Modeling Spacecraft Design Activities as Rugged Fitness Landscapes

Sponsor: DASD(SE)

By
Ms. Stephanie Sharo Chiesi
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1825 Connecticut Avenue NW
8th Floor
Washington, DC 20009

www.sercuarc.org

Overview

- Motivation
- Problem Description
- Design Spaces for Spacecraft System Design – Mars Rovers
- Rugged Fitness Landscapes
- Predictions and Tuning the Model
- Conclusions and Future Work

Motivation

- DoD Digital Engineering Strategy
  - —Published June 2018
  - —Modernize design, development, operation and sustainment
  - —Transform acquisition and implementation
  - —Improve speed for critical capability delivery to the warfighter
  - —Connected data in a digital environment

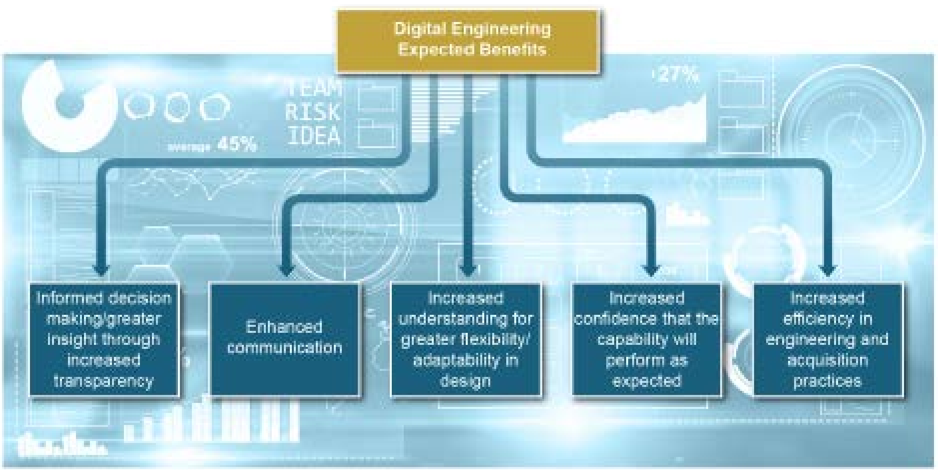


Image credit: DoD Digital Engineering Strategy, June 2018

SYSTEMS ENGINEERING RESEARCH CENTER

Problem Description

Raytheon

- Aerospace and defense projects are some of the most complex engineered systems
  - —Expensive and long duration design and development
  - —Multidisciplinary Design Analysis and Optimization (MDAO) does not capture all emergent behaviors
- Design models do not capture the impact of:
  - —Modes of communication in design and operation
  - —Effects of different communication types
  - —Correlation of these to design fitness
  - —Other coupling and relationships of design
- We need a way to study complex communications and collaboration in these types of projects to assess the impact on system design performance in the new digital engineering environments

Spacecraft System Design

- Describing the fitness of a spacecraft system
  - Define variables to represent the design and the operational environment
  - Use models and abstraction to represent complexity
  - Interaction and coupled or emergent behavior calculated with dependent model variables
  - Levels of decomposition and variable definition impact how well the model represents reality
  - May be impacted by design team organization and task structure

- Example: Mars Rovers
  - Complex spacecraft with specific mission goals
  - Coupled design solution space to maximize fitness
  - Fitness defined as number of samples collected per mission versus mission cost

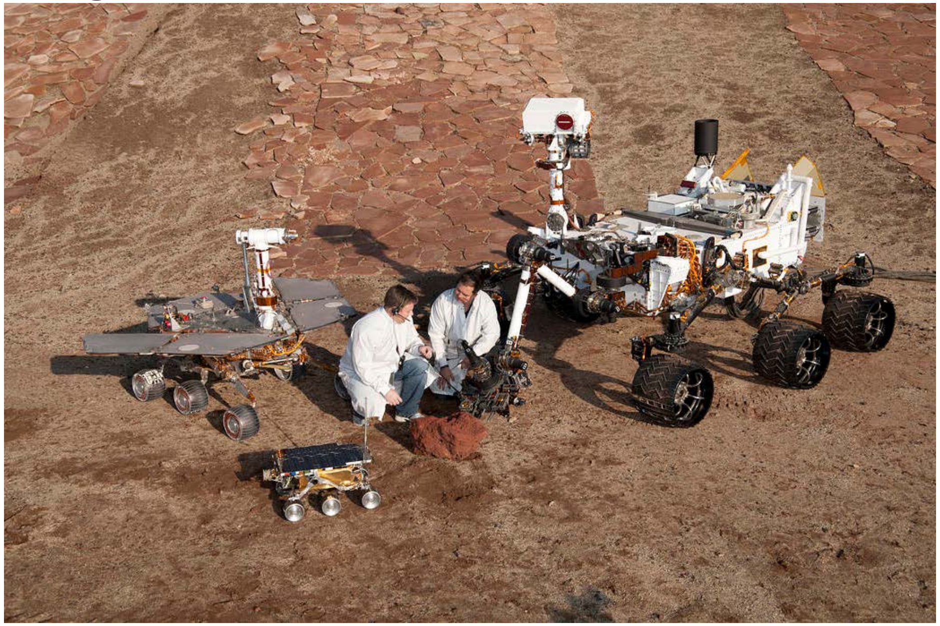
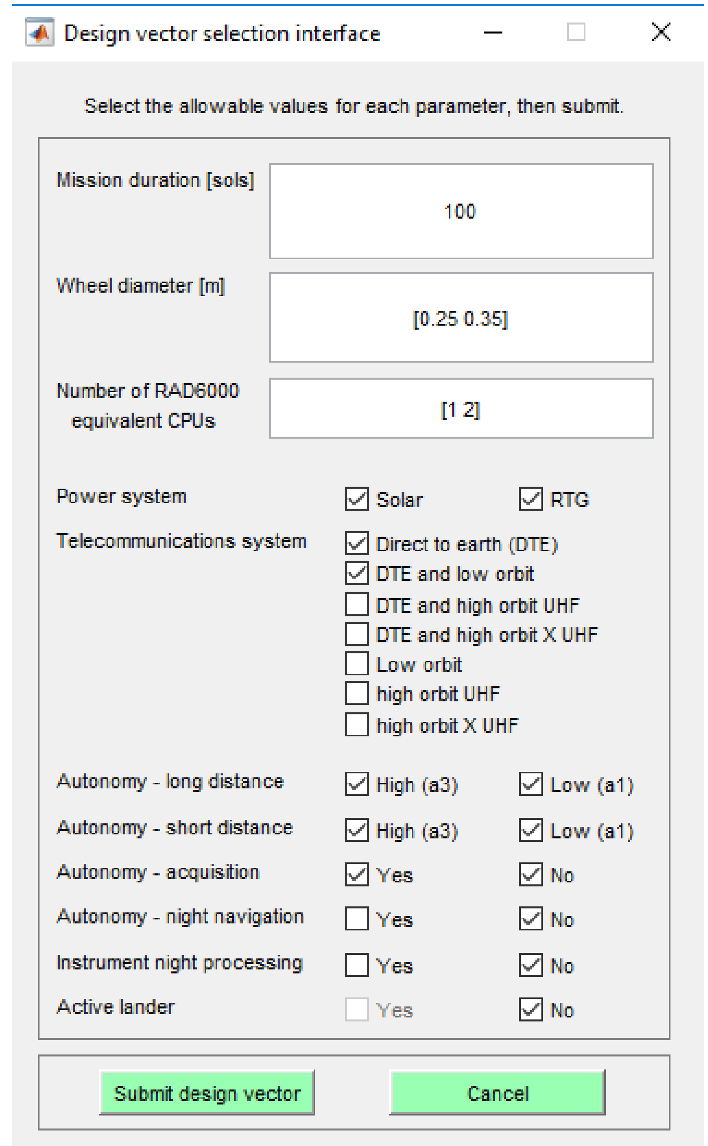


