Economic Efficiency and Equity Aspects of Urban Water Systems

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Sustainable Urban Water Infrastructure Systems

• Water Supply
  – Changing nature of urban water use in Florida and elsewhere
    • Indoor water use declining from 70 to 40 gpcd
    • Outdoor water use is increasing due to rapid growth in automatic sprinklers
    • Majority of urban water use in Florida will be for irrigating landscapes
    • State is requiring use of alternative water supplies after 2013
  – Dual water systems may be essential

• Waste Water
  – CSO and SSO control
  – Reuse favors decentralized systems to offset high piping costs

• Storm Water
  – Evaluation of LID & Other BMPs-Are decentralized systems the answer?
  – Stormwater Reuse

• System Integration
Masdar, UAE - City of the Future?

- 50,000 people
- No cars
- Solar powered
- Desalination
- 60% less water use
- Maximize reuse
- 1st phase completed in 2009
Economics and Related Tools to Evaluate Urban Water Systems

• Overview
• Engineering economics
• Microeconomics
• Optimization methods
• Cost allocation and finance
• Risk optimization
Five Feasibility Tests

• Technical-can it be built?
• Economic-should it be built (do the total benefits exceed the costs to whomsoever they may accrue)?
• Financial-who will pay and how will the costs be allocated?
• Environmental-what are its impacts and how are they to be remediated?
• Socio-political-is there sufficient public support across the various stakeholder groups?
Tools for Economic and Financial Analysis

- **Engineering economics** shows how to evaluate the time value of money and compare discrete alternatives.
- **Microeconomics** provides a theoretical framework.
- **Optimization methods** show how to find the optimal (least cost or maximize net benefits) solution for complex real world problems with a large number of discrete choices or blends of choices.
- **Game theory** allows us to evaluate the winners and losers to address equity and financial issues.
- **Risk analysis** methods show how to evaluate the reliability of the selected solution. How safe is it?
Engineering Economics


• Benefit-cost analysis and cost-effectiveness are fundamental to engineering
Engineering Economics

• Traditional required course for undergraduate engineering students. Often the only “economics” that they learn

• Topics covered
  – Time value of money
  – Interest rates and compounding
  – Personal finance
  – Simple benefit-cost analysis
  – Making decisions among a small number of discrete, mutually exclusive options

• Simple to do on a SS
Engineering Economics Examples

• Buy a new toilet that uses less water?
• Buy a more fuel efficient vehicle?
• Find the most cost-effective combination of low impact development stormwater controls
• Find the life cycle cost of gasohol including environmental impacts
• Invest in air pollution controls to save lives vs. investing in other public health options
Microeconomics

• Reference

• Economics—the study of the allocation of scare resources

• Normative social science that provides guidance on how people buy and sell commodities and how market prices evolve based on the relative scarcity of the resources
Resource Allocation

Find allocation of water that maximizes total benefits – total costs, or MB = MC. MB = demand curve and MC = supply curve.
Total water supply benefits—diminishing marginal returns

\[ B = 2.163Q^{0.3} \]

\[ R^2 = 1 \]
Nature of Residential Water Use - Average of 12 U.S. Cities

Gallons Per Capita Per Day

- Dishwasher: 1.0
- Bath: 1.2
- Other domestic: 1.6
- Leak: 9.5
- Faucet: 10.9
- Shower: 11.6
- Clothes washer: 15.0
- Toilet: 18.5
- INDOOR: 69.3
- OUTDOOR: 100.8
- UNKNOWN: 1.7
- TOTAL: 171.8
Effect of Price on Residential Water Demand in Florida
(Adapted from Whitcomb 2005)
Summary of Supply-Demand Analysis

• We have a “demand” for a product, not a “requirement”. Demand depends on its price. As products like water and oil become more scarce, then people will tend to use less of them.

