

# Modeling Spacecraft Design Activities as Rugged Fitness Landscapes

**Sponsor: DASD(SE)**

**By**

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Motivation

Problem Description

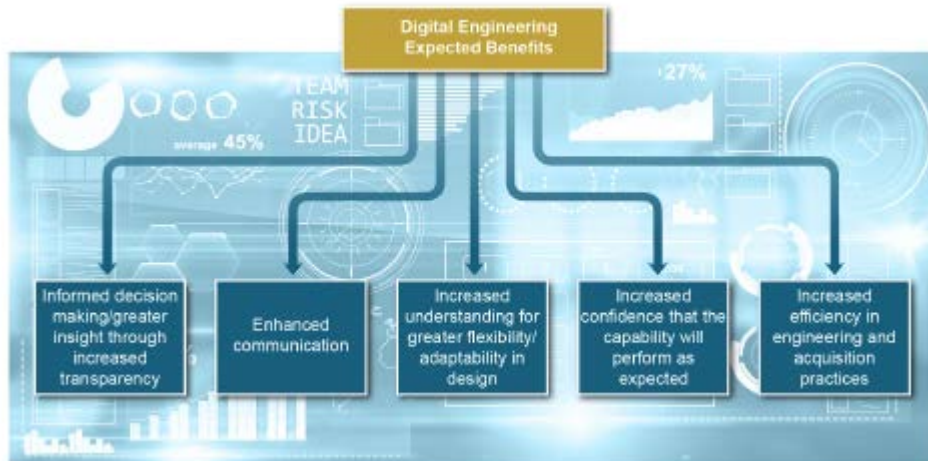
Design Spaces for Spacecraft System Design – Mars Rovers

Rugged Fitness Landscapes

Predictions and Tuning the Model

Conclusions and Future Work

- 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

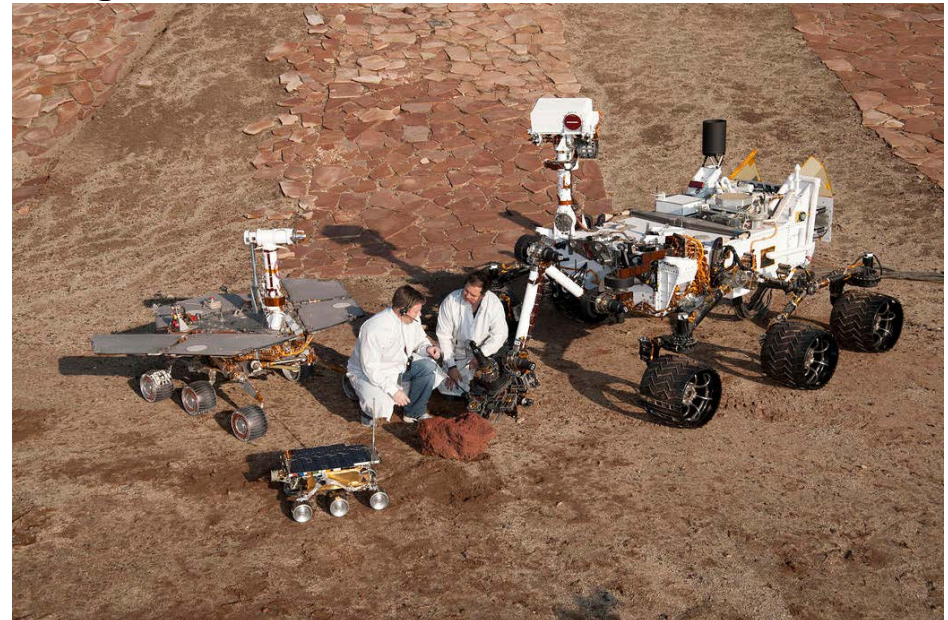


- Aerospace and defense projects are some of the most complex engineered systems
  - Expensive and long duration design and development
  - Multidisciplinary Design Analysis and Optimization (MDAO) does not capture all emergent behaviors
- Design models do not capture the impact of:
  - Modes of communication 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

