# DA/MCDA/CBA: An Overview of the State of the Science

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# Acronyms

- DA: **Decision Analysis**. Used in the sense of writings by Howard Raiffa, Ronald Howard, Ward Edwards on this subject
- MCDA: **Multi-Criteria Decision Analysis.** Used in the sense of Howard Raiffa and Ralph Keeney's writings
- CBA: **Cost Benefit Analysis.** Used in the sense of publications in the economics literature and writings and practices by US government agencies, especially OMB
- PRA: **Probabilistic Risk Analysis**. Used in the inclusive sense of methods based on probability theory to quantify uncertainty and calculate risk
- In my judgment, there is a great deal of overlap between DA, MCDA, and CBA, and PRA readily fits into all three as a means of formal logical reasoning about uncertainty in the context of managing risk from toxicological agents (Term "agent" defined in EPA 2005 Cancer risk guidelines, footnote page 1-3)

# Charge Questions

*I. What are key successes?

*II. What are the barriers?

*III. What opportunities exist?

IV. How to improve the interfaces?

V. What are research priorities?

VI. What current practice areas in toxicology most readily lead themselves to PRA methods?

VII. How, in theory or practice, can PRA improve the quality and acceptability of decisions?



# I. What Are Examples of Key Successes?

- Case study 1: NASA Program to land spacecraft ("Viking") on Mars in 1976. Risk of contamination by terrestrial microbes.
- Case study #2: Value of Information on whether a new theory is correct, such that weather modification will reduce damage from hurricanes. Nixon Administration decision in 1971 led to expanded research.
- Case Study #3: US Synthetic Fuel Program of 1 million barrels/day proposed in President Ford's State of the Union speech in 1975. Decision by Administration and Congress to scale this program down, then postpone it.
- Case Study #4: (from Igor Linkov): MCDA Applications for weight of evidence evaluation, sediment management, stakeholder involvement
- A few slides and references for each!

## Three Main Messages

- Probability elicitation needs to reflect the importance and urgency of the decision context.
  - Need to consider urgency and extent of resources appropriate to use
- Value of better information may be most important insight, not the probabilities elicited obtained from experts
- Use sensitivity analysis to help determine what uncertainties are important and how much analysis and elicitation is enough



## #1. Microbes on Mars

Do we infect Mars with terrestrial microbes by landing a spacecraft on its surface?

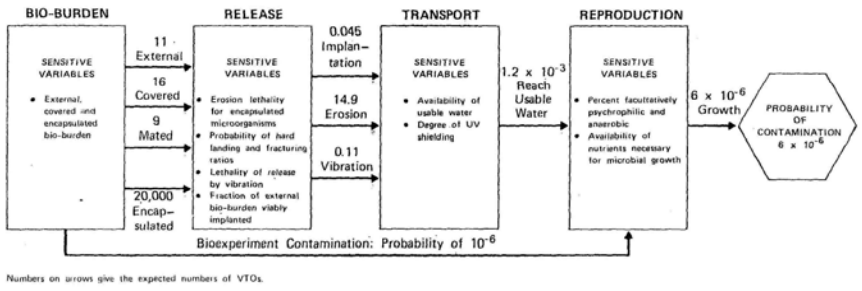
# *New Methodology for Assessing the Probability of Contaminating Mars*

D. W. North, B.R. Judd, and J.P. Pezier, ***Life Sciences and Space Research XIII***, P. A. Sneath, ed., Akademie-Verlag, Berlin, pp. 103-109, 1975.

"Limitations, Definitions, Principles, and Methods of Risk Analysis," Risk Assessment for Veterinary Biologicals, special issue, **Office International des Epizooties, Scientific and Technical Review**, Vol. 14, pp. 913-923, 1995. (on website, http://www.northworks.net/limitations.pdf )



# *Mission Contamination Model Results*




Numbers on arrows give the expected numbers of VTOs.

# Mission Contamination Model Marginal Sensitivity Analysis

| Contamination Model Variables | Values | | | | | Probability of Contamination Units: = 10**-6 Nominal: 5.9 | |
|---|---|---|---|---|---|---|---|
| | Extreme Low | Intermed. Low | **NOMINAL** | Intermed. High | Extreme High | **Low** | **High** |
| Bio-Burden Variables | | | | | | | |
| 1. bio External | 2.2 | 5.5 | 11 | 22 | 55 | 5 | 10.7 |
| 2. bio Covered | 3.2 | 8 | 16 | 32 | 80 | 3.1 | 20.2 |
| 3. bio Encapsulated | 4,000 | 10,000 | 20,000 | 40,000 | 100,000 | 5 | 10.4 |
| Release Variables | | | | | | | |
| 1. rel Hard Landing Probability | 0.0004 | 0.001 | 0.002 | 0.004 | 0.01 | 5.2 | 9.6 |
| 3. rel Newly Exposed/Hard, Encaps | 0.0001 | 0.0002 | 0.001 | 0.005 | 0.01 | 5.4 | 10.9 |
| 4. rel Implanted, Soft | 0.0001 | 0.0002 | 0.001 | 0.005 | 0.01 | 5.7 | 8.7 |
| 6. rel VTO/Vibration | 0.001 | 0.002 | 0.01 | 0.05 | 0.01 | 5.4 | 11.1 |
| 9. rel VTO/Erosion, Encaps | 0.00001 | 0.00002 | 0.0001 | 0.0005 | 0.001 | 5.4 | 10.9 |



