Title of Paper: System-Of-Systems Analysis Using Design of Experiments

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System-Of-Systems Analysis Using Design of Experiments

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A collaborative proof of principle study was undertaken with input from both the S4 team at the Physical Science Laboratory at New Mexico State University and the SEED Center at the Naval Postgraduate School. The work was sponsored by the Survivability and Lethality Analysis Directorate (SLAD) of the Army Research Laboratory.

Participants:
- ARL/SLAD: Dr. Jeffrey A. Smith
- PSL/S4: Dr. Jayashree Harikumar, Dr. Roger Hartley
- NPS: Dr. Tom Lucas, Dr. Dashi Singham, Maj. Russ Edmiston

SEED: Simulation Experiments and Efficient Designs
S4[1]: System of Systems Survivability Simulation
SoSA requires M&S of people in battlefield situations; situations that inherently possess complex multidimensional input parameter spaces and corresponding output spaces. These complexities make it difficult for decision makers to have confidence in the conclusions drawn from the M&S.
Objectives

1. Develop a methodology to cover a large input space of parameters in a statistically adequate manner while keeping the number of simulation runs needed in a test suite to a minimum.

2. Evaluate the experiment design techniques proposed by the NPS SEED Center to explore the relationships between S4’s input and output spaces.

3. Statistically examine the relationships between input and output spaces to enable assessments of the performance of the simulation.

SEED: Simulation Experiments and Efficient Designs
S4[1]: System of Systems Survivability Simulation
Latin Hypercube Sampling and SEED Center techniques

- S4 simulation has a **large input space** of discrete, continuous, categorical (rule based, tightly coupled) parameters.
- Exhaustive testing of this space for QA is impossible.
- **Latin Hypercube Sampling (LHS)** is a technique to uniformly sample an input space of factors and remain true to each factor’s probability distribution of values. Ideally, LHS wants input factors to be orthogonal, but in practice it is often necessary to use non-orthogonal factors.
- SEED center has techniques to pair non-orthogonal input factors.
- They can also provide methods to pair input variables such that with fewer “tuples” of input factors (design points, DPs) one can explore the output space **(reduction in computing cost)**.
### Collaboration timeline

<table>
<thead>
<tr>
<th>Dates</th>
<th>Major Milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 2010</td>
<td>1st meeting to discuss possible collaboration</td>
</tr>
<tr>
<td>November 2010</td>
<td>S4 training for Dr. Singham and Maj. Edmiston</td>
</tr>
<tr>
<td>December 2010</td>
<td>S4 scenario provided to Maj. Edmiston</td>
</tr>
<tr>
<td>January 2011</td>
<td>Initial Design of Experiment (DOE) specified</td>
</tr>
<tr>
<td>February 2011</td>
<td>Design of experiments conducted</td>
</tr>
<tr>
<td>March 2011</td>
<td>First scenario analysis completed</td>
</tr>
<tr>
<td>June 2011</td>
<td>Formal presentation of results by Maj. Edmiston</td>
</tr>
<tr>
<td>June 2011</td>
<td>Final deliverables to ARL</td>
</tr>
</tbody>
</table>
• An agent-based battlefield simulation.
• Limited to Battalion(-) and below force structure (in the order of 100 agents).
• Major areas of modeling emphasis:
  – Sensing (human, EO, IR)
  – Mobility (terrain, movement)
  – Engagement (weapons, damage)
  – Communications (radios, networks)
  – Decision making (C2, COAs, operational planning)
• Used to aid analysts (SLAD, AEC) to provide a mission context for the use of devices and/or platforms.
A screenshot using Sage (a S4 visualization tool)
• SEED center proposed a **NOLH design that could not be used** as is and had to be “custom” modified to a **NONBMD design** (specifics in later slides).

• NONBMD was tested with a input sample space of 11 communication factors, on 3 scenario variants, using communication failures and their impact on mission success as output variables.

• To test 11 communication factors using their high, mid, and low values across 3 scenarios would require **531,441** simulation runs. With the new technique, **2160** runs were adequate to cover the input-output space of possibilities (specifics on DP selection and analysis given in later slides).

• Data analysis of the small sample study indicates that the **design may be extended** to cover a larger space of inputs, and may be used in structured evaluation of S4 modules in a generic (non study) context.

_NOLH: Nearly Orthogonal Latin Hypercube_
_NONBMD: Nearly Orthogonal Nearly Balanced Mixed Design_
S4 simulation consists of software components that model sensors, terrain, ballistics effects, engagements, decision making processes (DMP), communications and networks.

Flow of information is critical to the S4 DMPs, so the proof of principle study was designed around communication factors.

The impact of these factors on the simulation output was measured predominantly in terms of operational delay.

Three guiding questions were used to address the objectives quantitatively.