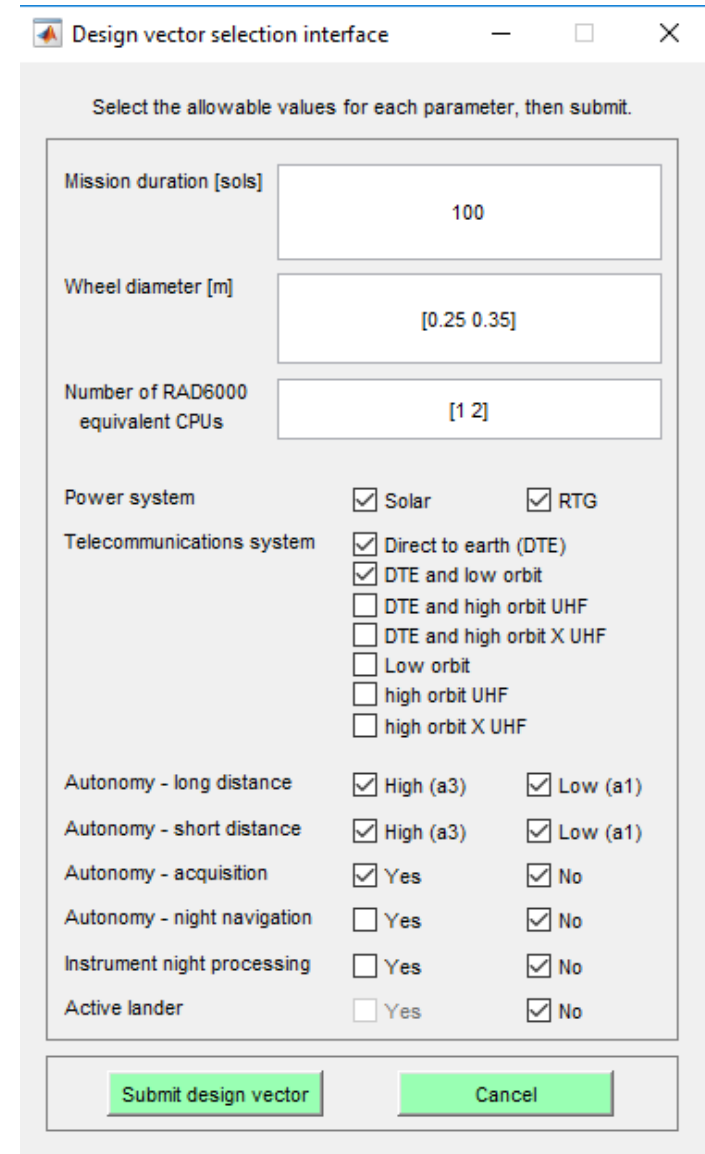
- Describing the fitness of a spacecraft system
  - Define variables to represent the design and the operational environment
  - Use models and abstraction to represent complexity
  - Interaction and coupled or emergent behavior calculated with dependent model variables
  - Levels of decomposition and 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



- Mars Rover Design Space Model
  - Can select the N variables to be included in evaluation
    - Variables in the Rover Design model that contribute to the fitness calculation for a particular point design
  - N = 7 for this dataset example
    - 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



