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Integrating System Design and Portfolio Optimization

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Motivation

- System design and fleet/portfolio modernization optimization for US Army clients
- Research sponsor: Program Executive Office (PEO) Ground Combat Systems (GCS)

- System design (WSTAT)
  - Solve with multiobjective genetic algorithm
    - Wish to interrogate multiobjective trade space
    - Highly nonlinear
    - Categorical variables
    - Few, simple constraints
  - Typically ignores fleet context
- Fleet modernization (CPAT)
  - Solve as a MILP
    - Highly constrained
    - Mix of discrete and continuous variables
    - Business rules linearizable
    - One primary objective; need optimality certificate
  - Typically assumes fixed designs

System/Fleet Design Interactions

- Individual system design and fleet modernization should be interdependent. Consider the following notional example:

Bradley ECP Option A
Cost: $2.0M per copy
Performance Score: 1.00

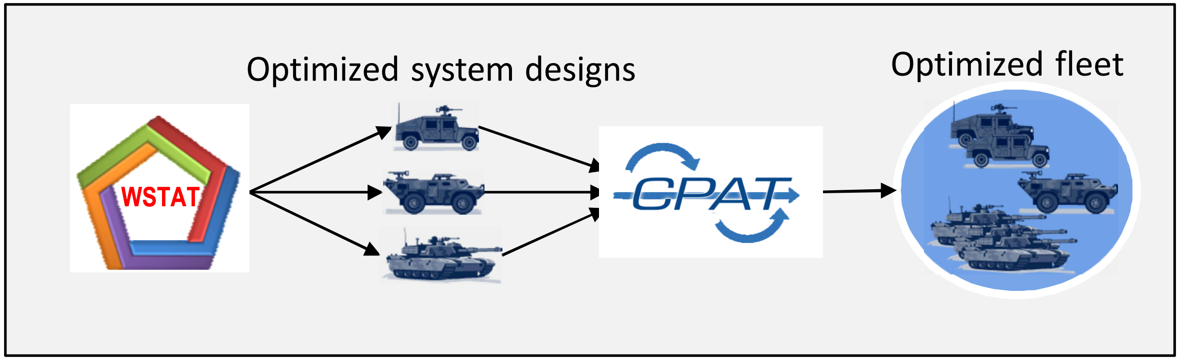
Bradley ECP Option B
Cost: $1.9M per copy
Performance Score: 0.96

Given its smaller cost, Option B might allow another entire S&T program to fit under budget whereas Option A wouldn't. Overall fleet performance could be higher with Option B, despite B's lower performance.

- If we had this holistic fleet optimization capability, we could answer questions such as
  - Of all possible ECP candidates, which one best integrates with the overall Ground Combat modernization plan?
  - What Bradley upgrade configuration would allow for earliest/quickest/highest-density modernization?
  - How much commonality amongst AMPV variants is desired by the optimal modernization plan?

Traditional Two-Stage Analysis

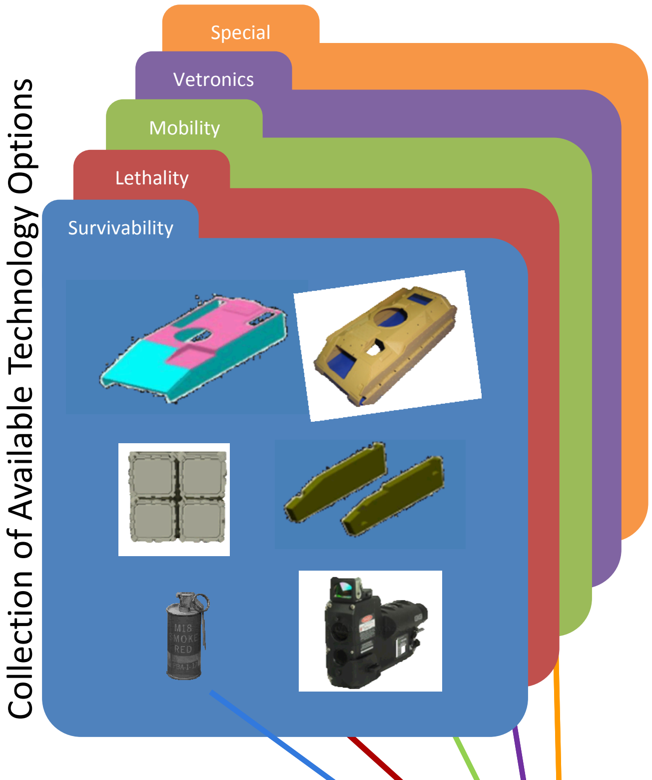
- The need for both an optimized fleet and optimized systems within that fleet has traditionally been approached in two stages
  - One stage optimizes the individual systems configurations
  - The other optimizes the mix of systems within the fleet



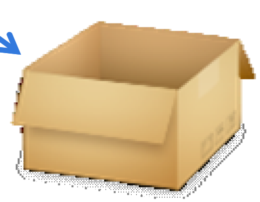
- Traditionally, analysis stages don't (directly) communicate
  - WSTAT may influence Army's planned system designs/requirements, which may eventually lead to CPAT data updates, but this process could take months
  - With consistent value models, it should be possible to do automatically – and the system design insights can then be informed by the fleet perspective!