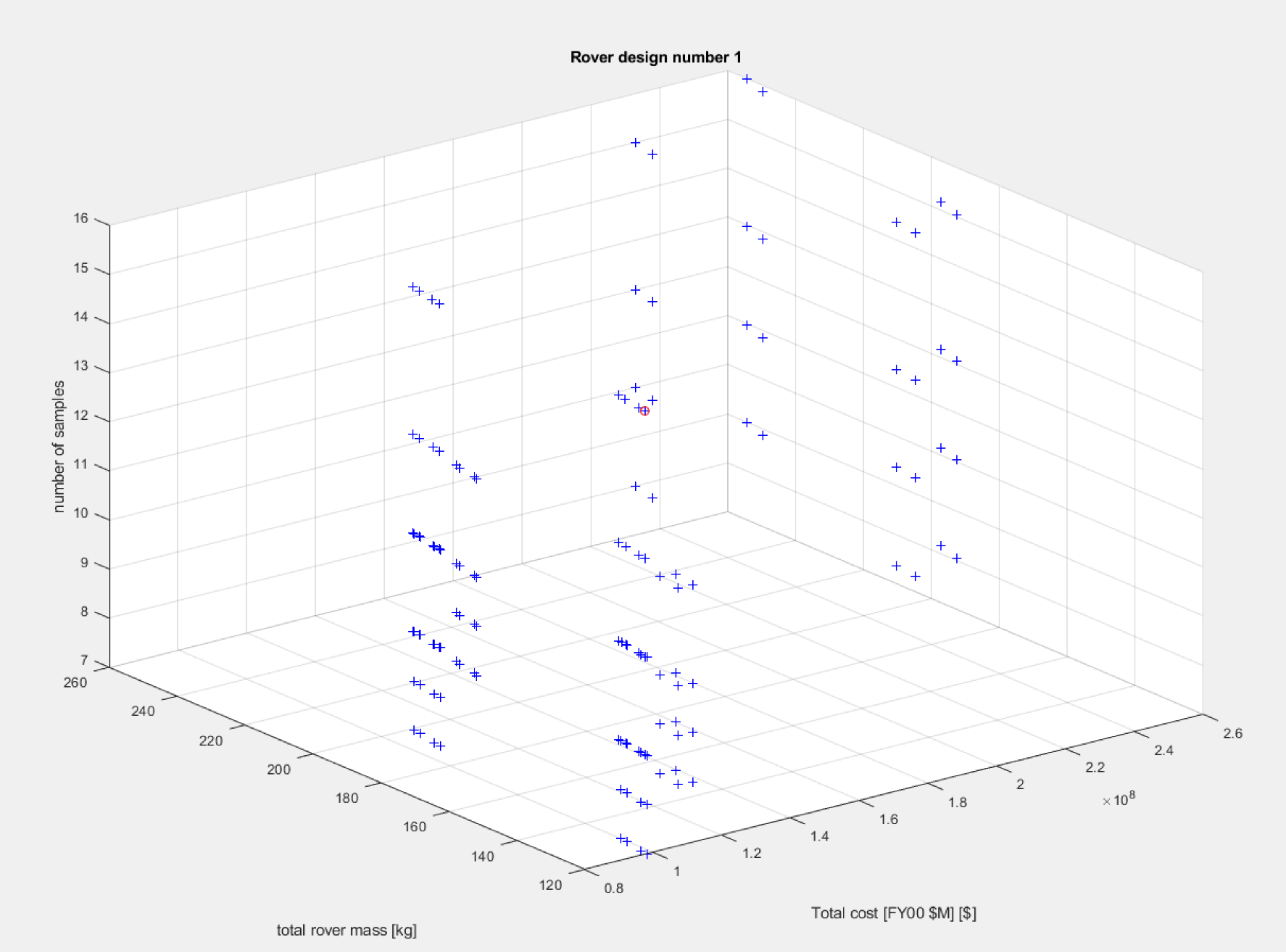
Image credit: https://www.nasa.gov/multimedia/imagegallery/image_feature_2154.html

