Resilience and Sustainability of Infrastructure Assets through Risk-Based Adaptive Incremental Revolution

Presented at the International Workshop on Performance-based Infrastructure Asset Management

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Questions

• Why do we need *Incremental Adaptive Revolution*?

• What are the challenges?

• Why do we need systems engineering and risk modeling, assessment, and management?

• What research is needed?
My Message
To manage emergent forced changes and to ensure resilience and sustainability of infrastructure assets, we need to develop theory and methodology that integrate scientific, technical, socioeconomic, and normative dimensions in an encompassing business case for infrastructure maintenance and maintainability.
Structure of the Presentation

The need for sustainable and resilient infrastructure assets in the face of emergent uncertain forced changes and thus for an adaptive incremental revolution to:

a. move from probability and reliability to risk-based planning, design and construction of infrastructure systems

b. adapt a culture of “six-sigma” quality throughout the lifecycle of infrastructures and across the organization

c. Embrace systems engineering and risk-informative decisionmaking in infrastructure and asset management

d. Identify research needs for an integrated management of the complex interdependent system of systems of infrastructure assets
“We know that we cannot continue to damage our life-support systems without eventually paying a price, but how will we be affected? What will be the price? Is it likely to be a build up of carcinogens in the environment so severe it increases the incidence of cancer, dramatically raising death rates? Or will the rising concentration of greenhouse gases make some regions of the planet so hot that they become uninhabitable, forcing massive human migration? Or will it be something we cannot even anticipate yet?”

Sustainable Infrastructure Assets

“We know that we cannot continue to damage our life-support systems without eventually paying a price, but how will we be affected? What will be the price? Is it likely that our vital critical infrastructure assets (water supply and treatment plants, bridges, levees, railroads, etc.) keep deteriorating to dramatically raising death rates? Or will the rising sea-level makes some regions of the planet so hot that they become uninhabitable, forcing massive human migration? Or will it be something we cannot even anticipate yet?”

An Example of Anticipated Forced Changes: Impacts of Climate Variability

Increased storm intensity may lead to increased service disruption and infrastructure damage over the next 50-100 years.

“64 percent of Interstates, 57 percent of arterials, almost half of the rail miles, 29 airports, and virtually all of the ports are below 7 m (23 feet) in elevation and subject to flooding and possible damage due to hurricane surge”

USDOT 2008
Historical Economic Losses Due to Flooding
[National Oceanic and Atmospheric Administration (NOAA)]

Source: http://www.nws.noaa.gov/oh/hic/flood_stats/flood_trends.JPG
Incremental adaptive revolution in the maintenance of infrastructure assets can protect against risks of extreme losses.

Probability of exceeding $10.4 billion loss is 0.05

Probability of exceeding $15.8 billion loss is 0.02

Probability of exceeding $19.9 billion loss is 0.01

Report Card on the Nation’s Public Works

Highways C+
Mass Transit C-
Aviation B-
Water Resources B
Water Supply B-
Wastewater C
Solid Waste C-
Hazardous Waste D
## ASCE progress report 2003

Revisiting the Report Card of the Nation’s Public Works

<table>
<thead>
<tr>
<th>Category</th>
<th>Grade</th>
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<tbody>
<tr>
<td>Roads</td>
<td>D+</td>
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<tr>
<td>Bridges</td>
<td>C</td>
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<tr>
<td>Transit</td>
<td>C-</td>
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<td>Schools</td>
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<td>Dams</td>
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<td>Solid Waste</td>
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<td>Navigable Waterways</td>
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<tr>
<td>Energy</td>
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How would the previous graphs and reports look, given the anticipated forced changes (including emergent climate change)?

What new advances in systems theory, modeling, and risk analysis do we need to develop to manage these forced changes and ensure resilience and sustainability of infrastructure assets?
We need better models and decision tools to:

• Prioritize Infrastructure Maintenance
• Budget and allocate financial resources
• Measure progress on the need for change
• Integrate databases from several potentially disparate sources
• Educate a new cadre of engineering professionals who understand the complexity and interdependency of infrastructure asset management
• Communicate the above needs with all stakeholders
The need for unified metrics for maintenance

Relating Extreme Events and Six Sigma

- A hurricane category 3 with 20-year return period
  - Expected loss of $16 billion

- A hurricane category 5 with 500-year return period
  - Expected loss of $48 billion

- PMF of 1 in $10^4$ years
  - Expected loss of $24 billion

- PMF of 1 in $10^6$ years
  - Expected loss of $28 billion
What Do We Mean by Adaptive Incremental Revolution?
It is a mind-set cultural philosophy

Midcourse Corrections

Continuing, Expanding, or Institutionalizing the Program, or Cutting, Ending, or Abandoning It

Testing a New Program Idea

Choosing the Best of Several Alternatives

Educational Dimension of Resilience and Sustainability of Infrastructure Assets

Versatile, knowledgeable, well-informed, and well-trained cadre of professionals with technical capability are essential to maintain sustainable operation of critical infrastructure assets.