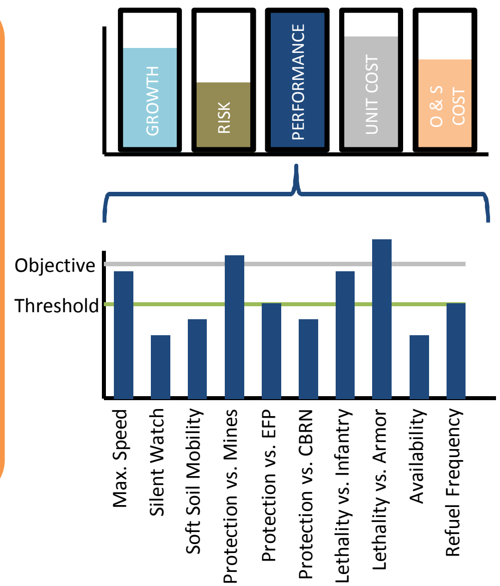
WSTAT Overview

Combine technologies into configurations; evolve in multiobjective GA

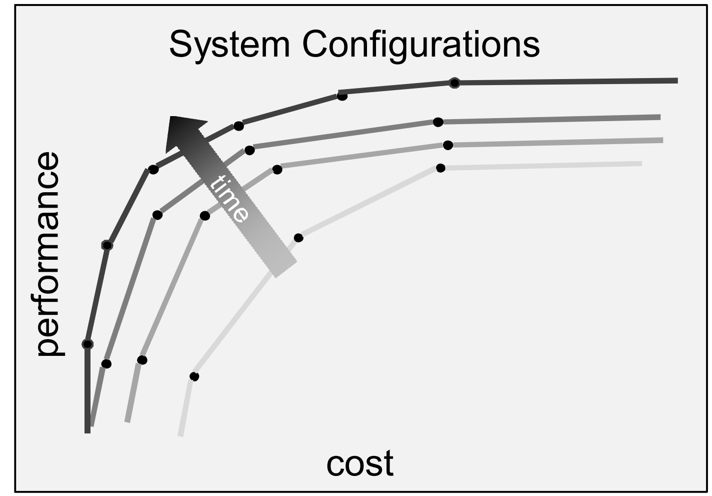


1) Technologies are selected to create configurations



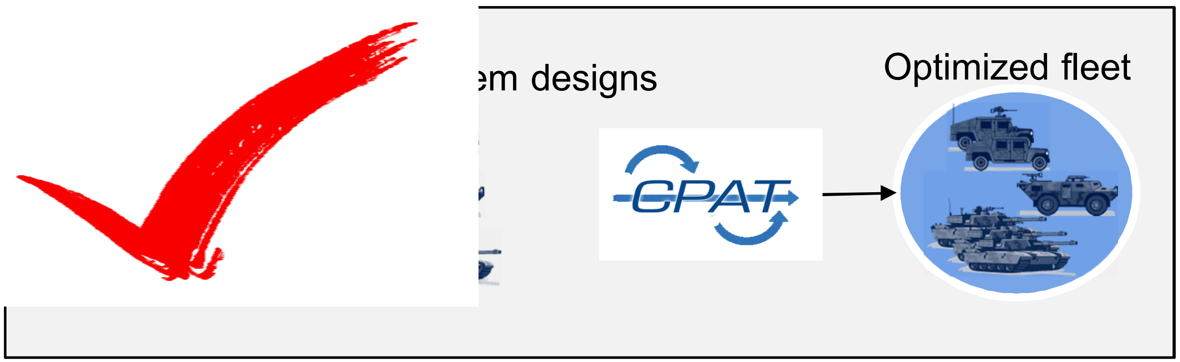


2) Each configuration is scored in lower-level metrics that contribute to higher-level dimensions



3) Configurations are bred and mutated within a Genetic Algorithm (GA), evolving the population towards optimality

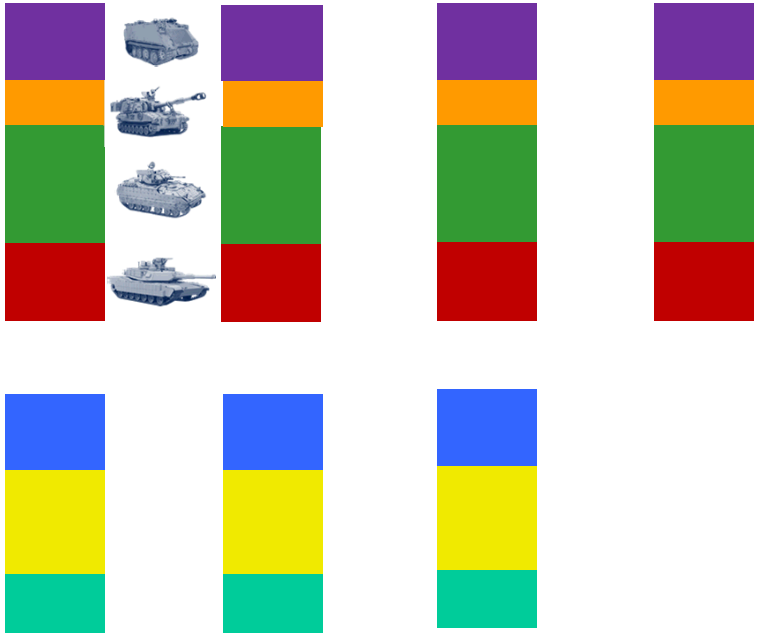
Typical solution space sizes of 10^{15} – 10^{150};
WSTAT returns several thousand near-Pareto solutions


CPAT
Optimized fleet

CPAT Introduction

Optimize fleet performance by updating/replacing systems over time

- CPAT optimizes the mixture of systems within the entire fleet through time (the systems themselves are not modified)
- CPAT uses a multi-stage mixed-integer linear program (MILP) to perform this optimization
- The fundamental unit of the Army fleet is the brigade.
- Each brigade has different mission roles, which are fulfilled by different specialized systems.
- There are multiple brigades of different types.



