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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 *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 = > 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)





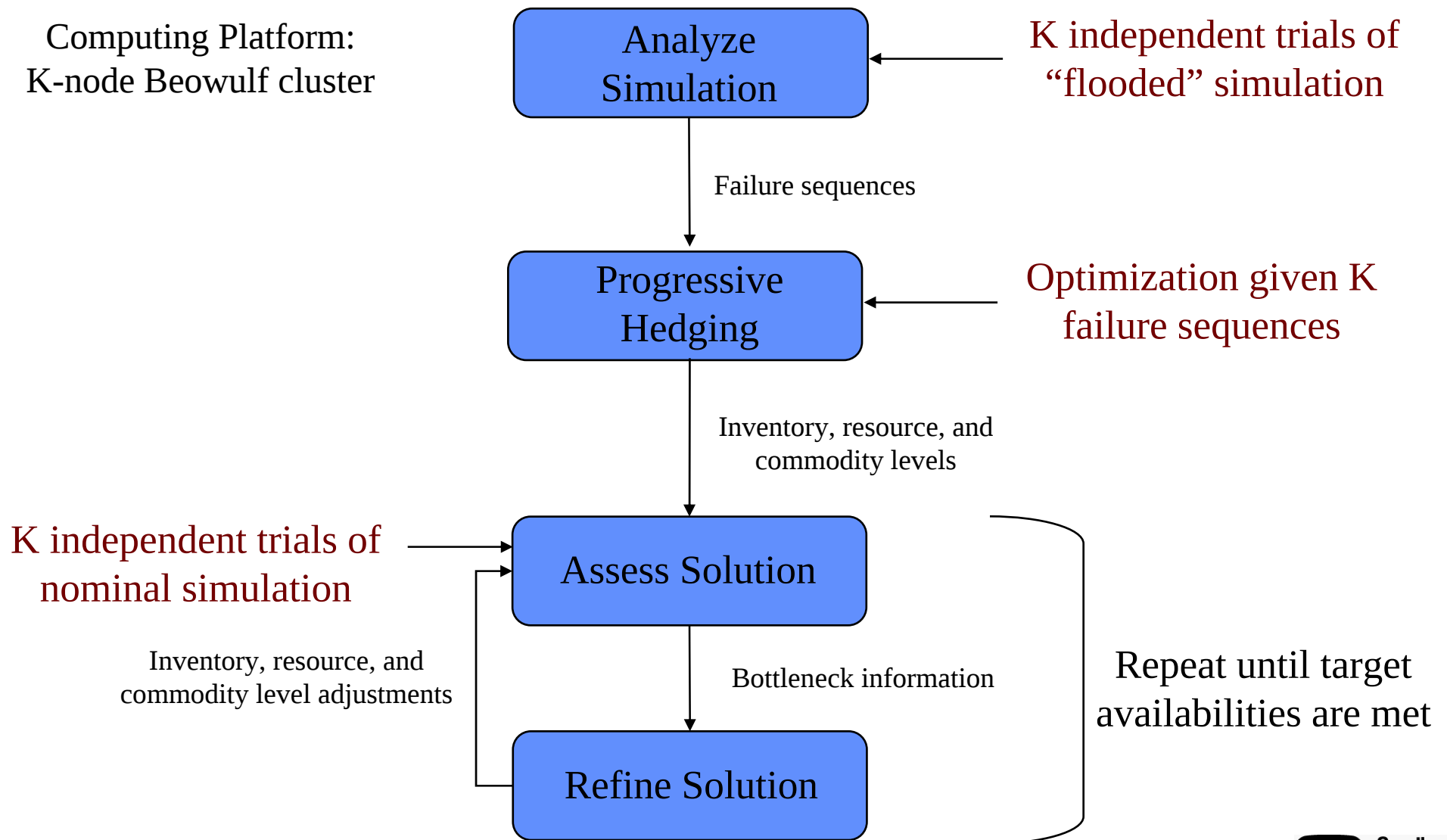
SoSAT: The System-of-Systems Analysis Toolkit (2)

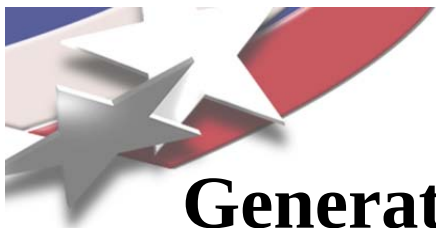
- Observation
 - Logistics solutions are increasingly being developed in the context of simulation, as opposed to analytic, models
- Sandia's SoSAT tool for Future Combat System logistics modeling
 - Time-stepped, PC-based, high-resolution logistics simulator
- What operations can SoSAT model?
 - Logistics / 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

