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Decision Analysis Society of INFORMS

R-B-C NASA Space Mission Probabilistic Evaluation
New NASA Strategic Environment

- Petallop (1016) computing capability
- Model-based design
- ISE: Intelligent Synthesis Environment
  - Proposal development: One week
  - Cost before commitment
  - LCA: Life-Cycle Cost Analyses
    - Implementation time: 18 months
    - Many launches a year
    - No more "Flagship" projects
- F-B-C: Faster, Better, Cheaper
Problem: How to close gap between design and knowledge and cost commitment.

Fact: Large percentage of knowledge

Fact: Large percentage of cost committed with only existing data into knowledge.

- Capture design knowledge early in life cycle.
- Use geographically distributed talent.
- Reduce uncertainty.
- Need end-to-end product life cycle simulation.
Cultural barrier.

- High-speed Information Corridors.
- Petascale (10^15) computing.
- Hardware Requirements.

Collaborative environment.
4. Tools to link complete life-cycle simulation in a virtual world.
3. Tools for rapid synthesis and simulation tools.
2. Infrastructure for distributed collaboration between diverse teams across world.
1. Dynamic interface between humans and computers.

**ISE Major Components**
INFORMS Special: Probability Elicitation

- Completeness (unknown unknowns)
- Specification error (Model uncertainty or IAEA Type B)
- Randomness of nature (Aleatory or IAEA Type A)

For all uncertainties:
  - Will require extensive probabilistic elicitation
  - Will minimize analysis time and cost
  - Requires extensive expert judgment
- Rapid development cycle
- Risk cannot be designed out of missions
- F-B-C does not permit "worst-case designs"
- Requires explicit incorporation of uncertainty
- Design and analysis done in real-time
- Mission level
- Experts provide models which are compounded up to

F-B-C Design Requirements

Model-Based designs
Launch: 1999.
Stardust Project.
Mars Pathfinder (July 4, 1997 landing).
Faster-Better-Cheaper Projects.
Earth flyby: August 1999.
Launch: October 1997.
Cassini to Saturn (1997).
Ulysses to Jupiter and over the Sun (1991).
Galileo to Jupiter (1989).

Statements.
Flagship projects with environmental impact.

Probabilty Elicitation
PL Experience in
- Risk assessment done to assess feasibility of design.
- Release science capsule to land in Utah desert.
- Flyby of Earth in 2006.
- Encounter Comet Wild-2 in 2004.
- Launch in 1999.
- Stardust Project.
- Entry, descent, and landing of Lander.
- Risk assessment done to assess feasibility of design.
- Mars Pathfinder.

Two E-B-C Missions.
Examine and discuss resulting CDF.

- Verifying
- Median
- Encoding
- Training
- Discussion
- Conditioning
- Done by System Engineer
- Structuring
- Viewing
- Purpose
- Motivating

Phases of Elicitation

IP Implememntation of SRI
Informal: Uncertainty Elimination

Training for the technology expert.

Provided by the elicitor.

Normative Goodness in Elimination.

Provided by the technology expert.

Substantive Goodness in Elimination.

Nothing in the model not needed for decisions.

Everything in the model needed for decisions.

Requisite Model.
Monte-Carlo simulation for mission CDF.

- CDF's of probabilities of failure.
- CDF's of normal distributions.
- Modelled as lognormal distributions.
- Uncertainties in failure of critical events.

Fault-Tree modelled in MS Excel.

Final result is expert opinion of project engineer.

1. Project system engineer and risk assessor jointly developed Fault-Tree Model.

2. Probability elicitation done with engineers cognizant for each critical event.

3. Results "rationalized" by project engineer.

Final result is expert opinion of project engineer.

Three step process.

Requisite Models.
Training Session

- Training session well received.
- 90 days previous data.
- Knowledge of market.
- Knowledge base.
- Forty-five minute training session.
- Used Closing Dow Industrial 30 for same day.
- Subsequently developed for Stardust Mission.
- Problems resulted in confusing process with elicitation.
- Not used for Mars Pathfinder EDL.
What are factors that could cause the Dow to be very high?