CPAT Approach

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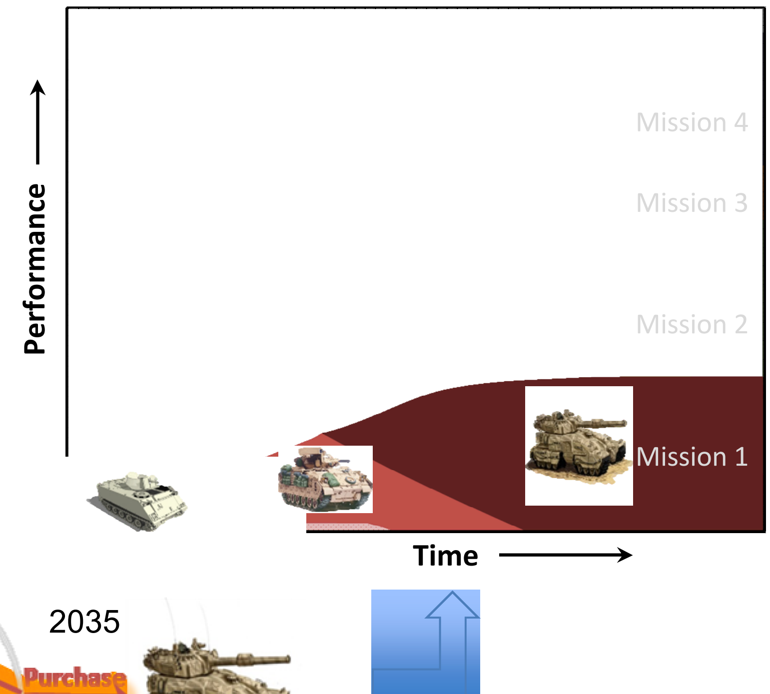
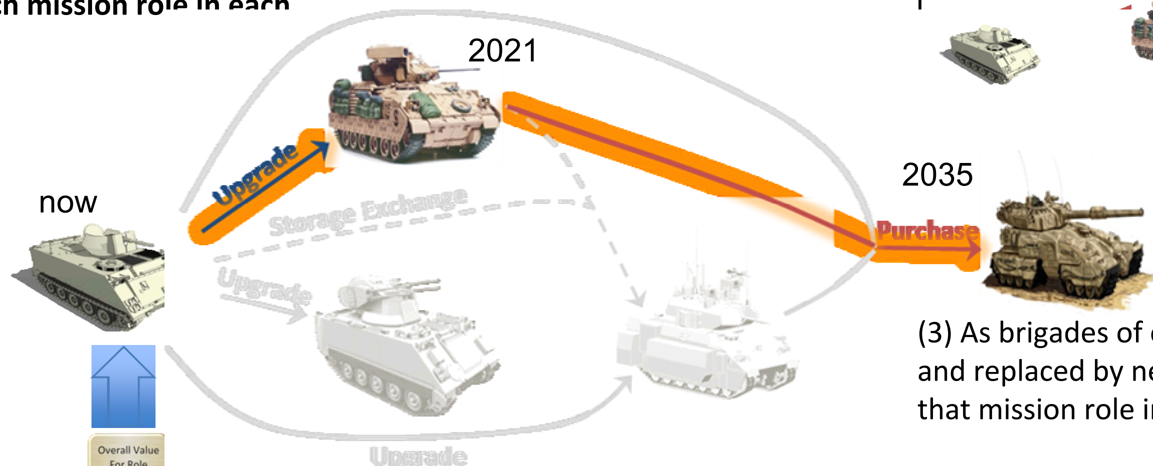
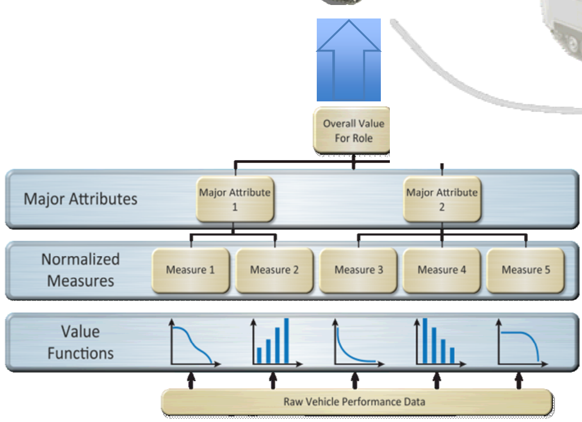
(4) Total fleet performance is the sum over all mission roles in all brigades; the optimization maximizes this area.



(2) Multiple possible modernization paths exist within a given mission role; the optimization chooses a path over time for **each mission role in each brigade**



(3) As brigades of old systems are phased out and replaced by new systems, performance of that mission role increases.



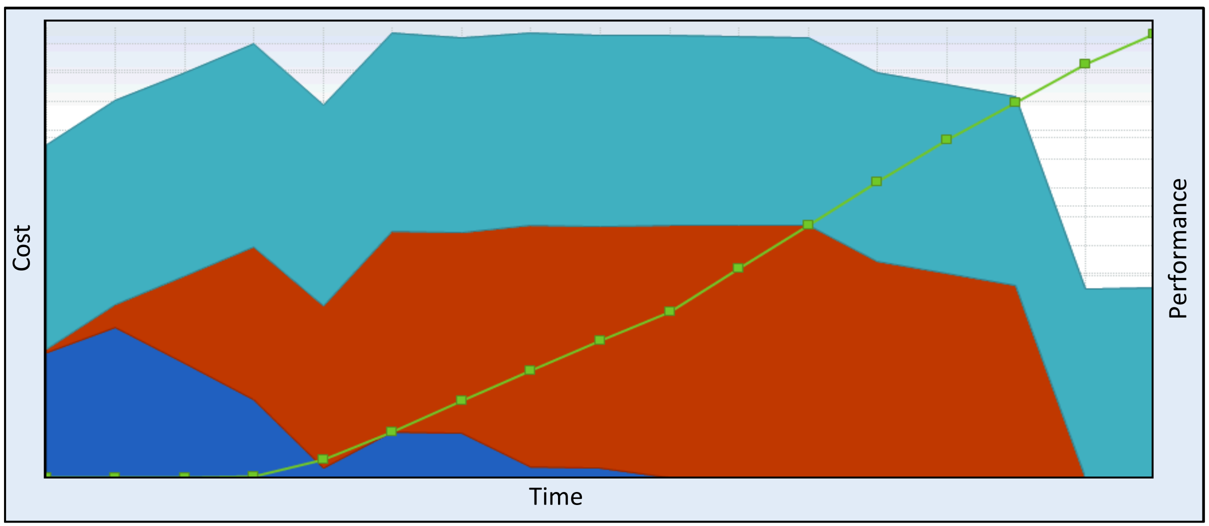
(1) Value model aggregates performance for a system type within a mission role, across multiple requirements areas

Modernization decisions are interdependent with detailed programmatic and production decisions subject to complex business rules. Typical solution space sizes of 10^{300} or more.

