Flexible Design of Urban Water Distribution Networks

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Abstract

With increasing global change pressures (urbanization, climate change etc.) coupled with existing un-sustainability factors and risks inherent to conventional urban water management, cities of the future will experience difficulties in efficient decision making on the infrastructure development. Projections of future global change pressures are plagued with uncertainties which cause difficulties when developing urban water infrastructures that are insensitive to these global change uncertainties.

In this paper a methodology is presented that generates optimal urban water networks that are adaptable and sustainable under future global change pressures. These flexible systems are characterized by their ability to cope with uncertainties and have the capability to adapt to new, different, or changing requirements.

The flexible design tool presented in this paper consists of two major components. The first component is a methodology for developing scenario trees that reflect uncertainties associated with future demand for water. These scenario trees represent the uncertainty envelope associated with demand projections over time. The second component is an optimization model that considers the phased design of the water network, taking into account the likeliness of different demand scenarios over time (as expressed by the scenario trees). The GA based optimization model identifies the optimal staged development of the network that gives the optimal expected value of the network both in terms of costs and benefits.

The flexible design tool is then applied to the design of an example network with a design horizon of 30 year. The solution is presented as a phased design in 5 year stages and is compared with a design undertaken in the traditional way. This comparison clearly highlights the benefits and the efficacy of applying flexible design approaches for water systems operating under future uncertainties.

Key words: uncertainties, flexible design, scenario tree, optimization
1 Introduction

Traditional practice dictates that the capacity of a water distribution design is determined by projected design parameters (for example, water demand and deterioration of water supply networks). This method tries to minimize capital and operational costs whilst satisfying these pre-defined requirements (such as water quantity and sufficient service pressure). Optimization models have been developed to search for this optimal/near-optimal solution (Dandy et al. 1996; Savic and Walters 1997; Wu and Simpson 2001). As the standard approach is based on the projected future changes, it does not inherently offer flexibility to adapt to the uncertainty that the system may face and also it does not subsequently analyze the consequences caused by such unpredictable circumstances. In consequence, this approach fails to deliver satisfactory value if there are large estimation errors on the design parameters. For instance, if the designed capacity is excess than the actual required capacity, it will cause unnecessary additional investment cost and there will be a possibility of some real time operation problems.

Water distribution systems (WDS) consists of many functional components, which as a whole provide a satisfactory service and would exist for a very long time. With the characteristics of complexity and long life cycle, design and operation of WDS are potentially subjected to uncertainty within its long lifespan (Lansey et al. 1989; Kapelan et al. 2005) and as a result WDS in many cities suffer with the consequences of these future changes and uncertainty. Both technical and non-technical (e.g. political circumstances) factors determine the future changes and uncertainty. Furthermore due to the inter dependency of these factors, it is difficult to make an appropriate estimation of these uncertain parameters. Previous research has shown that the point forecasts almost never equate to the actual real term conditions (Babajide, de Neufville et al. 2009). Decision making on WDS design is often complicated by the difficulty in forecasting design parameters. This therefore calls for us to reconsider the way we design systems and develop new innovative methods that can counter the uncertainty.

De Neufville (2004) mentioned three basic ways to manage uncertainty. There are uncertainty control, passive protection and active protection. One example for uncertainty control in WDS is to develop more sophisticated forecasting model for design parameters, which tries to minimize estimation errors by analyzing and building up the relationships between uncertainty and different factors. The passive protection methods, like reliable design in WDS (Babayan et al. 2005; Jayaram and Srinivasan 2008; Giustolisi et al. 2009), make system insensitive to wide range of future operational conditions. Though the uncertainty control and passive protection methods protect system performance from uncertainty to some degree, there are still some difficulties when applying in WDS. First the relationships between uncertainty and factors in WDS are complex and not easy to be captured. Also, uncertainty is not always a negative to be mitigated, but can also be a positive that may be exploited (de Neufville 2004). Therefore, active protection methodologies such as flexible design are advisable, which can give designers the ability to use the value of upside opportunity in addition to mitigation of down side risk. Flexible
design methodology delivers a system with the capability of responding to future changes in a more cost-effective way, thus decision-makers with built flexibility tools can reduce risks but may also benefit from upside opportunities, which as a whole will make the system deliver more value in an uncertain world.