This knowledge must transcend the entire life cycle of an infrastructure system, from planning, design, construction, operation, maintenance, and replacement.
Systems engineering and risk-informative decisionmaking are requisites for adaptive incremental revolution in infrastructure asset management
Strategic Infrastructure Asset Management

• **Strategic infrastructure asset management** (in this talk) refers to a **sustainable state** that builds on **maintenance and resilience** that results from **decisions and associated actions** implemented during the **entire lifecycle** of infrastructure assets, aimed at **reducing likelihoods of failures and consequences** to an acceptable level (in terms of response/recovery time and cost).

• **Adaptive incremental revolution** requires the: Development of **decision support methodologies** and tools to support the sustainability of physical infrastructure assets.
Harmonizing Maintenance with Strategic Resilience for Sustainable Infrastructure Assets

Certain Investment in Maintenance (Present) - Sustainable Infrastructure Assets

Uncertain Resilience (Future)

Various Losses

Resilience

No Resilience

Yacov Y. Haimes
RISK

A Measure of the Probability and Severity of Adverse Effects

William W. Lowrance, 1976
SAFETY

The level of [residual] risk that is deemed acceptable

William W. Lowrance, 1976
The Process of Risk Assessment, Management, and Communication

Organizational Knowledge Management

Human

Information Assurance

Hardware

Software
Knowledge Management

- Trust
- Communication and Empathy
- Exchange of Information
- Win-Win Or No Deal
- Fairness for All
- Coordination
- Exchange of Knowledge
- Collaboration

Geographic Boundary
Vertical Boundary
External Boundary
Horizontal Boundary

Y. Y. Haimes
Four Detrimental Boundaries to Knowledge Management

• **Vertical boundaries** represent layers within an organization

• **Horizontal boundaries** exist between organizational functions, product lines, or units.

• **External boundaries** are barriers between organizations and the outside world

• **Geographic, or global, boundaries** exist when complexly structured organizations operate in different “markets” and countries.

Adapted from
《The Boundaryless Organization: Breaking the Chains of Organizational Structure》
by Ron Ashkenas et al., 1995
The Process of Risk Modeling, Assessment, and Management through Risk Communication

Risk Assessment

1. What can go wrong?
2. What is the likelihood that it could go wrong?
3. What are the consequences?
   [Kaplan and Garrick 1981]
4. What is the time domain?

Risk Communication

1. What can be done and what options are available?
2. What are the associated trade-offs in terms of all costs, benefits, and risks?
3. What are the impacts of current management decisions on future options?
   [Haimes 1991]

Risk Management

Risk Management

Risk Management □ Acceptable Balance

System Management:
Human/Organization/Hardware/Software
• Planning
• Design
• Operation
Limitation of Expected Value of Risk

and its fallacy when it is used as the sole measure for risk

Risk = \( f (\text{Probability, Damage}) \)

or

Risk = \( f (\text{Likelihood, Consequences}) \)
Limitation of Expected Value of Risk

Consider the probabilities of two particular concentrations of a groundwater contaminant

\[ x_1 = 2 \text{ ppb} \quad p_1 = 0.1 \]
\[ x_2 = 20,000 \text{ ppb} \quad p_2 = 0.00001 \]

Contribution of \( x_1 \) to the expected value = \( x_1 \cdot p_1 = 2 \cdot 0.1 = 0.2 \text{ ppb} \)

Contribution of \( x_2 \) to the expected value = \( x_2 \cdot p_2 = 20,000 \cdot 0.00001 = 0.2 \text{ ppb} \)

Contributions are equal, but consequences are very different.
EPILOGUE

To manage emergent forced changes and to ensure resilience and sustainability of the complex system of systems of interdependent infrastructure assets, we need to develop theory and methodology that integrate scientific, technical, socioeconomic, and normative dimensions in an encompassing business case for their maintenance and maintainability.
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