development in context of blue green infrastructure.

Methodology followed in this paper is based on four steps to design and evaluating flexible engineering designs. The first step is building a baseline model, which is followed by uncertainty analysis where the major uncertainty factors are modeled using stochastic models. Subsequently, the flexible design is constructed and evaluated under the scenarios generated based on the uncertainty analysis. The last step is sensitivity analysis in which the performance of the system is re-evaluated under varied assumptions.

## 3. Introduction

In order to demonstrate application of the methodology introduced above, this study applies the approach to the feasibility analysis of a new water technology. Besides, the results from this section also work as a demonstration to show that the methodology is effective in terms of improving the performance of the urban water management systems. As an integrate part of an effort in investigation towards possible solutions for next generation water infrastructure systems, aiming to reduce damage caused by flood in rainy seasons and re-use of the run-offs, solutions under consideration entails technologies such as porous pavement and green roofs (see Figure 1). The technology allows rainwater to infiltrate into the sub-surface layer where it temporarily can be stored. This water is then either allowed to slowly seep into the ground, or be harvested as 'grey' water, or be channeled to reservoirs.

A test site has been chosen to conduct preliminary analysis on the possibility and limitation of this innovative solution. The site is located within the Kent Ridge campus of the National University of Singapore (NUS). The size of the catchment has an area of about 8.2 ha. The land use distribution of the catchment comprises of 41% of bushes, 35.5% of other green areas, mostly grass patches on mild and steep slopes, 16.8% of rooftop and 4.77% of road areas.

(a) (b)

Figure 1 Porous Pavement (a) and Green Roofs (b)

There are two considered design alternatives: a traditional expansion of the current drainage canal system (referred as design A), and alternative based on catchment measures such as porous pavement and green roofs (referred as design B). Apart from the advantage of generating revenue from the run-offs, which is not available in case of design A, there are other benefits brought by design B. The porous pavement surface and green roofs reduces frequency and peak flow rate of rainwater that enters drainage system. As consequence, less space is required for drainage and potentially causes less flooding damage [20]. However, since design B incurs a higher construction cost than design A, analysis is needed to understand the costs and benefits involved in those two design alternatives. Also, one aims to assess whether there is potential to further improve the economic performance of those two design alternatives under uncertainties by incorporating flexibility into the system.

| | | | |
|---|---|---|---|
| *Water Catchment Area* | | 82000 | $m^2$ |
| *Roads+Parking Area* | | 7500 | $m^2$ |
| *Roofs* | | 13000 | $m^2$ |
| *Steeved Upaved Area* | | 61500 | $m^2$ |
| *Time horizon* | | 50 | years |
| *Discount Rate (MARR)* | | | |
| | *For design A ($R_A$)* | 5.40% | % |
| | *For design B ($R_B$)* | 5.40% | % |
| *Current drainage Capacity* | | 1300 | $m^3$ |
| *Maximum projected storage capacity* | | | |
| | *design A* | 0 | $m^3$ |
| | *design B* | 5745 | $m^3$ |
| *Maximum drainage capacity* | | | |
| | *design A* | 5000 | $m^3$ |
| | *design B* | 1300 | $m^3$ |
| *Initial storage capacity* | | | |
| | *Baseline design A* | 0 | $m^3$ |
| | *Design A flex* | 0 | $m^3$ |
| | *Baseline design B* | 4596 | $m^3$ |
| | *Design B flex* | 2873 | $m^3$ |
| *Initial drainage expansion* | | | |
| | *Baseline design A* | 2700 | $m^3$ |
| | *Design A flex* | 1000 | $m^3$ |

| | | | |
|---|---|---|---|
| *Capacity expansion every time* | | | |
| | *design A* | 500 | $m^3$ |
| | *design B* | 575 | $m^3$ |
| *Cost for expansion every time* | | | |
| | *design A* | 10,000 | $ |
| | *design B* | 20,000 | $ |
| *Technology efficiency* | | | |
| | *Design B* | 40 | % |
| *Capital expenditure* | | | |
| | *Baseline design A* | 40,000 | dollars |
| | *Baseline design B* | 138,000 | dollars |
| | *Design A flex* | 18,000 | dollars |
| | *Design B flex* | 92,000 | dollars |
| *Flood Damage Cost* | | 0.5 | $/m³ |
| *Cost of the design B* | | | |
| *Operating costs* | | 1.0 | $/m³ |
| *Maintenance costs* | | 0.8 | $/m³ |
| *Cost of the design A* | | | |
| *Operating costs* | | 6000 | $/year |
| *Maintenance costs* | | 0.4 | $/m³ |