# Mission Contamination Model Marginal Sensitivity Analysis -2

| Contamination Model Variables | Values | | | | | Probability of Contamination Units: = 10**-6 Nominal: 5.9 | |
|---|---|---|---|---|---|---|---|
| | Extreme Low | Intermed. Low | **NOMINAL** | Intermed. High | Extreme High | **Low** | **High** |
| Transport Variables | | | | | | | |
| 1 tra Survive Transit | 0.001 | 0.002 | 0.01 | 0.05 | 0.1 | 2.2 | 45.2 |
| 2 tra Find Water | 0.0005 | 0.001 | 0.005 | 0.025 | 0.05 | 1.5 | 49.9 |
| 4 tra Water Deposition | 0.00005 | 0.0001 | 0.0005 | 0.0025 | 0.005 | 5 | 15.2 |
| 5 tra Stay Lodged | 0.1 | 0.2 | 0.5 | 0.8 | 0.9 | 5.5 | 10 |
| Reproduction Variables | | | | | | | |
| 1 rep Psychrophilic, Anaerobic | 0.005 | 0.01 | 0.05 | 0.1 | 0.25 | 0.6 | 29.6 |
| 2 rep Availability of Nutrients | 0.01 | 0.02 | 0.1 | 0.2 | 0.5 | 0.6 | 29.6 |

## *National Academy of Sciences, Viewpoint -1992*

"… it is the unanimous opinion of the task group that terrestrial organisms have almost no chance of multiplying on the surface of Mars and in fact have little chance of surviving for long periods of time, especially if they are exposed to wind and to UV radiation."

---- Space Studies Board, National Research Council, *Biological Contamination of Mars,* 1992, page 49.



## *2. New Technology with Uncertain Impacts – Benefits versus Harm*

Weather Modification (cloud seeding) applied to hurricanes

# New York Times - Sunday, August 11, 2002

- **If the Big One Hits the Big Easy, the Good Times May Be Over Forever**

By ADAM COHEN (NYT) 1018 words
Late Edition - Final , Section 4 , Page 12 , Column 1

- ABSTRACT - Adam Cohen Editorial Observer on grave threat that **big hurricane could wipe out low-lying city of New Orleans; describes complacency of its people and inadequate preparations by government** Dot Wilson knows how bad the Big One could be. When Hurricane Betsy hit New Orleans in 1965 with 125 m.p.h. winds, leaving 75 dead in Louisiana and South Florida, she walked more than a mile in chest-high water, holding her infant daughter overhead. But when Ms. Wilson held a hurricane-preparedness teach-in recently at the community center she heads, attendance was sparse. "A lot of people don't see storms as serious," she said with a sigh. But people who have been around for a while know better, she said, adding, "We saw the bodies."
- New Orleans -- home to the French Quarter's iron-latticed buildings and the Garden District's stately Greek Revival mansions, to Preservation Hall jazz and Mardi Gras parades -- may be America's most architecturally distinctive and culturally rich city. But it is also **a disaster waiting to happen**. New Orleans is the only major American city below sea level, and it is wedged between Lake Pontchartrain and the Mississippi. If a bad hurricane hit, experts say, **the city could fill up like a cereal bowl, killing tens of thousands and laying waste to the city's architectural heritage. If the Big One hit, New Orleans could disappear.**



# New York Times, Thursday, October 3, 2002

- **Thousands Seek Safety as Hurricane Nears Gulf Coast**

By JEFFREY GETTLEMAN (NYT) 1308 words
Late Edition - Final , Section A , Page 24 , Column 3

- ABSTRACT - About half million people flee southern Louisiana and Texas with approach of **Hurricane Lili**, which is heading toward Gulf Coast with winds of more than **140 miles per hour, making it daunting Category 4 storm**; map; chart of five most intense hurricanes to hit US since 1928; photos (M) Highways across southern Louisiana and Texas were solid columns of steel today as more than half a million people grabbed their valuables and fled their homes, looking for higher, safer ground before Hurricane Lili hit.
- The exodus of cars and trucks, some with furniture lashed down on their roofs, began in low-lying areas but quickly spread inland **as the storm intensified and threatened to become the worst natural disaster here in decades.**