Mars Rover Design Vector

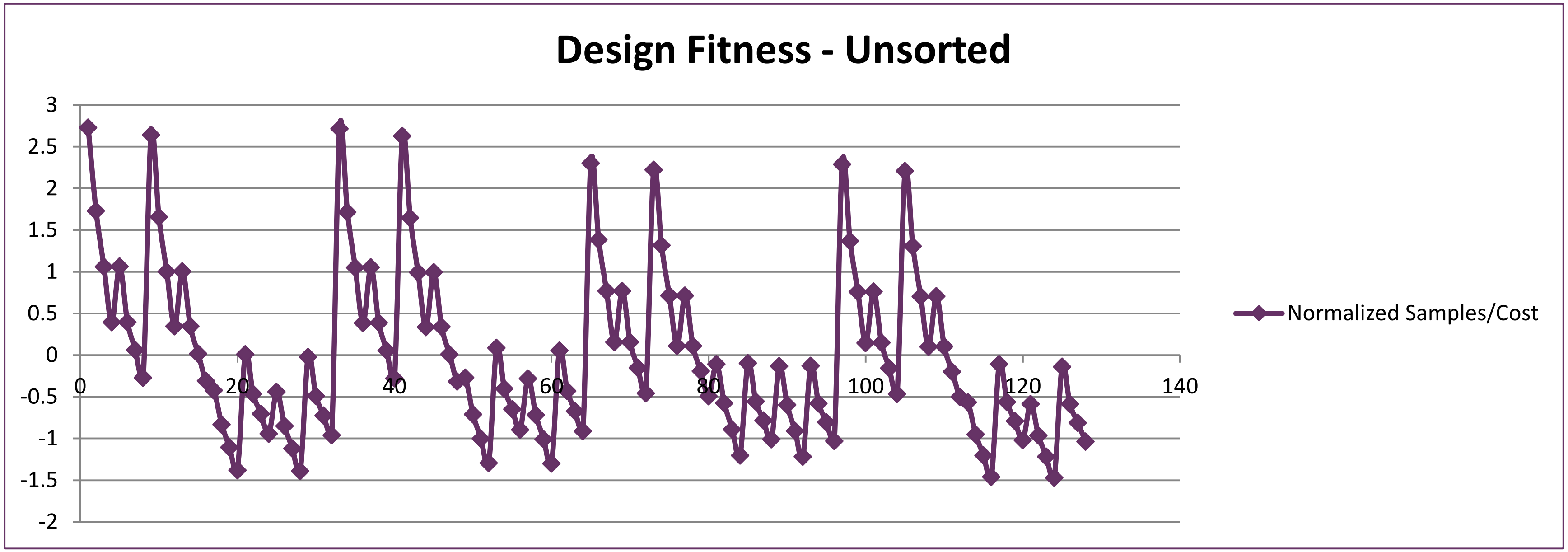
- Mars Rover Design Space Model
  - —Can select the N variables to be included in evaluation
    - o Variables in the Rover Design model that contribute to the fitness calculation for a particular point design
  - —N = 7 for this dataset example
    - o For each variable N there were 2 different values considered in the design space
  - —Using the selected variables for the design vector the potential valid system configurations are evaluated to determine the fitness of each system
  - —128 solutions generated
  - —Fitness defined as number of samples collected per mission versus mission cost