• Economic principles are very helpful in allocating scarce resources through the marketplace rather than by legislative fiat.
Early Critique of the California State Water Project

- No need for project if water markets were allowed to exist?
- 80% of water goes to irrigation at subsidized rates
Limitations with Classical Economics Approach

- Hard to find a mathematical representation of the production functions that describe the input-output relationships
- Weak databases on consumer behavior
- Major theoretical breakthrough was linking economic theory and linear programming
  - Shadow price of LP model can be used to estimate the marginal value of water
Early Academic Programs in Economics and Systems Analysis

• Harvard water program began in the late 1950’s and focused on water resources projects

• Northwestern U., led by Abe Charnes, promoted use of LP to optimize wastewater treatment plants (Walter Lynn-1962) and regional wastewater treatment (Rolf Deininger-1964)

• UCLA program led by Richard Bellman and Warren Hall promoted the use of dynamic programming (early 1960s)
4. Artificial Water Crisis in Southwestern U.S.? 

Heaney (1968)

- Prior appropriation water doctrine encourages overuse
- Federal water subsidies encourage waste
- Water markets could eliminate “shortages”
- Majority of water is allocated to low value irrigation that worsens salinity problems
- Found marginal value of water using a large LP
General Form of an Optimization Problem

MAX (of MIN): $f_0(X_1, X_2, \ldots, X_n)$

Subject to:

- $f_1(X_1, X_2, \ldots, X_n) \leq b_1$
- $\vdots$
- $f_k(X_1, X_2, \ldots, X_n) \geq b_k$
- $\vdots$
- $f_m(X_1, X_2, \ldots, X_n) = b_m$

Note: If all the functions in an optimization are linear, the problem is a Linear Programming (LP) problem.
Computer Solution of Optimization Problems

• Pre-1990. Total reliance on specialized optimization software that required a high level of mathematical and computer programming skills

• 1990-2000. Optimization solvers in spreadsheets expanded the user base tremendously

• 2000-2005. Excel Solver add-ins that incorporate evolutionary algorithms that can be used to solve any type of problem independent of its mathematical structure & link directly with simulation models

• 2009-. Software evaluates the nature of the problem and selects the best single or combination of methods to use
Good Reference

Some Categories of LP Problems

- Transportation Problem-Spatial Analysis – Very popular for environmental and water problems
- Blending Problem-e.g., blending chemicals to get a desired outcome
- Production and Inventory Problem-Any problem that has storage with multiple time periods, e.g., equalizing storage prior to treatment
Computer-based optimization methods that have been used during the past 60 years

- Linear programming
- Integer programming
- Multi-objective and goal programming
- Nonlinear programming
- Evolutionary programming
Impact of Evolutionary Solvers

• Prior to the mid-1990’s, we had to force fit all problems into the mathematical requirements of the classical optimization techniques of linear and nonlinear programming. However, few realistic design problems conform to these mathematical conditions. Thus, we only had a limited influence on design.
Some EES Applications of Mathematical Optimization

- Design water distribution systems
- Design sanitary and storm sewer systems
- Route garbage trucks
- Air pollution control in paper & pulp industry
- Locate and size BMPs to restore an urban stream
- Optimal design and operation of reservoirs to provide water supply, flood control and water quality control as part of the Everglades restoration
- Choose the “best” parameter estimates for a simulation model
- Allocate the cost of a multi-purpose project using game theory
Integration of Simulation and Optimization in Excel

• Use the optimizer to automate the what-if simulation analysis to find the best solution
Simulation/optimization Model
Optimized Design Curve
Advantage of Evolutionary Solvers (ESs)

• ESs can be used for any problem independent of its mathematical structure.

• ESs favor the use of integer variables, just the opposite of classical optimization wherein we prefer to have continuous variables.