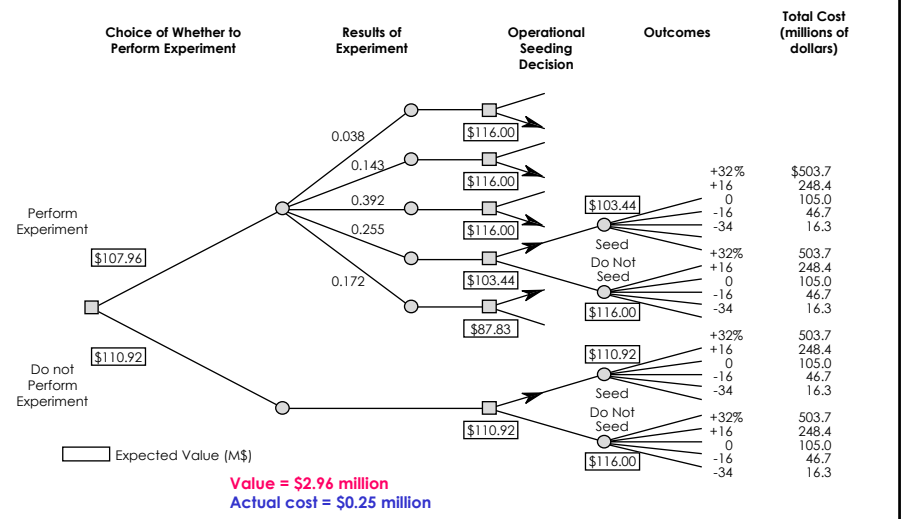
# *Case #2: The Decision to Seed Hurricanes*

*R.A. Howard, J.E. Matheson, D.W. North*

***Science*, 176**, 1191-1202, 1972

http://northworks.net/hurricanes.pdf

# *Value of A Seeding Experiment (Government Responsibility Cost Included)*



# *Summary of the Value of Additional Information on the Effect of Seeding (Values in Millions of Dollars)*

| | "Standard" Hurricane Used in Analysis of Chapters III and IV | Single Hurricane Season* | All Future Hurricane Seasons (discounted at 7%) |
|---|---|---|---|
| Expected Property Damage Without Seeding | $116 (100%) | **$220** | **$3,142** |
| Espected Value of Perfect Information | 13.6 (11.8%) | 26 | 370 |
| Expected Value of A Field Experimant Consisting of Two Experimental Seedings | 5.4 (4.7%) | 10.2 | 146 |
| Espected Value of Field Experiments, Assuming that Prior Operational Seeding is not Permitted: | | | |
| With Government Responsibilty costs | 8.8 (7.6%) | 16.6 | 238 |
| With Government Responsibility Costs Equal to Zero | 12.4 (10.7%) | 23.5 | 335 |

Considering only the 50% of hurricanes that are assumed to be possible candidates for seeding because of tactical consideration. If all hurricanes are assumed to be candidates for operational seeding, the figures of the last two columns should be doubled.



# *Findings and Recommendations*

## Findings

1. Current meteorological and economic information indicates that the seeding alternative stochastically dominated the non-seeding alternative
2. No firm legal basis for operational seeding appears to exist
3. The decision to seed a particular hurricane should take into account its specific characteristics
4. **Resolving meteorological uncertainty on the effect of hurricane modification is worth over $20 millions/year**

## Recommendations

1. The present policy prohibiting seeding any hurricane threatening the U.S. should be rescinded
2. A hurricane modification agency with authority to seed operationally should be established
3. Decision procedures supported by further analysis should be developed
4. **Modification experiments should be conducted on an expanded scale to provide a more refined basis for making each operational seeding decision**

# 3. National Synthetic Fuel Program

- Analysis for the Synfuels Interagency Task Force to the President's Energy Resources Council, Recommendations for a Synthetic Fuels Commercialization Program, Vol. 2, Cost-Benefit Analysis of Alternate Production Levels, November 1975. US Government Printing Office.
- Not on web; short description of decision analysis by Steven N. Tani, in *The Principles and Applications of Decision Analysis*, R.A. Howard and J.E. Matheson, eds, Menlo Park, CA: Strategic Decisions Group, 1989, p. 435-443.
- Costs and Benefits of having a synthetic fuels program calculated with large energy model, uncertainties incorporated via a decision tree, about 3000 end points.