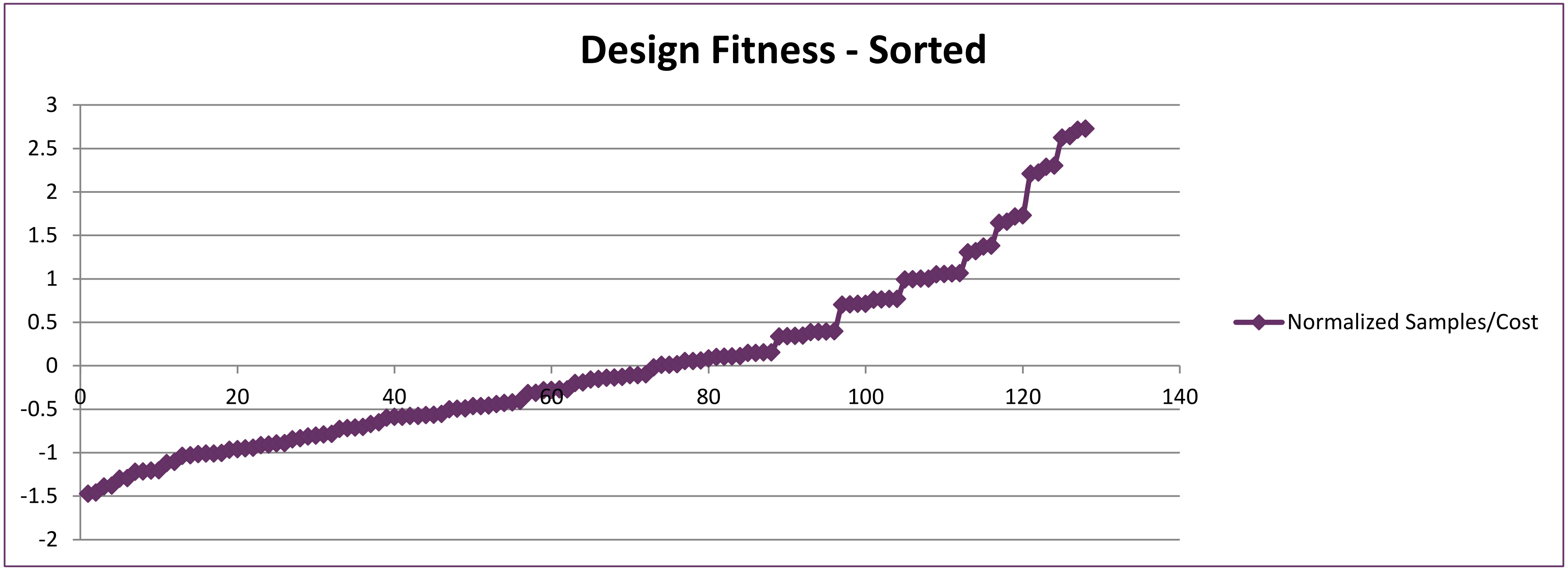


Highlighted design delivers most samples for lowest cost



How fit are the resultant rover designs





Rugged Fitness Landscapes

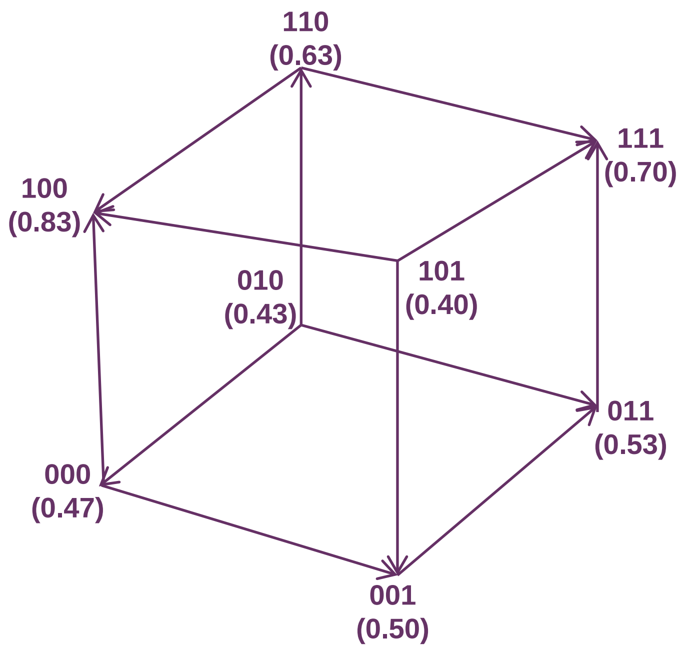
- We need a way to look at the impact of team communication and collaboration on design fitness without relying on a detailed design space model
  - Valid over a range of design problems
  - Before lengthy design and development process to build design models
- Candidate approach is an NK model from a class of mathematical (statistical) models
  - Describe the richness of epistatic interactions
    - The value of a given variable is affected by the values of other variables
  - Have been used to describe adaptive evolution in immune response as well as fitness of organizations
- Can the NK model can be tuned to show that it can be representative of the fitness space defined by complex design models?

The Basic NK Model

- Basic model description
  - —A system has N variables, each variable can take on A possible values
  - —The model assigns a "fitness contribution" to each variable (w_i)
  - —This can be assigned at random from the uniform distribution on (0,1)
  - —The total fitness (W) of a system is an average of the fitness contributions of each variable

$$W = \frac{1}{N}\sum_{i=1}^{N} w_i$$

1	2	3	w_1	w_2	w_3	W
0	0	0	0.6	0.3	0.5	0.47
0	0	1	0.1	0.5	0.9	0.50
0	1	0	0.4	0.8	0.1	0.43
0	1	1	0.3	0.5	0.8	0.53
1	0	0	0.9	0.9	0.7	0.83
1	0	1	0.7	0.2	0.3	0.40
1	1	0	0.6	0.7	0.6	0.63
1	1	1	0.7	0.9	0.5	0.70



Assessing System Fitness

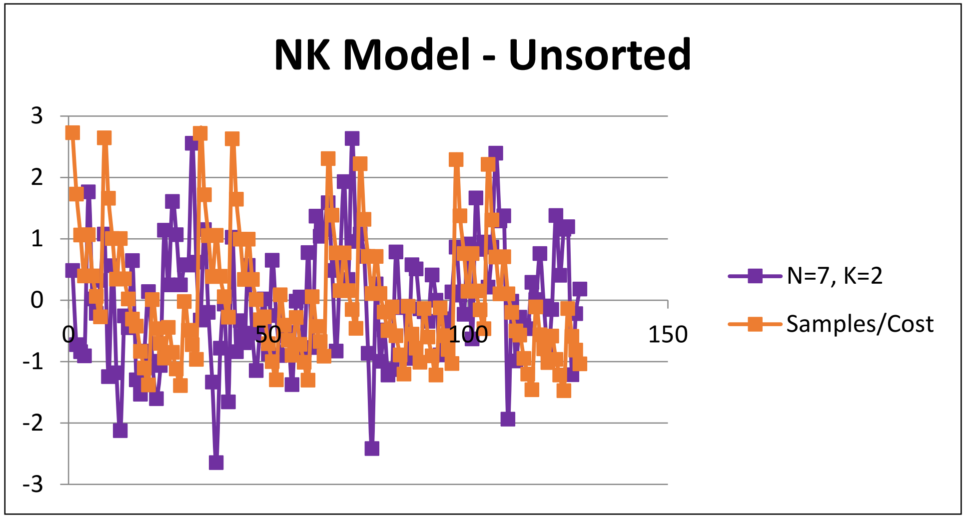
- Contributions to fitness between coupled variables
  - K defines the number of coupled variables influencing the fitness value of w_i
  - K = 0 yields a smooth solution fitness landscape with a single peak for the solution with the optimal fitness
    - The contributions of each variable to the system fitness are entirely independent of all other variables
  - As K increases relative to N, the fitness landscape becomes rugged with multiple peaks representing local optima
    - For K = N-1 the contributions of each variable are entirely dependent of the values for all other variables in the system
- The statistical model could represent local optima and the distance to reach a local optima

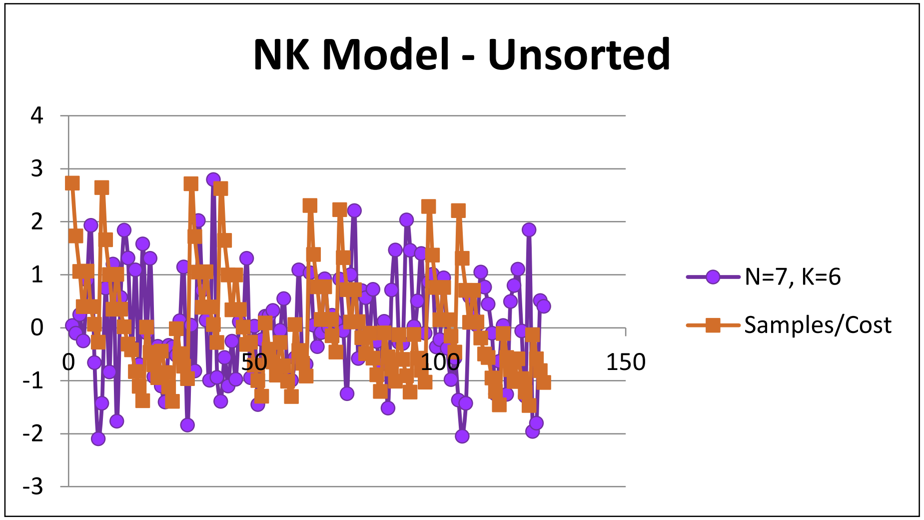
NK model to align with Rover Design Fitness Landscape