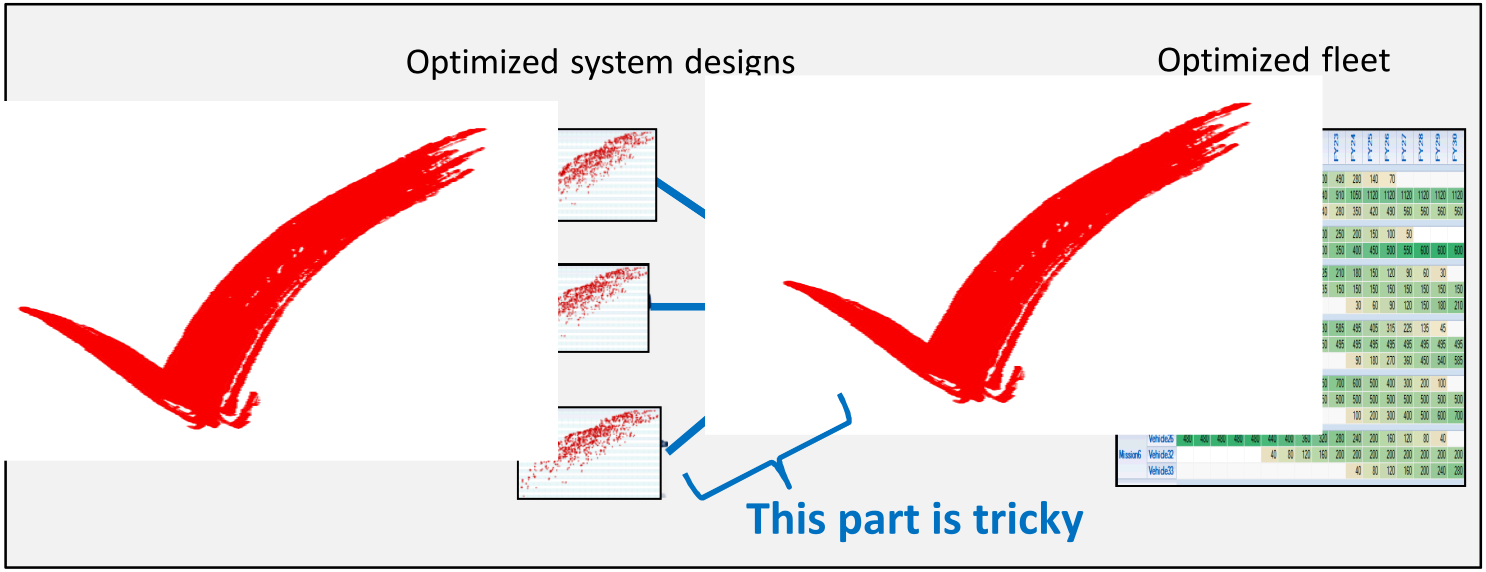
Modernization Schedule Example

Notional Data

		FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
Mission1	Vehicle4	1680	1680	1680	1680	1540	1330	1120	910	700	490	280	140	70				
	Vehicle5					140	350	560	700	840	910	1050	1120	1120	1120	1120	1120	1120
	Vehicle7								70	140	280	350	420	490	560	560	560	560
Mission2	Vehicle20	600	600	600	550	500	450	400	350	300	250	200	150	100	50			
	Vehicle21				50	100	150	200	250	300	350	400	450	500	550	600	600	600
Mission3	Vehicle23	360	360	360	360	345	315	285	255	225	210	180	150	120	90	60	30	
	Vehicle32					15	45	75	105	135	150	150	150	150	150	150	150	150
	Vehicle33											30	60	90	120	150	180	210
Mission4	Vehicle24	1080	1080	1080	1080	990	900	810	720	630	585	495	405	315	225	135	45	
	Vehicle32					90	180	270	360	450	495	495	495	495	495	495	495	495
	Vehicle33											90	180	270	360	450	540	585
Mission5	Vehicle25	1200	1200	1200	1200	1100	1050	950	850	750	700	600	500	400	300	200	100	
	Vehicle32					100	150	250	350	450	500	500	500	500	500	500	500	500
	Vehicle33											100	200	300	400	500	600	700
Mission6	Vehicle26	480	480	480	480	480	440	400	360	320	280	240	200	160	120	80	40	
	Vehicle32						40	80	120	160	200	200	200	200	200	200	200	200
	Vehicle33											40	80	120	160	200	240	280

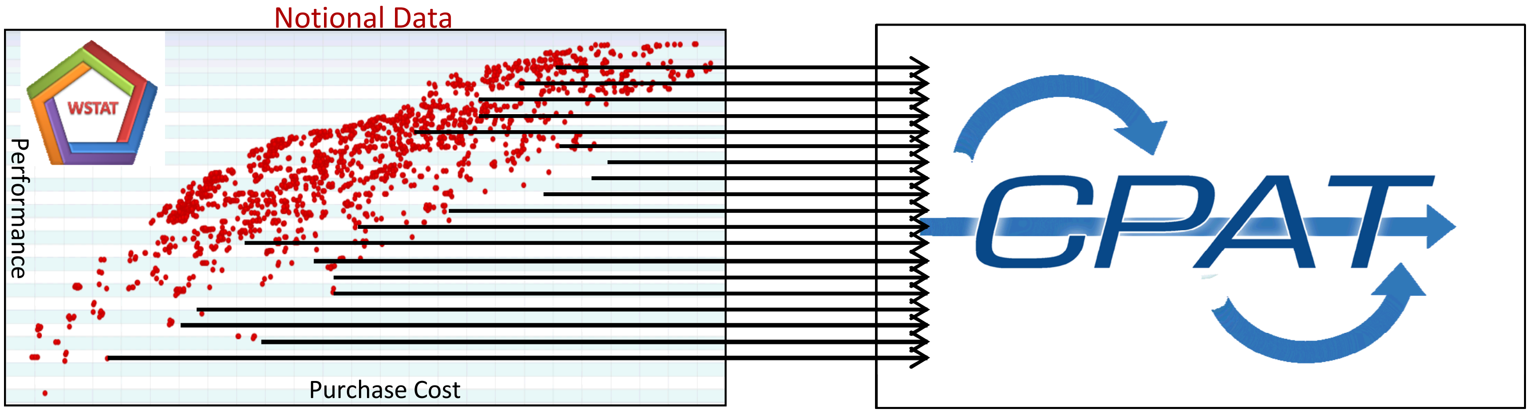


- Population schedule shows the entire fleet modernization plan
  - What's in fleet
  - What's upgraded
  - When
  - How many
- Quick comparison of performance vs. costs through time
  - Costs broken down by R&D, Procurement, and O&S


