Optimization Techniques: Improving Effectiveness for Defense Simulation Models

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Topics

- What is simulation optimization?
- Why is it important?
- Approaches (metaheuristics)
- Use cases

Simulation

- "Simulation is the imitation of the operation of a real-world process or system over time."
  - Banks, J., Carson, J. S., & Nelson, B. L., *Discrete-Event System Simulation, 2nd Ed.,* Prentice Hall (1999)
- Real-world systems are often:
  - Uncertain
  - Nonlinear
  - Complex
- Very powerful method to ensure model is <u>close</u> to real-world system
- Discrete event vs. continuous
- Live/virtual vs. constructive

Optimization

- Optimization is a prescriptive methodology
  - Prescribe decisions that produce the “best” outcome for the real-world system
- Again, we must model the real-world system
- General optimization model:

Minimize $f(\boldsymbol{x})$

Subject to: $\boldsymbol{x} \in \Omega$

$\Omega = \{x \ \in \mathbb{R}^n \mid g_i(\boldsymbol{x}) \geq 0, i = 1, \ldots, m, h_j(\boldsymbol{x}) = 0, j = 1, \ldots, k\}$

- Linear vs. nonlinear
- Continuous vs. discrete
- Single vs. multiobjective

Combining Simulation With Optimization

- Constructive simulations are often “black boxes” where a given input results in a random output, i.e.,

$$\boldsymbol{x} \longrightarrow \boxed{\textbf{Simulation}} \longrightarrow \boldsymbol{Y}$$

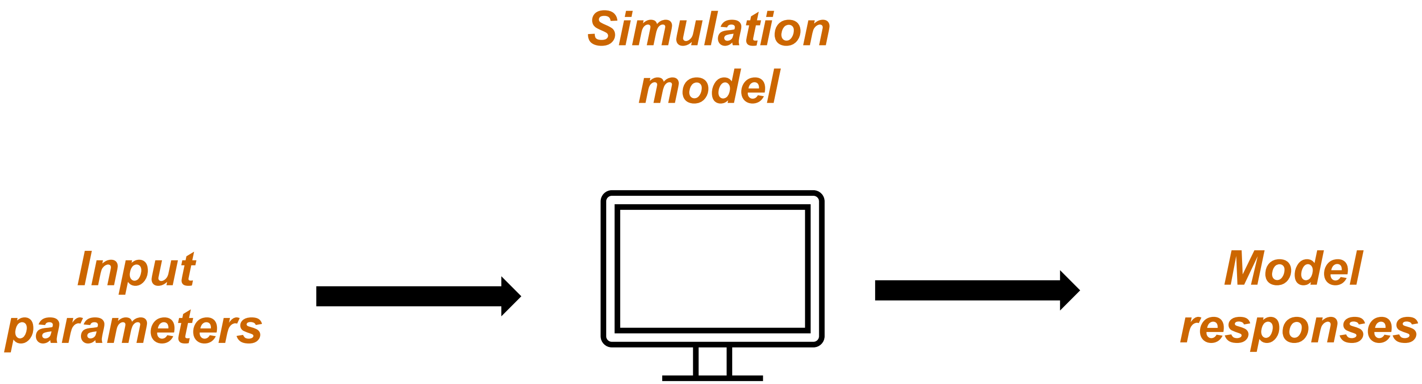
- In optimization, suppose at least one of our functions is determined by a simulation model, i.e.,

$$\boldsymbol{x} \longrightarrow \boxed{f_j(\boldsymbol{x})} \longrightarrow \boldsymbol{Y}$$

- Then:
  - Optimization model is a simulation optimization problem
  - Classic optimization solution methods break down, i.e., “black-box optimization” or “gradient-free optimization”

Simulation Optimization

- Which possible sets of model specifications (i.e., input parameters and/or structural assumptions) lead to optimal performance?



Why Is Simulation Optimization Required?