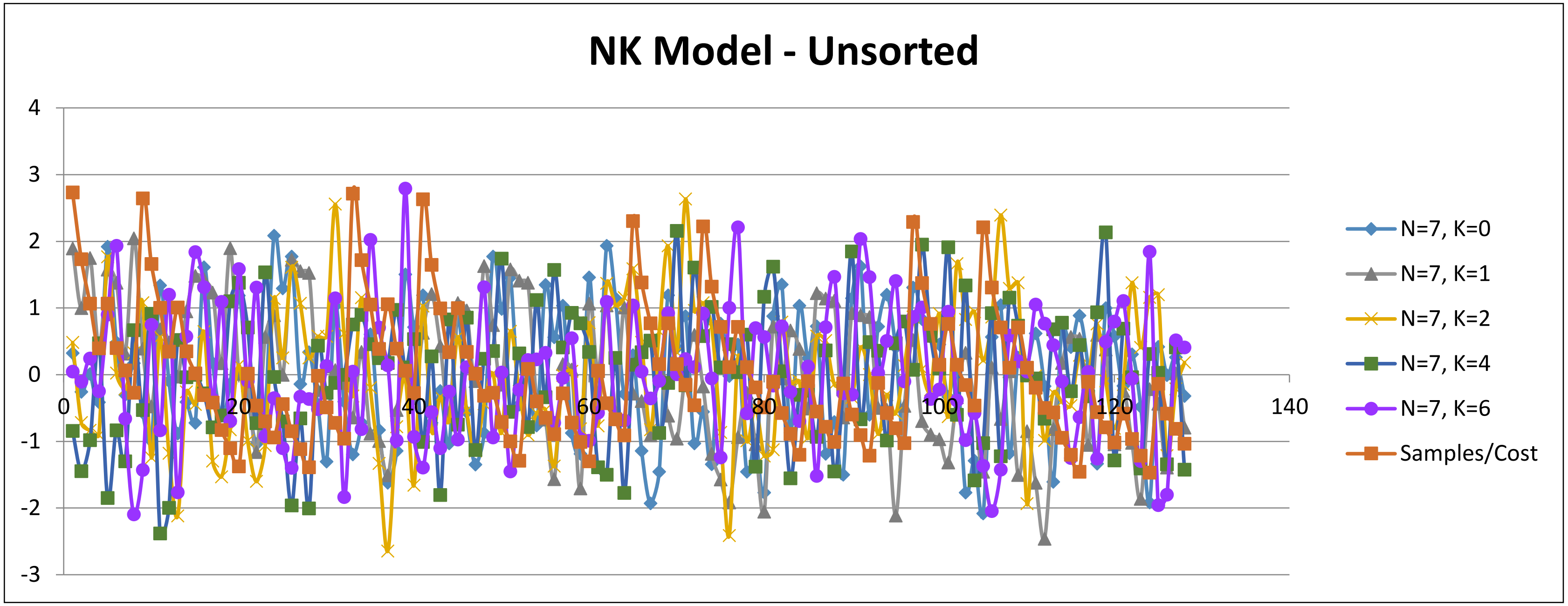
- Match the model setup of the Mars Rover design model
  - N = 7 variables, A = 2 possible values for each variable
  - Results in 128 potential solutions

Design	N1	N2	N3	N4	N5	N6	N7	Design Point N=7, K=0 Fitness	Design Point N=7, K=1 Fitness	Design Point N=7, K=2 Fitness	Design Point N=7, K=4 Fitness	Design Point N=7, K=6 Fitness
1	0	0	0	0	0	0	0	0.4513	0.7083	0.5510	0.4090	0.4835
2	0	0	0	0	0	0	1	0.4090	0.6144	0.4194	0.3421	0.4674
3	0	0	0	0	0	1	0	0.4287	0.6930	0.4069	0.3938	0.5052
4	0	0	0	0	1	0	0	0.3977	0.5531	0.3993	0.5553	0.4521
5	0	0	0	1	0	0	0	0.5679	0.6747	0.6914	0.2974	0.5757
6	0	0	1	0	0	0	0	0.4632	0.6540	0.5009	0.4100	0.6871
7	0	1	0	0	0	0	0	0.4058	0.5426	0.4748	0.3586	0.4076
8	1	0	0	0	0	0	0	0.4405	0.7240	0.5338	0.5770	0.2530
9	0	0	0	0	0	1	1	0.3863	0.5504	0.6160	0.4438	0.3250
10	0	0	0	0	1	0	1	0.3553	0.4592	0.3621	0.6042	0.5596
11	0	0	0	1	0	0	1	0.5255	0.5808	0.5598	0.2384	0.3889
12	0	0	1	0	0	0	1	0.4208	0.5601	0.3693	0.2812	0.6081
13	0	1	0	0	0	0	1	0.3634	0.5061	0.2664	0.5607	0.2886
14	1	0	0	0	0	0	1	0.3981	0.6091	0.4702	0.4983	0.5404
15	0	0	0	0	1	1	0	0.3750	0.6648	0.4496	0.5023	0.6770
16	0	0	0	1	0	1	0	0.5452	0.6594	0.5686	0.4716	0.6202
17	0	0	1	0	0	1	0	0.4405	0.6387	0.3568	0.4152	0.4389

