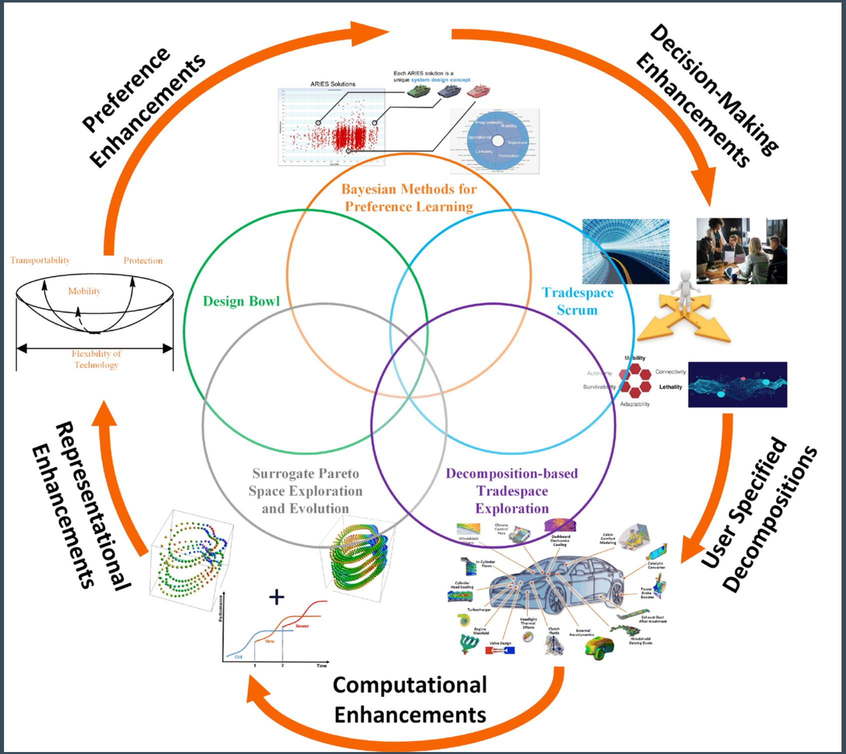
College of
ENGINEERING, COMPUTING
AND APPLIED SCIENCES

Simulating the Tradespace with Synthetic Data

AI4SE/SE4AI Workshop

Dr. Cameron J. Turner

Project Context



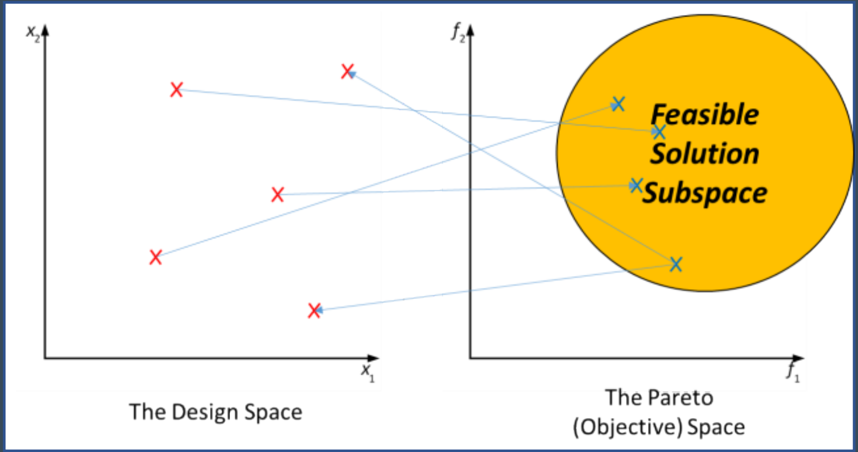
- **Scope:** Enhance the abilities of stakeholders to balance vehicle performance or capabilities versus project risk, budget, and schedule in a visual virtual environment
- **Key Goal:** Enhance rapid, effective trade space exploration and analysis to guide the development of vehicle-level requirements
- **Efforts in:**
  - Decomposition-Based Tradespace Exploration
  - Surrogate Pareto Space Exploration and Evolution
  - Design "Bowl" Modeling
  - Bayesian Methods for Preference Learning
  - Best-Practices in Tradespace Scrums

The Tradespace

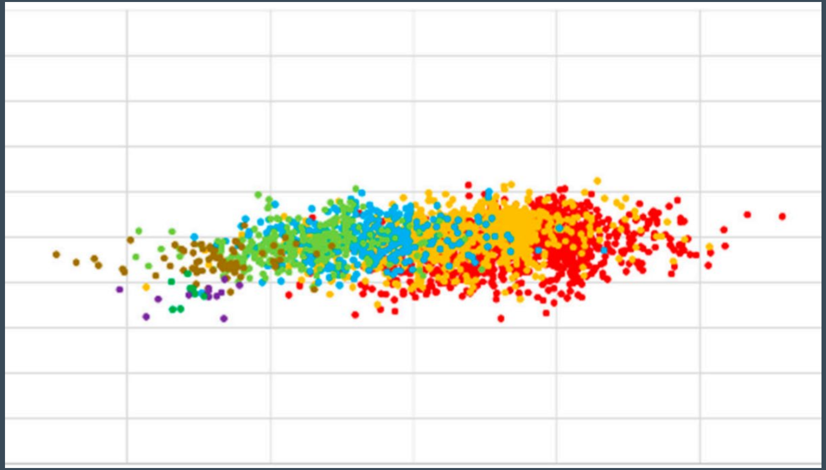
Function	Soln 1	Soln 2	...	Soln N
Convert	100 hp ICE	120 hp ICE	...	50 hp Hub Motors
Store	10 gal JP7	15 gal JP7	...	1kW-hr Battery
...	...	...	...	...
Convert	4-Wheels	6-Wheels	...	Oval Tracks