- Complex models contain many variables and constraints as well as uncertainty.
- What-if approach unlikely to result in an optimal answer due to large number of possible solutions.
- Inability of pure optimization to model complexities, uncertainties, and dynamics of scenarios.
- Simulation-optimization removes these inabilities by combining both approaches.

Why Is Simulation Optimization Required? (cont.)

- A total solution requires both capabilities.
- Integrated two-step solution:
  1. Simulation
  2. Optimization
- Both are necessary, neither is sufficient.
- Simulation enables **understanding/modeling** and communications of uncertainty.
- Optimization enables the **management** of uncertainty.

Common Simulation Analyst Tasks

- Analysts use simulation models to determine:
  - Future acquisition and investment strategy
  - Best mix and placement of assets to counter threats and meet operational objectives
  - Best parameters, rule sets, or CONOPS under which to operate
  - Design parameters for a planned system to meet operational requirements

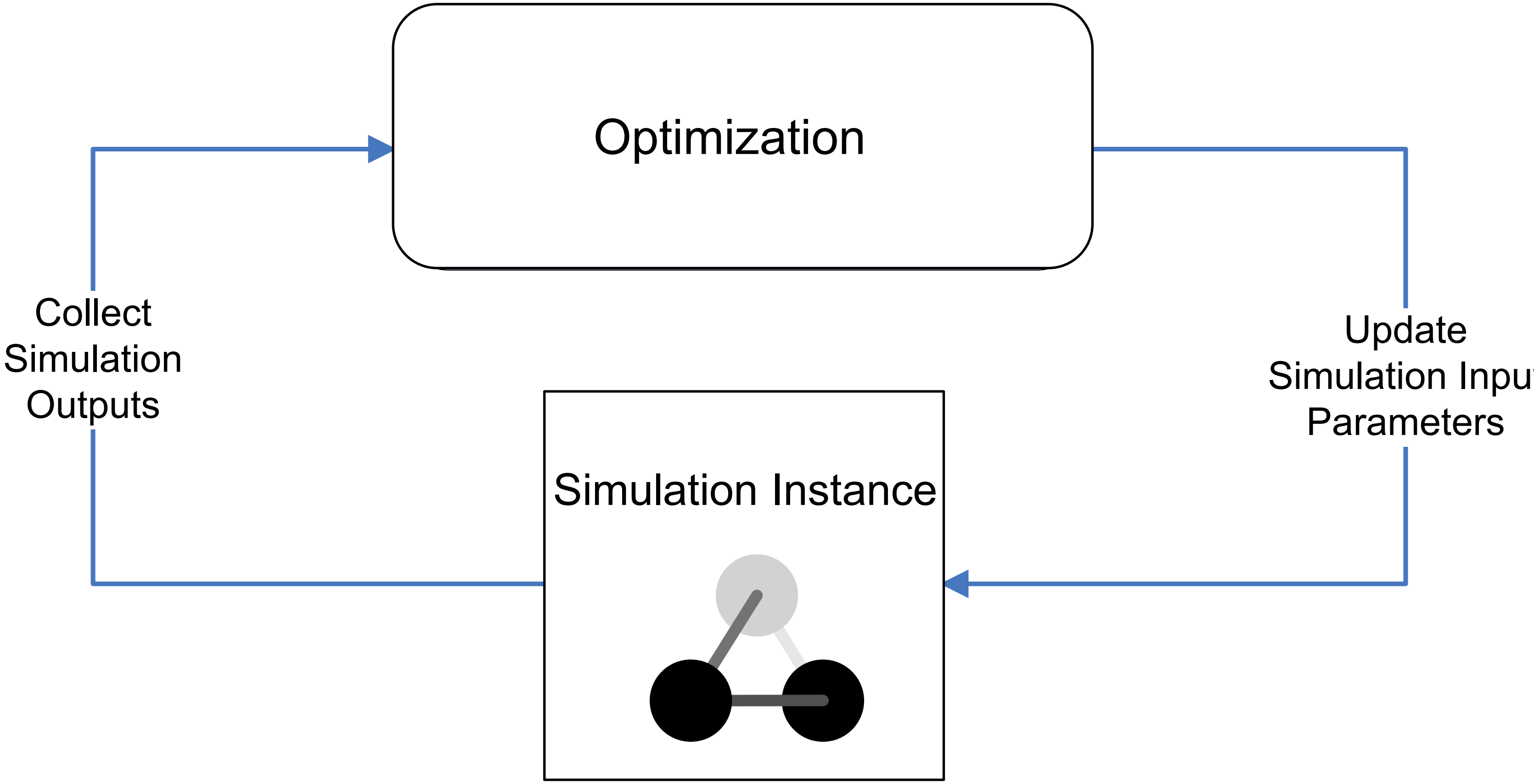
Analyst & Simulation Models

- Set up and run a limited number of excursions
  - Manual modifications
    - Sometimes scripting
  - Limited exploration and time
    - Limitations with design of experiments
  - Sometimes enumeration
    - Limited variables and levels due to complex combinations
  - Rarely optimization
    - Never true multiobjective
- Manual post-run data collection and analysis

Studies are often behind schedule, and the simulation run and analysis period is shortened.

Integrating Optimization and Analytics With Existing Models

- Optimization, meta-model, design of experiments, batch, and external sampling modes



Approaches

Metaheuristics

- Heuristic
  - "a technique which seeks good (i.e., near-optimal) solutions at a reasonable computational cost without being able to guarantee either feasibility or optimality, or even in many cases to state how close to optimality a particular feasible solution is."
    - Reeves, C. R. (editor), *Modern Heuristic Techniques for Combinatorial Problems,* McGraw Hill (1995)

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- Metaheuristic
  - "a master strategy that guides and modifies other [solution procedures] beyond those that are normally generated in a quest for local optimality."
    - Glover, F., Laguna, M., *Tabu Search*, Kluwer Academic Publishers (1997)
  - A heuristic that guides another heuristic

Metaheuristic Examples

- Heuristic examples:
  - Nearest neighbor for traveling salesperson problem (TSP)
  - Bang-per-buck for knapsack problem
  - Local search