Optimized system designs
Optimized fleet
This part is tricky

Communication Breakdown

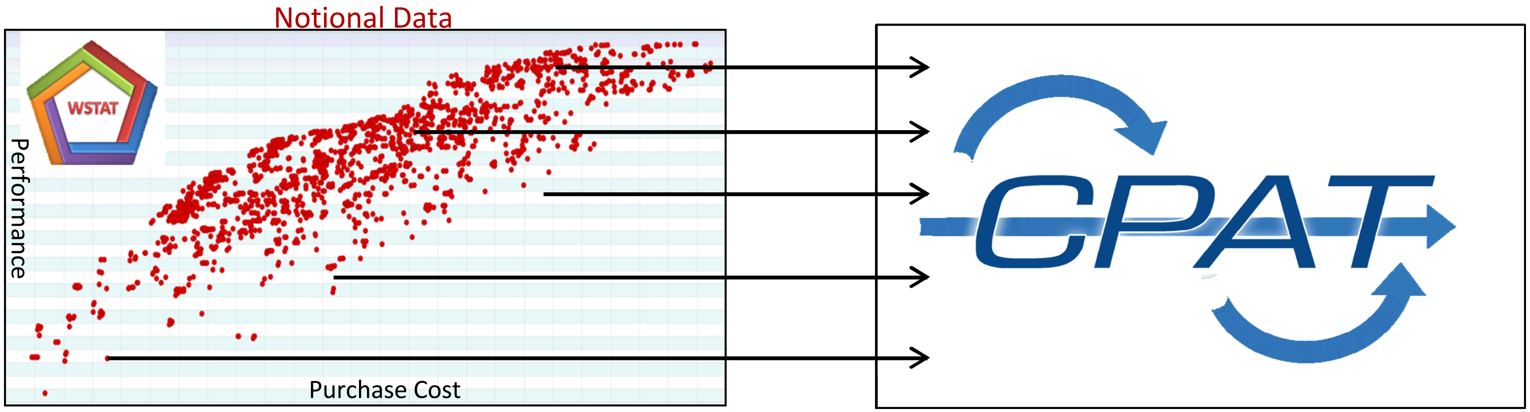
- Let's consider just a single system from WSTAT
- How could we get all the configuration possibilities into CPAT?
- Possibility 1: Naively enter every configuration from WSTAT as a separate system in CPAT



- Advantages:
  - The ability to add new systems to CPAT already exists (though we would want to automate the input of 2000 systems)
- Disadvantages:
  - Each system creates hundreds of integer and binary variables. Doing this for ~2000 variants is totally intractable

Communication Breakdown

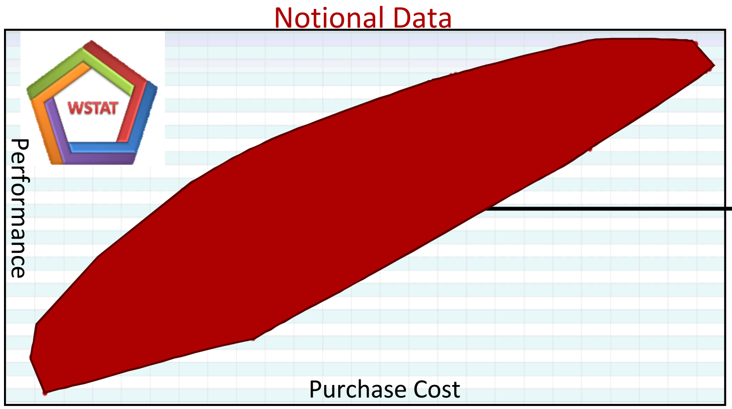
- Let’s consider just a single system from WSTAT
- How could we get all the configuration possibilities into CPAT?
- Possibility 2: Naively enter a few configurations from WSTAT as a separate systems in CPAT



- Advantages:
  - This functionality is already built-in, and with few systems can be done manually
- Disadvantages:
  - Most of the WSTAT information is left behind and tradeoffs are made in a very coarse manner
  - Complexity still grows very quickly with number of configurations
  - Challenging to decide which configurations “best” represent tradeoffs

Communication Breakdown

- Let’s consider just a single system from WSTAT
- How could we get all the configuration possibilities into CPAT?
- Possibility 3: enter a linear approximation of the WSTAT Pareto solutions into CPAT

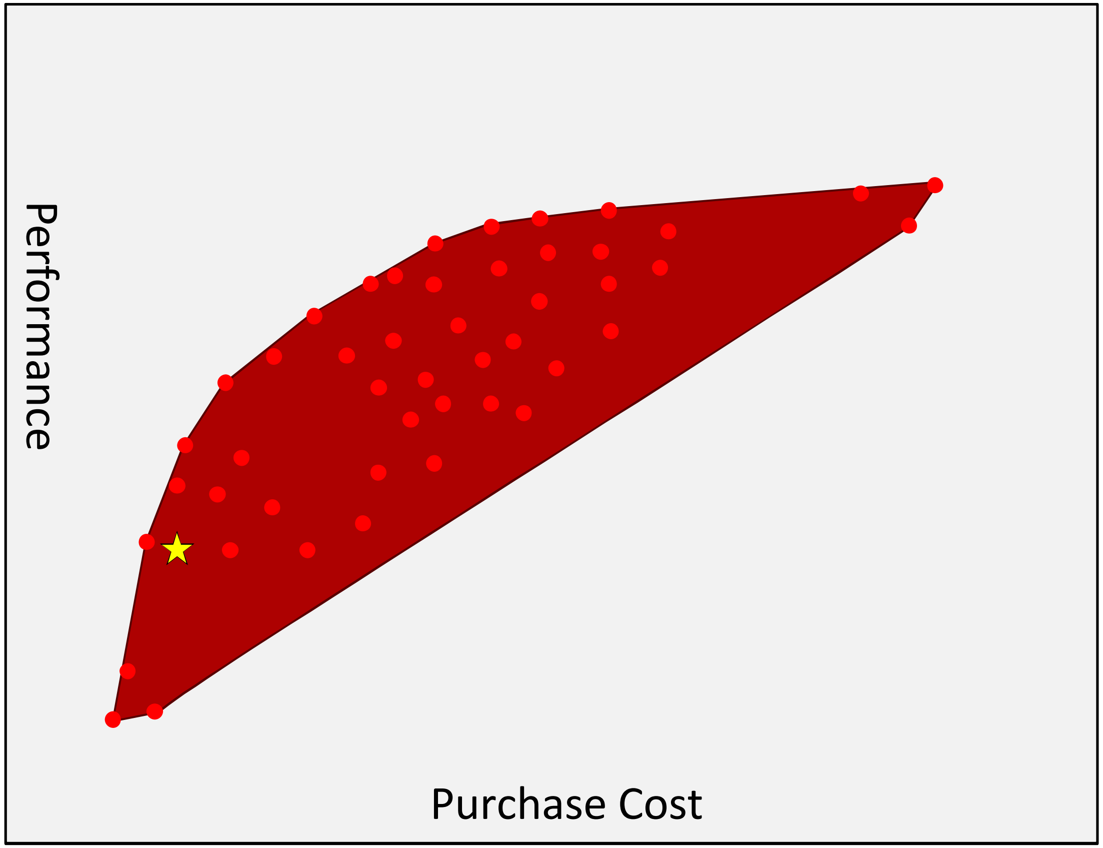


- Advantages:
  - We are capturing a great deal about the WSTAT Pareto space without entering systems one-by-one
- Disadvantages:
  - Requires a new concept within CPAT (i.e. some systems are “adaptive”)
  - “Adaptive” systems chosen by CPAT may not correspond with an actual WSTAT configuration