# Synthetic Fuels Program Decision Tree

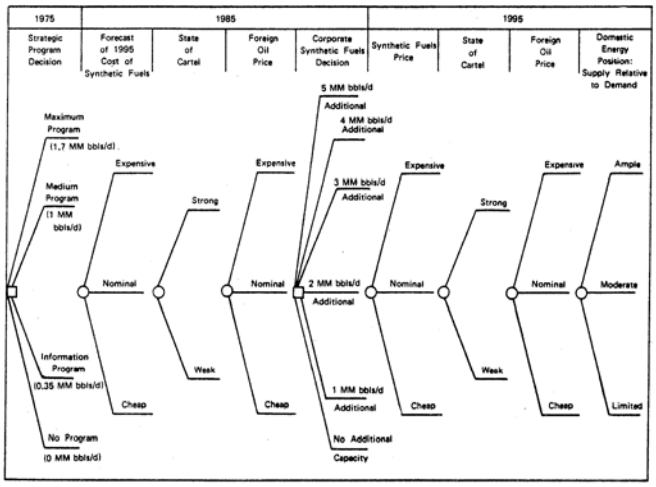



Figure 4—Decision tree

# *The "Cocktail Napkin" Summary: 1 million B/D Synthetic Fuel Program*

Expected Discounted Net Benefit (billions of 1975 dollars)

| | | | | | | |
|---|---|---|---|---|---|---|
| | -5.41 | | | | | |
| | 1985 OPEC Cartel | | | | | |
| | Weak | | | Strong | | |
| US. Energy Position: | -14.30 | | | 3.48 | | |
| Supply relative to | Synthetic Fuel Cost (1985 forecast) | | | | | |
| Demand, 1995 | Low | Medium | High | Low | Medium | High |
| | -3.36 | -13.60 | -28.63 | 14.68 | 5.40 | -11.56 |
| Ample | -4.52 | -14.57 | -27.50 | 10.98 | 1.43 | -15.33 |
| Moderate | -3.40 | -13.66 | -26.71 | 14.54 | 5.33 | -11.76 |
| Limited | -2.11 | -12.53 | -25.60 | 18.69 | 9.51 | - 7.41 |



# *Synthetic Fuel Program Outcome*

- Ford Administration Program scaled down to one plant of each type, 1/3 million B/D to propose to Congress
- Congress disapproved it, by a close vote
- Program established under Carter Administration, very poor performance, facilities abandoned, program discontinued.
- 30 years later, our very complex decision analysis still looks good; communication to decision makers seemed to work!

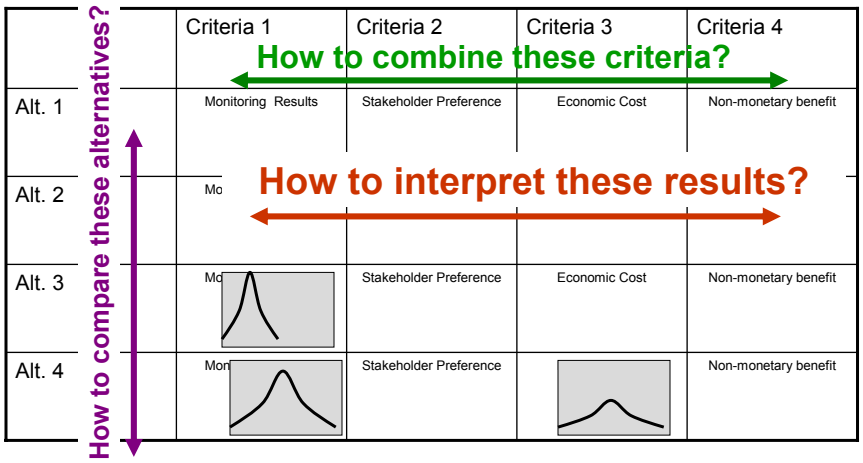
# *Case #4: MCDA Applications*

Linkov, I., Satterstrom, K., Kiker, G., Bridges, T., Benjamin, S., Belluck, D. (2005, in press). **From Optimization to Adaptation: Shifting Paradigms in Environmental Management and Their Application to Remedial Decisions**. *Integrated Environmental Assessment and Management.*

Kiker, G., Bridges, T., Varghese, A.S., Seager, T.P., and Linkov, I. (2005). **Application of multi-criteria decision analysis in environmental management**. Integrated Environmental Assessment and Management 1 v. 2 49-58.

Linkov, I., Satterstrom, K., Kiker, G., Ferguson, E., Bridges, T. (2005, in press). "**Multi-Criteria Decision Analysis and Adaptive Management: a Review and Framework for Application to Superfund Sites**." In: Macey, G.P. and Cannon, J. Reclaiming the Land: Rethinking Superfund Institutions, Methods, and Practices, Springer, 2006.