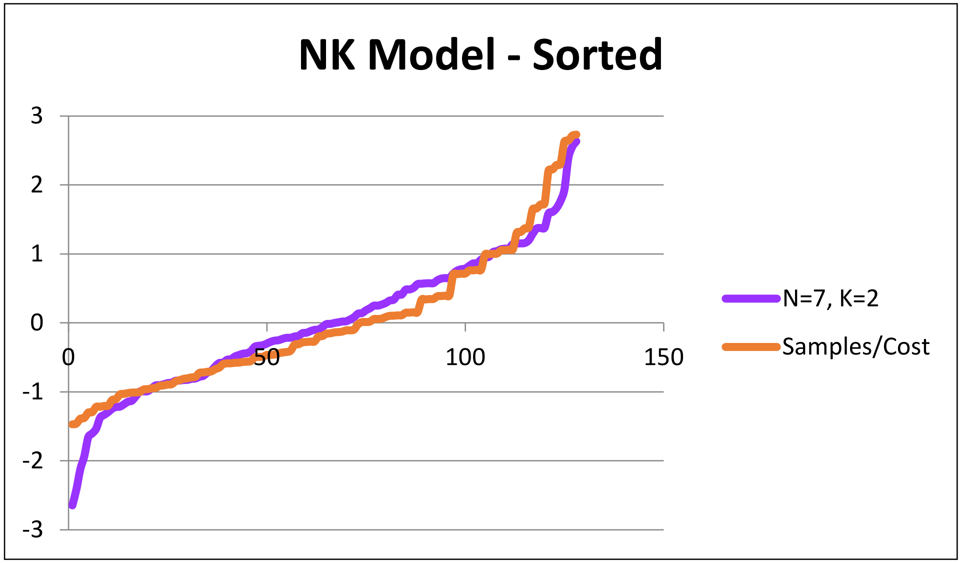
How well would an NK Model approximate the fitness space (1)

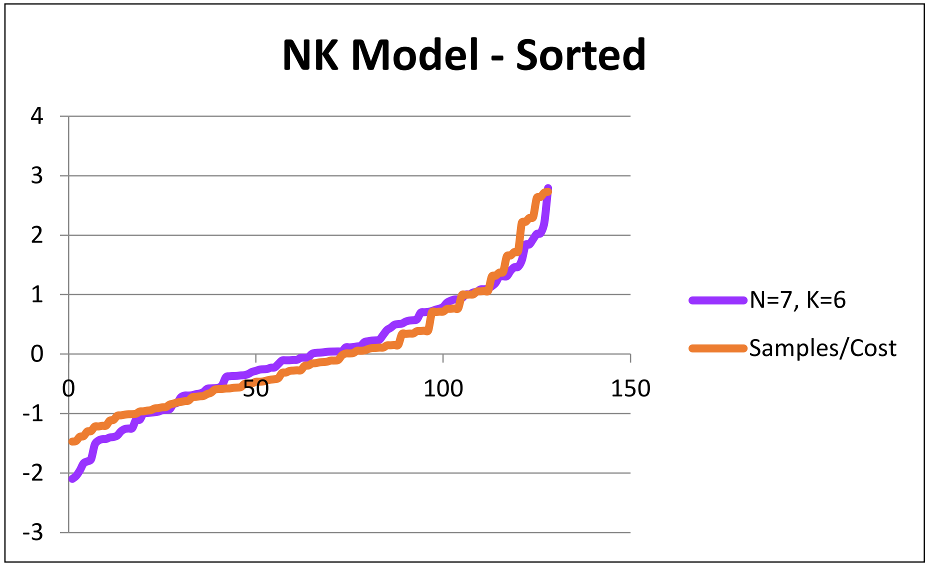


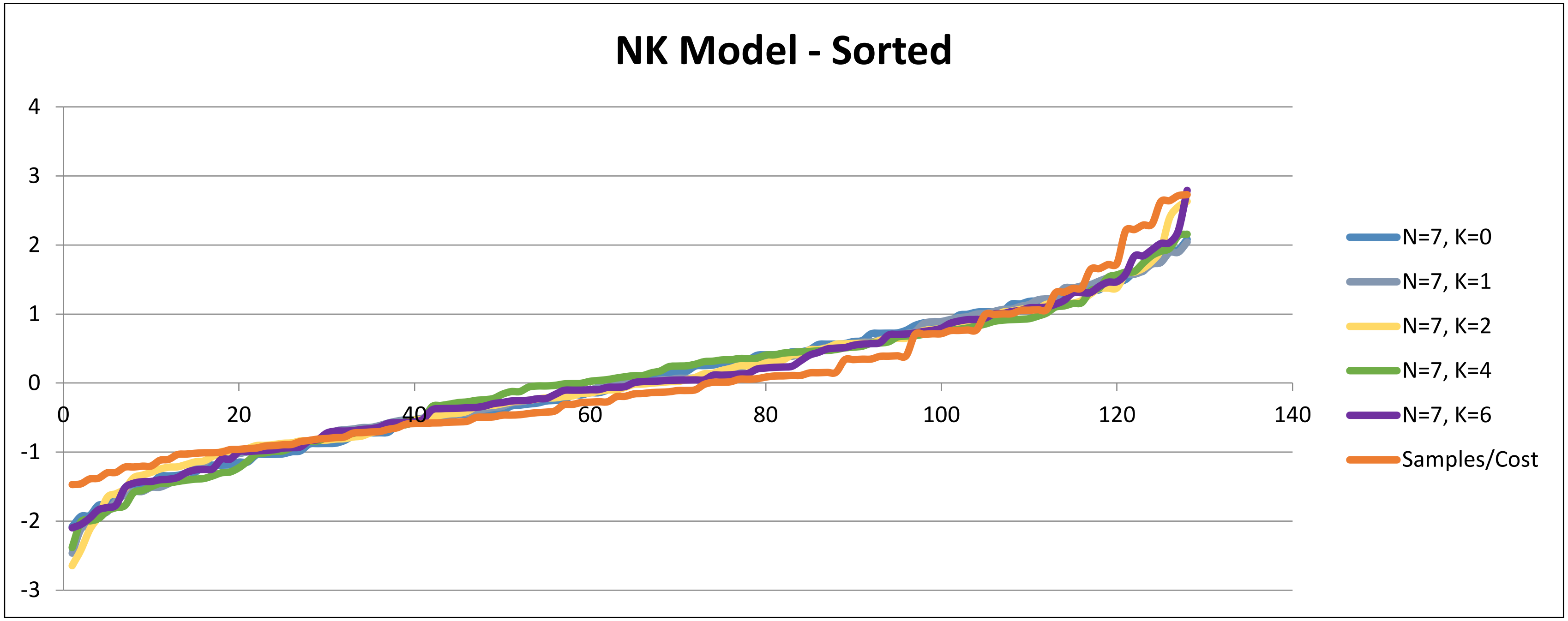




How well would an NK Model approximate the fitness space (2)