Figure 2 Assumptions on Parameters and Input Data

***Step 1: Baseline DCF Model***

The assumptions for the design parameters and input data needed for the baseline model have been based on communication with the design team members. While the assumptions may not be perfectly accurate, they are based on experienced designers' inputs, and reflect the essence of the system to some degree. For design A, there are no mechanisms to generate revenue and, we only need to quantify the costs involved. There are three categories of costs under consideration. Flood damage cost is calculated based on the occurrence of the rain events where the rainfall quantity exceeds the drainage capacity. Operating cost is assumed to be a fixed cost every year, while maintenance cost is a variable cost which links with the drainage capacity.

As to design B, more refined equations are developed since here we not only need to quantify costs but also need to define the revenue generated as cost savings by the "grey water" from the recycle use of rainfall water. In this case, the extra rainfall water that can neither be evacuated through drainage system nor be captured by the porous pavement and green roofs incurs flood damage cost. For the existing drainage system, the maintenance and operating costs are estimated using the same approach with design A. As for the porous pavement and green roofs, both operating cost and maintenance cost are determined by the storage capacity.

**Step 2: Uncertainty Analysis**

Uncertainty analysis addresses two research objectives: generate a large number of scenarios related to major uncertainty sources, and evaluate the performance of the design alternatives under those scenarios. To simplify the analysis, only two major uncertainty sources are identified at the current stage: price of water and rainfall. More uncertainty drivers can be introduced if needed.

For the unit price, the study calibrates it by Geometric Brownian Motion (GBM) Process. As for the scenarios of rainfall quantity, the following parameters have been chosen for simulation:

1) Intensity Duration Frequency (IDF) curves are used to generate rainfall scenarios. The time periods displayed on the left side of the figure is the return period for each specific scenario, which also indicate the probability that this scenario can happen.
2) Return period: 10 years. This is based on Public Utilities Board (PUB) code of practice for surface water drainage [**Error! Reference source not found.**]. Since the area is less than 100 ha, a return period of 10 years is sufficient.
3) In order to simplify the simulation process, two seasons are under consideration: dry season and rainy season. For the rainy season (Oct, Nov, Dec, Jan), the number of rainfall events in a month is an integer uniformly distributed between 4 and 30; while for the dry season (the rest of the time in a year), the number of rainfall events in a month is an integer uniformly distributed between 1 and 8.
4) Duration of a single rainfall event is uniformly distributed between 10 minutes and 700 minutes.

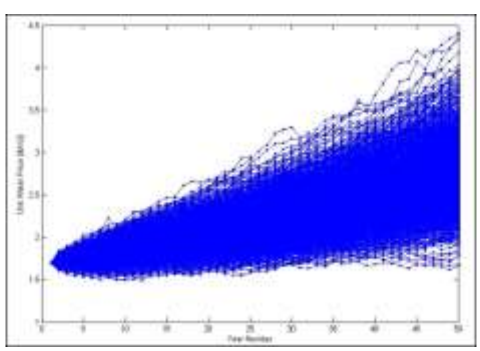

Figure 3 2000 Scenarios of Annual Unit Water Price

A deterministic analysis is also carried out, where the deterministic values of the unit water price, the average rain quantity of a single rain event, and the average number of monthly rain events are used to assess the NPV of the two design alternatives. And combined with results from the deterministic analysis and uncertainty analysis, a probabilistic distribution and a multi-criteria comparison table (see in Table 1) are constructed. In the multi-criteria comparison table, the P5 value indicates the VAR, and P95 value is the VAG. The standard deviation of ENPV is shown in the last column named as Sted.