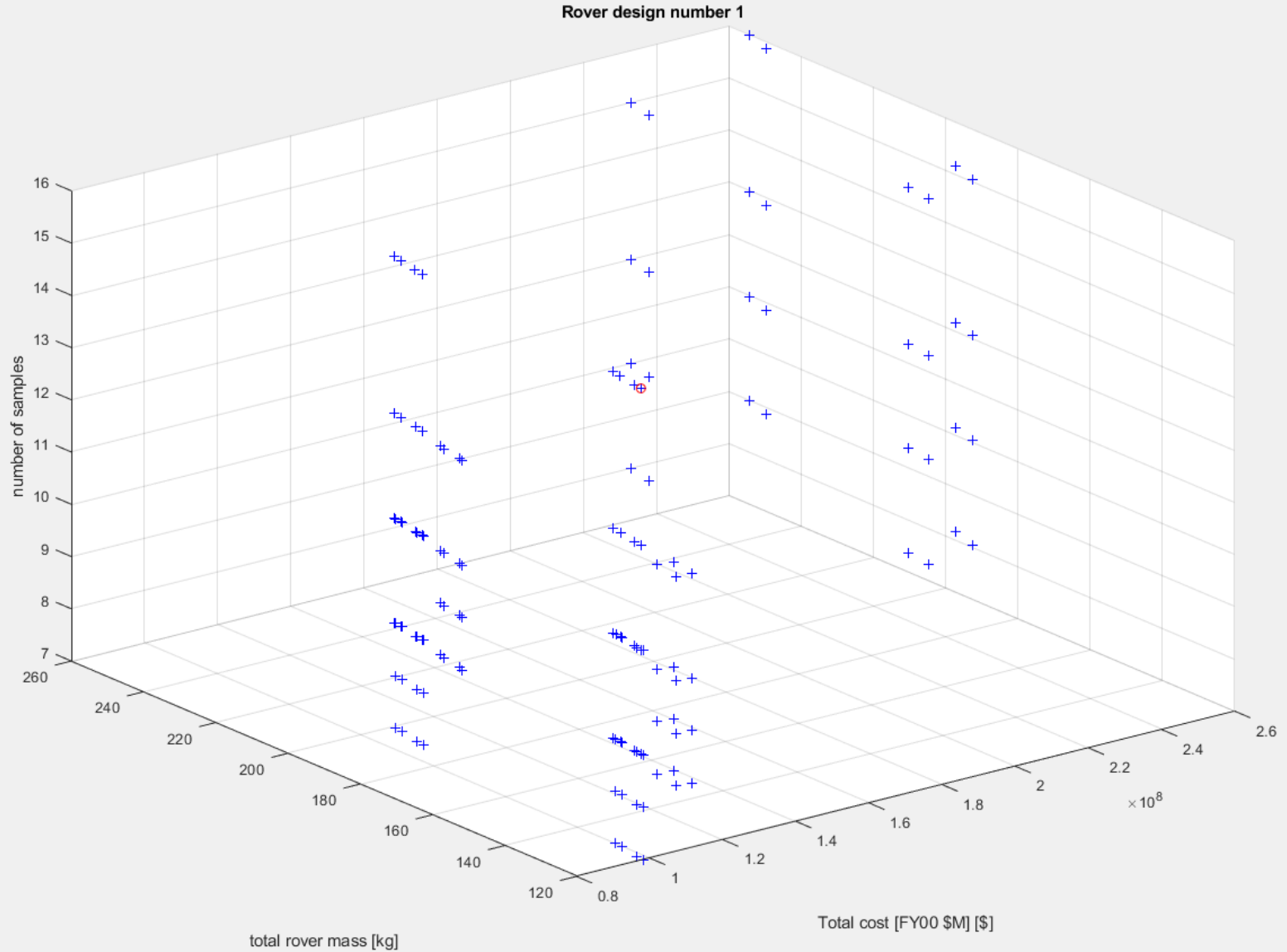
Design vector selection interface

Select the allowable values for each parameter, then submit.

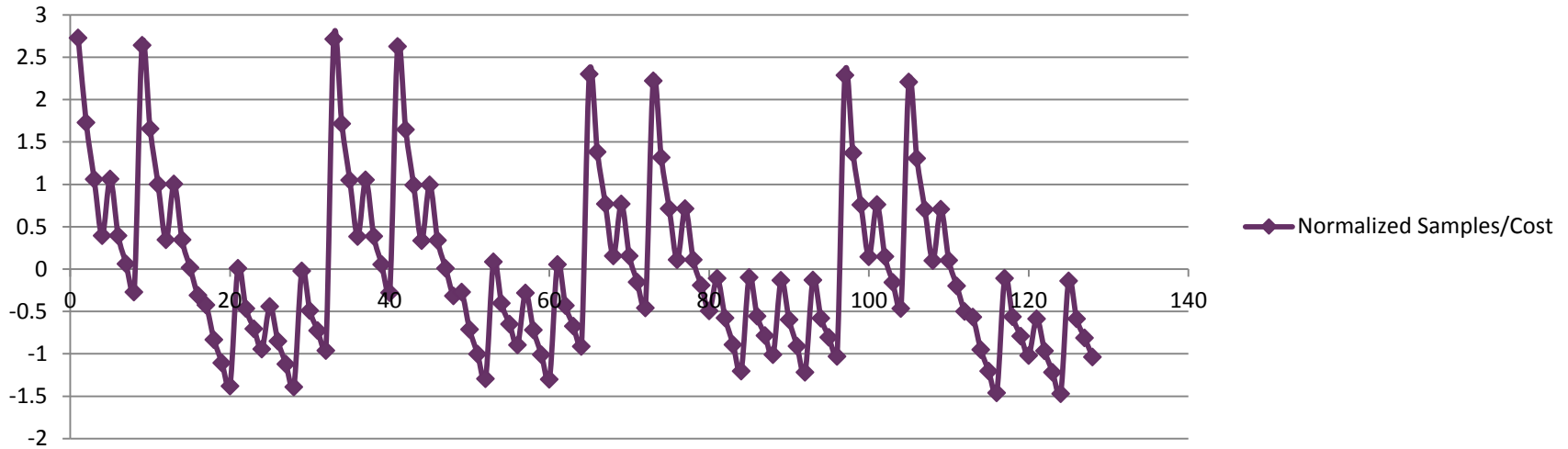
Mission duration [sols]	100	
Wheel diameter [m]	[0.25 0.35]	
Number of RAD6000 equivalent CPUs	[1 2]	
Power system	<input checked="" type="checkbox"/> Solar	<input checked="" type="checkbox"/> RTG
Telecommunications system	<input checked="" type="checkbox"/> Direct to earth (DTE) <input checked="" type="checkbox"/> DTE and low orbit <input type="checkbox"/> DTE and high orbit UHF <input type="checkbox"/> DTE and high orbit X UHF <input type="checkbox"/> Low orbit <input type="checkbox"/> high orbit UHF <input type="checkbox"/> high orbit X UHF	
Autonomy - long distance	<input checked="" type="checkbox"/> High (a3)	<input checked="" type="checkbox"/> Low (a1)
Autonomy - short distance	<input checked="" type="checkbox"/> High (a3)	<input checked="" type="checkbox"/> Low (a1)
Autonomy - acquisition	<input checked="" type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
Autonomy - night navigation	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
Instrument night processing	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
Active lander	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No

