AMSC Complex Systems M&S Workshop
February 3 2010

Modeling and Validation Challenges for Complex Systems

Mikel D. Petty, Ph.D.
Center for Modeling, Simulation, and Analysis
University of Alabama in Huntsville

UAHuntsville
Center for Modeling, Simulation, and Analysis
Presentation outline

- **Background definitions**
  - Complex systems
  - Modeling
  - Validation

- **Modeling and validation challenges**
  - Sensitivity to initial conditions
  - Emergent behavior
  - Component model composition

- **Summary**

---

Practical suggestions on developing and building models of complex systems; not theoretical limits of predictability of complex systems using models.
Background definitions
Complex systems

“A system comprised of a (usually large) number of (usually strongly) interacting entities, processes, or agents, the understanding of which requires the development, or the use of, new scientific tools, nonlinear models, out-of-equilibrium descriptions and computer simulations.” [1]

“A complex system is one whose evolution is very sensitive to initial conditions or to small perturbations, one in which the number of independent interacting components is large, or one in which there are multiple pathways by which the system can evolve.“ [2]

Characteristics of complex systems

- Defining characteristics
  - Sensitivity to initial conditions
  - Emergent behavior
  - Composition of components
  - Uncertain boundaries
  - Nesting
  - State memory
  - Non-linear
  - Feedback loops
  - ...

- Any specific characteristic arguable
Modeling and Validation Challenges for Complex Systems

Modeling [3]

Simuland

Referent

<table>
<thead>
<tr>
<th>t</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td>1</td>
<td>1084</td>
</tr>
<tr>
<td>2</td>
<td>1136</td>
</tr>
<tr>
<td>3</td>
<td>1156</td>
</tr>
<tr>
<td>4</td>
<td>1144</td>
</tr>
<tr>
<td>5</td>
<td>1100</td>
</tr>
<tr>
<td>6</td>
<td>1024</td>
</tr>
<tr>
<td>7</td>
<td>916</td>
</tr>
<tr>
<td>8</td>
<td>776</td>
</tr>
<tr>
<td>9</td>
<td>604</td>
</tr>
<tr>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>11</td>
<td>164</td>
</tr>
</tbody>
</table>

Modeling

\[ h(t) = -16t^2 + vt + s \]

/* Height of an object moving in gravity. */
/* Initial height v and velocity s constants. */
main()
{
  float h, v = 100.0, s = 1000.0;
  int t;
  for (t = 0, h = s; h >= 0.0; t++)
  {
    h = (-16.0 * t * t) + (v * t) + s;
    printf("Height at time %d = %f\n", t, h);
  }
}

Results

Simulation

Validation [4]

Modeling and validation challenges
Complex systems evolution highly sensitive to initial state. Small differences in state become magnified over time. [5]

Sensitivity to initial conditions: Modeling

• Challenges
  ▪ Model implementation side effects
  ▪ Sensitivity consistency
  ▪ Input data precision

• Mitigation methods
  ▪ Ensemble forecasting [6]

Sensitivity to initial conditions: Validation

- Challenges
  - Broad results distributions [7]
  - Input data precision
- Mitigation methods
  - Increased trials
  - Sensitivity analysis [8]
  - Observation precision compensation

**Emergent behavior** [9]

Behavior not explicitly encoded in agents or components. Emerges from interaction of agents or components with each other and environment.

Emergent behavior: Modeling

• Challenges
  ▪ Incomplete simuland observation
  ▪ Indirect representation
  ▪ Abstraction risk

• Mitigation methods
  ▪ Increase simuland observations
  ▪ Explicit conceptual model focus

Emergent behavior: Validation

- Challenges
  - Face validation unreliability
  - Test case design
- Mitigation methods
  - Structured face validation [11]
  - Heuristic search in scenario space

Composition of components

Complex systems composed of interacting components. Complex system models composed of submodels.
Composition of components: Modeling

- Challenges
  - Interface compliance
  - Architecture selection [12]
  - Model correlation [13]
- Mitigation methods
  - Interface analysis [14]
  - Conceptual model comparison
  - Known interoperability problems [15]

Composition of components: Validation

- Challenges
  - Weakest link validity
  - Error location
  - Unsuitability of conventional statistics
  - Validity under composition [16]

- Mitigation methods
  - Uncertainty estimation [17]
  - Non-linear multivariate statistics [18]
  - Component and composition validation

Summary
Summary

- Complex systems have defining characteristics
- These characteristics create challenges
  - Modeling
  - Validation
- Mitigation methods available for each
End notes

- More information
  - Mikel D. Petty, Ph.D.
  - UAHuntsville Center for Modeling, Simulation, and Analysis
  - 256-824-4368, pettym@uah.edu

- Slides: http://cmsa.uah.edu/?downloads

- Questions?