As indicated from the above results, if only the deterministic values of the uncertainty sources are considered, although the ranking of design alternatives remains the same, the economic value of two design alternatives is severely overestimated. For design A, as shown in the cumulative probability curve, the likelihood that the realized NPV is smaller than the deterministic NPV is 1, which means there is no chance that such NPV can be obtained in real world. Since we take the average of uncertainty drivers (unit price, rainfall quantity and number of rainfall events), the NPV in the upside scenarios cannot be averaged out by the downside scenarios. In fact, since here the flood cost is incurred when rainfall quantity is higher than drainage capacity, as long as the assumed deterministic value of single rainfall quantity is lower than the drainage capacity, there is no flood damage cost resulted in the whole life cycle of the system. However, in the real world, the single rainfall quantity is subjected to high fluctuation, which leads to the presence of flood damage cost. The Flaw of Averages [12] is also indicated in the result of design B. As shown in Figure 4, the deterministic value of NPV is even higher than P95 value, which means the chance of obtaining such a high NPV in real world is very slim. As for the standard deviation, since design A is only subjected to the fluctuation in rainfall while design B is influenced by both rainfall and price of water, the variance of design A is relatively lower.

Table 1 Multi-metrics Table of Design A and Design B

| | **Deterministic NPV** | **ENPV** | **P5** | **P95** | **Sted** |
|---|---|---|---|---|---|
| **Design A** | -496,400 | -588,441 | -627,442 | -551,725 | 22,479 |
| **Design B** | 187,243 | -188,165 | -442,980 | 74,294 | 155,022 |
| $E[f(x)] \neq f(E[x])$ | | | | | |
| **Better Alternative** | Design_B | Design_B | Design_B | Design_B | Design_A |

**Step 3: Flexibility Analysis**

To improve further the life cycle performance of the two design alternatives, flexibility analysis is carried out. This is done by incorporating an expansion option into both designs A and B.

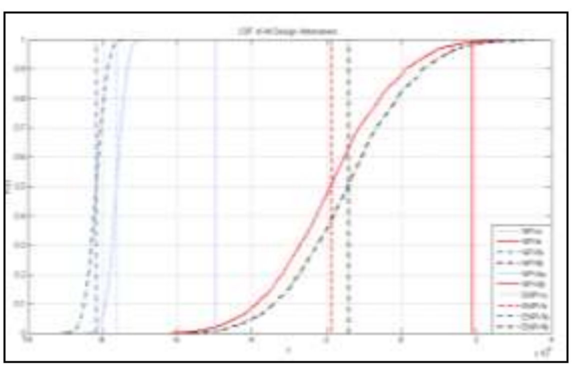

Figure 4 Distribution of NPV of All Design Alternatives

For design A, if the average of the monthly highest rainfall volume is higher than the drainage capacity in the past two consecutive years, the drainage capacity will be expanded by 5% of the maximum size until it reaches the upper bound (5000$m^3$). As for design B, if the highest monthly average rainfall volume is higher than the storage capacity in the past two consecutive years, the storage capacity will be expanded by 5% of the maximum size until it reaches the upper bound (5745$m^3$). Details of this expansion option are shown below.

The following analysis is carried out to evaluate the two flexible designs under the same 2000 scenarios generated from uncertainty analysis. By summarizing results from the flexibility analysis and the first two steps, Figure 4 and Table 2 are obtained. Figure 4 shows the distribution of the NPV of all alternatives, while Table 2 summarizes the information on the predefined metrics.

Table 2 Multi-metrics Comparison Table of All Design Alternatives

| | **Deterministic NPV** | **ENPV** | **P5** | **P95** | **Sted** |
|---|---|---|---|---|---|
| **Flex_A** | NA | -816,857 | -857,841 | -776,756 | 24,333 |
| **Flex_B** | NA | -142,165 | -396,980 | 120,294 | 155,022 |
| **Design A** | -496,400 | -588,441 | -627,442 | -551,725 | 22,479 |
| **Design B** | 187,243 | -188,165 | -442,980 | 74,294 | 155,022 |
| **Better Alternative** | Design_B | Flex_B | Flex_B | Flex_B | Design_A |

For design B, based on equation (2), the value of flexibility is $46,000. The results show that incorporating flexibility has brought 24.4% of improvement on ENPV compared with the baseline design. One interesting observation is that the value of flexibility corresponds to the difference in CAPEX between flexible design B and baseline design B, which indicates that baseline design B is designed with unnecessary extra storage capacity whereas flexible design B gains the advantage by reducing this redundant initial investment.