- Each point in the Tradespace represents a solution to a Morphological Matrix

- The Tradespace is visualized in terms of an objective space



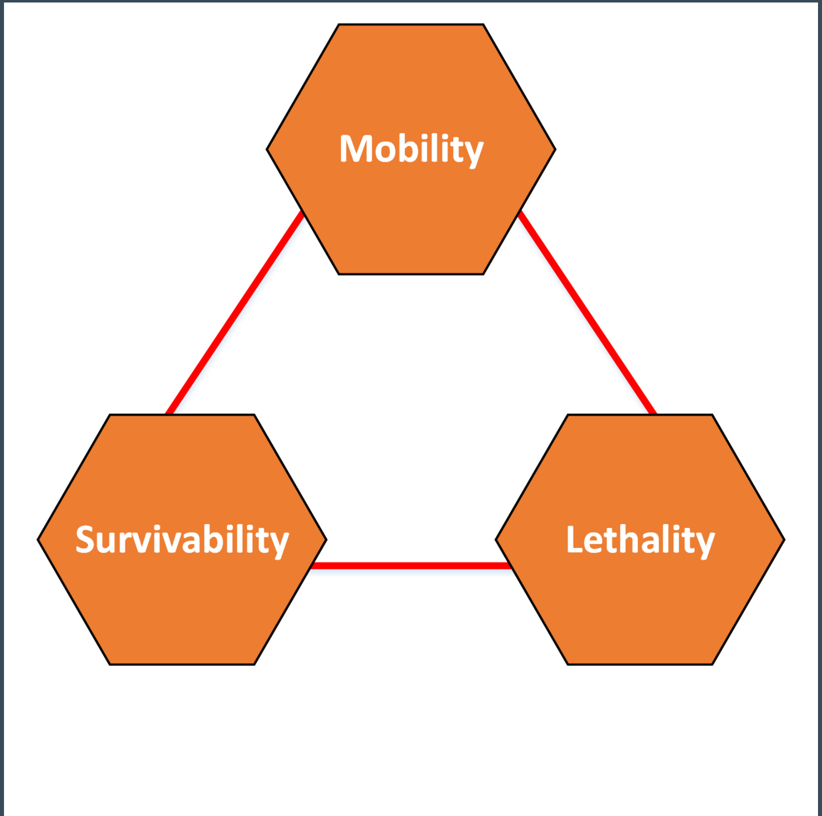
Tradespace Modeling



- Generating a representation of the Tradespace has been a significant effort

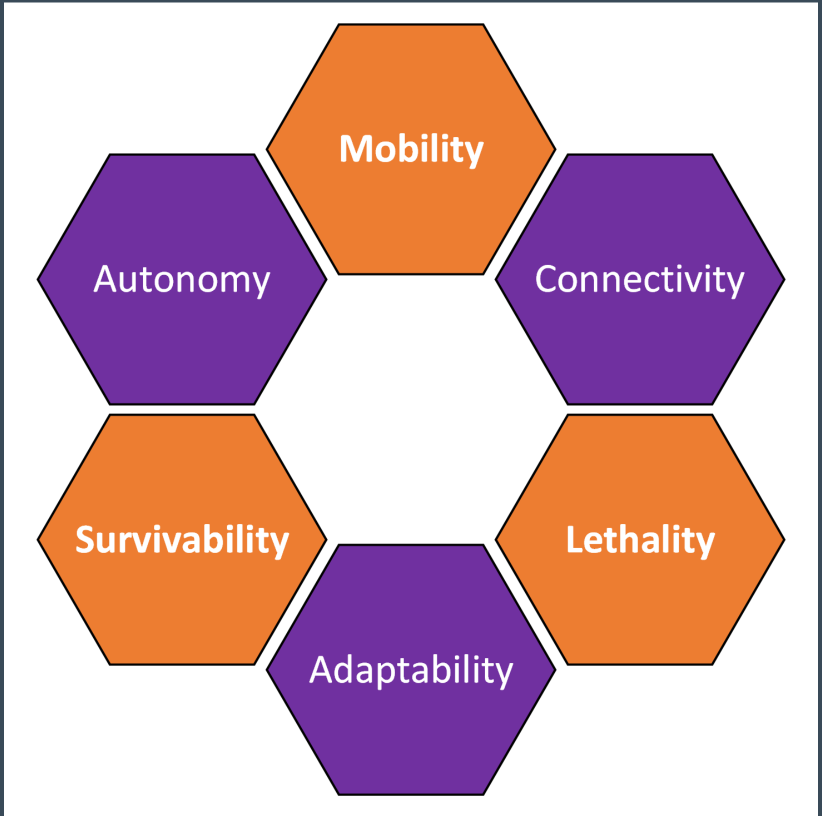
- Need to represent "-ilities"
  - Functional Objectives (FO)
  - Input Variables
  - Derived Attributes
  - Intermediate Calculated Parameters
  - Defined Constants
  - Other FO

“-ilities”



- Represent subsets of the considerations of the Steel Hexagon
  - Developed from the concept of the Steel Triangle
  - Mobility – Survivability – Lethality

"-ilities"

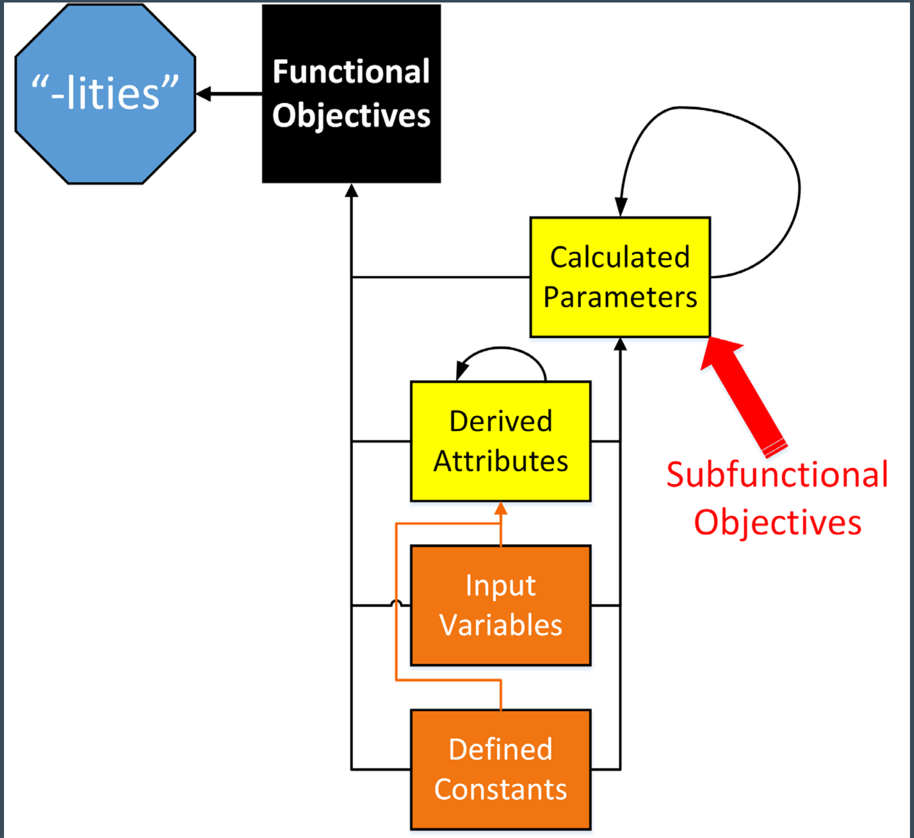


- Represent subsets of the considerations of the Steel Hexagon
  - Developed from the concept of the Steel Triangle
  - Mobility – Survivability – Lethality
  - Add – Autonomy – Connectivity - Adaptability

"-ilities"

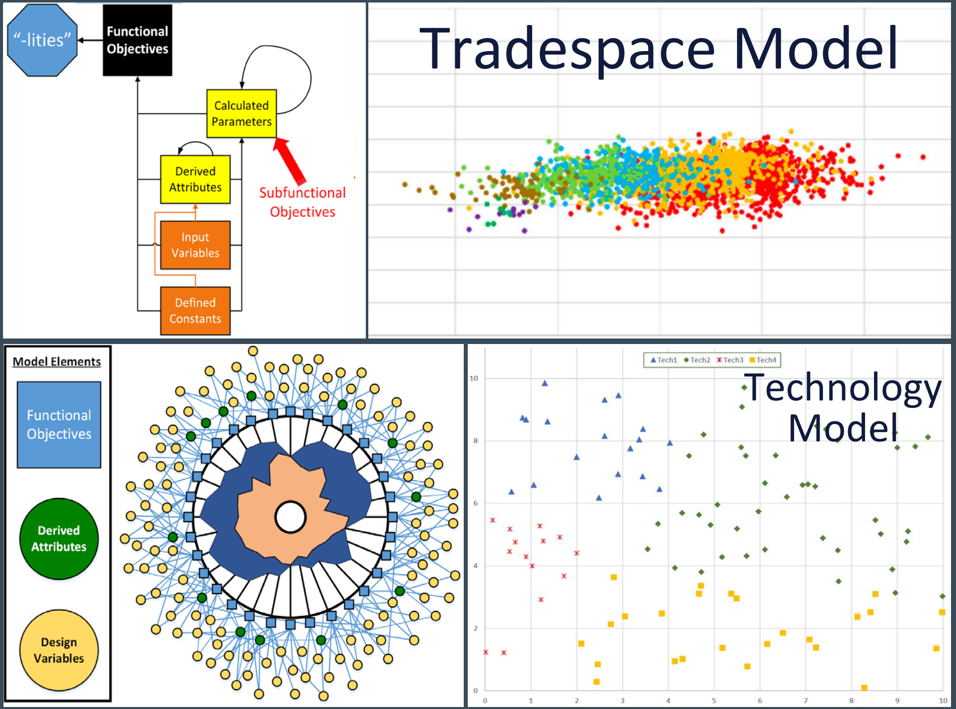
- Represent subsets of the considerations of the Steel Hexagon
  - Developed from the concept of the Steel Triangle
  - Mobility – Survivability – Lethality
  - Add – Autonomy – Connectivity - Adaptability