Results and Conclusions

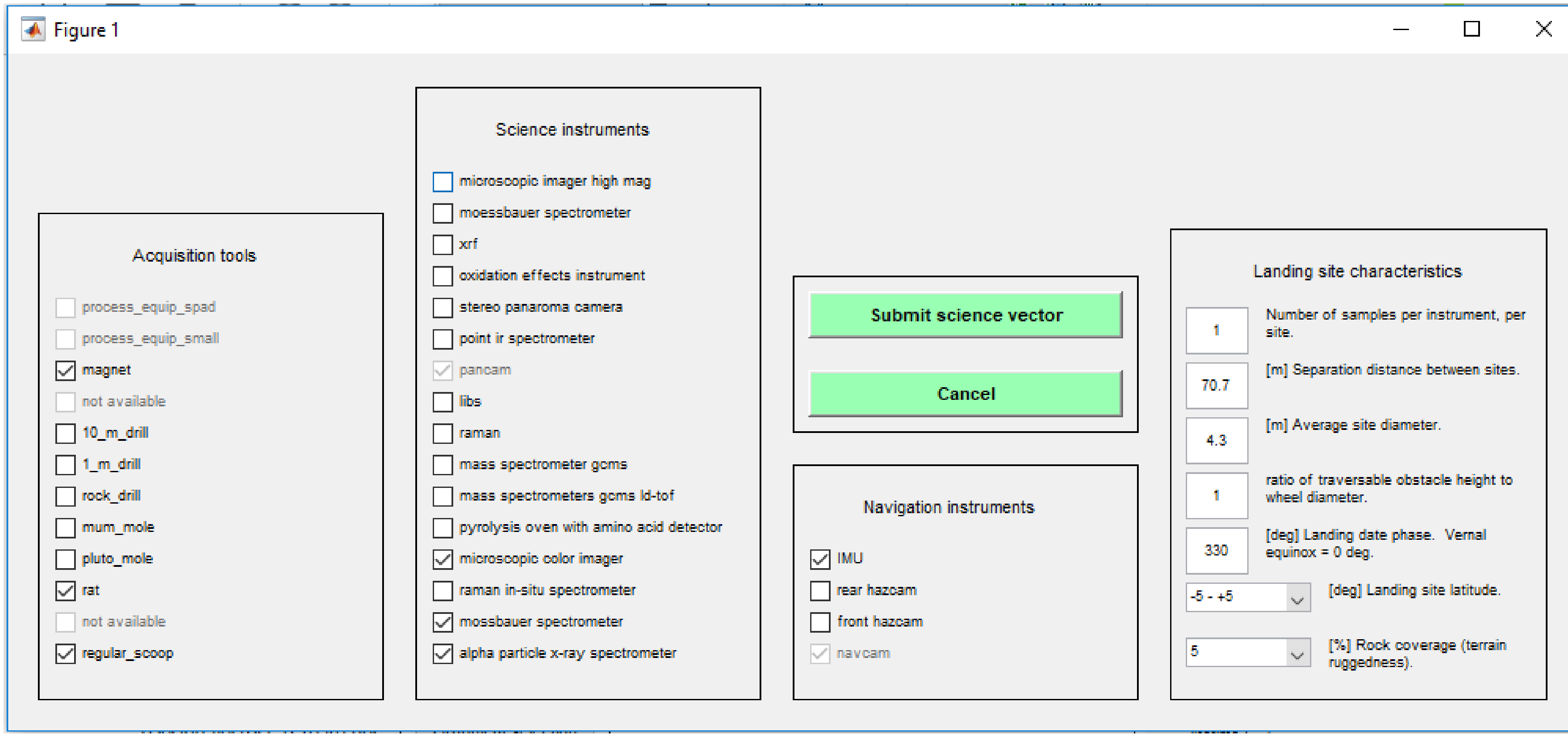
- Created a fitness landscape of potential solutions for Mars rover designs to compare to a randomly generated fitness landscape defined by an NK model
  - K=2 and K=6 have promising potential for representing the design dataset using both the unsorted and sorted fitness plots
- Limitations of this preliminary assessment
  - Single snapshot fitness assessment of the NK model as setup
    - Need to apply Monte Carlo analysis and look at confidence intervals to determine if this could be accepted or rejected as a feasible representation
  - Comparison to a single design fitness model
    - Other design fitness models may have different results in terms of fitness and tuning the NK model to it
  - The evaluation metric needs to be assessed for determining potential of the representation
    - Perhaps sorted fitness is not the best way to evaluate the goodness of fit

