Propagating Uncertainties in Simulation Assessments of Rockets, Artillery and Mortars Intercept Alternatives

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- Summarizing a sensitivity analysis with descriptive statistics
- Principles & past usage of uncertainty / risk analysis
- Comprehensive inventory of error sources
- Sources of uncertainty for life-cycle effectiveness
- Life-cycle cost & effectiveness with error & uncertainty for the rockets, artillery and mortars (RAM) intercept example
- Concluding observations
Simulation analyses are not error-free

Sampling errors in Monte Carlo simulations can be estimated & controlled by sample size and designs of experiments

Analyses are subject to limited information imposed by schedule & limited resources

Errors propagate when the outputs are used in another analysis or in decision making

The risk in errors & uncertainty in analysis is the consequence of a “wrong” decision

Error and uncertainty in analysis can be analyzed in a holistic framework that includes limited information and decisions with risk

Errors & uncertainties in analysis are also sources of risk
Current practice in simulation analysis

Fixed-point assumptions conceal effects of unknowns on operational effectiveness analysis
- Likelihood of a “stressing scenario”
- Variations on the type of operation
- Variations in threat capabilities & tactics
- Variations in terrain and weather
- Unknown performance parameters for future solutions, threats and competitors

Assumptions should be transparent

Use authoritative sources to validate fixed-point assumptions
  - Authoritative sources, study advisory groups, program direction, subject matter experts, peer review

Even when “validated”, over-reliance on fixed-point assumptions can lead to an illusion of certainty (Janis 1973)

Employ extensive sensitivities to understand how assumptions affect the outcomes (Office of Aerospace Studies 2010, Morrow 2011)

Expose, document and estimate all sources of error
  - Assumptions, inputs, modeling & simulation limitations, Monte Carlo sampling, response surface fit, generalization

*How to present comprehensive sensitivities in a way that recognizes risks and facilitates decisions?*

Comparisons and sensitivity analysis for RAM intercepts simulation in EADSIM

The systems and threats in these examples are notional and presented for illustrative purposes.
Descriptive statistics summary of sensitivity studies

The graphics show summaries of 3600 engagement simulations and 600 cost outcomes.

These show central location, spread and extreme-values of outcomes.

Not a substitute for sensitivity graphs that link variation to particular factors.

Cumulative probability graphs show more detail in the distributions but are less intuitive to some viewers.

All sources of variation are included:
- Sensitivity of 16 factors
- Monte Carlo variation within simulation

All points treated equally likely.

*A descriptive statistics summary shows distributions of the data without inference.*

The systems and threats in these examples are notional and presented for illustrative purposes.
Principles of an outcome-based risk analysis

A reality: decisions are made with incomplete information

Expected values of consequences are not sufficient to evaluate alternatives (Markowitz 1952, Kaplan & Garrick 1981)

Subjective probabilities represent the current state of knowledge (Jaynes 1968)

Quantitative risk assessment approach: evaluate alternatives with probability distribution on a scale of outcomes (Garrick & Christie 2008)

Transparency: the risk analysis should trace to the detailed sensitivities

The risk analysis should help identify the principal sources of risk

*Risk is best understood in terms of a population of measurable consequences*

![Graph](image1)

Common risk decisions are evaluated on extreme value as well as expected outcome

![Graph](image2)

Frequency of man-caused disasters (fires, explosions, air crashes, dam failures, Kaplan & Garrick, 1981)

A risk reporting matrix (AMSAA Risk Team, 2013)
Identify *all* sources of error and uncertainty in the analysis

In Monte Carlo error analysis, all sources of error and uncertainties are assigned probability distributions for sampling. The distributions should represent the current state of knowledge. Capability to change distributions & update results in real time can facilitate presentation.