1. Which input factors have the most influence on the model’s output?
2. How sensitive are the model’s DMPs to the success or failure of communications?
3. Is the model output a result of the equipment capabilities being analyzed or a product of the communication environment modeled?
<table>
<thead>
<tr>
<th>Number and type of parameters</th>
<th>Communications parameters considered</th>
<th>Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Discrete</td>
<td>Max TCP Retries</td>
<td>□ ☑</td>
</tr>
<tr>
<td>2 Discrete</td>
<td>Bits in Data Unit</td>
<td>□ ☑</td>
</tr>
<tr>
<td>3 Discrete</td>
<td>Bits of Overhead</td>
<td>□ ☑</td>
</tr>
<tr>
<td>4 Continuous</td>
<td>Antenna Gain</td>
<td>☑ ☑</td>
</tr>
<tr>
<td>5 Continuous</td>
<td>Link Refresh Meters</td>
<td>☑ ☑</td>
</tr>
<tr>
<td>6 Continuous</td>
<td>Link Refresh Seconds</td>
<td>☑ ☑</td>
</tr>
<tr>
<td>7 Continuous</td>
<td>TCP* Retransmit Interval</td>
<td>□ ☑</td>
</tr>
<tr>
<td>8,9 Categorical</td>
<td>Propagation Mode + P(Message Receipt)</td>
<td>☑ ☑</td>
</tr>
<tr>
<td>10,11 Categorical</td>
<td>Available Bandwidth + Duration Mode</td>
<td>□ ☑</td>
</tr>
</tbody>
</table>

*A categorical parameter comprises of 2 or more tightly coupled parameters*
Sample scenario with EAST variant to emphasize analysis of communications parameters and their impact on DMPs.

- 1 scenario (3 variations in the start positions) for Blue
- 21 Agents (16 BLUE, 5 RED)
- Communication heavy, no engagements
## Design of experiment: Communications networks

<table>
<thead>
<tr>
<th>Network Name / LDR</th>
<th>Description</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN / BN Cdr</td>
<td>Provide C2</td>
<td>CO Cdr, Recon Cdr</td>
</tr>
<tr>
<td>CO / CO Cdr</td>
<td>C2 to Maneuver PLT.</td>
<td>HMMWV 4</td>
</tr>
<tr>
<td>RECON / Recon Cdr</td>
<td>C2 to UAV, Scout Teams</td>
<td>UAV, Scouts 1-4, 2-4</td>
</tr>
<tr>
<td>Maneuver PLT / HMMWV-4</td>
<td>Platoon and Platform DMP</td>
<td>HMMWV -1, 2, 3</td>
</tr>
<tr>
<td>SCOUT Team-1 / Scout 1-4</td>
<td>Scout team leaders provide information collected by their teams to Recon Cdr</td>
<td>Scouts 1-1, 1-2, 1-3</td>
</tr>
<tr>
<td>SCOUT Team-2 / Scout 2-4</td>
<td></td>
<td>Scouts 2-1, 2-2, 2-3</td>
</tr>
<tr>
<td>INSURGENT / Insurgent Ldr</td>
<td>Provides C2 to entire RED force</td>
<td>Truck-1, Truck-3</td>
</tr>
<tr>
<td>TRUCK Team 1 / Truck-1</td>
<td>Platform DMP; Team leaders relay information collected by their team to Insurgent Ldr.</td>
<td>Truck-2</td>
</tr>
<tr>
<td>TRUCK Team 2 / Truck-3</td>
<td></td>
<td>Truck-4</td>
</tr>
</tbody>
</table>

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NONBMD: Nearly Orthogonal Nearly Balanced Mixed Design

DP: Design point (DP) is a unique combination of values of input variables
Design of experiment: Design Point (DP) replication

- Runs with the same input parameters but different seeds produce different results, which makes it necessary to replicate the DPs so that statistical inferences can be made.

- To address the impact of changing parameter values and random draws, a different seed was used for every run.

- To determine the number of replications, from 12 seed variance runs we computed the variance ($\sigma = 11.9$) and used the power formula:
  \[ n = \left( \frac{2Z_{\alpha/2} \sigma}{w} \right)^2 \]
  (Maj. Edmiston 2011).
We examined communication failures by type (4) and by agent (21) from 2160 runs (144 DP x 5 replications per run x 3 scenario variants).

We used the operational impact of communication failure as the output to do the analysis. By operational impact, we mean, the time delay between the RED Insurgent teams’ first being spotted in the area of interest (AOI) and the BLUE Maneuver Platoon’s receiving a new mission information package (MIP).

The assumption made was that communications do not affect physical movement and once RED begins moving to its AOI it should reach there approximately within the same amount of time.

Failure Distributions (Maj. Edmiston 2011)
- Mean of total failures ~84.9 (95% confidence interval [83.34, 86.46]).
- 77 % failures because time to send message expired.
- Agents with low failures were predominantly receivers of information.
• We examined parameters influence using regression models (2-way interactions) with communication failures as the response, and partition trees.
  – P(Message Receipt) and Max TCP Retries were the most influential factors. They showed influence across their entire range.
• Quality of the communications environment affected the decisions made by the DMPs.
  – In a “good” communications environment, a mission order was received ~6 minutes earlier than in the base case.
  – In a “poor” but effective environment, mission order was delayed by ~15 minutes compared to the base case.
• Communications environment played a critical role between equipment sending and receiving information.
NONBMD shows promise in handling a small sample space. More conclusions on the extendibility of this design can be made only after more testing of the design using a larger sample space.

