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Simultaneous Consumables, Resources, and Spares Optimization for Future Combat System Logistics

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Talk Overview

- Motivation
- The System-of-Systems Analysis Toolkit (SoSAT)
- Hybrid Simulation and Optimization Strategies
- Randomized Greedy Search
  - Generating Solutions for Individual Scenarios
- Progressive Hedging
  - Aggregating Solutions Across Multiple Scenarios
- Conclusions
- In-Progress and Future Research Directions
Motivation

• Logistics optimization in the context of Future Combat Systems poses many difficult challenges for the algorithm designer
  – Same goes for SBCT, HBCT, IBCT, …
• Feature #1: Simultaneous consideration of spares, resources, and commodities
  – Aspects are typically treated independently, and combined \textit{a posteriori}
  – Yields sub-optimal solutions due to lack of separability
  – Yields infeasible solutions due to log footprint constraints
• Feature #2: Short time-scales
  – Ground combat operations are a transient phenomenon
  – Day to week-long missions $\Rightarrow$ marginal analysis solutions are unstable
• Feature #3: Non-parametric failure distributions
  – Damage incurred due to force-on-force action is non-parametric
  – Extant logistics optimization algorithms assume parametric distributions
SoSAT: The System-of-Systems Analysis Toolkit (1)
SoSAT: The System-of-Systems Analysis Toolkit (2)

• Observation
  – Logistics solutions are increasingly being developed in the context of simulation, as opposed to analytic, models
• Sandia’s SoSAT tool for Future Combat System logistics modeling
  – Time-stepped, PC-based, high-resolution logistics simulator
• What operations can SoSAT model?
  – Logistics / reliability for brigade-level ground combat systems
    • FBCT, SBCT, HBCT, IBCT
    • Thousands of platforms, each with tens to hundreds of parts
  – 15 minute time-steps
  – Stochastic models of combat damage via CASTFOREM runs
  – Dynamic business rules, platform inter-dependencies
• What analytic capabilities does SoSAT provide?
  – Tracks operational availability, lethality, mobility, etc., over time
    • On platform/squad/platoon/etc. levels
  – Quantifies variability and related statistics over N trials
  – “What-if” assessment of structure / platform modifications
Integrating Simulation and Optimization Models

Computing Platform:
K-node Beowulf cluster

Analyze Simulation

Failure sequences

Progressive Hedging

Inventory, resource, and commodity levels

Assess Solution

Bottleneck information

Refine Solution

K independent trials of “flooded” simulation

Optimization given K failure sequences

K independent trials of nominal simulation

Inventory, resource, and commodity level adjustments

Repeat until target availabilities are met

Slide 7
Generating Solutions for Individual Scenarios (1)

• Output from a single flooded simulation run yields
  – Failure sequence for each part on each platform
  – “Run-out” times for each commodity on each platform
• Analysis of simulation model yields
  – Impact of not having a spare part, commodity, or resource
  – E.g., lack of a tread downs M1A2 mobility and availability
• Optimization objective
  – Determine a “minimal-cost” solution that will achieve target performance metrics (e.g., 95% availability) given a particular failure sequence
• Observations
  – Approach assumes independence of failures => solution is conservative
    • E.g., lack of a tread on day N might delay engine failure on day N+2
  – Aggressive performance targets => conservatism is not significant
    • E.g., delays are not long given requirement of 95% availability
  – Assumes prescience; solution does not generalize!
Generating Solutions for Individual Scenarios (2)

• Short time horizons facilitate very high-speed simulation
  – Few numbers of failures during training missions
  – Moderate number of failures during combat missions
• Developed a discrete-event “surrogate” of SoSAT
  – Input: Failure sequence under flooded SoSAT simulation
  – Input: Proposed spares, resource, and commodity levels
  – Output: Performance metrics for the provided solution given
    the particular failure sequence (i.e., scenario)
  – Execution time: *Milliseconds*
• Domain-specific heuristics are used to obtain an initial solution
  – Highly sub-optimal, typically infeasible
• “Marginal analysis” is used to iteratively adjust spares / resource / commodity levels
  – ROI is quantified (exactly) using the surrogate simulator
  – Executed until feasibility w.r.t. footprint and performance is achieved
• Optimality gap has been assessed off-line using a Mixed-Integer Program
  – Within *at worst 5%* of optimality, more likely 1-2%
The Single-Scenario Solution Approach: Discussion

• This approach is a dramatic shift from traditional marginal analysis
  – Why bother?