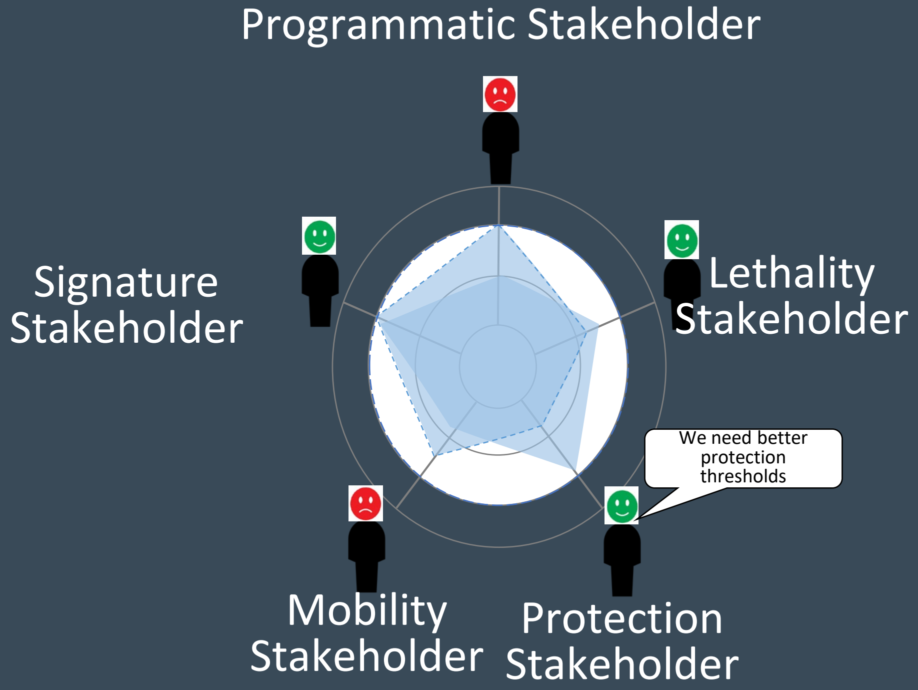
Functional Objectives



- Functional Objectives provide metrics to evaluate the “-ilities”
  - Functional Objectives are built from
    - Calculated Parameters
    - Derived Attributes
    - Input Variables
    - Defined Constants

Tradespace Decision-Making



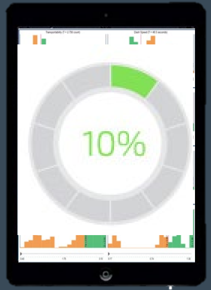


DEVCOM GROUND VEHICLE SYSTEMS CENTER

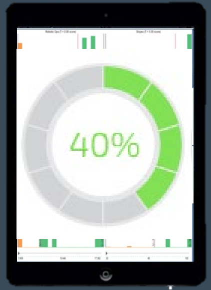
CLEMSON VIPR-GS VIRTUAL PROTOTYPING GROUND SYSTEMS

Tradespace Decision-Making

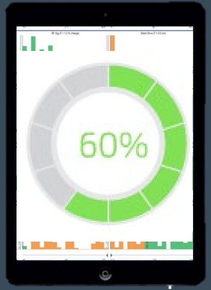
VSME 1



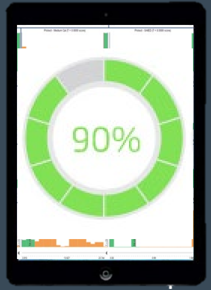
VSME 2

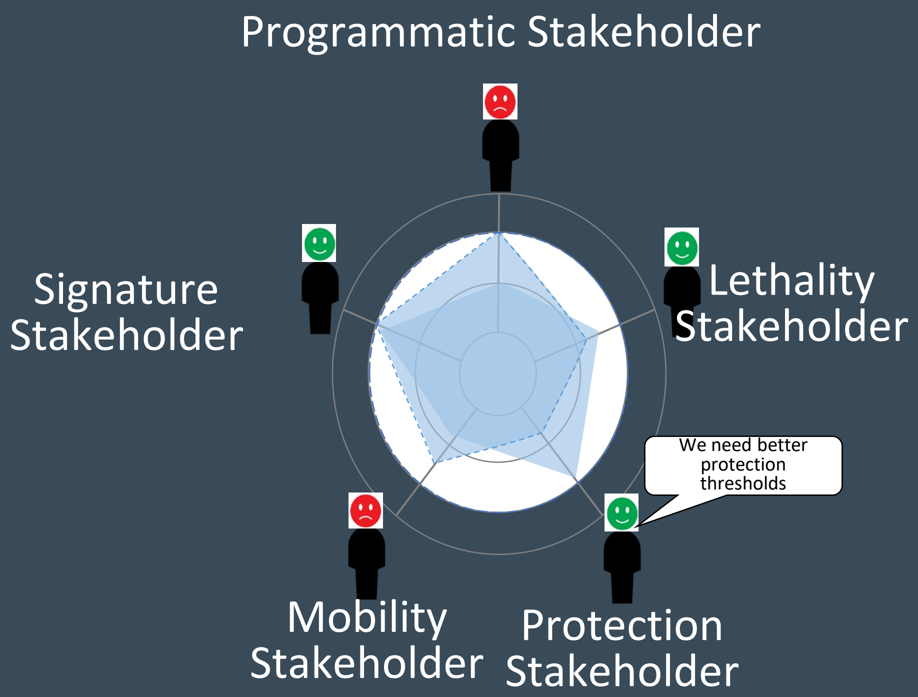


VSME 3



VSME 4





DEVCOM GROUND VEHICLE SYSTEMS CENTER

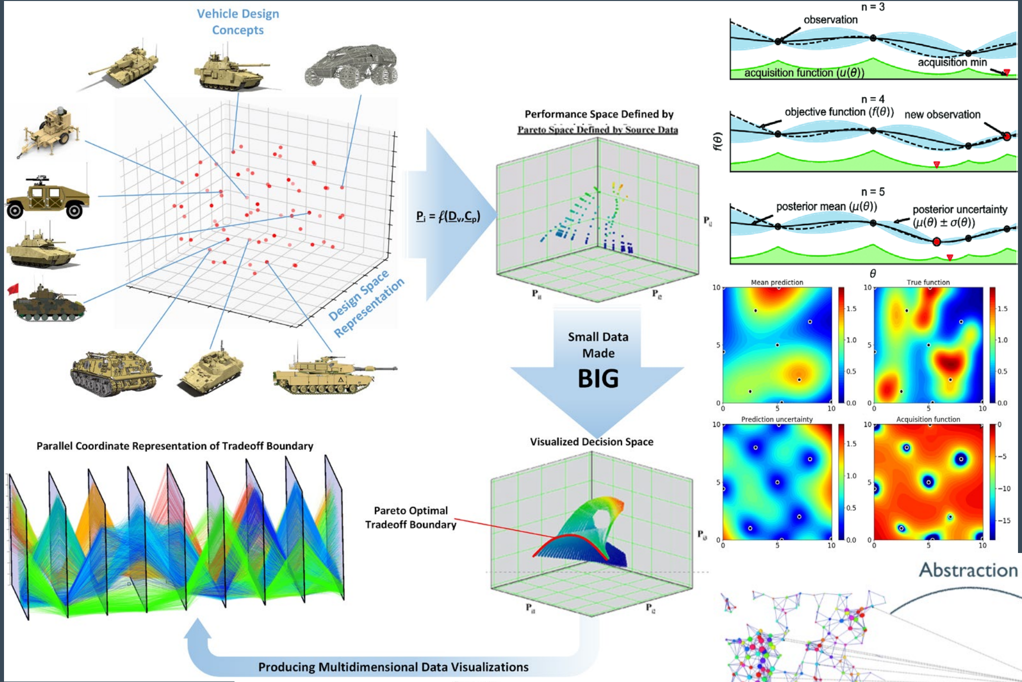
CLEMSON VIPR-GS VIRTUAL PROTOTYPING GROUND SYSTEMS