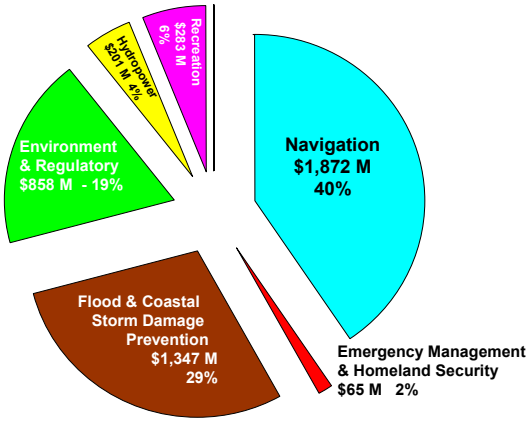
# *Decision Matrix*



# MCDA Application: Performance-based Budgeting

## Army Corps of Engineers

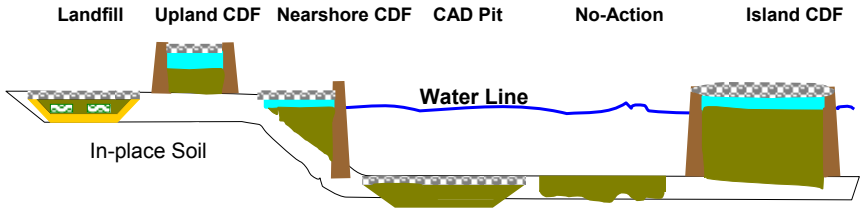
- **MCDA Inputs:**
  - Comparison Criteria
  - Performance Measures
  - Relative weights/values
- **What did MCDA show?**
  - Project prioritization
  - Geographic priorities
  - Sensitivity





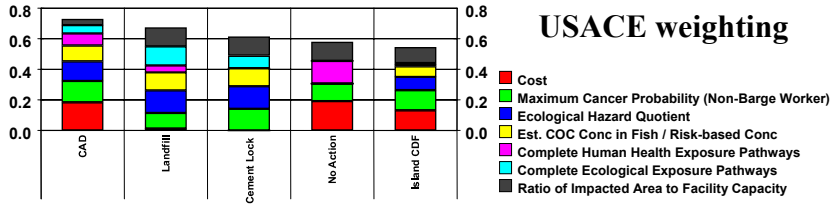

# MCDA Application: Management of Contaminated Sediments/ Stakeholder Issues

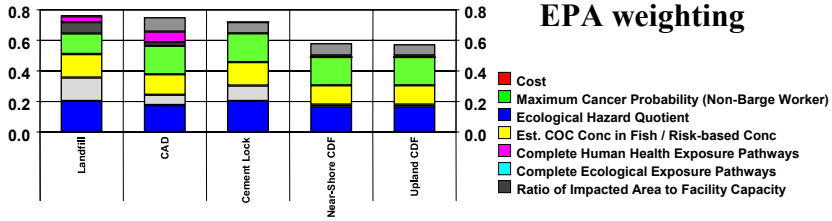
## Sediment Management Alternatives




- **MCDA Inputs**
  - Hierarchy of criteria
  - Performance measures
  - Relative weights/values
- **What did MCDA show?**
  - Prioritization of sediment management options
  - Hierarchy of values and weights
  - Sensitivity analysis

# *Sediment Management Alternative Prioritization (EPA and ACE values)*






# *II. Barriers*

- Traditions in the toxicology community. Decades of experience using default assumptions, safety factors, and deterministic analysis with conservative choices to protect public health (and the environment).
- The language and practices of mathematical probability, especially Bayesian methods and elicitation of expert judgment in the form of probabilities
- Resource limitations; DA/MCDA/CBA is expensive, needs specialists/training
- Time pressure/lack of long range planning, integration of risk assessment and analysis in support of risk management

(Talk by Tim Barry addresses "Barriers" in much more detail)

# *III. Opportunities*

- Time is right:
  - OMB report, 2003
  - EPA 2005 Cancer Guidelines:
  - Toxicology now dealing with harder problems – more uncertainty, more importance to value judgments - where PRA is needed.
  - More people know the mathematical probability, have experience with Bayesian methods, elicitation of judgment as probabilities
  - Very powerful numerical computation widely available.



# *QUOTE: National Research Council 1994 and EPA 2005 Guidelines for Carcinogen Risk Assessment*

NRC [1994] recommended that where the Agency "reports estimates of risks to decisions-makers [sic] and the public, it should present not only point estimates of risk, **but also sources and magnitudes of uncertainty associated with these estimates.**"

- EPA *Guidelines for Carcinogen Risk Assessment*, page 1-3, citing the final recommendation from the Executive Summary of *Science and Judgment in Risk Assessment*, National Research Council, 1994

## *QUOTE: Next Sentence in the EPA 2005 Guidelines for Carcinogen Risk Assessment*

NRC [1994] recommended that where the Agency "reports estimates of risks to decisions-makers [sic] and the public, it should present not only point estimates of risk, but also sources and magnitudes of uncertainty associated with these estimates." **Thus, the identified uncertainties serve as a feedback loop to the research community and decisionmakers, specifying areas and types of information that would be particularly useful.**

- EPA *Guidelines for Carcinogen Risk Assessment*, page 1-3



## *Another **Quote** from the EPA 2005 Guidelines for Carcinogen Risk Assessment*

Rather than viewing default options as the starting point from which departures may be justified by new scientific information, **these cancer guidelines view a critical analysis of all of the available information that is relevant to assessing the carcinogenic risk as the starting point from which a default option may be invoked if need to address uncertainty or the absence of critical information.**

- EPA *Guidelines for Carcinogen Risk Assessment*, page 1-7, emphasis by underlining in the original.