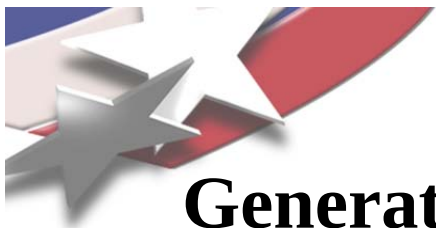
Computing Platform:
K-node Beowulf cluster





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

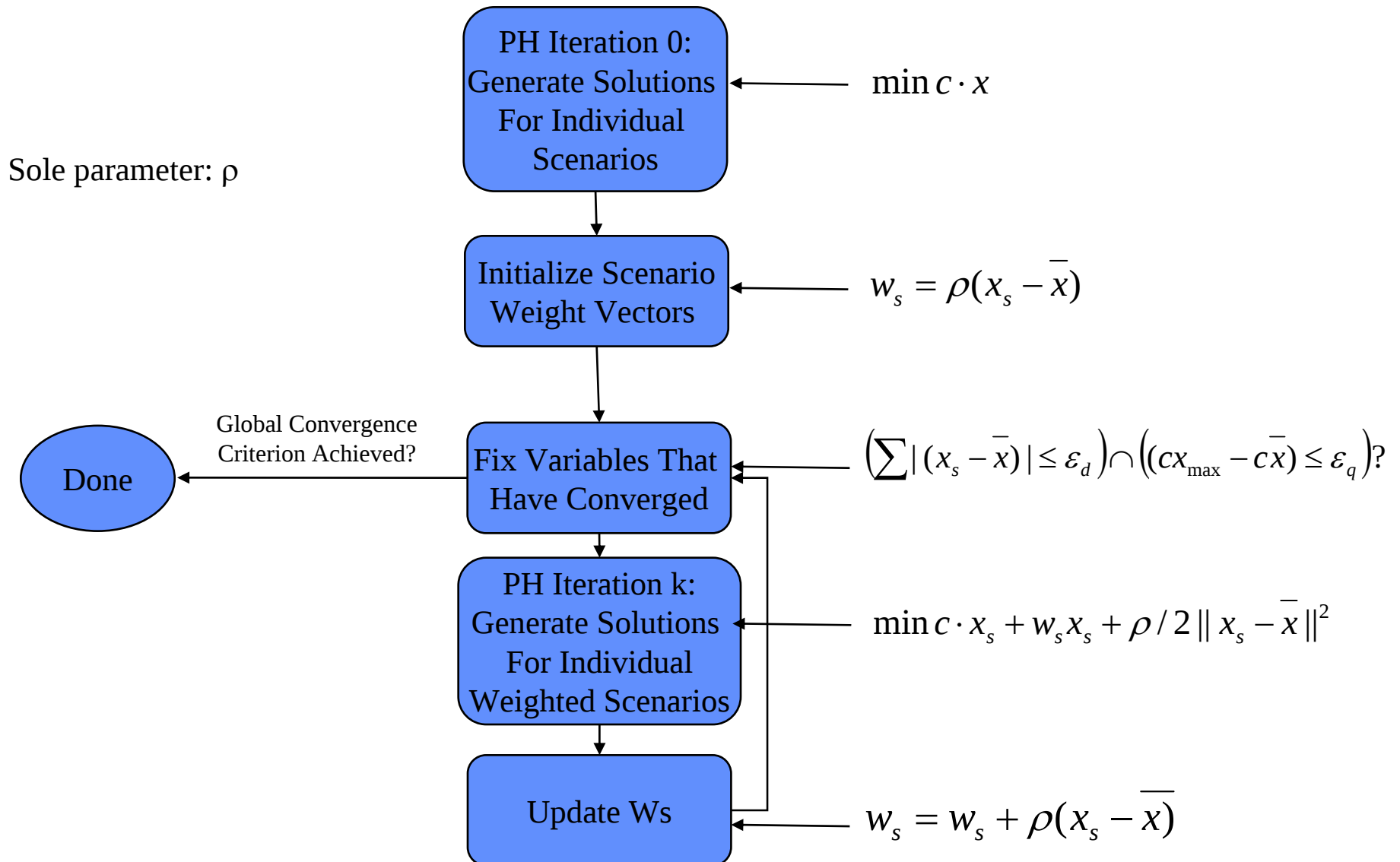


Progressive Hedging: Overview

- 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





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 ρ 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 ρ selection methods
 - Improved convergence accelerators



Questions?

- Thanks!
- Progressive Hedging Innovations for a Stochastic Spare Parts Support Enterprise Problem (Watson, Woodruff, Strip)
 - *Submitted*