* Aleatory uncertainty, subject to averaging. Others are epistemic uncertainties.
Applications of uncertainty & risk analysis

Timson applies subjective probabilities and Monte Carlo simulation to model probability distributions for critical performance parameters in engineering program management (1968)

Cuff demonstrates how quantitative risk analysis in performance, cost and schedule can support program decisions (1973)

Armacost & Pet-Edwards incorporate uncertainty in ice flow reporting in ice patrol operations planning (1995)

Fredley (1995) includes uncertainty in numbers and types of future operations in a force structure analysis approach

Pate-Cornell & Guikema present a model for prioritizing terrorism threats and countermeasures in homeland security (2002)

Monte Carlo sampling is used to propagate uncertainty of inputs in complex physics and environmental models (Christie, et al. 2005; Lloyd & Ries 2007)

Simulation-based sampling is used to propagate uncertainty through cost models (Anvari 2011)

Monte Carlo sampling has been used to propagate uncertainty in physical systems and cost modeling

The systems and threats in these examples are notional and presented for illustrative purposes
Linking vignette results to life-cycle cost effectiveness

How will the acquisition will be judged after the fact?

The acquisition was well-matched to the threat and operations that actually occurred; the investment could not have achieved greater ends elsewhere.

The acquisition was exceeded by the threat; high casualties and constraints on joint commander.

The acquisition overmatched the actual threat to the extent that excess dollars could have been used to improve other capabilities.

Sources of uncertainty for the life cycle

What types of global threats will emerge?

What types of operations will be undertaken?

How many vignettes will occur over the life cycle?

What is the distribution of “vignette intensity” (numbers of threat RAM employed)?

How should vignette to vignette variability be treated?

*We can assign probability distributions to numbers of vignettes, threat size and intensity to derive a probability distribution of life-cycle casualties.*

[Graphs showing cumulative number of RAM incidents and threat size distribution]
Application to RAM intercept alternatives

Monte Carlo sampling of 3000 vignettes grouped into 200 futures

Grouping is necessary to separate epistemic and aleatory factors (epistemic factors should not be averaged over vignettes)

Discussion of alternatives can address extreme value as well as expected value outcomes

Distributions are highly skewed in this example

Ability to zoom the ordinate scale would help discriminate alternatives

A RAM intercept comparison showing life cycle effectiveness and cost as probability distributions

The systems and threats in these examples are notional and presented for illustrative purposes
Pulling the thread: cases resulting in >5,000 casualties for Devel interceptor

Six of 200 samples (3%) resulted in high 10-year casualties

Except for Threat Size and Number of RAM Attacks, these samples are representative of uncertainty distributions

A source of risk is a decade of recurring RAM attacks at near full threat strength

Remaining options are to re-evaluate the uncertainty, improve alternative resilience or accept the residual risk
Some observations

The need for sensitivities of many uncertainty factors makes modern designs of experiments more attractive
   The examples in this presentation used a space-filling design with 16 uncertainty factors and 410 scenarios

Replicate the DOE of uncertainty factors for each alternative; then there will be side-by-side simulations of the alternatives

Bayesian inference can produce posterior probability densities of some simulation inputs that are anchored to past observations
   Example: use past data on RAM incidents to develop the probability density of future incidents

Whether or not to use surrogate models
   It is possible to run simulations with directly sampled random inputs, directly summarizing outputs without surrogate models
   Pro: surrogate models allow reconstruction of sensitivities
   Pro: surrogate models allow real-time changes in the input probability densities for collaborative workshops
   Con: surrogate models introduce an estimation error that needs to be incorporated into the error modeling

If a surrogate model is used, Bayesian inference can produce a probability density of estimation error

*Modern DOE and response surface methods facilitate simulation error & uncertainty analysis*
Summary of Key Points

Errors & uncertainties in analysis are sources of risk

A descriptive statistics summary shows distributions of the data without inference

Risk is understood in terms of a population of measurable consequences

Identify all sources of error and uncertainty

Monte Carlo sampling can be used to propagate uncertainty through simulations

Assign probability distributions to numbers of vignettes, threat size and intensity to derive a probability distribution of life-cycle benefits