WSTAT Pareto Set Linearization

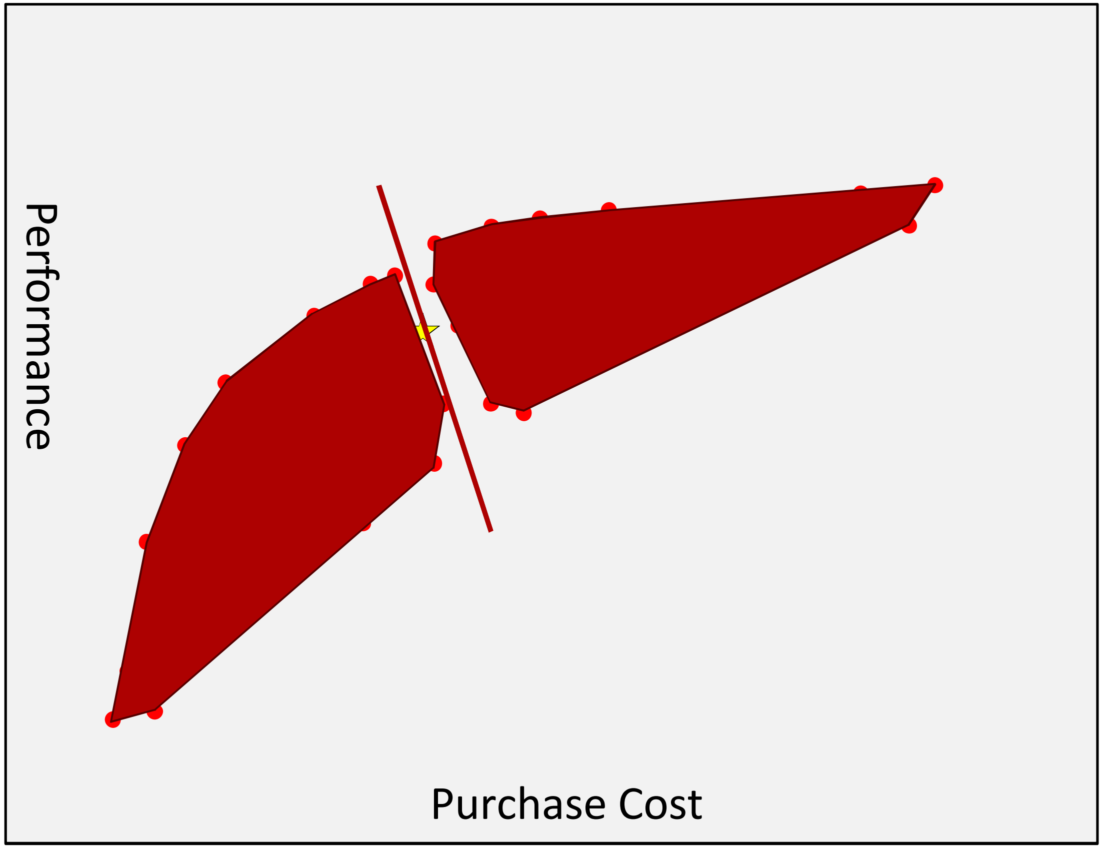
- Consider a WSTAT Pareto set and (recall it is in the 5 dimensions of performance, purchase cost, sustainment costs, risk, and growth potential).
- How would we linearize even the 2-D projection of this set?

  - Start by forming the convex hull of the Pareto set
  - CPAT could chose a performance/cost configuration anywhere inside this convex hull
  - Actual WSTAT configurations falling close to the CPAT optimal approximation could be obtained as a post-processing step
  - Good: It will choose the system's optimal tradeoff of cost and performance holistically, relative to the needs of the entire fleet
  - Bad: It may choose something far from an actual WSTAT configuration