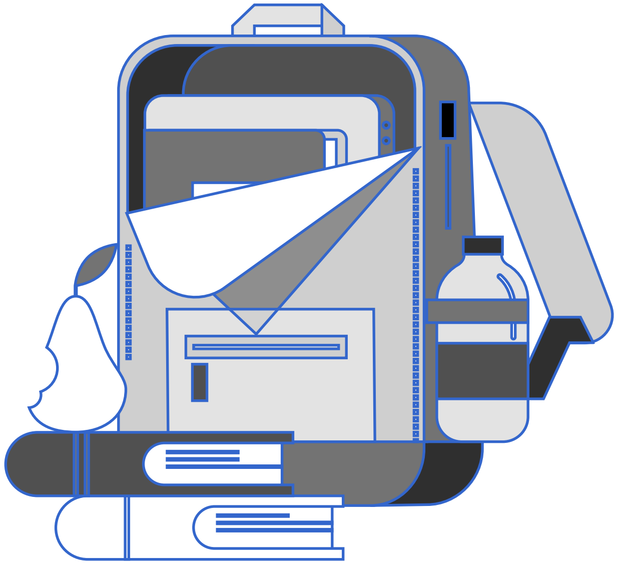


Image Source: Microsoft 365 Stock Image

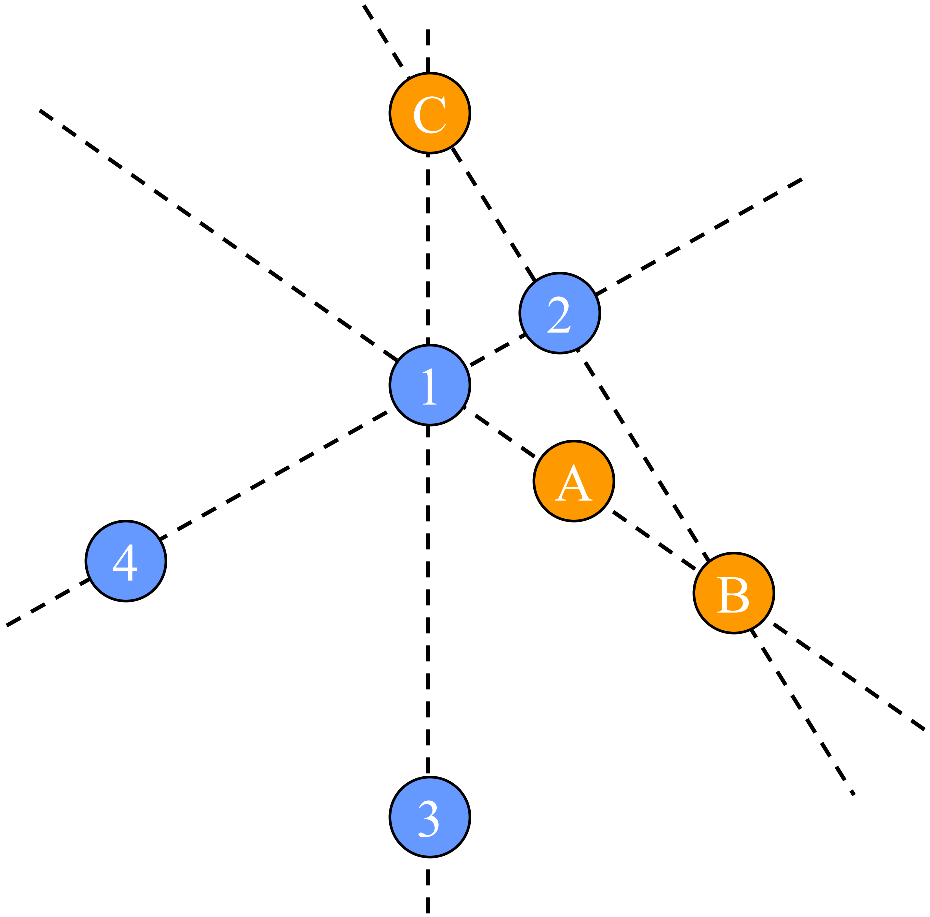
Metaheuristic Examples

- Heuristic examples:
  - Nearest neighbor for traveling salesperson problem (TSP)
  - Bang-per-buck for knapsack problem
  - Local search
- Metaheuristic examples:
  - Neighborhood based
    - Simulated annealing
    - Tabu search
  - Evolutionary or population based
    - Scatter search
    - Genetic algorithms

Evolutionary Metaheuristics - Scatter Search

- Evolutionary method that combines solutions in a reference set to create new solutions
- The notion of combining items to create new ones was originated in the 60s:
  - Combining choice rules in scheduling
  - Combining constraints in integer programming (surrogate constraint method)