Risk-based error and uncertainty analysis presents effectiveness and cost as probability distributions
References


Backup Material
Monte Carlo sampling of 3000 vignettes grouped into 200 futures

Grouping is necessary to separate epistemic and aleatory factors (epistemic factors should not be averaged over vignettes)

Discussion of alternatives can address extreme value as well as expected value outcomes

Distributions are highly skewed in this example

Ability to zoom the ordinate scale would help discriminate alternatives

*A RAM intercept comparison showing life cycle effectiveness and cost as probability distributions*
Alternatives used in illustrative RAM defense risk analysis

<table>
<thead>
<tr>
<th>Development</th>
<th>Sense &amp; Warn</th>
<th>Near term (NT) interceptor</th>
<th>Developmental (Devel) interceptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magazine (interceptors/launcher)</td>
<td>Maintain other RAM defense pillars without intercept capability</td>
<td>In production Integrate in RAM defense system of systems</td>
<td>Develop new start interceptor &amp; new fire control radar</td>
</tr>
<tr>
<td>Nominal speed (m/sec)</td>
<td>525</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td>Nominal range (m)</td>
<td>7000</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>PK (&lt;240 mm threats)</td>
<td>.85-.99</td>
<td>.85-.99</td>
<td></td>
</tr>
<tr>
<td>PK (≥240 mm threats)</td>
<td>.5-.9</td>
<td>.85-.99</td>
<td></td>
</tr>
<tr>
<td>Common elements</td>
<td>RAM intercept system consists of surveillance radar, fire control radar, C4I and four launchers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The systems and threats in these examples are notional and presented for illustrative purposes*
## Error & uncertainty sources inventory

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threat size factor</td>
<td>% of threat full strength scenario</td>
</tr>
<tr>
<td>Threat aiming accuracy</td>
<td>Uncertainty multiplier of CEP</td>
</tr>
<tr>
<td>Threat standoff range</td>
<td>% between min &amp; max range</td>
</tr>
<tr>
<td>Surveillance radar range</td>
<td>Types of radars available in future is uncertain</td>
</tr>
<tr>
<td>Fire control radar range</td>
<td></td>
</tr>
<tr>
<td>C3I decision time</td>
<td>Uncertainty in time to clear engagement</td>
</tr>
<tr>
<td>Kill assessment time</td>
<td>Uncertainty in time to assess intercept</td>
</tr>
<tr>
<td>Simultaneous engagements</td>
<td>Number of interceptors in flight</td>
</tr>
<tr>
<td>FCR availability</td>
<td>Actual availability will differ from program requirement</td>
</tr>
<tr>
<td>Launcher availability</td>
<td></td>
</tr>
<tr>
<td>Interceptor speed</td>
<td>Uncertainty scale factor of nominal speed</td>
</tr>
<tr>
<td>Interceptor range</td>
<td>Uncertainty scale factor of nominal range</td>
</tr>
<tr>
<td>PK</td>
<td>Actual PK will vary from program requirement</td>
</tr>
<tr>
<td>Secondary PK</td>
<td>NT alternative PK vs large caliber rockets</td>
</tr>
<tr>
<td>EADSIM internal sampling</td>
<td>PK success, threat &amp; defense systems availability, impact points</td>
</tr>
<tr>
<td>Response surface error</td>
<td>Errors due to DOE &amp; interpolation</td>
</tr>
<tr>
<td>Vignette rate of occurrence</td>
<td>Mean occurrence rate per year</td>
</tr>
<tr>
<td>% of each type vignette</td>
<td>Occurrence rate as % of total</td>
</tr>
<tr>
<td>Number of each type vignette</td>
<td>Actual number, each type of vignette over 10 years</td>
</tr>
<tr>
<td>Personnel at risk</td>
<td>Number of personnel in defended area</td>
</tr>
<tr>
<td>Cost growth</td>
<td>Uncertainty factors in program and ownership cost</td>
</tr>
</tbody>
</table>