AI Agents to the Rescue

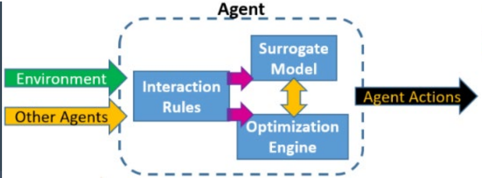
- Can we use AI Agents to simulate real decision-makers
  - With Human DMs in the Loop
  - Or, as pure simulations
- Allowing:
  - To Identify conflicts of importance in advance
  - Study the efficacy of the tradespace problem
  - Explore the downstream impacts of trades

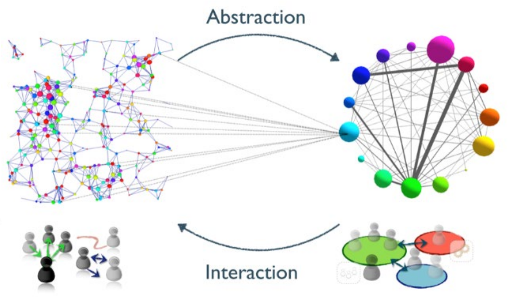
Adapted from https://clearcode.cc/blog/game-theory-attribution/

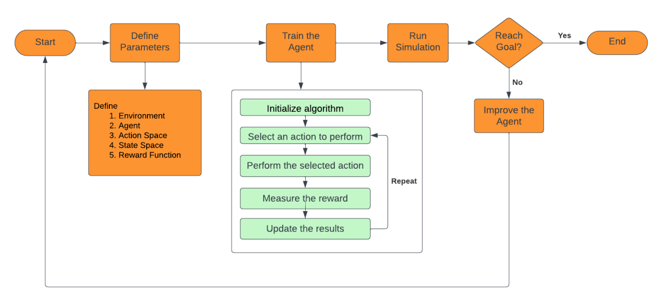
How to Accomplish This…



- Synthetic Tradespaces to Study
- Formulating tradestudies into optimization problems
- Applying Game Theory and Machine Learning Agents to Tradespace DM







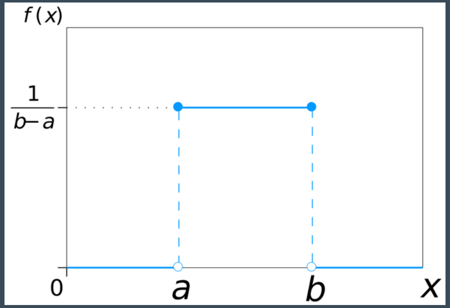
DEVCOM GROUND VEHICLE SYSTEMS CENTER

CLEMSON VIPR-GS VIRTUAL PROTOTYPING GROUND SYSTEMS

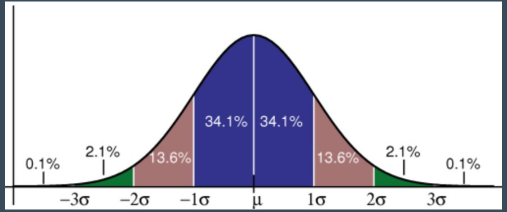
Synthetic Tradespace: Defining Variables

- Variables are defined using several methods
- Constant Variables
  - Have 1 known value
- Binary Variables
  - 1 if on, 0 if off
- Discrete Valued
  - Result of a selection of Binary Variables

- Continuous Variables
  - Defined by a range (uniform)



  - Defined by a distribution (gaussian)



Initial Synthetic Tradespace

- 4 Subfunctional Objectives
  - Back Deck Overhang
  - Running Gear Contact Patch Area
  - (SMET FCC) Length
  - (SMET FCC) Curb-to-Curb Turning Diameter
- Requires 54 Input Variables
  - 13 are continuous
  - 6 are discrete valued
  - 27 binary variables
  - 6 constant variables
  - 2 functional variables
- 12 Derived Attributes
- 9 Constants

Formulating Optimization: All-in-One (AiO) MOP

$$\begin{aligned} &\text{minimize} \quad \mathbf{f}(\mathbf{x}_g, \mathbf{x}_{loc}) = [\mathbf{f}_1(\mathbf{x}_g), \mathbf{f}_2(\mathbf{x}_g, \mathbf{x}_{loc})] \\ &\text{s.t.} \quad \mathbf{x}_g \in X_g, \mathbf{x}_{loc} \in X_{loc} \end{aligned}$$

Goal:

1. Compute Pareto points to AiO MOP
2. Perform tradespace analysis to choose a preferred efficient design

Strategy:

1. Decompose AiO MOP into two subproblems (SP1 & SP2)
2. Find a preferred efficient design to AiO MOP by computing efficient designs and Pareto points to SP1 & SP2

SP1:

$$\begin{aligned} &\min \mathbf{f}_1(\mathbf{x}_g) \\ &\text{s.t.} \quad \mathbf{x}_g \in X_g \end{aligned}$$

SP2:

$$\begin{aligned} &\min \mathbf{f}_2(\mathbf{x}_g, \mathbf{x}_{loc}) \\ &\text{s.t.} \quad \mathbf{x}_g \in X_g, \mathbf{x}_{loc} \in X_{loc} \end{aligned}$$

Formulating Optimization: Coordination Problem (COP)

SP 1:

$$\begin{aligned} \min \quad & \mathbf{f}_1(\mathbf{x}_g) \\ \text{s.t.} \quad & \mathbf{x}_g \in X_g \end{aligned}$$

SP 2:

$$\begin{aligned} \min \quad & \mathbf{f}_2(\mathbf{x}_g, \mathbf{x}_{loc}) \\ \text{s.t.} \quad & \mathbf{x}_g \in X_g\,,\ \mathbf{x}_{loc} \in X_{loc} \end{aligned}$$

Let

$\mathbf{x}_g^* \in X_g$ be preferred design for SP1

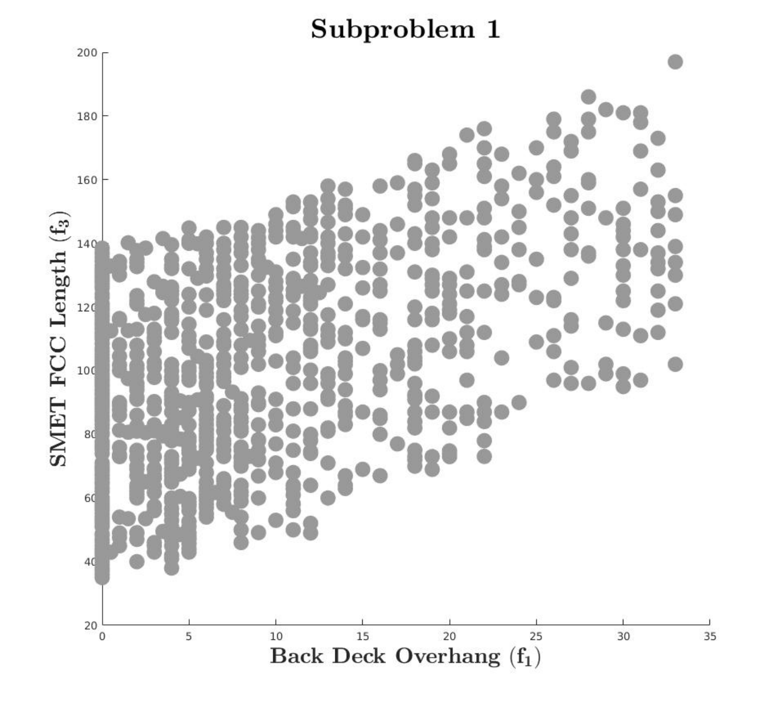
$\varepsilon = (\varepsilon_1, \varepsilon_2) \geqq \mathbf{0}$ be relaxation for two objectives in SP1