Recent research has demonstrated the application capability of flexibility in system design. Zhao and Tseng (2003) showed a successful application of flexibility in a car park design. The flexibility (enhanced foundation and columns) was embedded at the beginning of a car park construction, which provided options for future expansion. The uncertain car park demand was modeled by Monte Carlo simulation and the flexibility value was calculated by comparison on the expected profit between a baseline design and flexible design. Zhao et al. (2004) presented a multistage stochastic model for decision making in highway development, operation, expansion, and rehabilitation. The model used real options as flexibility sources in both development and operation phases of a highway and Monte Carlo simulation to account for the evolution of uncertainties. This approach achieves decision-making optimality by maximizing the expected profit. The applications are also in communications satellite constellations (De Weck et al. 2004), space systems (Nilchiani and Hastings 2007), mining operations (Cardin et al. 2008), offshore oil platforms (Lin 2008), transportation network design (Ukkusuri and Patil 2009), here just name a few. These fruitful applications in other fields demonstrate that flexibility has value for uncertain future circumstances and should be implemented in system design. However, its use in WDS design is still in its infancy and there is a gap in the literature, which requires further investigation.

This paper tries to develop a methodology that gives an opportunity to decision makers to design flexible water distribution system. Unlike robust design which characterizes a system ability to be insensitive towards changing environments, flexible design deals with uncertainty proactively and gives system managers the “right but not obligation” to do implement actions to respond to future changes. With embedded flexibilities, the system can adapt to changes more pragmatically and efficiently. The proposed flexible design methodology involves uncertainty modelling and flexibility based optimization by Genetic Algorithms (GA). The uncertainties are modeled by scenario tree method. And then the flexibility based optimization tries to find the optimal combinations of identified flexibility sources for the assumed possible future circumstances. The system generated provides efficient use of resources in the current climate, whilst also allowing for future potential changes within its life cycle. The main contributions of this work are 1) modeling of uncertainties explicitly on multi-stage; 2) identification of different flexibility sources for assumed uncertainties; 3) development of a flexibility-base optimization using GA.

2 Proposed Method

The proposed flexible design methodology recognizes the uncertainties and builds flexibilities in water distribution system with ability to respond to future changes in timely and cost-effective manner. This method consists of two major components. The first component is a methodology for modeling of uncertainty using scenario tree. The second
component is flexibility based optimization model that considers the phased design of the water network and the likeliness of different scenarios within the life cycle. This GA based optimization model identifies the optimal staged development of the network that gives the optimal expected value of the network both in terms of costs and benefits. The proposed approach allows the WDS to be optimally responsive to the future scenarios. The framework of proposed method is presented (see Figure 1).

![Figure 1. Flexibility analysis framework](http://www.ascelibrary.org)

### 2.1 Uncertainty in WDS and modeling

There exist many uncertainties during the life-cycle of a system. De Weck et al. (2007) categorize the uncertainties into endogenous ones and exogenous ones. Further suggestions were given that the uncertainties during the system design and operation should be described by separate models and then to be brought together to use an integrated uncertain model. This paper just focuses on uncertain water demand, as water demand is one of the parameters to determine the required capacity of the water distribution system and is difficult to make estimation (Obradovic and Lonsdale 1998). This uncertain parameter influences the value of flexibility in WDS significantly, so the uncertainty on water demand should be expressed using proper methods when designing flexible WDS. Since the major emphasis of this paper is given on developing the methodology that can be used in designing flexible water distribution system, the simplest forecast model (per capita requirements method) is chosen for the demand prediction (more forecast method see Baumann et al. 1997). The forecast method used depends only on the population:

\[
Q_{t+n} = b \cdot P_t (1 + r \cdot n)
\]  

(1)

Where: \(Q_{t+n}\) is the average daily aggregate water use, \(P_t\) is the residential population in service area at year \(t\), \(b\) is the per capita water use, \(n\) is the forecast period, and \(r\) is the annual population growth rate during each forecast period.
In the employed scenario tree method, different water demand scenarios with specific happening probability are generated based on different annual population growth rates. One example scenario tree with two forecast period is provided (see Figure 2). Starting from current state (known as root node), there are two possible future states for the next stage related to different water uses due to different population growth rates.

\[
Q_{\eta_1}(r_1)^n = \frac{Q_{\eta_1}(r_1)^0}{(1 + n \cdot r_1)^i}
\]

where:
- \(i\) is the number of periods that water demand increases with \(r_1\)
- \(j\) is the number of periods that water demand increases with \(r_2\).