Post-processing

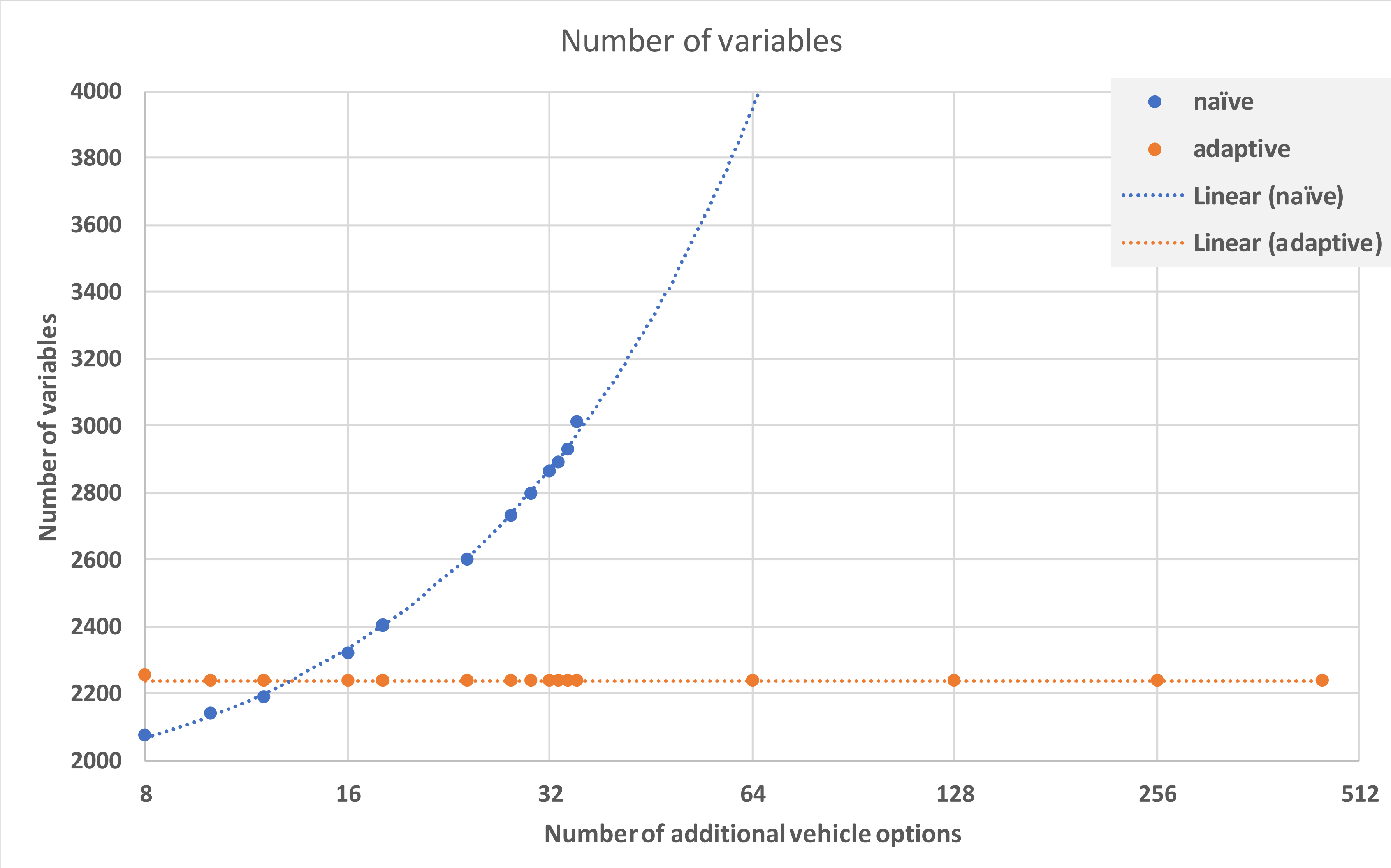
- We have found empirically that CPAT usually chooses a vertex point (makes sense if you think about it). If it does not, choosing the nearest point may be acceptable (albeit suboptimal) for some applications. Otherwise:
  - Generate hyperplane that separates two nearest points
    - Random for now
    - Better methods likely exist
  - Generate convex hulls of points on either side of the hyperplane
  - Model union of disjoint polytopes using disjunctive technique of Balas 1979
  - Re-solve MILP and repeat process as needed
  - Guaranteed to converge eventually (although many iterations undesirable)
  - Empirically, will usually converge in an iteration or two



Computational Study

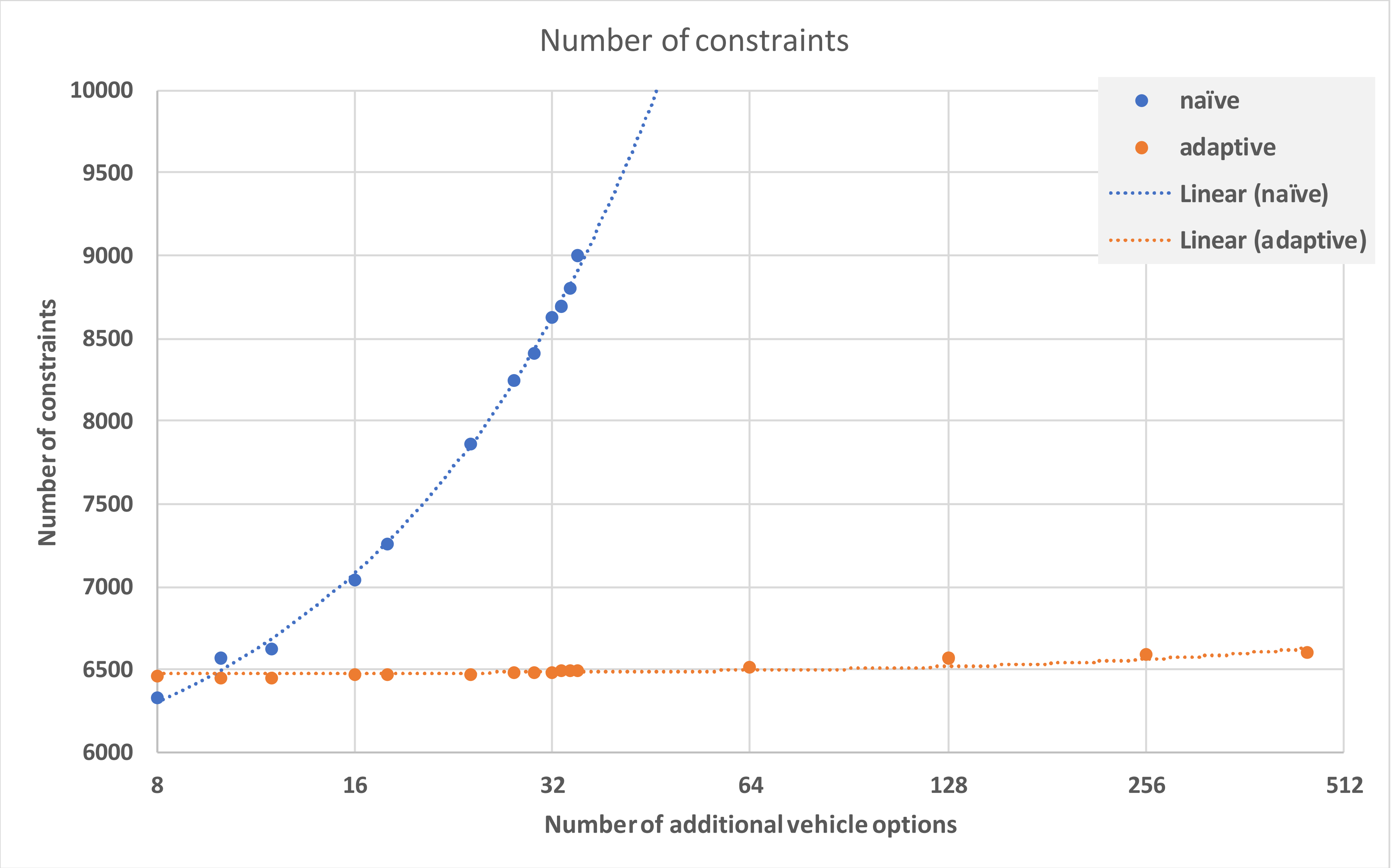
- Performed realistic tests @ different system design quantities
  - WSTAT model based on Bradley Infantry Fighting Vehicle
  - CPAT model based on PEO GCS fleet modernization problem
    - At the edge of tractability in CPLEX 32-bit depending on inputs
- Includes two new attributes in addition to performance & purchase cost
  - Up-front research, development, test and engineering costs
  - Production start delays (informed by technology risk)
- WSTAT solutions in consistent order from run to run
  - E.g., the first 16 designs are the same in the 32-design and the 16-design run
  - Arbitrary order. There are likely intelligent ways to order them so that the best coverage is achieved regardless of quantity
- Ran to zero optimality gap to prevent *arbitrary* selection of non-vertex system designs
- Compared against "naïve" method of injecting designs directly