What are factors that could cause the Dow to be very low?

Given the data you are presented with and your prior knowledge, assess where the Dow will be at the end of the day.

Consider the Dow 30 Industrials Stock Index as an example of probability assessment.
Probability (1%) =

Day?

One chance in 100 of being lower at the end of the year. For what value do you believe the Dow has only twice a year.

Then your prediction could be lowered for which the end-of-year values would correspond to Dow values.

This is your most pessimistic assessment, it would

This is called a "Bear Market"
= Probability (99%) •
= Probability (90%) •
= Probability (50%) •
= Probability (10%) •
= Probability (1%) •

Day? only x% chance or being lower at the end of the
For what probability do you believe the Dow has

Assessment of Dow Probabilities
Expert Judgment always present.

Sources:
Almost all knowledge is a combination of these:
- Expert Judgment
- Analyses
- Testing
- Flight experience
- Knowledge

Taxonomy for sources of F-B-C NASA space

F-B-C Missions
Sources of Knowledge for
Thinking About Failures

Three perspectives on failure probabilities.

1. Think about design, implementation, and operations of similar complexity. How often would this result in failure?

2. Repeat the design, implementation, and operation for your event many times. How often would this result in failure?

3. Think of failure events in your life for which statistical evidence exists. Is the failure of your event more or less probable?
For what probability do you believe the true value, if it could be known, has only one chance in 100 of being lower?

This is your most optimistic assessment. It would

\[
\text{Probability (1\%)} = \frac{1}{100}
\]
Descent and Landing
Mars Pathfinder Entry
9. Did alert project to areas needing extensive testing.

10. PRA done too late in development to influence design.

11. Results presented at launch-readiness review.

12. Probability of failure at mission level.

13. Two Deputy Project engineers independently assessed project.

14. No training session for probability elicitation.

15. Contractor engineers for each failure event interviewed.

16. Monte-Carlo simulation in @RISK.

17. Mission modeled as series elements in MS Excel.

18. All events in series-no redundancy.


20. Mars Pathfinder Risk Assessment
<table>
<thead>
<tr>
<th>Event</th>
<th>Mode</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Median</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry, Descent, and Landing</td>
<td>Lognormal Dist.</td>
<td>9.32</td>
<td>2.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Mars Pathfinder EDL Failure Probability:**

- MAV Flight Computer 0.08%
- 23 Platform Deploy 0.08%
- 23 Audience Impact 0.08%
- 23 Surface Impact 0.08%
- 26 Bridge Out 0.08%
- 25 Ramrod Runner 0.08%
- 24 Alpaca Motion 0.08%
- 24 Armament Operations 0.08%
- 22 Bridge Deploy 0.08%
- 21 Heatshield Separate 0.08%
- 22 Bridge Deploy 0.08%
- 21 Heatshield Separate 0.08%
- 14 Parachute Deploy 0.08%
- 13 Thermal Protection 0.08%
- 12 Guidance Error 0.08%
- 11 Fence Stakes Sep 0.08%
- 9.32 | 2.12 |

Mars Pathfinder Fault Tree

Informs Satellite: Probability Ectation
Mars Pathfinder PDF
Design conservatism obscured true risk.

- Design.

- Results not formally presented by Project.

- Mission Level.

- Project Engineer reassessed probability of failure at

- Probabilities elicited from cognizant engineers.

- Training sessions for all probability assessors.

- Monte-Carlo simulation in JPL Excel Add-in.

- Mission modeled as series elements in MS Excel.

- All events in series--no redundancy modeled.

- Recovery of science capsule in Utah desert.

- Assessment from Launch Vehicle Separation to

Stardust Risk Assessment
5. Use structured group processes.
4. Aggregate multiple experts.
3. Decompose the problem.
2. Effective techniques for reducing overconfidence.
1. Experts are poor processors of information.
Reluctance to accept PRA in general.
Reluctance to accept subjective probabilities.
Engineers don't understand statistical processes.
Management and engineering biases present.
Done too late to influence design.

Critique of Process
For Future Research
References

Probability Elicitation