**Figure 2.** Two-period scenario tree

In this example, \(Q_{\eta_1}(r_1)^n\) is initial water demand, \(r_1\) and \(r_2\) are two different annual population growth rates. The superscript on \(r\) expresses the number of periods that water demand increases with \(r\). For a general problem with one forecast period of \(n\) years, the future state in each stage would be:

\[
Q_{\eta_1}(r_1)^n = \frac{Q_{\eta_1}(r_1)^0}{(1 + n \cdot r_1)^i}
\]

(2)

Where: \(i\) is the number of periods that water demand increases with \(r_1\) and \(j\) is the number of periods that water demand increases with \(r_2\).

### 2.2 Flexibility-based Optimization Model

#### 2.2.1 Flexibility Sources

There are two types of flexibility: flexibility “in” a system and flexibility “on” a system (Wang and de Neufville 2004). Flexibility “in” a system relies more on technical components within the system while flexibility “on” a system uses operational and managerial strategies. Both flexibility “in” and “on” the system allow more delivered value. Many flexibility sources for WDS could be considered to deal with the uncertain water demand. In this work three general flexibility sources are identified and discussed in more detail: staged deployment strategy, scenario planning strategy and capacity expansion flexibility.

The first flexibility source is staged deployment strategy that allows developing the system progressively. The uncertain parameters on different stages are analyzed, then decision on system development can be made to adapt to uncertainty in the best possible manner. Since uncertain parameters are observed through time, the risks from the uncertainty are reduced. Furthermore, an economic opportunity is represented because this strategy tries to minimize
the life cycle cost by pushing the expenditures towards future times as much as possible which can be discounted.

The second flexibility source is scenario planning strategy that allows setting up different system development packages to different water demand scenarios. The scenario planning considers the value of information and captures the nature of decision for engineering system that it is a dynamic process yet not a static one, so leads to a design choice that is more suited to different future scenarios, which clearly improves the overall value of the system.

The third flexibility source is capacity expansion flexibility that considers the possibility of system expansion. When demand grows temporally and spatially, the additional system capacity should be ready, which normally requires large expenditures if the capacity expansion flexibility is not included in the initial system. Therefore it is necessary to build capacity expansion flexibility in the system to service more demand in a more cost-effective way, which enables system to expand to meet future requirement with relative ease, thus potentially improves the life cycle value of the systems.

2.2.2 Measure of flexibility

An important part of flexible design is defining measurable value delivery by the system. In general, the service of a water distribution system is hard to be measured only by monetary value. In this paper, the uncertainty level was predefined by the scenario tree method. Furthermore, we assumed that the benefit from system modification for the next stage pre-defined uncertainty level is always larger than the expenditures. Then the flexibility value can be shown using an indirect indicator: life cycle cost. The life cycle cost includes the cost from the initial system and all other costs from switching system for the next stage. As a result, the flexibility value maximization could be realized by minimizing the system life cycle cost.

2.2.3 Mathematical model for flexibility

The overall optimization objective for flexible WDS is to minimize the expected life cycle cost on various design variables \( x \) while at the same time meeting the specification of providing enough water with sufficient pressure under the pre-defined uncertain level. Consider system life cycle of \( T \) and time window of \( \Delta t \). The water demand state \( j \) in stage \( i \) is expressed by a vector, \( Q_j^i \). \( \{ j \in N_{state} \text{ and } i \in [0,1,\ldots,T / \Delta t] \} \). Full version for \( Q_j^i \) is \( [q_{j,1},q_{j,2},\ldots,q_{j,N_{state}}] \). The uncertain water demand would be modeled by scenario tree method. One scenario, \( s \), represents one possible water demand evolution process: \( [Q_0^s,Q_1^s,\ldots,Q_T^{s/\Delta t}] \). The scenario tree, \( S \), includes all (or at least the most interesting) possible futures. Here we define “decision making scenario” to include the inputs for the optimization model on all stages for one specific scenario \( s \): \( [Q_{0,s}^s,Q_{1,s}^s,\ldots,Q_{T/\Delta t,s}^s] \). Then the mathematical formulation for this flexibility-based optimization is:
\[
\begin{align*}
\min & \left\{ \sum_{s \in S} \sum_{j=1}^{T} P_{s_j} \cdot f(x_{s_j}^{j}) \mid x_{s_j}^{j} \in X \right\} \\
\text{s.t.} & \sum Q_{In} - \sum Q_{Out} = q_{i,s_i}^{*} \\
& \sum h_f - \sum E_p = 0 \\
& H \geq H^{\text{min}}
\end{align*}
\]

Where: \( R \) is discount rate, \( P_{s_j} \) is the probability of scenario \( s_i \), and \( f(\cdot) \) is the cost function. Eq (4) and Eq (5) are continuity constraint on each node and energy constraint for each loop, which will be solved by Epanet (Rossman 2000).

