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Managing technological and economic uncertainties in design of long-term infrastructure projects: An info-gap approach

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Abstract

Infrastructure for water distribution must operate reliably for many decades. Planners face technological and economic uncertainties. The Net Present Worth (NPW) of a long-term infrastructure project is highly uncertain because of these uncertain variables. We use info-gap decision theory for infrastructure planning to manage these uncertainties. We study the robustness question: how much can our estimates of the uncertain variables err, and the NPW will still be acceptable? The answer is expressed by the info-gap robustness function. Large robustness implies great immunity to uncertainty, while low robustness implies high vulnerability to uncertainty. A plan whose robustness is large is preferred over a plan with low robustness. In other words, the info-gap robustness function prioritizes the alternative plans. We illustrate the planning procedure with long-term planning-analysis for maintenance and replacement of Asbestos Cement (AC) pipes owned by the East Bay Municipal Utility District (EBMUD) in Oakland, California. Our example illustrates the evaluation of alternatives based on robustness against uncertainty in both technological and economic variables.

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Keywords: technological uncertainty; economic uncertainty; info-gaps; robustness; long-term planning; water infrastructure;

1. Introduction

Infrastructure for water distribution—pipes, pumps and reservoirs—provides an essential service in densely populated urban areas and must operate reliably for many decades. Infrastructure design, construction and maintenance requires large capital investment. Planners face technological and economic uncertainties. Technological uncertainties are of three kinds. First, the requirement for long reliable operation creates an incentive to use innovative technologies. However, what is new is less well understood, especially for long-term service, and hence may be more uncertain than what is conventional. This "innovation dilemma" creates a major uncertainty in the choice between design alternatives [1]. Second, demands on the system (e.g. flow requirements or land use) in the distant future may differ unexpectedly from current demands. Third, material or mechanical properties may change over time in unanticipated ways. Economic uncertainties facing the long-term infrastructure planner arise primarily from uncertainty in the future cost of financing the infrastructure construction and maintenance.

This paper explores the application of info-gap decision theory [2] for infrastructure planning in the face of these uncertainties. We formulate the Net Present Worth (NPW) of a long-term infrastructure project, depending on uncertain technological and economic variables. The planner requires that the NPW be no less than a critical value, below which the project cannot be justified to the stake holders. However, since critical technological and economic variables are uncertain, our estimate of the NPW is also uncertain. Nonetheless, we are able to answer the robustness question: how much can our estimates of the uncertain variables err, and the NPW will still be acceptable? The answer to this question is expressed by the info-gap robustness function. Large robustness implies great immunity to current uncertainty, while low robustness implies high vulnerability to uncertainty. A design whose robustness is large is preferred over a design with low robustness. In other words, the info-gap robustness function prioritizes the alternatives.

We illustrate the planning procedure with the long-term planning-analysis for maintenance and replacement of Asbestos Cement (AC) pipes owned by the East Bay Municipal Utility District (EBMUD) in Oakland, California [3]. EBMUD owns about 3,840 miles (6,180 km) of water-distribution pipes, including 1,145 miles (1,843 km) of AC pipe. An increase in AC pipe failures in the past 7 years led to a study of corrosion by leaching lime from pipe walls. Several studies indicated the need for long-term replacement of existing pipes and raised the possibility of extending the replacement timeline through modified chemical treatment of the carried water [4]. Our example will illustrate the evaluation of alternatives based on robustness against uncertainty in both technological and economic variables.

2. Basic Models

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Nomenclature

A_o: original AC pipe wall thickness [inches].
A: estimated degraded wall thickness now [inches].
C_{chem}: water treatment cost [$/mile].
C_{fix}: maintenance cost for old pipe [$/mile].
C_{pipe}: pipe replacement cost [$/mile].
C_{op}: discounted treatment and maintenance cost [$/mile].
C_{rep}: discounted pipe replacement cost [$/mile].
$C_{tot}(S_i)$: total discounted cost for strategy S_i [$/mile].
d: pipe diameter [inches].
d_{max}: maximum pipe diameter [inches].
D_{cr}: critical wall thickness; less is unreliable [inches].
f_{cr}: fraction of A_o which defines D_{cr}.
$G_{tot}(S_i)$: total inventory discounted cost for strategy S_i [$].
i: annual interest rate.
$N(d, r, v)$: number of miles of pipe of diameter d from region r and vintage v.
N_{reg}: number of regions.
r: index of geographical region.
$R_b(S_i)$: inner wall degradation rate for S_i, [inches/year].
R_b^{hist}: historical inner wall corrosion rate [inches/year]. May change in future due to chemical treatment.
R_c: historical outer wall corrosion rate [inches/year]. Same in past and future.
S_i: water treatment strategy.
t_{cr}: number of years from now to reach D_{cr} [years].
t_{plan}: number of years (into future) of planning analysis.
$t = 1, 2, \ldots, t_{plan}$: year index into the future.
t_{start}: number of years from now until starting water treatment strategy S_i.
v: vintage year, (year the pipe was installed, e.g. 1985).
y_{now}: current year (e.g. 2014).
v_{max}: maximum vintage [years].