Future Work

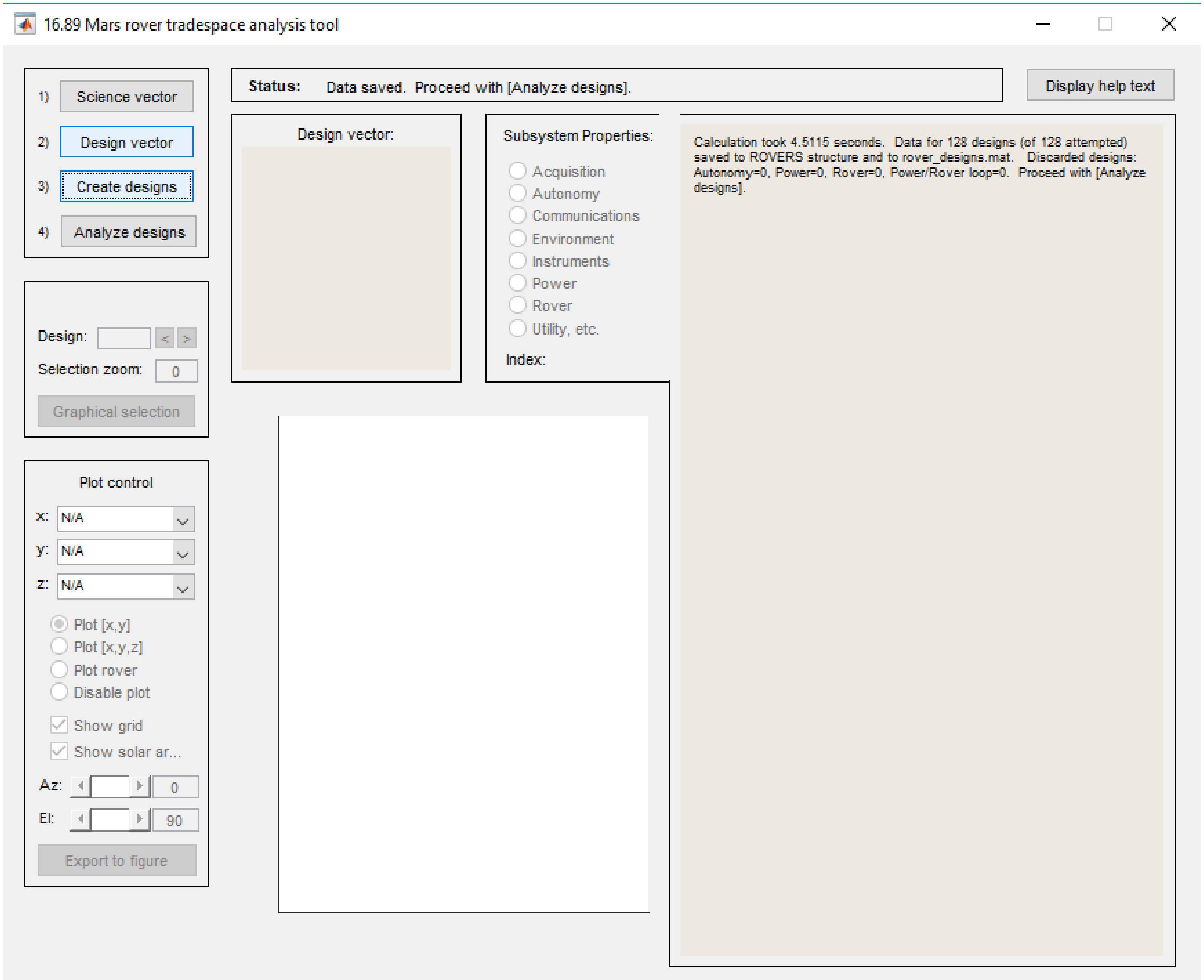
- There is more work to be done to determine if statistical models can represent a design fitness space
  - More tuning required to align NK model with design fitness models
  - More analysis to be conclusive, versus a single snapshot representation
  - Challenge of dealing with a noisy landscape with randomly generated fitness values
  - Identifying the evaluation metric to determine success of representation
- Additional challenges need to be investigated as part of tuning
  - What is the impact of the definition of the Ns and As
  - How are non-homogenous problem structures handled
  - Are there indications of the parameter K in other aspects of linked digital models

Backup

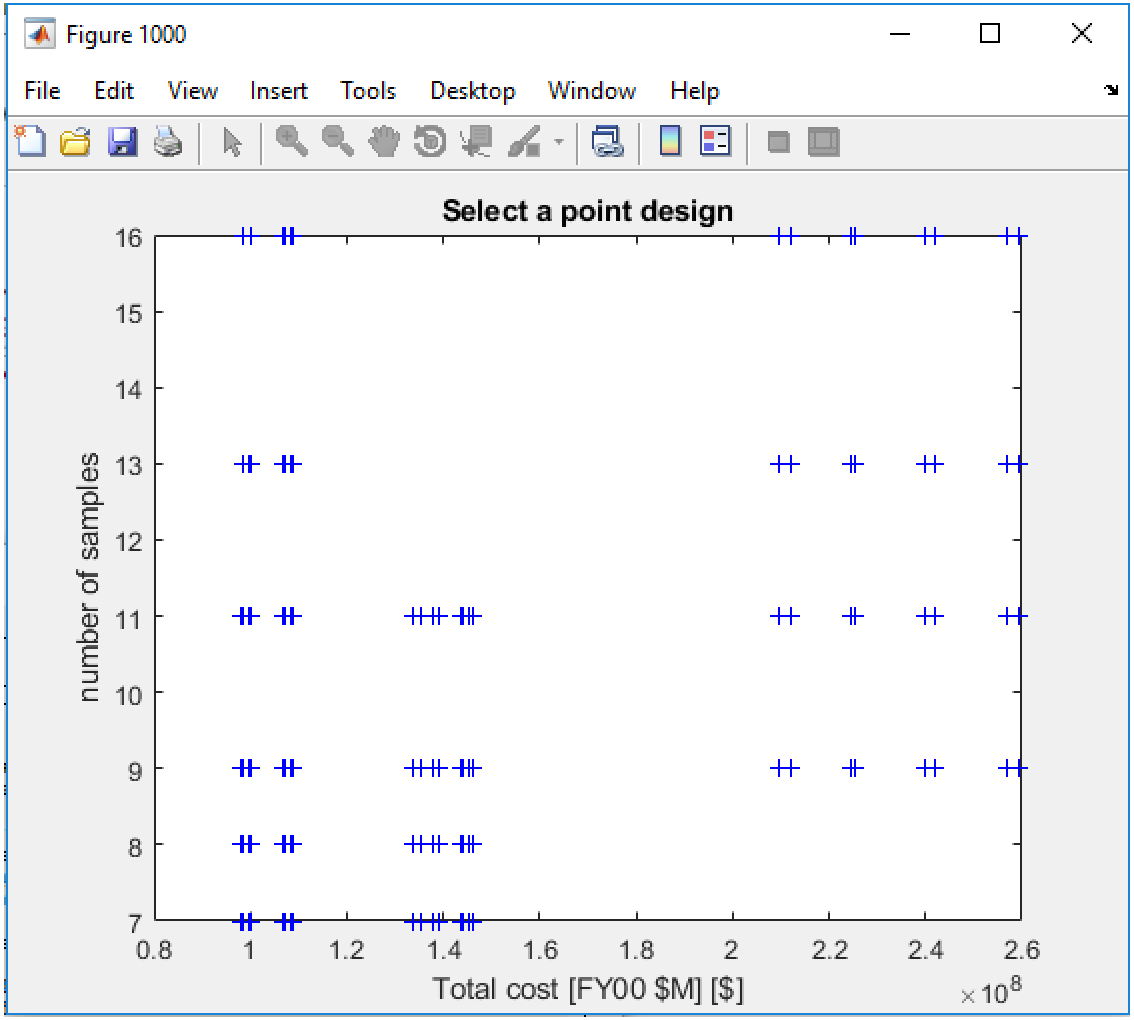
MER-like Science Vector



128 designs created



Selecting a point design to explore



Analyze designs: 128 generated solutions