## *Yet Another **Quote** from the EPA 2005 Guidelines for Carcinogen Risk Assessment*

When there are alternative procedures having significant biological support, the Agency **encourages assessments to be performed using these alternative procedures**, if feasible, in order to shed light on the uncertainties in the assessment, recognizing that the Agency **may decide to give greater weight to one set of procedures than another** in a specific assessment or management decision.

- EPA *Guidelines for Carcinogen Risk Assessment*, page 1-8



## *Another **Quote** from the EPA 2005 Guidelines for Carcinogen Risk Assessment, citing NRC 1994*

The full extent of model uncertainty usually cannot be quantified; a partial characterization can be obtained by comparing the results of alternative models. Model uncertainty is expressed through comparison of separate analyses from each model, coupled with a **subjective probability statement**, where feasible and appropriate, **of the likelihood that each model might be correct**.

- EPA *Guidelines for Carcinogen Risk Assessment*, page 3-29

## *And Still Another **Quote** from the EPA 2005 Guidelines for Carcinogen Risk Assessment*

With appropriate data and expert judgment, **formal approaches to probabilistic risk assessment** can be applied to **provide insight** into the overall extent and dominant sources of human variation and uncertainty. In doing this, it is important to note that **analyses that omit or underestimate some principal sources of variation or uncertainty** could provide a misleadingly narrow description of the true extent of variation or uncertainty and **give decisionmakers a false sense of confidence in estimates of risk**.

- *Guidelines for Carcinogen Risk Assessment*, page 3-31



## *4. Applications to Environmental Pollutants: SOx → FPM*

- OMB 2003 report, http://www.whitehouse.gov/omb/inforeg/2003_cost_ben_final_rpt.pdf . (see p. 61 for North-Merkhofer and other papers on value of information on environmental regulation.) North-Merkhofer paper available as paper copy
- Risk Commission Report, http://www.riskworld.com/riskcommission/Default.html
- Air Quality and Stationary Source Emissions Control (1975): on National Academy Press website. http://books.nap.edu/catalog/10840.html
  - See especially transmittal letter (p. v), main text p. 220-231, and chapter 13.

# Social Cost of Air Pollution

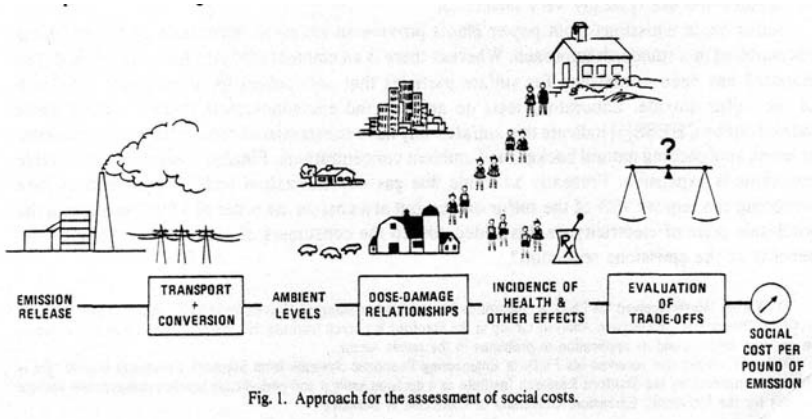



Fig. 1. Approach for the assessment of social costs.

Source: North and Merkhofer, *Computers and Operations Research*, 1976
Analysis: See National Research Council, 1976, Chapter 13: http://books.nap.edu/catalog/10840.html



# Expert: Dr. Bernard Goldstein

- Judgment, relative to baseline estimates of health effects from sulfur oxides (CHESS Studies)
- "Could be twice as much, could be 1/10 as much"
- "To proceed with a quantitative description of the uncertainty we shall assume that the range of uncertainty in the dose-response relationship (of 10 percent to 200 percent of the values given in Table 13–12) can be treated as having a probability of 90 percent." (NAS Report, p. 615)

# *Value of Information*

… A rough calculation of the value of resolving these uncertainties gives a value of about $2 million per year for the representative 600 MW plant in the remote rural location. If low-sulfur coal is not available, the value of resolving uncertainty drops to a little over $1 million per year. For the urban location, the value of resolving uncertainty on the sulfur oxide emission to ambient sulfate relationship and on the magnitude of the health effects is in the range of $1 million a year.