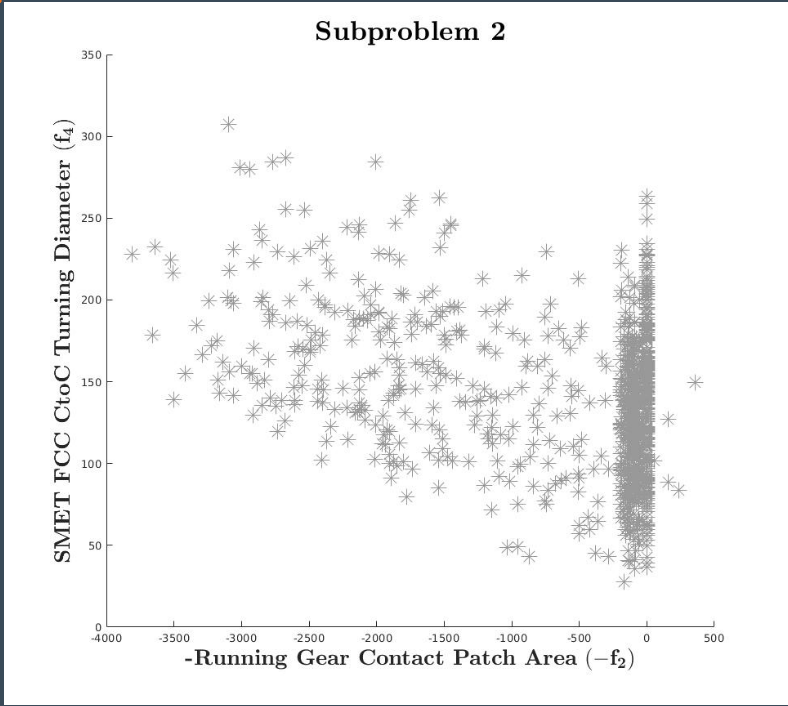
COP:

$$\begin{aligned} \min \quad & \mathbf{f}_2(\mathbf{x}_g, \mathbf{x}_{loc}) \\ \text{s.t.} \quad & \mathbf{f}_1(\mathbf{x}_g) \leqq \mathbf{f}_1(\mathbf{x}_g^*) + \varepsilon \\ & \mathbf{x}_g \in X_g,\ \mathbf{x}_{loc} \in X_{loc} \end{aligned}$$

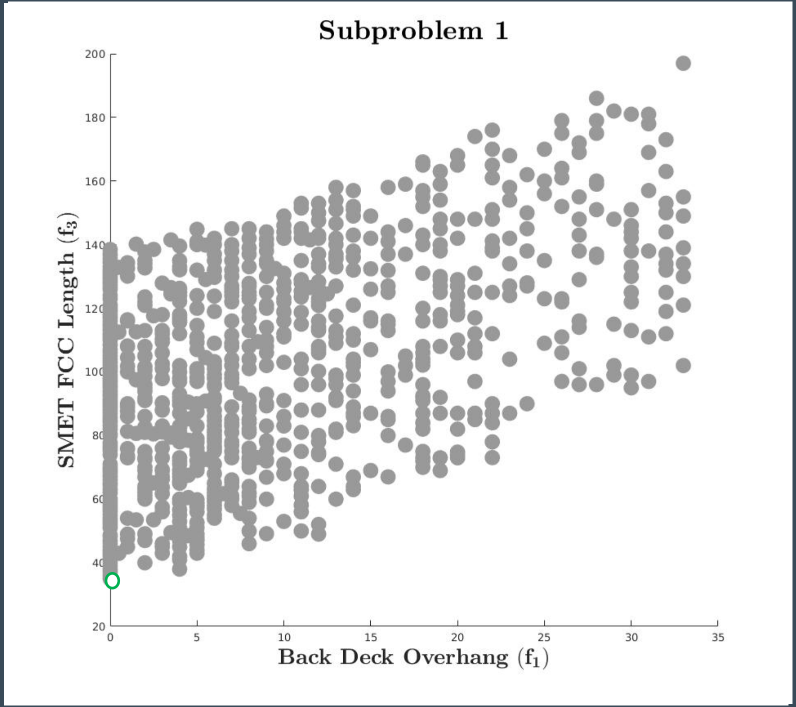
- Let $\mathbf{x}_g^* \in X_g$ be weakly efficient to SP1. If there exists $\mathbf{x}_{loc}^* \in X_{loc}$ such that $(\mathbf{x}_g^*, \mathbf{x}_{loc}^*)$ is weakly efficient for SP2, then $(\mathbf{x}_g^*, \mathbf{x}_{loc}^*)$ is weakly efficient for AiO MOP.
- If $(\mathbf{x}_g, \mathbf{x}_{loc})$ is weakly efficient to COP then it is weakly efficient to AiO MOP.