• Offers several advantages over marginal analysis and other approaches
  – Paradigm simplification; focus is on individual scenarios
  – Natural to simultaneously consider spares, resources, and commodities
  – Non-parametric; can handle any form of failure type
  – Far easier to impose business rules and side constraints
  – Meet performance targets – not just “in expectation”
  – Expression and satisfaction of complex performance metrics

• But with the baggage of
  – Increased computational costs (more later)
  – Exact solutions, restrictive assumptions => heuristic solutions, few assumptions
  – Far less developed problem domain theory
Progressive Hedging: Overview

• We now have solutions to N independent scenarios
  – So what? We aren’t prescient…
• The next stage is intelligent solution blending
  – No individual solution yields good performance in all scenarios
  – Taking the “maximum” solution yields infeasibilities, unacceptable cost
• An effective alternative: Progressive Hedging (PH)
  – A “horizontal” scenario decomposition technique
    • Stochastic (mixed-integer) programming
    • Contrast with “vertical” or stage-based decomposition techniques
    • Rockafellar and Wets (1991)
  – In general, multi-stage (decision making with recourse)
    • Not used yet, but an interesting future avenue
• General observation
  – Logistics optimization problems can be canonically expressed as Stochastic Mixed-Integer Programs
Progressive Hedging: High-Level Architecture

PH Iteration 0:
Generate Solutions For Individual Scenarios

\[ \min c \cdot x \]

Initialize Scenario Weight Vectors

\[ w_s = \rho (x_s - \bar{x}) \]

Fix Variables That Have Converged

\[ \left( \sum | (x_s - \bar{x}) | \leq \varepsilon_d \right) \cap \left( (c x_{\text{max}} - c \bar{x}) \leq \varepsilon_g \right) ? \]

PH Iteration k:
Generate Solutions For Individual Weighted Scenarios

\[ \min c \cdot x_s + w_s x_s + \rho / 2 \| x_s - \bar{x} \|^2 \]

Update Ws

\[ w_s = w_s + \rho (x_s - \bar{x}) \]

Sole parameter: \( \rho \)

Global Convergence Criterion Achieved?

Done
Progressive Hedging: Discussion

- Convergence proofs for PH
  - Global optimum in the case of convex problems (SLP)
  - Local optimum in the case of non-convex problems (SMIP)
- Selection of “good” values for the $\rho$ parameter is an art
  - Magnitude dictates convergence speed
  - Intuitively should be cost-proportional
  - Mathematically-motivated heuristics (Watson, Woodruff, and Strip)
  - Goal is to trade off optimality for convergence speed
- Other algorithmic engineering techniques
  - Fix lags (fix variables if they have stabilized over last N iterations)
  - Cycle detection and cycle breaking
  - Acceleration once termination criteria is “nearly” achieved
- Progressive Hedging is trivially and efficiently parallelized
  - Individual scenario solves are independent
  - Barrier synchronizations to compute/update weights and solution statistics
Progressive Hedging: Results

• Unclassified, real-world-inspired test problem
  – 100 platforms, 50 parts per platform
  – One-week surge
  – 30 scenarios
• Optimization objective
  – 95% operational availability in all scenarios
  – All scenarios are feasible
• Solution obtained via PH in ~500 aggregate minutes of run-time
  – Parallelization on Beowulf cluster yields 25 minutes wall-clock time
  – Within 5% of optimality (determined via expensive MIP solves)
• Scalability to FCS-sized problems is under way
  – Understanding algorithm behavior as a function of proportion of spares, resources, and consumables levels
Conclusions

- Logistics optimization for the Future Combat System raises several key and novel algorithmic challenges
  - Simultaneous spares, resources, and commodities
  - Non-parametric analysis
  - Short time horizons
- Simulation-based optimization can be leveraged to yield solutions to individual mission scenarios
- Progressive hedging can effectively blend individual solutions into a consistent global solution
- New approach offers advantages over traditional logistics optimization approaches, but simultaneously incurs unique costs
- Much work remains in this area
  - Potential to ignite novel, interesting algorithmic work
In-Progress and Future Research Directions

- “Outlier-Aware” optimization
  - Empirically, there are many scenarios for which feasible solutions are extremely expensive
  - New design objective: Generate the minimal-cost logistics solution that satisfies the performance targets in 95% of the mission scenarios

- Robust optimization
  - To what solution components is performance most sensitive?
  - How can generate less sensitive solutions?
  - What is the trade-off between cost and robustness?

- Run-time reductions in Progressive Hedging
  - Even better $\rho$ selection methods
  - Improved convergence accelerators
Questions?

• Thanks!

• Progressive Hedging Innovations for a Stochastic Spare Parts Support Enterprise Problem (Watson, Woodruff, Strip)
  – Submitted