Extrapolating these values to the collection of eastern power plants that now or in the near future might burn high sulfur coal yields an estimate of the order of a quarter of a billion dollars per year. **This is roughly 25 times the annual cost estimated by EPA for a research program to resolve these uncertainties.**

(p. 229, emphasis added)



# *Regulatory Costs for Air Pollution, Oct 1,1992- Sept 30, 2002*

**OFFICE OF MANAGEMENT AND BUDGET, 2003 Report to Congress on the Costs and Benefits of Federal Regulations**

**Benefits and costs for past ten years** (millions of 2001 US$):

| | **Benefits** | **Costs** |
|---|---|---|
| EPA Office of Air | **117,888 to 177,330** | **17,861 to 20,561** |
| All Federal agencies | **146,812 to 230,896** | **36,625 to 42,813** |

Source: Tables 2, p. 7; Table 3, p. 9

# *Regulatory Costs for Air Pollution, 2003*

**OFFICE OF MANAGEMENT AND BUDGET:** ***Informing Regulatory Decisions, 2003 Report to Congress on the Costs and Benefits of Federal Regulations and Unfunded Mandates on State, Local, and Tribal Entities,*** p. 8. See also Tables 2, 3

"… **four EPA rules – two rules limiting particulate matter and $NO_x$ emissions from heavy duty highway engines, the Tier 2 rule limiting the emissions from light duty vehicles, and the Acid Rain rule** … account for a substantial fraction of the aggregate benefits reported in Table 2. These four EPA rules have estimated benefits of $101 to $119 billion per year and costs of $8 to $8.8 billion per year. The aggregate benefits and costs for the other 103 rules are $41 to $107 billion, and $29 to $34 billion, respectively."



# *OMB Report, fine print in footnote 9, p. 8*

9. These four EPA rules will reduce ambient levels of fine particulate matter by reducing direct PM emissions and/or the emissions of precursor pollutants like $SO_2$ and $NO_x$ that contribute to the formation of secondary fine PM. Studies show an association between both short- and long-term exposure to fine PM and a variety of adverse health effects ranging from increases in the frequency of hospital admissions to premature mortality. There are, however, **important uncertainties** associated with translating this scientific evidence into benefit estimates. There are **five key assumptions** underlying the benefit estimates. These include the following:

# OMB Report, fine print in footnote 9, page 8

1. The analysis assumes that inhalation of fine particles is **causally associated with premature death** at concentrations near those experienced by most Americans on a daily basis. Although studies have yet to establish the specific biological mechanisms responsible for such effects, the weight of the available evidence supports an assumption of causality.
2. The analysis assumes that **all fine particles**, regardless of their chemical composition, are **equally potent in causing premature mortality**. This is an important assumption because fine particles from power plant emissions are chemically different from those emitted from both mobile sources and other industrial facilities. However, no clear scientific grounds exist at this time for supporting differential effects estimates by particle type.

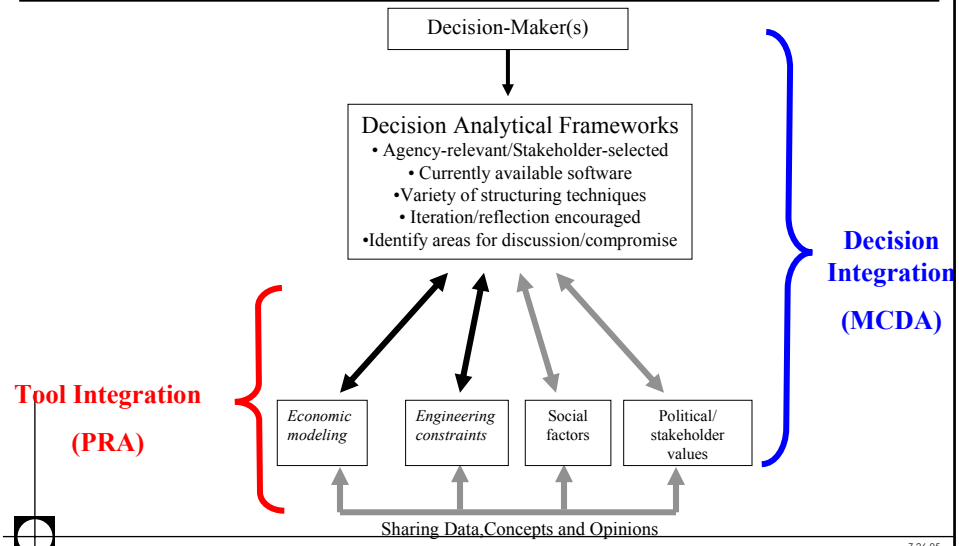


# OMB Report, fine print in footnote 9, page 8 (cont'd)

3. The analysis assumes that the concentration-response function for fine particles is approximately **linear** within the range of ambient concentrations under consideration. Thus, the analysis estimates health benefits from reducing fine particles in both attainment and non- attainment regions.
4. The benefits analysis assumes that we have the ability **to accurately forecast** future emissions and associated air quality modeling.
5. The analysis assumes that the **valuation** of the estimated reduction in mortality risk is appropriately represented by studies of the tradeoff associated with wage premiums for workers facing fatality risks in labor markets.