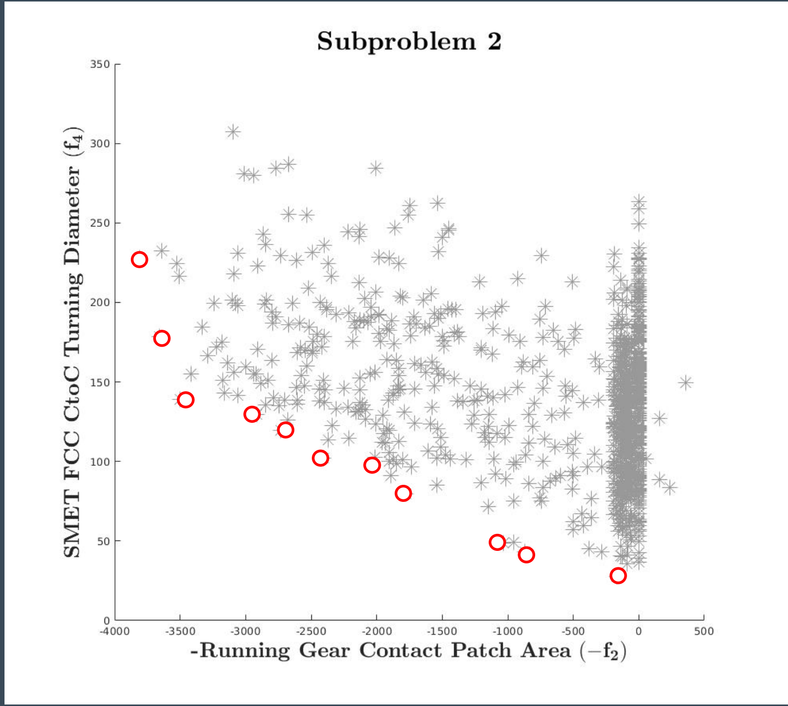
Example: Outcome sets in Tradespaces





Pareto sets in Tradespaces





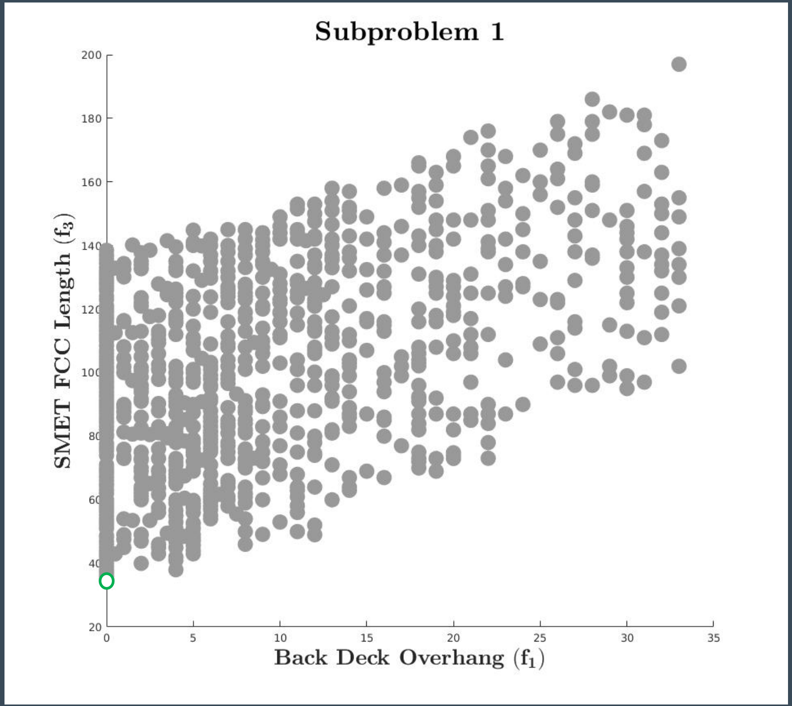
Pareto set
(singleton)

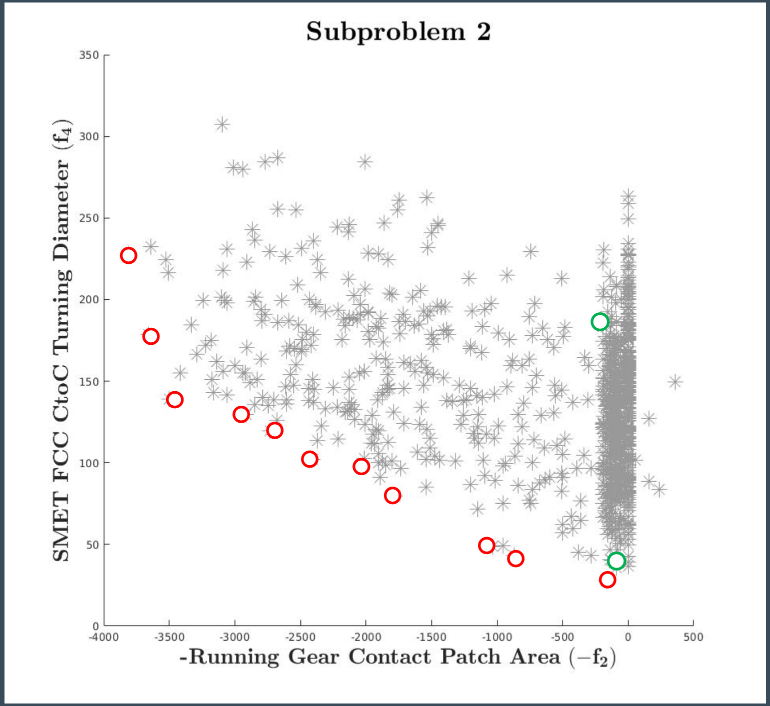
Pareto set

DEVCOM GROUND VEHICLE SYSTEMS CENTER

CLEMSON VIPR-GS VIRTUAL PROTOTYPING GROUND SYSTEMS

Pareto sets in Tradespaces

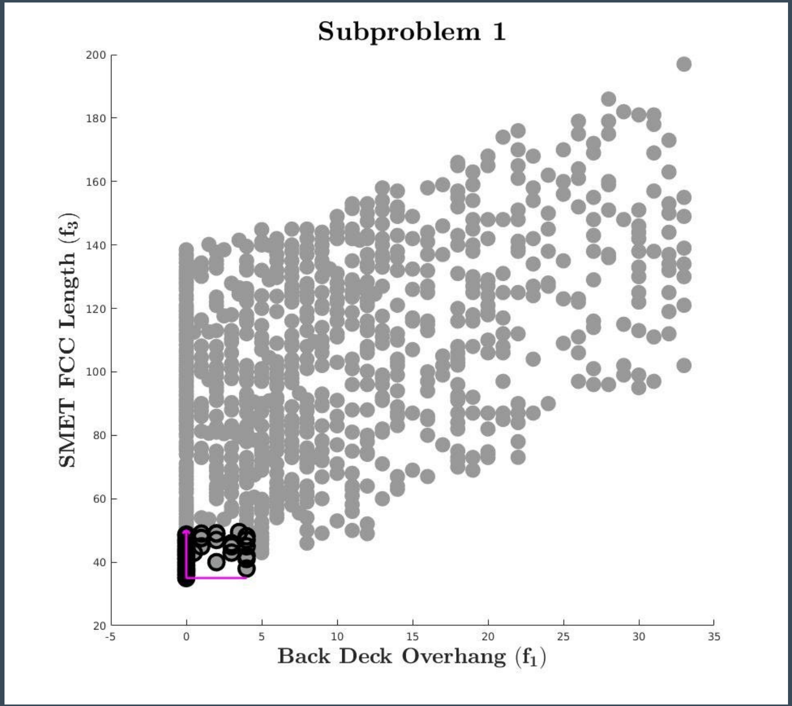


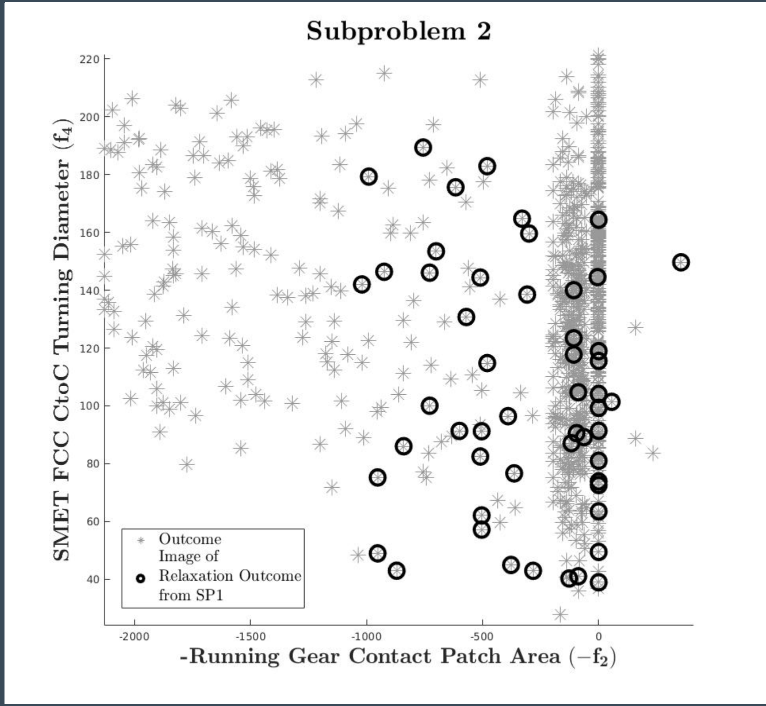


Pareto set
(singleton)