3 Model Application on Hypothetical Network

The flexible design methodology was applied to one hypothetical network (see Figure 3). Water demand was considered as uncertain parameter and then the result from flexible design was compared with two rigid designs. The problem of flexible design was formulated as a multi-stage decision model and simply assumed that only the envelope of the uncertain parameters is known in the first stage. The proposed method is to help the decision maker find the best system development strategy, which has the minimum expected life cycle cost.

![Network layout for the case study](image)

Figure 3. Network layout for the case study

The network topology is pre-determined. This network needs to be phase designed for 30 years which is divided into three design periods. The network consists of 7 nodes in the first period, 10 nodes in the second period and 13 nodes in the third period. The only supply source is a reservoir with the fixed hydraulic grade line (HGL) elevation of 60 m. The minimum pressure requirement on each demand node is 30 m at instantaneous peak flow, which is 1.8 time average day flow. The fire flow condition is not considered in the application. There would be 18 pipes in the network finally, the lengths of which are all 2000 m and the Hazen-Williams coefficient \( C \) values of which are 130 (constant in all
stages). 10 commercial pipes are available in the market, the costs of which are shown in Table 1. Costs are given in $/ft. Cost for new pipes are given in the column labeled “new”. Costs for replacing pipe in developed area are given in the column labeled “urban”.

### Table 1. Costs for Pipe Laying (Walski et al. 1987)

<table>
<thead>
<tr>
<th>Pipe Diameter (in)</th>
<th>New ($/ft)</th>
<th>Urban ($/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>12.8</td>
<td>26.2</td>
</tr>
<tr>
<td>8</td>
<td>17.8</td>
<td>27.8</td>
</tr>
<tr>
<td>10</td>
<td>22.5</td>
<td>34.1</td>
</tr>
<tr>
<td>12</td>
<td>29.2</td>
<td>41.4</td>
</tr>
<tr>
<td>14</td>
<td>36.2</td>
<td>50.2</td>
</tr>
<tr>
<td>16</td>
<td>43.6</td>
<td>58.5</td>
</tr>
<tr>
<td>18</td>
<td>51.5</td>
<td>66.2</td>
</tr>
<tr>
<td>20</td>
<td>60.1</td>
<td>76.8</td>
</tr>
<tr>
<td>24</td>
<td>77.0</td>
<td>109.2</td>
</tr>
<tr>
<td>30</td>
<td>105.5</td>
<td>142.5</td>
</tr>
</tbody>
</table>

Uncertain average water demand is modeled in 6 periods with time window of 5 years. The initial demand on each node is assumed as 15 L/s, which will increase by an annual growth rate either of 2% or 4% with a same probability of 50%. The decision making scenario is generated from the full scenario tree (see Figure 4).

![Figure 4](image-url)

**Figure 4.** Decision making scenario for the case study

The system will be developed on three different methods. The Rigid design 1 is developed based on the assumption that the high demand scenario always happens in the system lifecycle. The Rigid design 2 is generated to have optimal performance under the most likely scenario. The objectives of these two approaches are to find the least-cost solution under the specific scenario (see Table 3 for more detail).
The flexible design would be generated from the flexible design methodology in this paper. With the decision making scenarios, identified flexibility sources and specific cost related to different development plan, more detail mathematical formulation for Eq (3) can be:

\[
\text{Minimize } \left\{ \sum_{s \in S} P_s \sum_{t=1}^{3PP} \sum_{j=1}^{PP} S_j \left( \frac{\text{Unit} (D_{i,j}^t) \cdot L_j}{(1 + R)^{t \cdot \Delta t}} \right) D_{i,j}^t \in D \right\}
\]  \hspace{1cm} (7)

Where: the discount rate is set as 5%. The decision variables \( S_j \) is the replacement status of the pipe \( j \) in year \( t \) (\( S_j^t = 1 \) if pipe \( j \) replaced in year \( t \), \( S_j^t = 0 \) else), for the first stage the replacement status of all the pipes is known and set as \( 1 \), and \( D_{i,j}^t \) represents the diameter of pipe \( j \) in year \( t \), which is discrete, taking any values from a predefined vector \([D_1, D_2, \ldots, D_{\text{max}}]\).