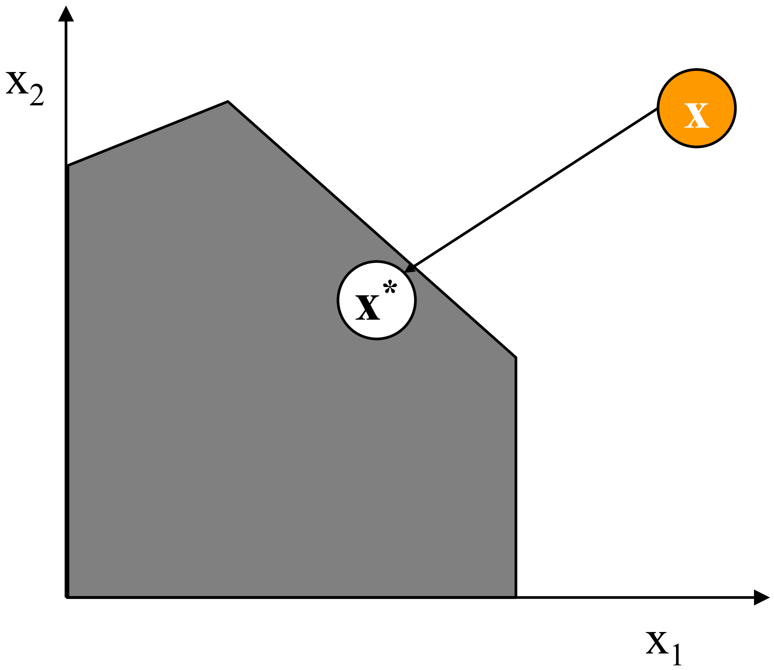
Graphical Representation



Constraint Mapping

- Combination methods may generate new trial solutions that violate the linear constraints and variable restrictions.
- The mapping consists of finding a feasible solution that is as close as possible to the infeasible trial solution.

Graphical Interpretation



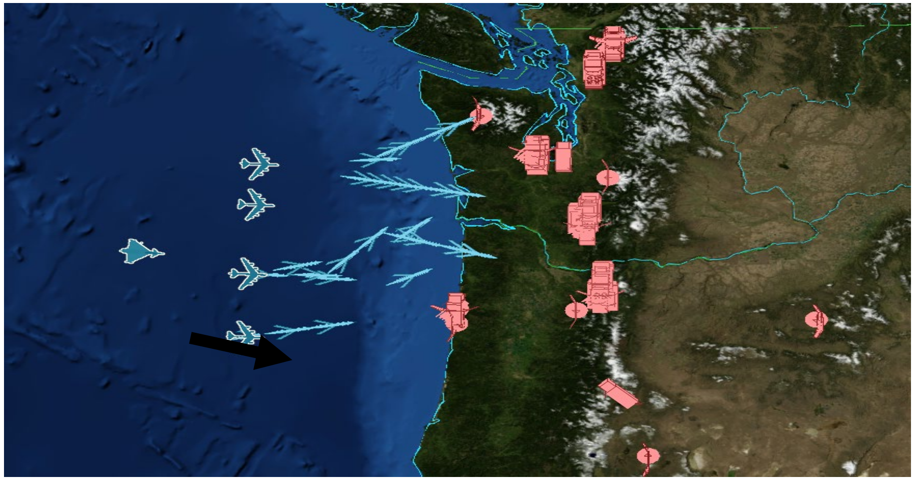
Simulation Optimization Conclusion

- Real-world systems are often:
  - Complex: lots of uncertainty with nonlinear relationships
  - Often modeled using simulation and/or optimization
- Simulation: very powerful methodology to ensure model is close to real-world system
- Optimization: needed for prescriptive analysis
  - Large-scale classic optimization problems are hard … so we use metaheuristics
  - Classic optimization techniques often do not apply to simulation optimization problems … so we use metaheuristics

Use Cases

Optimize Blue Response

- **Optimize the location and configuration of blue forces to meet objectives:**
  – Maximize number of leakers
  – Minimize number of blue resources



AFSIM Notional Scenario

Image Source: Original Screenshot

Maximal Satellite Coverage

- **Optimize target coverage varying spacecraft orbital parameters and system configuration:**
  - Vary orbits, number and type of spacecraft, and configurations
  - Add constraints to designate coverage thresholds for priority targets/areas

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Cyber Optimization and Analysis

- **Optimize solution to minimize loss of function and duration of effect against cyber attacks:**
  - Explore scenarios in the cyber kill chain that are most detrimental
  - Test limits of the system and identify key components that must be protected at all costs

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Launch and Deployment Optimization

- **Optimize launch parameters for minimal deployment cost while meeting mission parameters:**
  - Launch cost is a large part of satellite cost
  - Subsystems performance affects the launch vehicle
  - Optimize flight trajectory until orbit injection
  - Vary parameters such as initial launch angle, subsystem speed, altitude, aimpoint, and orbital maneuvering systems

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Training Scenario Optimization

- **Optimize training scenarios to meet the most training requirements:**
  - Tailor individual training scenarios for large groups of trainees
  - Provide post-event reviews with automated discovery of optimal choices

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Questions?