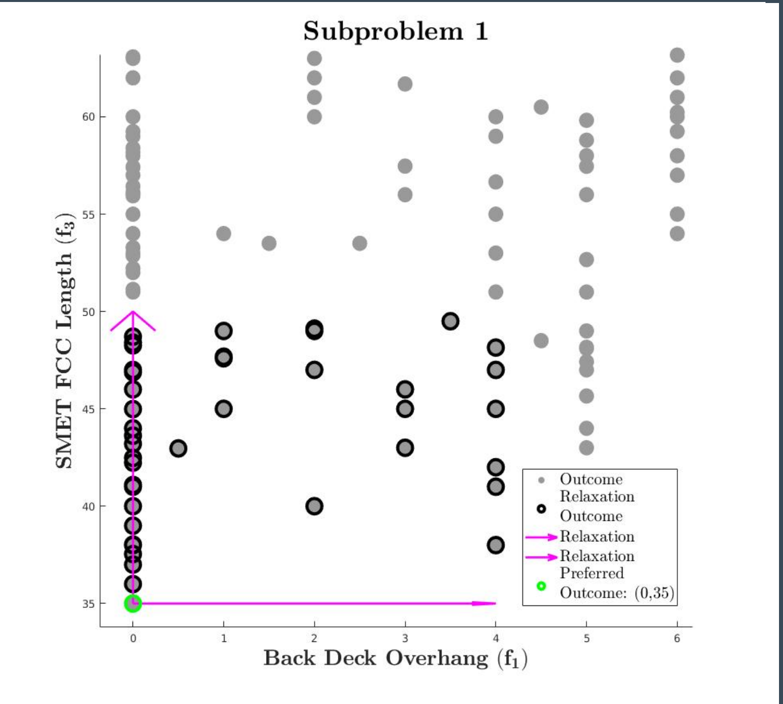
Pareto set

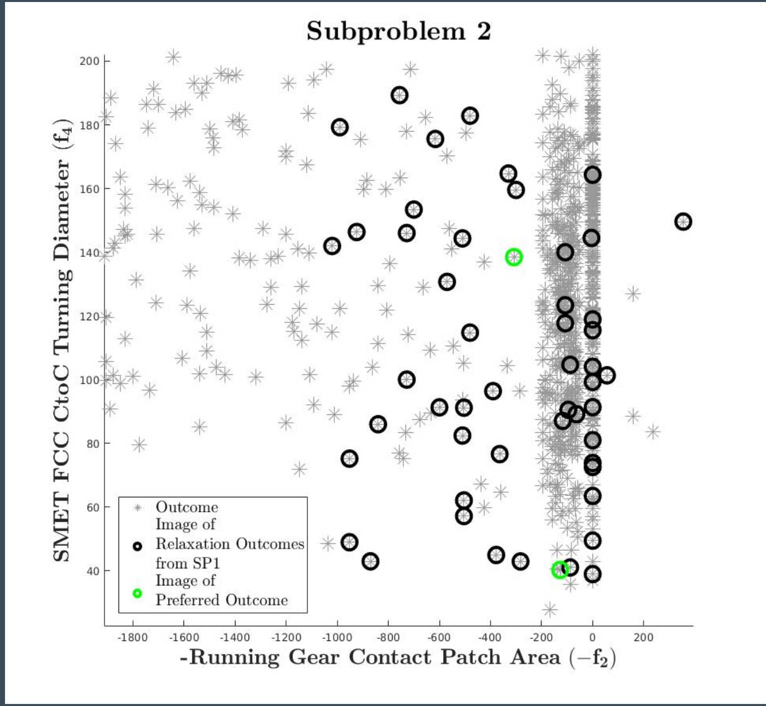
Relaxation in Subproblem 1



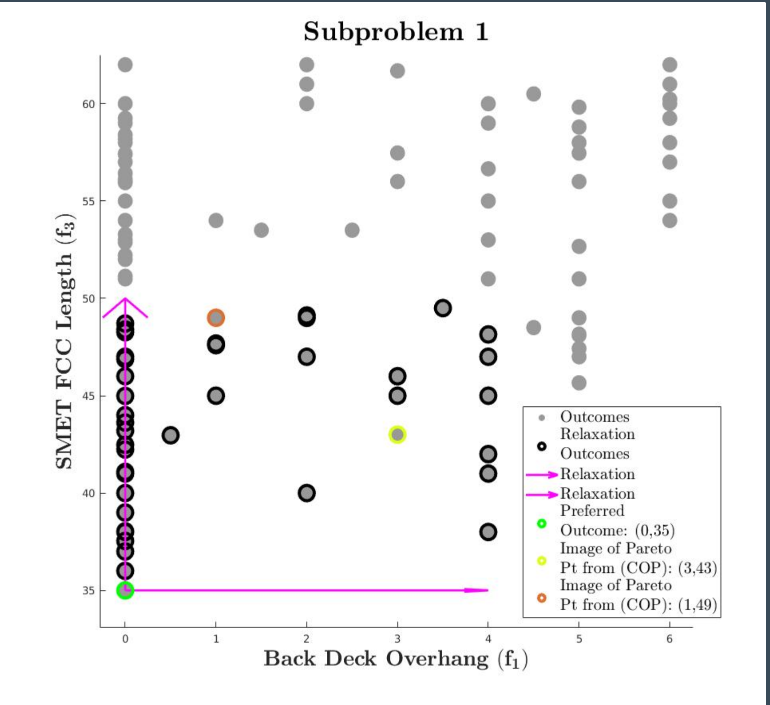


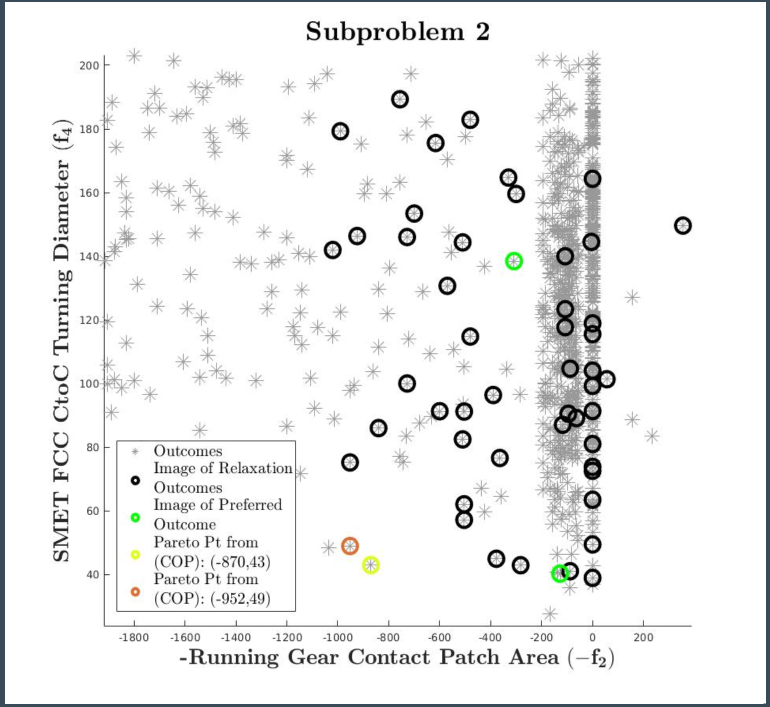
Relaxation in Subproblem 1



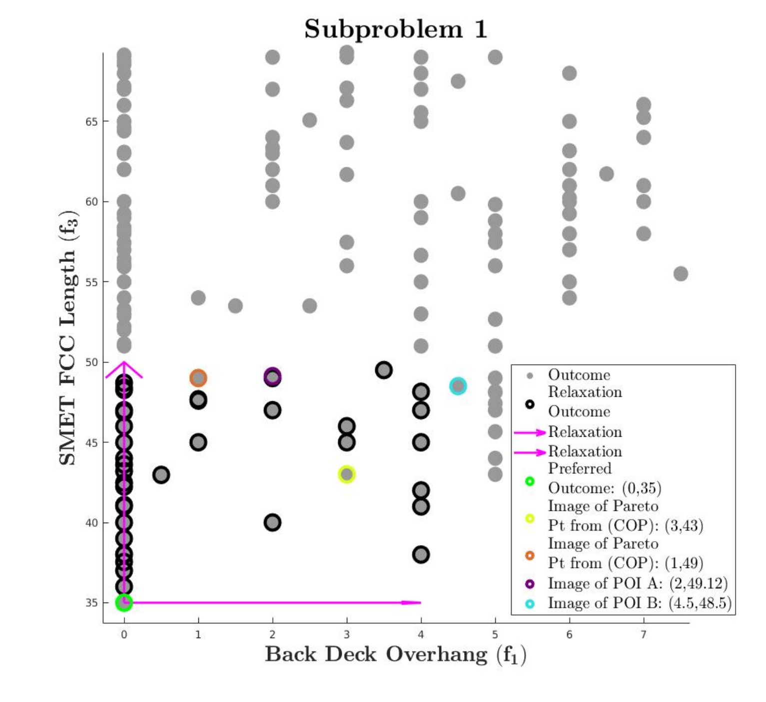


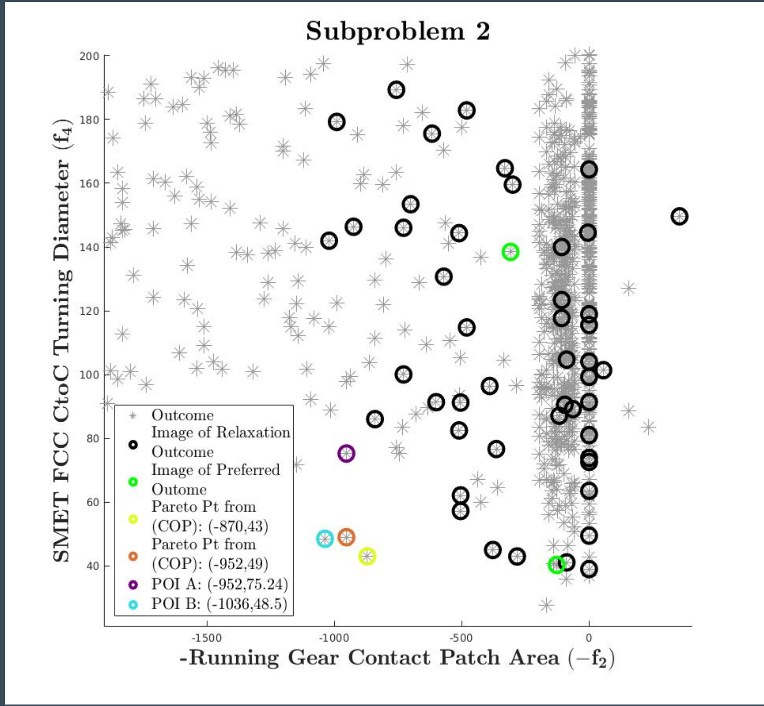
Pareto points to Coordination





Choosing preferred Pareto point for AiO MOP





POI B = AiO preferred Pareto point

DEVCOM GROUND VEHICLE SYSTEMS CENTER

CLEMSON VIPR-GS VIRTUAL PROTOTYPING GROUND SYSTEMS

Analysis in the design space

Preimage (design)	Pareto point for SP1 o	POI A o	POI B o
Drive configuration	identical		
Total volume	similar		
Length, width, heights	different		
Includes	-	winch or offload generator	winch and offload generator

DEVCOM GROUND VEHICLE SYSTEMS CENTER

CLEMSON VIPR-GS VIRTUAL PROTOTYPING GROUND SYSTEMS

Now comes the AI Agents

- Current Work
  - Defining and Training the Agents

Challenge – Acquiring sufficient data from Decision-Makers

- Future Work
  - Once we have trained agents

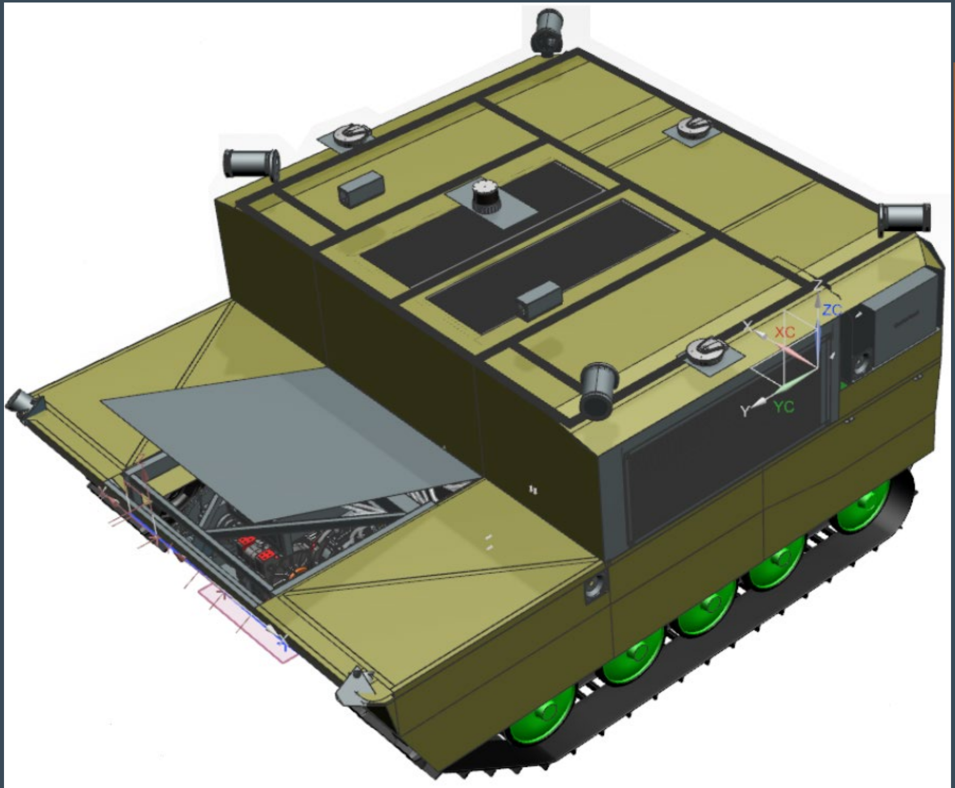
1. Can we run Human-In-the-Loop Simulations?