Wall thickness. Our analysis of pipe wall thickness is based on [3, 4]. Wall thickness of pipe degrades linearly in time:

$$A = A_o - (R_b^{hist} + R_c)(y_{now} - v) \quad (1)$$

A pipe is unreliable and eligible for replacement when the wall thickness reaches a fraction f_{cr} of the original thickness:

$$D_{cr} = f_{cr} A_o \quad (2)$$

Future inner degradation may change due to treatment strategy, S_i, so, using eq.(1), the critical thickness is:

$$\begin{aligned} D_{cr} &= A - [R_b(S_i) + R_c]t_{cr} \quad (3) \\ &= A_o - (R_b^{hist} + R_c)(y_{now} - v) - [R_b(S_i) + R_c]t_{cr} \quad (4) \end{aligned}$$

t_{cr} is the number of years to reach the critical wall thickness.

Combining eqs.(2) and (4) determines t_{cr}:

$$t_{cr} = \frac{(1 - f_{cr})A_o - (R_b^{hist} + R_c)(y_{now} - v)}{R_b(S_i) + R_c} \quad (5)$$

Costs. The annual maintenance cost for fixing old pipes, C_{fix}, runs from now up to replacement, t_{cr}, or up to the end of the planning time, t_{plan}, whichever comes first. A typical value of C_{fix} is $20,000/mile. The replacement cost for new pipe, C_{pipe}, is typically $2.2M/mile, with a typical lower bound of $1.3M/mile and a typical upper bound of $2.5M/mile. The annual water treatment cost, $C_{chem}(S_i)$, depends on the treatment strategy S_i, $i = 0, 1$ or 2. The water treatment cost runs thoughout the planning time, t_{plan}, and is applied to the water but calculated on a per-pipe-mile basis for all pipe, regardless of whether a pipe is replaced or not. Typical annual water treatment costs per mile for the three strategies are $C_{chem}(S_0) = \$165$/mile, $C_{chem}(S_1) = \$421$/mile and $C_{chem}(S_2) = \$842$/mile. Capital costs differ between the strategies: S_0: $0, S_1: $10,000,000 and S_2: $20,000,000.

3. Evaluating Net Present Worth

We first consider 1 mile of a specific pipe, and then consider the entire pipe inventory.

1 mile of a specific pipe. We evaluate the Net Present Worth (NPW) of 1 mile of pipe of a given diameter, d, and from a given region, r, using water treatment strategy S_i. In the next section we consider the info-gap robustness analysis.

Step 1. Calculate t_{cr} with eq.(5) for the pipe diameter, region of interest and vintage.

Step 2. Calculate the NPW, with discount rate i, of the operating costs up to the time of pipe replacement, C_{op}:

$$C_{op} = \sum_{t=t_{start}}^{t_{plan}} \frac{1}{(1+i)^t} C_{chem} + \sum_{t=1}^{\min[t_{cr},\ t_{plan}]} \frac{1}{(1+i)^t} C_{fix} \quad (6)$$

The idea behind each term in the sums in eq.(6) is that if you need to spend C_{chem} or C_{fix} in t years from now, you need less than that now because you can put $\frac{1}{(1+i)^t} C_{chem}$ or $\frac{1}{(1+i)^t} C_{fix}$ in the bank now and earn compounded interest at the rate i per year for t years. If i is small then you initially need more money. Hence the NPW is large if i is small.

Eq.(6) shows that the NPW of the operating cost is **small** if t_{cr} is **small** because there are few terms in the equation.

Step 3. Calculate the NPW of the future replacement cost at t_{cr}. If t_{plan} is less than t_{cr} then the replacement cost is zero. If not, the replacement cost is positive. We first define an indicator function that tests which time is greater:

$$\mathcal{I}(x) = \begin{cases} 0, & \text{if } x < 0 \\ 1, & \text{if } x \geq 0 \end{cases} \quad (7)$$

Now the discounted replacement cost can be expressed as:

$$C_{rep} = \mathcal{I}(t_{plan} - t_{cr}) \frac{1}{(1+i)^{t_{cr}}} C_{pipe} \quad (8)$$

The NPW of pipe replacement is **large** if t_{cr} is **small.** This is the reverse of the situation in eq.(6).

Step 4. Calculate the total discounted cost for strategy S_i on 1 mile of pipe with diameter d from region r with eqs.(6) and (8) and using t_{cr} from eq.(5):

$$C_{tot}(S_i, d, r, v) = C_{op} + C_{rep} \quad (9)$$

The entire pipe inventory. $N(d, r, v)$ is the number of miles of pipe of diameter d from region r and of vintage v.