Computational Results



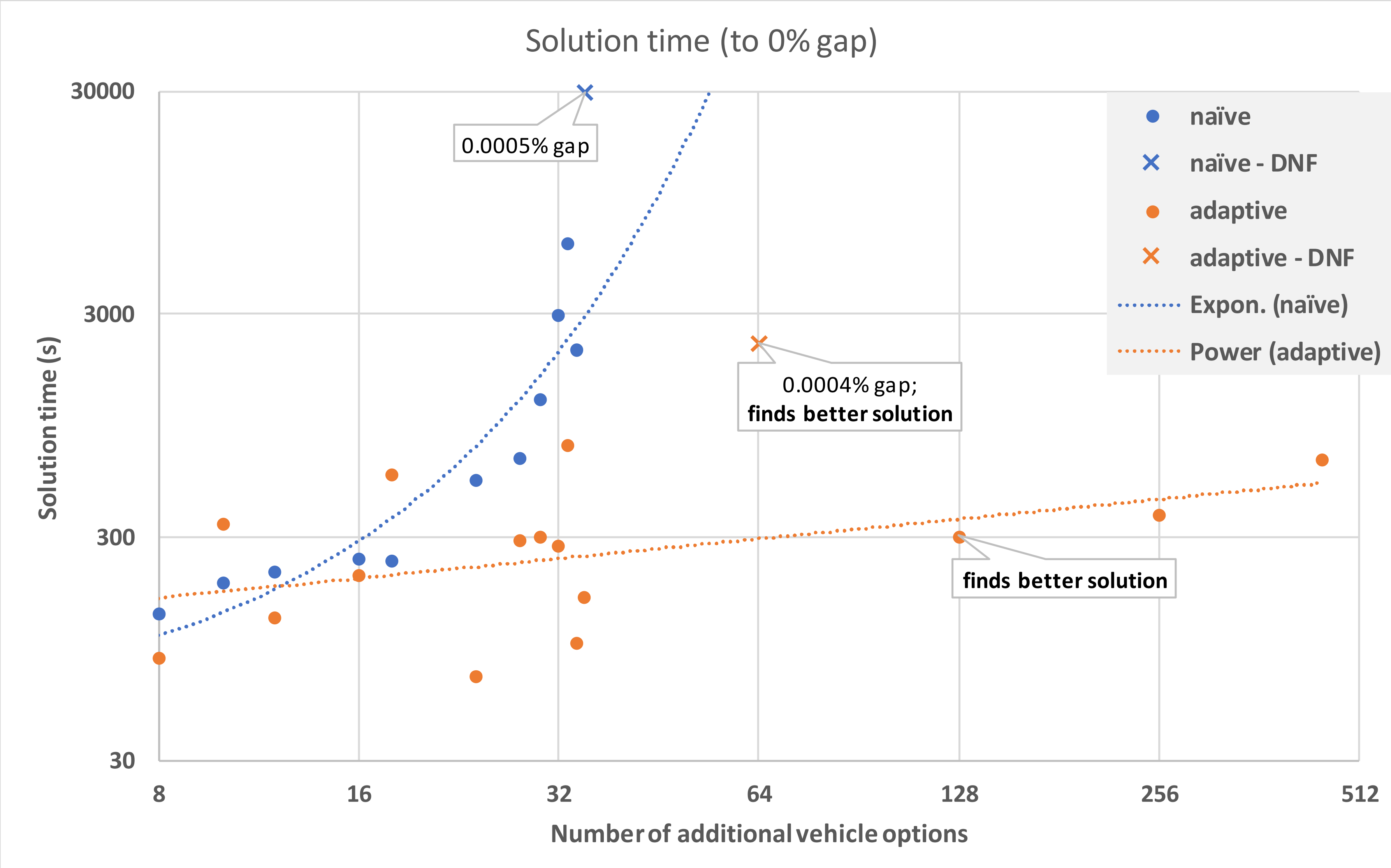
*disjunctive post-processing method adds one variable each iteration

Computational Results, cont'd



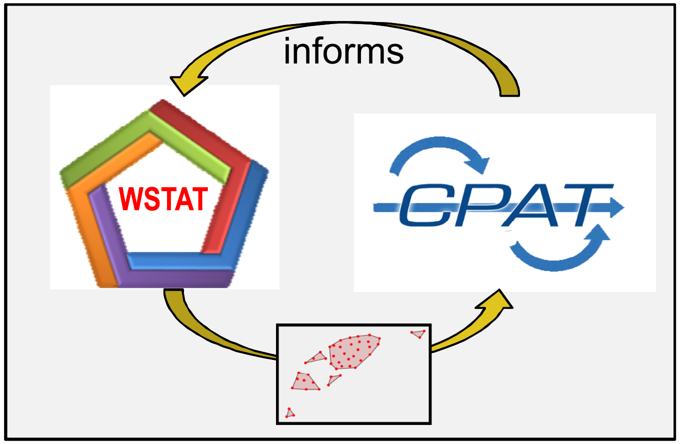
*disjunctive post-processing method adds at least two constraints each iteration

Computational Results, cont'd



Conclusions

- Combining system design and fleet problems can result in better answers for both (improves fleet performance, better informs vehicle design selection)
- One way to approach this challenge is to bring more information about system configurations from the system design problem into the fleet optimization.
- Forming a linear approximation for a large quantity of discrete system design solutions can capture the richness of the trade space without overwhelming the portfolio formulation.



Questions?