Submit design vector      Cancel

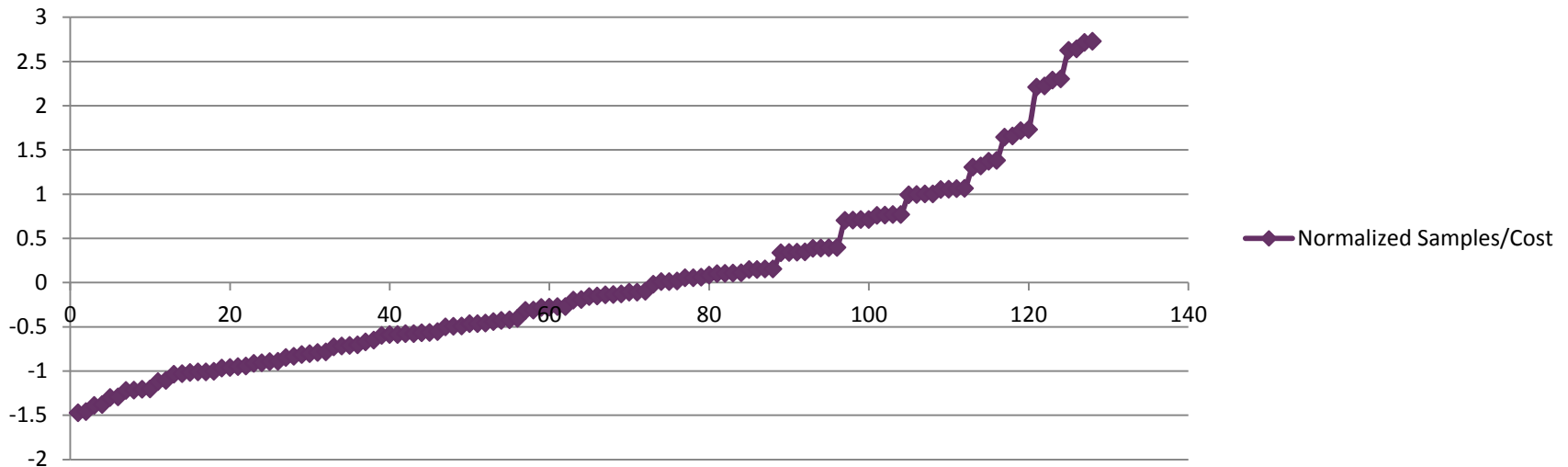
# Highlighted design delivers most samples for lowest cost



### Design Fitness - Unsorted



### Design Fitness - Sorted





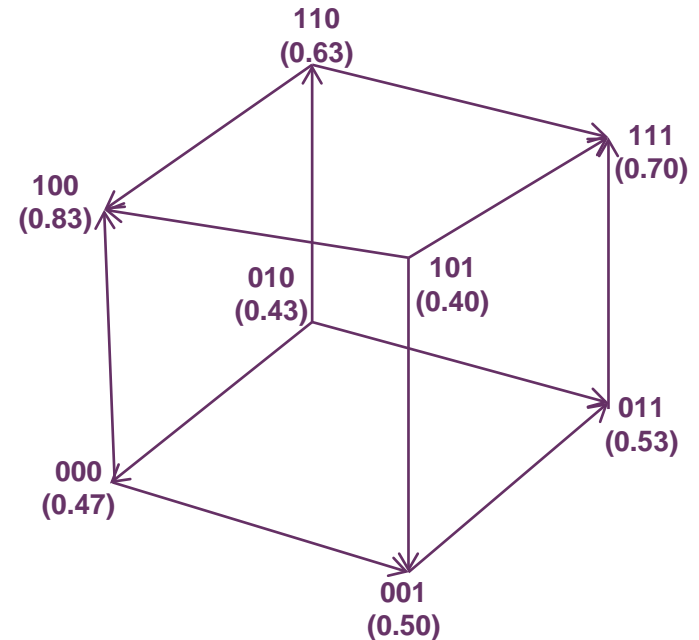
- We need a way to look at the impact of team communication and collaboration on design fitness without relying on a detailed design space model
  - Valid over a range of design problems
  - Before lengthy design and development process to build design models
- Candidate approach is an NK model from 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?