2. Can we run simulated DM sessions and identify key points of contention
3. Can we evaluate the Tradespace

The Research Team

- Clemson University
  - **Cameron Turner, John Wagner**
    Mechanical Engineering
  - **Margaret Wiecek, Qiong Zhang, Yongjia Song**
    Mathematics
  - **Philip de Castro, Hannah Stewart, Jon Charron, Aaditya Kothavade, Nate Rogers**
    Graduate Students

- US Army Ground Vehicle Systems Center
  - **Greg Hartman**
  - **Denise Rizzo**
  - **David Gorsich**
  - **Annette Skowronska**
  - **Rachel Agusti**
  - **Matthew Castanier**
  - **Stephen Rapp**

Acknowledgements



This work was supported by Clemson University's Virtual Prototyping of Autonomy Enabled Ground Systems (VIPR-GS), under Cooperative Agreement W56HZV-21-2-0001 with the US Army DEVCOM Ground Vehicle Systems Center (GVSC).

DEVCOM GROUND VEHICLE SYSTEMS CENTER

CLEMSON VIPR-GS VIRTUAL PROTOTYPING GROUND SYSTEMS

College of
ENGINEERING, COMPUTING
AND APPLIED SCIENCES

Questions?

Dr. Cameron J. Turner

cturne9@clemson.edu

DISTRIBUTION STATEMENT A. Approved for public release: distribution is unlimited. OPSEC # (7903)