• We don’t need equations to represent functional relationships. We can use lookup tables.
Efficiency and Equity

• Efficiency-Maximize the size of the pie
• Equity-How to divide the pie among stakeholders? E.g., for two people dividing the pie,
  – You cut, I pick first.
• Must assign ownership before exchange can occur
• Economics ignore equity issues
Cost Allocation

• Optimization methods allow us to increase economic efficiency by taking advantage of:
  – Economies of scale
  – Assimilative capacity of the receiving environment
  – Excess capacity in existing facilities
  – Multi-purpose opportunities
  – Multi-group cooperation

• Overall solution is a complex blend of management options that involve many stakeholders who need to somehow share the cost of this project

• Result is a complex cost allocation problem
Cost Allocation Problem
How to apportion the total cost among various purposes and/or groups in an efficient and equitable manner?

Examples

- How to pay for a regional water supply system that serves multiple cities
- Apportioning the cost of a wastewater treatment plant among the pollutants that are removed
- Apportioning the cost of a multipurpose reservoir among water supply, flood control, and hydropower
- Assessing “fair” impact fees on new developments
Cost Allocation in Urban Water Supply Cooperative Game Theory

Table 5-9. Construction cost allocation for indoor, outdoor, and fire protection demand

<table>
<thead>
<tr>
<th>Demand pattern</th>
<th>Max</th>
<th>Min</th>
<th>Max-Min</th>
<th>Allocated</th>
<th>Savings</th>
<th>( \beta(i) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>I</td>
<td>$266,542</td>
<td>$22,317</td>
<td>$244,225</td>
<td>$163,330</td>
<td>15%</td>
<td>$103,212</td>
</tr>
<tr>
<td>O</td>
<td>$227,744</td>
<td>$5,180</td>
<td>$222,563</td>
<td>$133,686</td>
<td>12%</td>
<td>$94,057</td>
</tr>
<tr>
<td>F</td>
<td>$883,182</td>
<td>$652,084</td>
<td>$231,097</td>
<td>$785,518</td>
<td>73%</td>
<td>$97,564</td>
</tr>
<tr>
<td>I+O+F</td>
<td>$1,377,467</td>
<td>$679,581</td>
<td>$697,886</td>
<td>$1,082,534</td>
<td>100%</td>
<td>$294,933</td>
</tr>
</tbody>
</table>

IOF $1,082,534  OF $1,060,218  IF $1,077,354  IO $430,450  RC $402,953

The core of the three-purpose construction cost allocation is shown in Figure 5-12.

Figure 5-12. Core of three-purpose game for construction costs
Finance and Accounting

• Some background in finance and accounting is very helpful to dealing with monetary questions.

• In each case, major decisions are made regarding cost and revenue allocation based on very simple rules that don’t relate well to their correct values.

• Cooperative n person game theory provides a solid theoretical and computational foundation for addressing these difficult questions.
Risk Management

• Traditional engineering approach relies on use of safety factors and “conservative” assumptions
• Inherent tradeoff between cost and reliability
• Powerful computing tools and software allow us to do meaningful risk optimization
• Two examples
  – Incorporating risk into an engg. econ. problem
  – Extending a deterministic optimization problem to include risk
Toilet Example—Deterministic Formulation

- A new high efficiency toilet costs $120 to buy and $80 to install. The old toilet will be removed free of charge. The estimated water savings are two gallons per flush. Two people live in this house and there is only one toilet. Each person flushes the toilet an average of five times per day. The new toilet has an expected service life of 10 years. Assume a discount rate of 5% per year. Water costs $5.00/1,000 gallons. What is the net present value of this proposed investment? Should the old toilet be replaced?