However, for design A, the flexible design makes the situation worse. As shown in the distribution curve in Figure 4, flexible design A is dominated by baseline design A. Table 2 provides summary of data whereas baseline design A is better than flexible design A under every criterion. The result may originate from the fact that currently the system has a relatively small drainage capacity. If a large capacity is not deployed at the beginning, there may be a huge amount of flood damage cost during the first several years, which may have a strong impact on the performance of the system. Also, the economies of scale may be another factor that benefits the decision of deploying a larger capacity at the beginning. The results here indicate that the incorporating flexibility into the system cannot guarantee a contribution to performance improvement under any circumstance. It is not accurate to make any generic conclusions.

**Step 4: Sensitivity Analysis**

After the flexibility analysis has been carried out, the best design alternative is selected and subjected to the sensitivity analysis. Namely, here the performance of the selected design alternative is subjected to the change of major assumptions made in Step 1.

For the case of the water catchment site, technical efficiency, operating cost, maintenance cost, flood damage cost, discounted rate and expansion cost are assumed to be the major influence on the performance of the system. Through communication with the design team, the lower and upper bound values of those factors are obtained (referred in Table 3).

Following this the flexible design B is reevaluated under those values. Since the influence due to the change of expansion cost is close to negligible, its values are hardly reflected in the diagram. This is because the current storage capacity is considered as sufficient based on the decision rule of the flexible design and yielding rare chance of expansion in the future. This finding here is also a confirmation on the conclusion made when explaining the value of flexibility of design B in the previous section that the advantage of flexible design B mainly comes from the reduction on excessive storage capacity. Based on the results shown in the diagram, the technical efficiency is considered as the factor carrying the most influential weight on the ENPV. Operating cost and maintenance cost also influence the ENPV to some degree. Compared with those three factors, unit flood damage cost and discounted rate have not shown so much impact.

Table 3 Bound Values of Major Influencing Factors

| Factors | Low | High |
|---|---|---|
| **Technical Efficiency** | 0.3 | 0.5 |
| **Operating Cost ($/m$^3$)** | 0.75 | 1.25 |
| **Maintenance Cost ($/m$^3$)** | 0.6 | 1 |
| **Flood Damage Cost ($/m$^3$)** | 0.4 | 0.6 |
| **Discounted Rate** | 4% | 6% |
| **Expansion Coast ($/m$^3$)** | 16000 | 24000 |

Another finding regarding to the decision making can be observed from the sensitivity analysis. Although the ENPV of flexible design B varies with the change of assumptions, even in the worst case it is still better than the design alternative A. This result indicates the robustness of choosing design B.

**4. Discussion and Conclusions**

This study describes a systematic methodology to consider flexibility in engineering design in urban water management systems. Through relevant literature it has been shown that the typical system design approach and evaluation may lead to suboptimal system performance and flaws in the evaluation results. This finding is also confirmed by uncertainty analysis of the water catchment site in this study, which shows that the deterministic analysis results in overestimated economic performance of design alternatives to a large extent. Another advantage of applying the described methodology into systems design is the effectiveness in improving the life cycle performance. The improvement is achieved by taking pro-active actions to mitigate critical uncertainty sources. For example, for the flexible design B in the application analysis, the extra benefits are brought by reducing the initial excessive capacity but enabling an expansion option, so that the system is able to avoid unnecessary initial investment if downside scenarios happen and meanwhile prepare for the upside scenarios. This action is similar to buying insurance for the system by which the distribution of the system performance is shifted to the right side. However, incorporating flexibility cannot always result in improvement on system performance. For example, flexible design A in the case study of the water catchment site makes the situation somewhat worse. The reason is that there are many additional factors one would need to consider. For example, cost of installing and maintaining the flexibility, loss of economies of scale when a smaller capacity is adopted, opportunity costs, etc., are all critical factors that can make a difference in the final conclusion. Designers need to be careful about the trade-offs between those factors so that the system performance can be maximized.

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