Additional constraints for this non-return and dependent decision process are:

\[
D_{s=1}^1 = D_{s=2}^2 = \cdots = D_{s=27}^3, \hspace{1cm} j = 1, 2 \ldots PP_1
\]  \hspace{1cm} (8)

\[
D_{x=0}^2 = D_{x=9}^2 = D_{x=18}^2, \hspace{1cm} x = 0, 9, 18 \text{ and } j = 1, 2 \ldots PP_2
\]  \hspace{1cm} (9)

\[
D_{x=3}^3 = D_{x=12}^3 = D_{x=21}^3, \hspace{1cm} x = 0, 3, 6, 9, 12, 15, 18, 21, 24 \text{ and } j = 1, 2 \ldots PP_3
\]  \hspace{1cm} (10)

This flexibility-based optimization is coded in C and solved by GA. GA provides an effective means to solve very large, path dependent, and non-convex problems (Holland 1975) and is proved to be efficient in water distribution system optimization (Dandy et al. 1996; Savic and Walters 1997; Wu and Simpson 2001; Vairavamoorthy and Ali 2005; Kadu et al. 2008).

Table 2 compares the results of the optimal rigid and the best flexible designs. Table 3 gives details about the optimal rigid 1, 2 and the best flexible design. It demonstrates that flexible designs provide a range of advantages over rigid designs. The flexibility value here is defined as the performance improvement and expected life-cycle cost reduction between the rigid designs and flexible design. In this case, the best flexible design:

- Search an initial system platform which can evolve to different future states (the initial system configuration is developed based on a little modification requirement for the future scenarios). The model also check the decision that compare whether it is cheaper to lay big pipe in the platform configuration than to lay small initially and then replacing later. For example, the model output shows that laying small pipe (6 inch) first than replacing with a big one (10 inch) for the pipe “04-05” is cheaper than laying big pipe (10 inch) initially.
• Improve the expected value of the project (Reduces the expected life-cycle cost about 9.1%, compared with the optimal rigid 1)

• Improve the ability of system to avoid expected risk (The optimal rigid 2 has expected 1.39% supply deficiency and maximum 12.17% supply deficiency)

Table 2. Summary of performance metrics of optimal rigid 1, 2 and flexible designs

<table>
<thead>
<tr>
<th>Value Metric</th>
<th>Rigid 1 (High Demand)</th>
<th>Rigid 2 (Most Likely Demand)</th>
<th>Flexible (Uncertain Demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (Deficiency)</td>
<td>None</td>
<td>1.39%</td>
<td>None</td>
</tr>
<tr>
<td>E (PV(Cost))</td>
<td>3.49 (million $)</td>
<td>3.26 (million $)</td>
<td>3.33 (million $)</td>
</tr>
</tbody>
</table>

Table 3. Lists of the optimal Rigid 1, 2 and the best flexible design

<table>
<thead>
<tr>
<th>Start Node</th>
<th>End Node</th>
<th>Optimal Rigid 1</th>
<th>Optimal Rigid 2</th>
<th>Best Flexible Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>01</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>04</td>
<td>16</td>
<td>18</td>
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<td></td>
<td>01</td>
<td>30</td>
<td>24</td>
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<tr>
<td></td>
<td>02</td>
<td>6</td>
<td>14 (10&lt;sub&gt;20&lt;/sub&gt;)</td>
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<tr>
<td></td>
<td>05</td>
<td>20</td>
<td>18</td>
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<td>02</td>
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<td>07</td>
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<td>11</td>
<td>14</td>
<td>10</td>
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Note: 6 (10<sub>20</sub>) means replacing the pipe with diameter 6 inch using the pipe with diameter 10 inch on year 20.
4 Conclusions

This paper demonstrates an approach of designing flexible water distribution system. The method integrates uncertain modeling and flexibility based optimization model for developing a system which has the ability to cope with uncertainties and have the capability to adapt to new, different, or changing requirements. In this paper, a scenario tree was used to model uncertain water. Then different possible flexibility sources were discussed. Flexibility sources considered for uncertain future water demand are staged deployment strategy, scenario planning strategy and capacity expansion flexibility. Finally, the uncertain model and identified flexibility were integrated into an optimization model (GA-based) to determine the solution with minimum expected life cycle cost.

In particular, the method was applied in a hypothetical water distribution network, and the comparison between flexible and non flexible system of these networks has been done. The rigid designs without considering flexibility lead to higher lifecycle cost and poor performance when conditions in the future change. However, the flexible design using the developed methodology shows significant expected lifecycle cost saving and expected performance improving. Furthermore, the application in the paper shows higher computational efficiency. Thus it is proved that the developed method is efficient in designing and managing flexible water distribution system.

Reference