Source: http://www.whitehouse.gov/omb/inforeg/2003_cost-ben_final_rpt.pdf

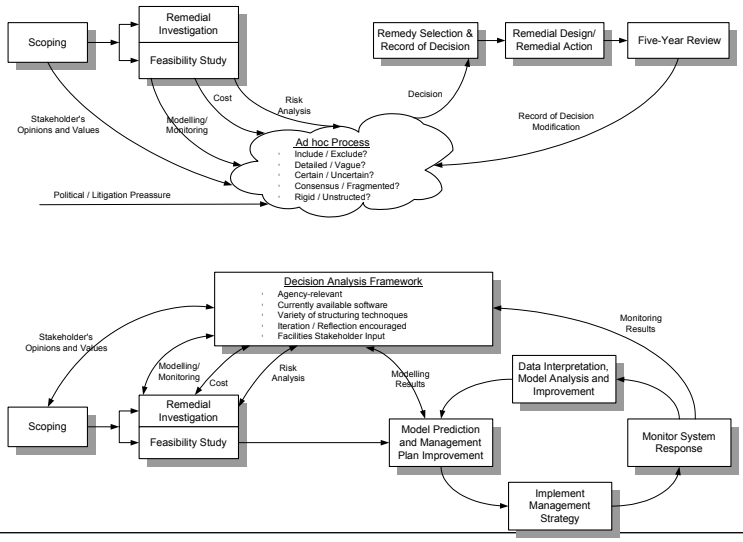
# IV. How to Improve Interfaces?



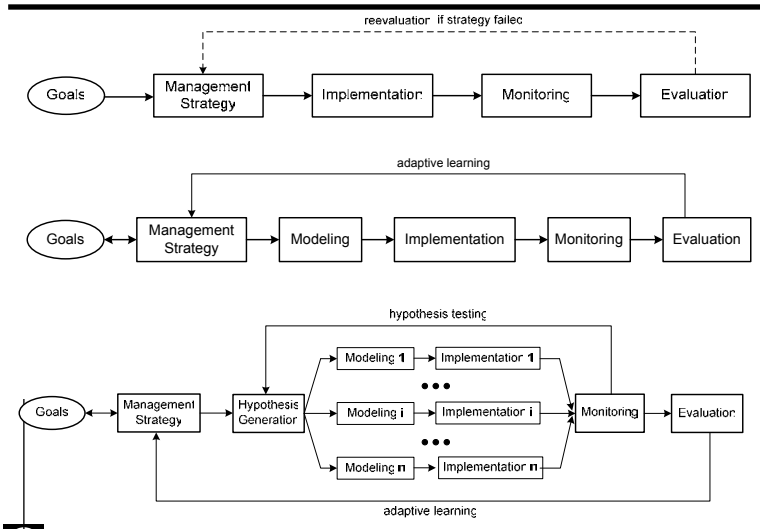



# V. What Are Research Priorities?

## Command-control vs. Adaptive Management



# *Adaptive Management Approaches*






# *Charge Questions VI and VII: Opportunities to Improve Quality and Acceptability of Decisions*

- **Where are traditional methods from toxicology not working so well?** My candidates: low level cancer risks, fine particulate matter and ozone in the air. Many other possible candidates.
- Need to describe the **sources and magnitudes of uncertainty**, not just give a point estimate of risk. [Reaffirm Recommendation in 2005 EPA Guidelines for Carcinogen Risk Assessment, 1994 NaRC Report.]
- Need to **avoid conflict among "brands"**: DA, MCDA, CB similar in concept and approach for using RPA to support decision making

## *Charge Questions VI and VII: Opportunities to Improve Quality and Acceptability of Decisions*

- **Small steps and case studies** are needed to establish PRA in agency practices. Do not try to overturn traditional practices where these are working!
- Need **transparency, credibility, proper problem formulation**. Promote an iterative analytic-deliberative process involving stakeholders. [NAS 1996 *Understanding Risk* report].
- Respect roles, **encourage responsible and honest communication between scientists, public, and decision makers about uncertainties and value judgments**. Analysts can provide integration, logical reasoning with mathematical tools. They do not provide clairvoyance or overcome ideological disagreements.