- 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



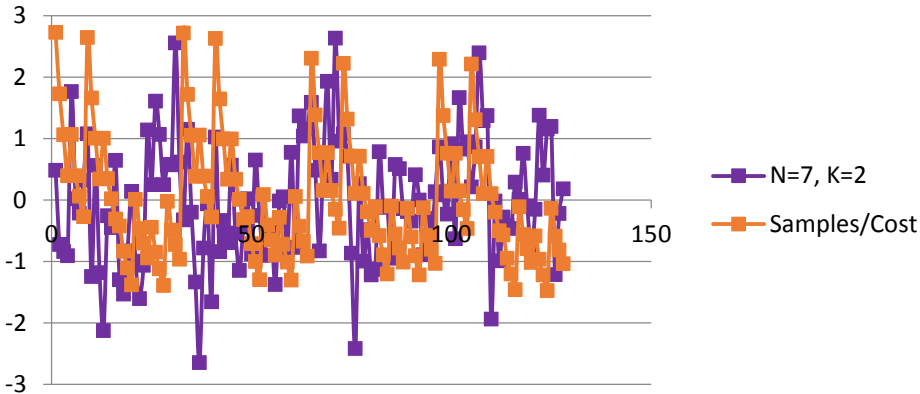
- Contributions to fitness between coupled variables
  - $K$  defines the number of coupled variables influencing the fitness value of  $w_i$
  - $K = 0$  yields a smooth solution fitness landscape with a single peak for the solution with the optimal fitness
    - The contributions of each variable to 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

- 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

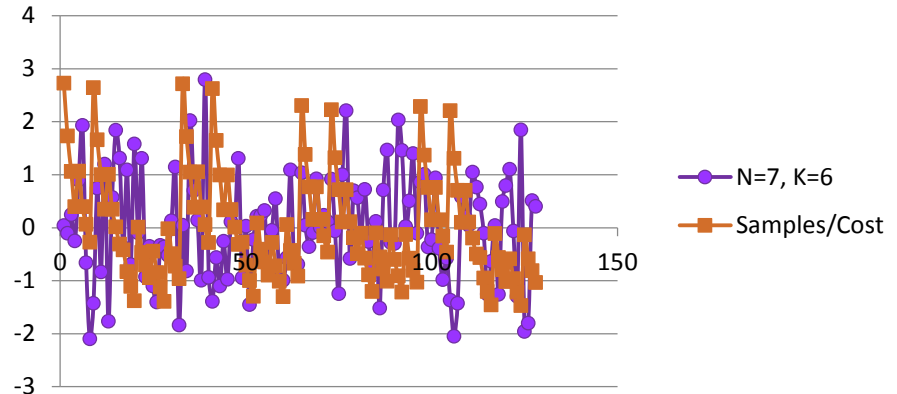
									Design Point N=7, K=0 Fitness	Design Point N=7, K=1 Fitness	Design Point N=7, K=2 Fitness	Design Point N=7, K=4 Fitness	Design Point N=7, K=6 Fitness
Design	N1	N2	N3	N4	N5	N6	N7						
1	0	0	0	0	0	0	0	0.4513	0.7083	0.5510	0.4090	0.4835	
2	0	0	0	0	0	0	1	0.4090	0.6144	0.4194	0.3421	0.4674	
3	0	0	0	0	0	1	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)