<table>
<thead>
<tr>
<th>Case 1. Deterministic Formulation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All parameters known with certainty.</td>
<td></td>
</tr>
<tr>
<td><strong>P</strong></td>
<td>$200.00</td>
</tr>
<tr>
<td><strong>i</strong></td>
<td>0.05</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>10</td>
</tr>
<tr>
<td><strong>SV</strong></td>
<td>0</td>
</tr>
<tr>
<td>Savings, gal./flush</td>
<td>2</td>
</tr>
<tr>
<td>Flushes/person/day</td>
<td>5</td>
</tr>
<tr>
<td>Persons/toilet</td>
<td>2</td>
</tr>
<tr>
<td>Savings, 1000gal./yr.</td>
<td>7.3</td>
</tr>
<tr>
<td>$/1,000 gal.</td>
<td>$5.00</td>
</tr>
<tr>
<td>Water savings, $/yr.</td>
<td>$36.50</td>
</tr>
<tr>
<td><strong>NPV (Series PWF)</strong></td>
<td>$81.84</td>
</tr>
</tbody>
</table>
Monte Carlo Simulation-Engg. Econ. Example

Buy a new toilet?

- P is known with certainty - price quote from Home Depot
- i could range from 0.02 to 0.10
- N ranges from 5 to 25 years
- Flushes/day range from 0 to 10
- People/toilet ranges from 0 to 3.
- How to account for uncertainty?

Case 1. Deterministic Formulation

All parameters known with certainty.

\[ P = 200.00 \] $         
\[ i = 0.05 \]
\[ N = 10 \]
\[ SV = 0 \]
Savings, gal./flush 2
Flushes/day 5
Savings, 1000gal./yr. 3.65
$/1,000 gal. 10.00 $           
Water savings, $/yr. 36.50 $           
NPV (Series PWF)  81.84 $
Ways to Handle Uncertainty

1. “Best” case & “worst” case analysis. If NPV is still positive, even under the worst case scenario, then the project is worthwhile.

2. Monte Carlo simulation by solving the problem a large number of times with randomly generated values for the inputs. SS software such as @Risk makes it very easy to do.
Problems with Best and Worst Case Analysis

• Very wide range of NPVs
  – Best case, NPV = $1,820
  – Expected value, NPV = $82
  – Worst case, NPV = -$288

• What is the probability of any of these three cases occurring?

• How to define “best” and “worst”?
Monte Carlo Simulation

- Values for uncertain cells are selected in an unbiased manner.
- The computer generates hundreds of scenarios.
- Output is the CDF of the performance metrics of interest.
- Avoids the use of arbitrary safety factors and “conservative” assumptions that can lead to very inefficient design and operations decisions.
Results of Monte Carlo Analysis

CDF of NPV for Toilet

% <= indicated value

NPV, $

$(500) - $1,000 - $1,500 - $2,000

Conserve Florida Water
Promoting Conservation in Our Public Water Supplies
Optimization Problem with uncertainty in the criterion elements, the activity coefficients, and/or the RHS terms

MAX (of MIN): \( f_0(X_1, X_2, \ldots, X_n) \)

Subject to:

\( f_1(X_1, X_2, \ldots, X_n) \leq b_1 \)

\[ \vdots \]

\( f_k(X_1, X_2, \ldots, X_n) \geq b_k \)

\[ \vdots \]

\( f_m(X_1, X_2, \ldots, X_n) = b_m \)
Risk Optimization

- Combine optimization and Monte Carlo simulation methods to determine the final risk-reward tradeoff curve.
- Our contribution is to generate this curve.
- Stakeholders make final decision.

![Tradeoff between rate of return and risk](chart.png)
Risk Optimization Applications

- Strategy for solving sanitary sewer overflow problem with high uncertainty re the locations of the problem areas
- Minimize the cost of a water system design subject to a reliability constraint
  - Optimizers tend to pick lower reliability solutions since they meet constraints with a minimum amount of slack
Economics and Related Tools to Evaluate Urban Water Systems

- Overview
- Engineering economics
- Microeconomics
- Optimization methods
- Cost allocation and finance
- Risk optimization
Summary & Conclusions

• Cost-reliability tradeoff is fundamental to engineering
• A fundamental difference exists between engineering and scientific analysis
• Your students need to understand and use these economic and financial evaluation tools to be effective engineers