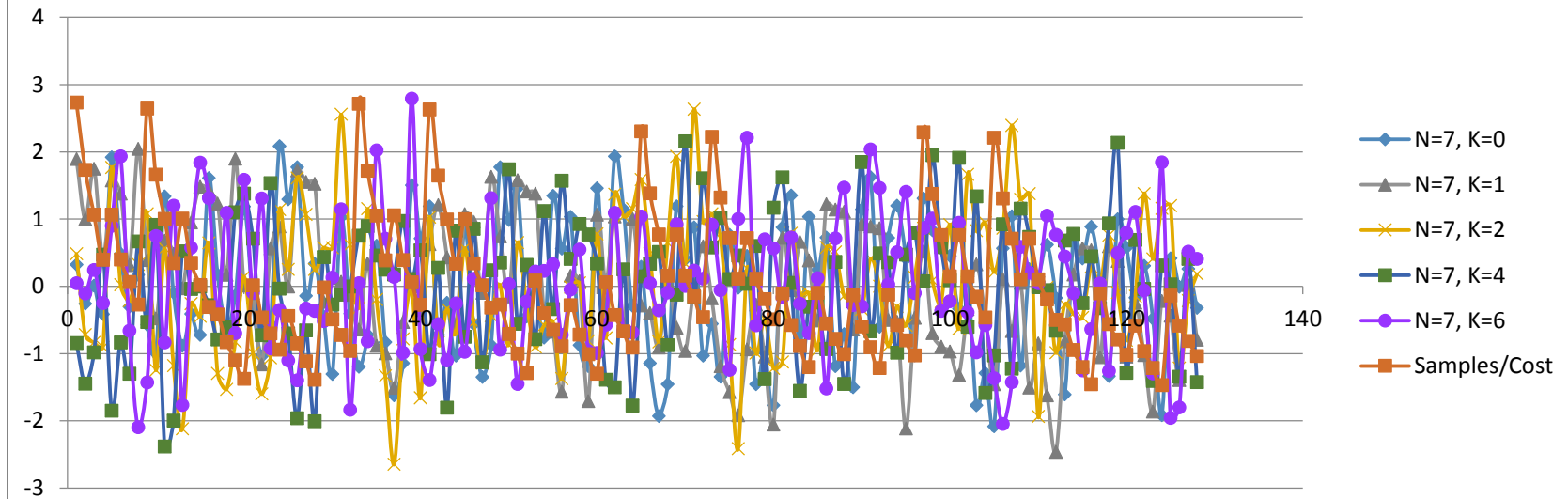
### NK Model - Unsorted



### NK Model - Unsorted

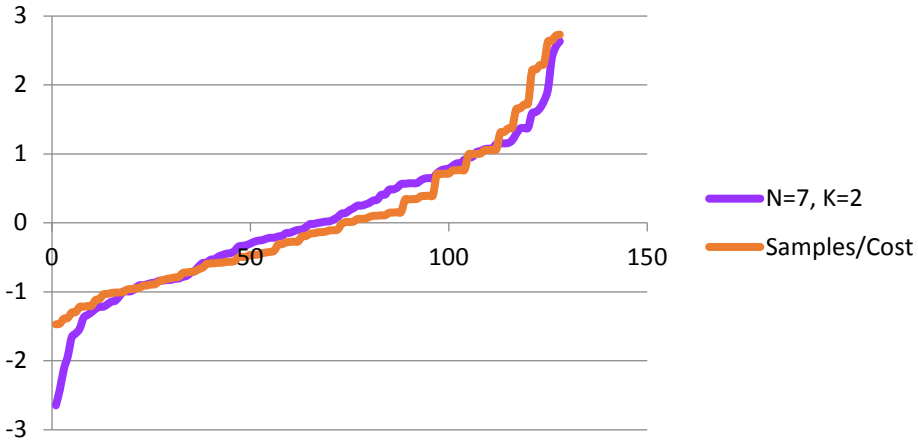


### NK Model - Unsorted

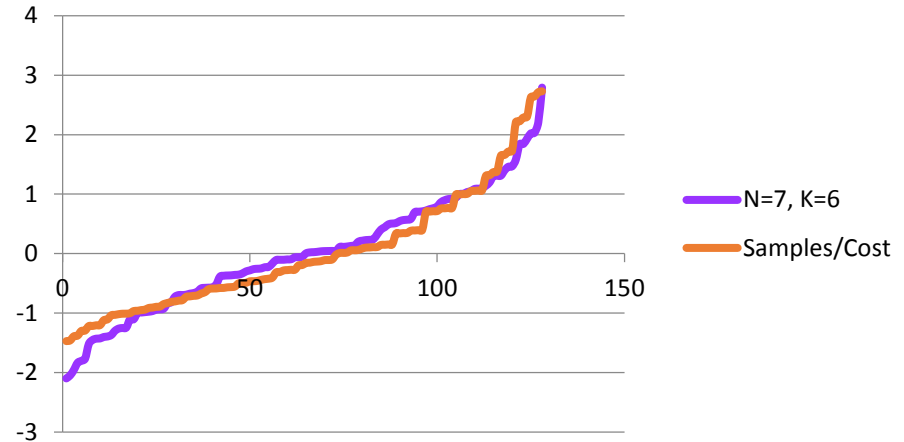


# How well would an NK Model approximate the fitness space (2)

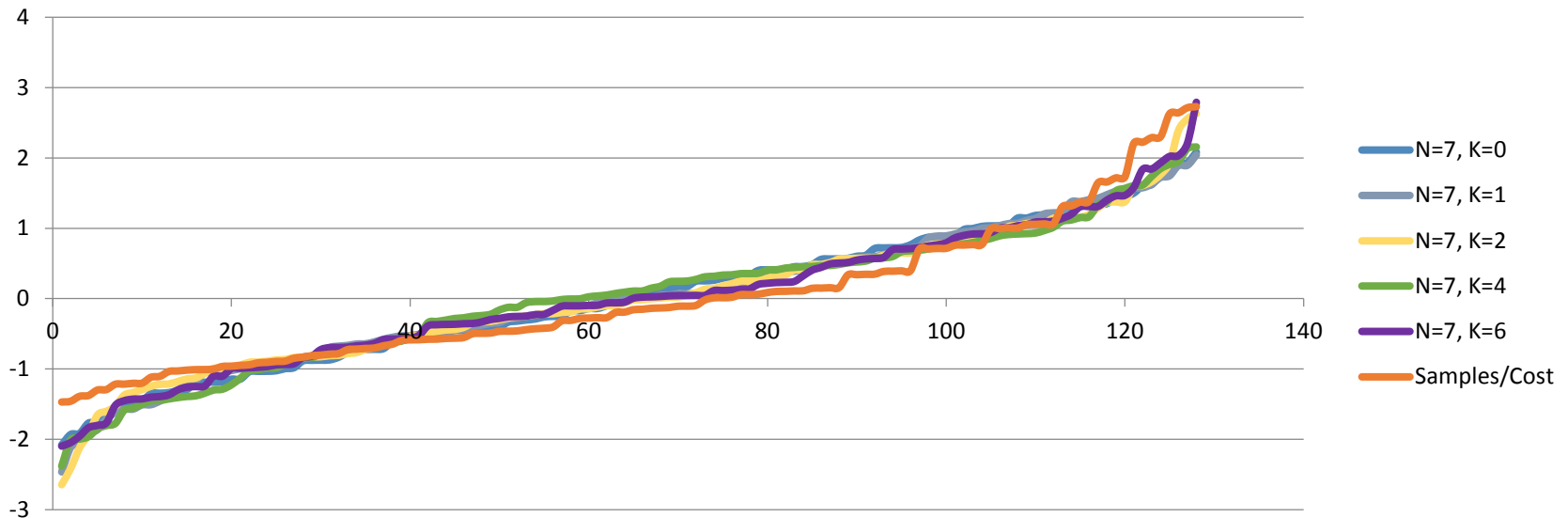
### NK Model - Sorted



### NK Model - Sorted



### NK Model - Sorted



- 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

- 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  $N_s$  and  $A_s$
  - How are non-homogenous problem structures handled
  - Are there indications of the parameter  $K$  in other aspects of linked digital models





Figure 1
— □ ×

**Acquisition tools**

- process equip spad
- process equip small
- magnet
- not available
- 10\_m\_drill
- 1\_m\_drill
- rock\_drill
- mum\_mole
- pluto\_mole
- rat
- not available
- regular\_scoop

**Science instruments**

- microscopic imager high mag
- moessbauer spectrometer
- xrf
- oxidation effects instrument
- stereo panorama camera
- point ir spectrometer
- pancam
- libs
- raman
- mass spectrometer goms
- mass spectrometers goms ld-tof
- pyrolysis oven with amino acid detector
- microscopic color imager
- raman in-situ spectrometer
- moessbauer spectrometer
- alpha particle x-ray spectrometer

**Submit science vector**

**Cancel**

**Navigation instruments**

- IMU
- rear hazcam
- front hazcam
- navcam

**Landing site characteristics**

- Number of samples per instrument, per site.
- [m] Separation distance between sites.
- [m] Average site diameter.
- ratio of traversable obstacle height to wheel diameter.
- [deg] Landing date phase. Vernal equinox = 0 deg.
- [deg] Landing site latitude.
- [%] Rock coverage (terrain ruggedness).

16.89 Mars rover tradespace analysis tool

Status: Data saved. Proceed with [Analyze designs].

Display help text

- 1) Science vector
- 2) Design vector
- 3) Create designs
- 4) Analyze designs

Design:  < >

Selection zoom:

Graphical selection

Plot control

x:  ▾

y:  ▾

z:  ▾

Plot [x,y]  
 Plot [x,y,z]  
 Plot rover  
 Disable plot

Show grid  
 Show solar ar...

Az:  ▾ ▹

El:  ▾ ▹

Export to figure

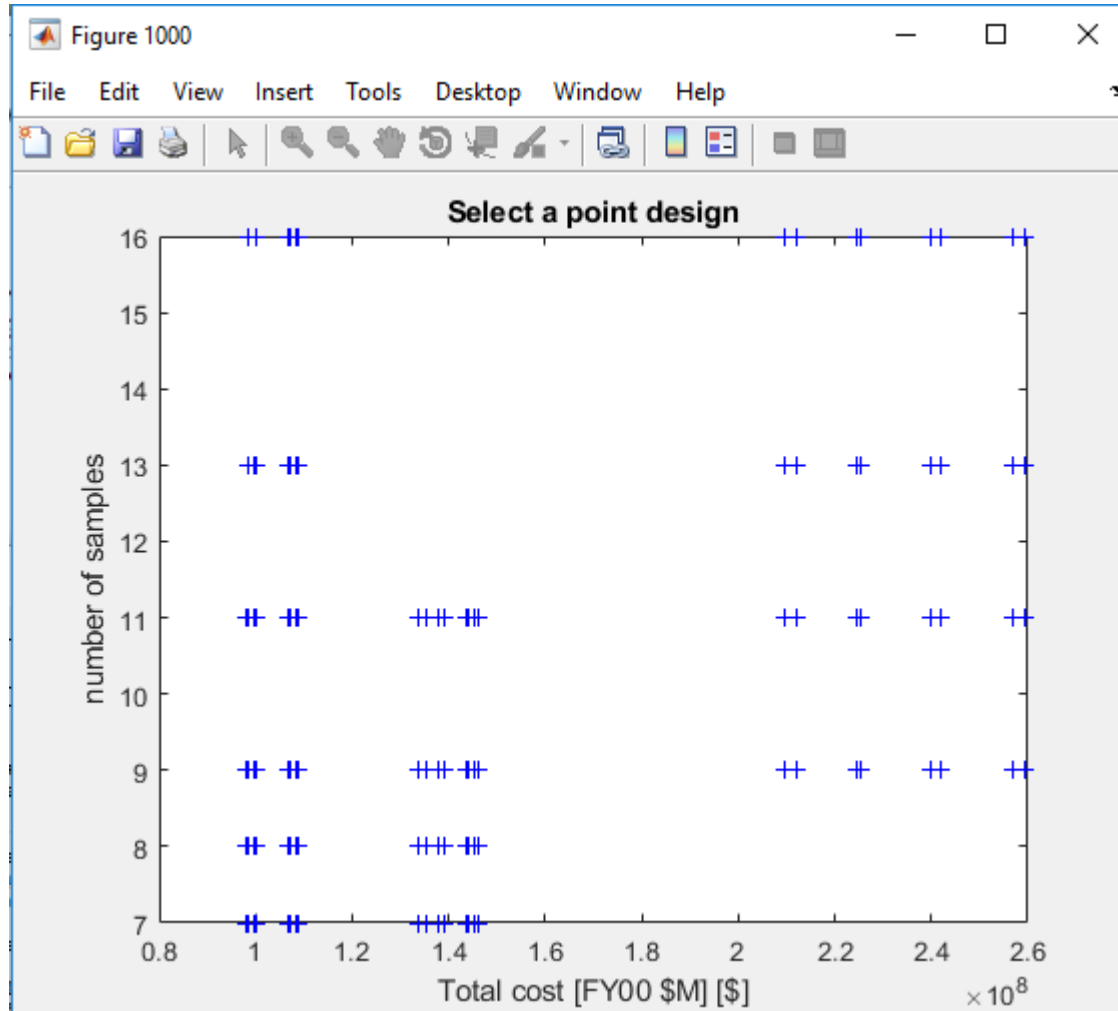
Design vector:

Subsystem Properties:

- Acquisition
- Autonomy
- Communications
- Environment
- Instruments
- Power
- Rover
- Utility, etc.

Index:

Calculation took 4.5115 seconds. Data for 128 designs (of 128 attempted) saved to ROVERS structure and to rover\_designs.mat. Discarded designs: Autonomy=0, Power=0, Rover=0, Power/Rover loop=0. Proceed with [Analyze designs].



16.89 Mars rover tradespace analysis tool

1)

2)

3)

4)

**Status:** Displaying design number 1 properties: UTILITY.

**Design vector:**

```
lifetime : 100
wheeldiameter : 0.25
number_computers : 1
power_system : sol
telecom : dte
autonomy_l_d : a3
autonomy_s_d : a3
autonomy_acq : y
autonomy_night_navigation : n
instrument_night_proc : n
lander : n
```

**Subsystem Properties:**

- Acquisition
- Autonomy
- Communications
- Environment
- Instruments
- Power
- Rover
- Utility, etc.

**Index:**

**SUMMARY :**

```
long_distance_path : 73.6901
mass_total : 120.665
size_total : [1.175 1.075 1.2585]
speed_average : 0.0142395
speed_max : 0.047612
total_data_obtained : 11.072
total_samples_analyzed : 16
```

**COST :**

```
operations : 3.30602e+07
payload : 5.11e+07
power : 813848
rover : 6.522e+07
total : 9.82802e+07
total_margin : 1.27764e+08
```

**COMPLEXITY :**

```
autonomy_acq : 4
l_d_nav : 4
lifetime : 2
power : 3
s_d_nav : 4
telecom : 1
total : 3
```

Loaded 128 designs.

Design:

Selection zoom:

**Plot control**

X:  ▼

Y:  ▼

Z:  ▼

Plot [x,y]  
 Plot [x,y,z]  
 Plot rover  
 Disable plot

Show grid

Show solar ar...

Az:

Et:

