Trade Space Exploration Using Visual Steering and Multi-Dimensional Data Visualization*

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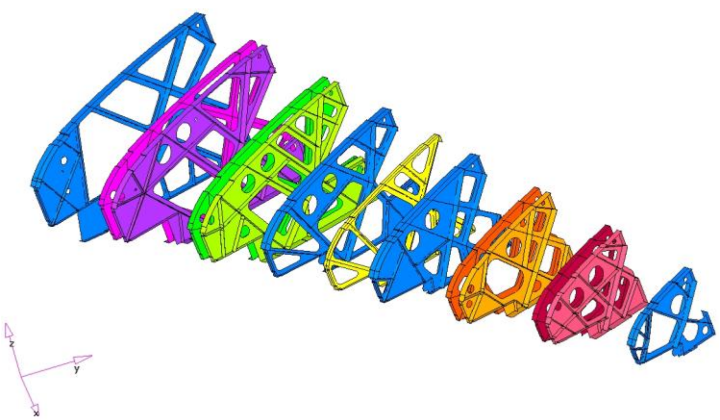
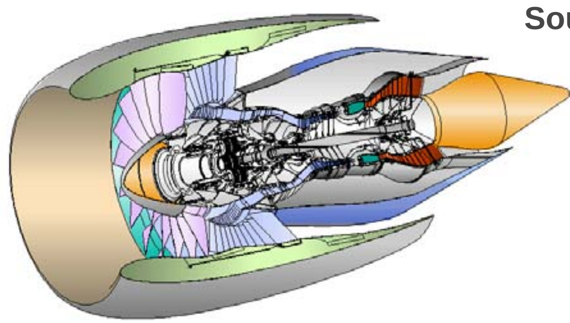
Modeling, Analysis, Simulation, and Computation

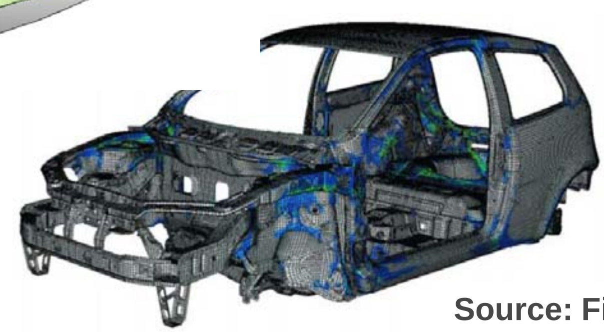
- Recent advances in computing power and speed allow designers to simulate and evaluate thousands, if not millions, of design alternatives more cheaply and quickly than ever before
- These advancements provide new opportunities to revolutionize trade space exploration for the design of complex systems



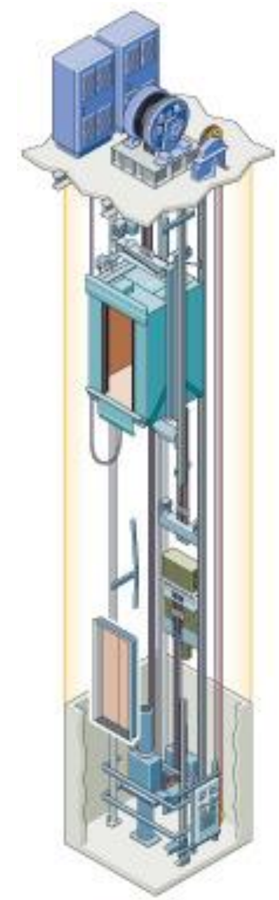
Source: Altair Engineering



Source: Trevor Bailey



Source: Fiat



Source: www.otis.com

Which is the best design?

A	B	C	D	E	F	G	H	I	J	K	Mass	ConVio	Obj1	Obj2	Obj3	Obj4	Obj5
0.624649	0.754049	0.876689	0.343205	0.212124	0.933273	0.57122	3	0.696767	0.520956	0.061564	1.065553	85.3757	1.062015	0.988355	0.975157	0.949053	1.015516
0.060985	0.157698	0.100316	0.147226	0.723355	0.954276	0.18665	5	0.147579	0.594634	0.546073	0.869276	280.5069	0.821385	1.062017	0.984424	1.02363	0.845335
0.79029	0.753857	0.374672	0.23151	0.568749	0.966105	0.926726	5	0.861844	0.206967	0.152046	1.087959	162.1251	1.025622	1.009793	0.935661	0.962082	0.950406
0.386879	0.088587	0.001015	0.89747	0.369036	0.575776	0.907945	1	0.425441	0.129497	0.930208	0.897125	0	1.27605	1.128511	0.925916	1.095028	0.727479
0.00745	0.664116	0.161524	0.613925	0.45661	0.734871	0.954844	6	0.944188	0.415194	0.177407	0.861764	418.1174	0.605767	0.90523	0.961853	0.973201	0.965639
0.995651	0.743935	0.320403	0.090145	0.48886	0.393002	0.876449	4	0.828249	0.673172	0.795096	1.183174	297.2661	0.918957	0.864233	0.994303	1.079725	1.043906
0.328119	0.856472	0.01425	0.842507	0.451588	0.130799	0.974695	1	0.758214	0.163655	0.641987	0.858018	0	1.210881	1.153077	0.930213	1.064094	0.973342
0.435725	0.714144	0.590085	0.488513	0.195516	0.353903	0.095564	6	0.800199	0.121332	0.74331	0.980696	84.54371	0.69339	0.882991	0.924889	1.072899	0.920315
0.140543	0.619531	0.286546	0.547551	0.700957	0.820492	0.122013	3	0.54486	0.027115	0.396837	0.81166	75.67446	0.798757	1.070938	0.913038	1.004613	0.871374
0.053287	0.967234	0.027151	0.285497	0.11165	0.493894	0.312822	2	0.834215	0.607056	0.965347	0.856679	190.3453	0.994475	1.086928	0.985987	1.103027	1.099647
0.016589	0.081024	0.077573	0.970116	0.236366	0.197258	0.299823	4	0.897914	0.996856	0.145421	0.899552	314.8964	0.689412	0.930108	1.035018	0.984929	0.904823
0.339073	0.804103	0.194134	0.595187	0.893329	0.173013	0.599763	3	0.682347	0.211061	0.433533	0.936625	0	0.92971	1.026089	0.936176	1.030417	0.966879
0.807105	0.355682	0.698499	0.347406	0.147357	0.833227	0.239664	5	0.180274	0.339442	0.126236	1.107651	142.5201	1.046443	1.001878	0.952325	0.962201	0.854032
0.461698	0.808808	0.448971	0.555792	0.308602	0.078053	0.713475	1	0.804761	0.911746	0.592818	1.005789	0	1.455601	1.070847	1.024313	1.058098	1.113506
0.893653	0.178552	0.302888	0.772328	0.540938	0.210228	0.633615	2	0.242687	0.707757	0.370249	1.158954	197.4329	1.352289	0.997158	0.998654	1.019435	0.875256
0.593384	0.607663	0.564	0.670026	0.432504	0.034409	0.42949	1	0.765861	0.284269	0.456763	0.990321	25.37839	1.406297	1.099572	0.945385	1.038328	0.920959
0.011539	0.850963	0.099594	0.619666	0.527305	0.132944	0.404533	4	0.163654	5.26E-04	0.410111	0.78425	153.0766	0.593367	0.965405	0.909694	1.028025	0.937833
0.917945	0.354331	0.360415	0.949183	0.654889	0.883763	0.858601	1	0.113017	0.578143	0.005751	1.111352	342.9728	1.58323	1.057398	0.98235	0.941924	0.903065
0.629985	0.367476	0.030701	0.823217	0.751167	0.709767	0.134882	2	0.418778	0.074323	0.700772	1.010063	76.0458	1.163879	1.05292	0.918976	1.055243	0.802774
0.052335	0.607279	0.051817	0.635463	0.083765	0.384859	0.553443	3	0.246573	0.031671	0.894493	0.793414	128.5993	0.786491	1.064864	0.913611	1.095411	0.868508
0.26956	0.542476	0.324995	0.205405	0.925943	0.712346	0.350751	1	0.603615	0.889306	0.925155	0.930262	33.28389	1.350634	1.090706	1.02149	1.090002	1.026037
0.113861	0.023778	0.544848	0.464351	0.032314	0.264167	0.608364	2	0.312497	0.737143	0.487076	0.884893	155.3781	1.022127	1.085544	1.00235	1.0359	0.833215
0.790459	0.561394	0.075355	0.0309	0.604376	0.881564	0.38648	2	0.126824	0.425601	0.840445	1.102166	155.5182	1.286927	1.01118	0.963162	1.071595	0.935852
0.925059	0.529395	0.398783	0.664759	0.711469	0.374232	0.432993	1	0.835886	0.999606	0.914148	1.164511	175.0352	1.718627	1.002366	1.035364	1.098793	1.044821
0.492116	0.483754	0.11385	0.268324	0.139095	0.327651	0.775126	6	0.621833	0.201755	0.208674	1.00229	58.42594	0.706126	0.884241	0.935005	0.990701	0.865333
0.714184	0.664542	0.11446	0.017024	0.642118	0.80771	0.881159	1	0.732738	0.829098	0.932108	1.097304	48.51039	1.606783	1.02979	1.013917	1.088121	1.051521
0.118918	0.017629	0.924812	0.061686	0.046908	0.643381	0.633561	4	0.393291	0.268319	0.75947	0.838012	88.64945	0.640139	0.944516	0.943378	1.066418	0.734174
0.255594	0.214463	0.598632	0.714721	0.033801	0.594344	0.049352	1	0.324555	0.549029	0.104542	0.887475	52.14604	1.250313	1.145112	0.978688	0.966251	0.853539
0.007185	0.837426	0.285541	0.180206	0.001931	0.242974	0.695136	3	0.981152	0.061027	0.13798	0.787168	176.7205	0.771164	1.084224	0.917304	0.982354	0.946158
0.193436	0.59333	0.575079	0.123012	0.805085	0.819283	0.574159	2	0.184029	0.347939	0.975802	0.857098	43.93821	0.990329	1.09325	0.953393	1.094545	0.929693
0.928198	0.389419	0.115175	0.613135	0.762898	0.396141	0.017512	4	0.304104	0.677509	0.91514	1.168977	234.6986	0.909056	0.865166	0.994849	1.098267	0.934562
0.222651	0.467807	0.951467	0.56811	0.520733	0.053605	0.928277	3	0.88145	0.383813	0.740516	0.901219	26.40954	0.90048	1.025809	0.957906	1.08179	0.898092
0.811201	0.133245	0.378015	0.68068	0.872205	0.49669	0.520425	5	0.0733	0.350462	0.452241	1.109873	81.78877	1.053422	0.994934	0.953711	1.023271	0.787145
0.423361	0.642631	0.712732	0.891548	0.734774	0.993534	0.88727	1	0.784954	0.059616	0.47451	0.896664	13.57533	1.260446	1.145038	0.917126	1.011299	0.885291
0.632001	0.461677	0.108156	0.912385	0.016923	0.345369	0.191936	4	0.336829	0.668814	0.53677	1.08797	0	0.83955	0.888839	0.993755	1.041094	0.955231
0.873147	0.508414	0.360317	0.405932	0.222425	0.053973	0.93098	4	0.314139	0.515362	0.294384	1.137171	214.504	0.874249	0.884942	0.974453	1.012508	0.937973
0.885007	0.781797	0.714749	0.35023	0.385047	0.487096	0.690444	4	0.458081	0.539834	0.562325	1.142733	220.8034	0.882082	0.87889	0.977531	1.040661	1.028056
0.036627	0.355758	0.005696	0.757361	0.319842	0.561181	0.406254	2	0.751786	0.880089	0.388129	0.8844	257.4996	1.022278	1.084719	1.020331	1.011313	0.966064
0.621134	0.26736	0.115896	0.698524	0.324068	0.943496	0.557317	2	0.1309	0.522604	0.896984	1.0619	0	1.241092	1.020734	0.975364	1.07845	0.864514
0.493668	0.564122	0.60814	0.117899	0.772721	0.605714	0.547454	4	0.819652	0.090314	0.471688	0.958514	30.04471	0.730484	0.927495	0.920988	1.022904	0.867237
0.273529	0.548112	0.988656	0.882654	0.25439	0.246603	0.397196	5	0.288987	0.436134	0.337391	0.927578	95.88232	0.874011	1.051251	0.964487	1.013204	0.933903
0.149734	0.317481	0.19274	0.388216	0.898963	0.313182	0.953739	5	0.388612	0.048113	0.646596	0.82531	170.1594	0.773724	1.085413	0.915679	1.059146	0.781797
0.653178	0.273579	0.629722	0.666803	0.995326	0.352516	0.104895	4	0.263001	0.49329	0.815411	1.071509	17.21235	0.827531	0.890659	0.971677	1.084137	0.860374
0.472799	0.156696	0.041151	0.345065	0.351738	0.483427	0.93028	6	0.766748	0.388929	0.282111	1.020344	56.32071	0.72098	0.878103	0.958549	0.997266	0.802407
0.907584	0.818911	0.940492	0.757801	0.051914	0.137225	0.701082	5	0.757653	0.958448	0.353178	1.205011	44.55034	1.155917	0.958121	1.030187	1.019052	1.126324
0.861104	0.686593	0.484355	0.998615	0.749554	0.084413	0.891419	1	0.204854	0.612706	0.701557	1.103201	185.3407	1.598347	1.040067	0.986697	1.074784	1.013548
0.160185	0.382135	0.774365	0.092991	0.177952	0.221956	0.016188	3	0.723065	0.144779	0.924658	0.829475	63.8893	0.825459	1.04983	0.927839	1.105154	0.821929
0.031606	0.779571	0.563722	0.351247	0.772206	0.162459	0.396974	4	0.866714	0.130713	0.28886	0.803458	141.0366	0.608358	0.961513	0.926069	1.008282	0.942604
0.04231	0.856992	0.241613	0.63364	0.712683	0.199528	0.611167	1	0.740617	0.473581	0.957145	0.801906	41.5925	1.144678	1.156734	0.969197	1.110894	1.037713

Philosophical Underpinnings of Our Work

- The assumption that we can capture a decision-maker's preferences *a priori* is wrong
  - ❑ Designers, like people, want to "shop" to gain intuition about trades, what is feasible and what is not, and to learn about their alternatives first
- We need new paradigm(s) for trade space exploration
  - ❑ "Design by Shopping," coined in 1998 by Rick Balling (BYU), enables an *a posteriori* articulation of preferences:
    - Allow decision-makers to view a *variety* of feasible designs
    - Form a preference *after* viewing the trade space
    - Choose an optimal design based on this preference

Our Approach to Trade Space Exploration

Build Models

- Assemble models based on design rules and analyses specific to the system being designed
- Model set up to run in batch mode to generate design alternatives

Run Experiments

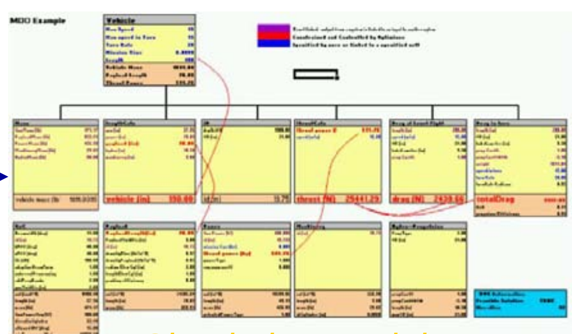
- Focus on trade study of interest
- 3000-4000 designs
- Augment design with geometry and more

Explore/Visualize

- Look for known trends
- Apply constraints
- Visualize preference structures and Pareto frontiers; optimize
- Identify best design(s)

Explore

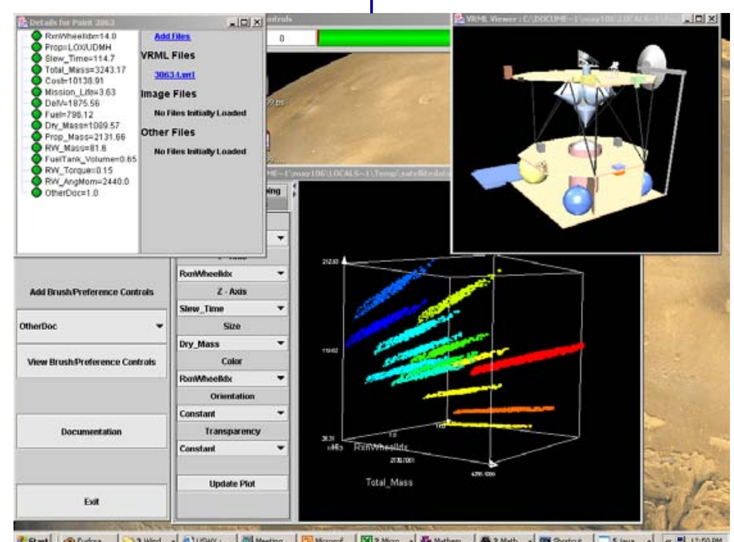
Sample Points in the Input Space



Simulation Model

Record Output and Performance Variables

Design Database



Repeat 1000+ times

Iterate until feasible design is calculated

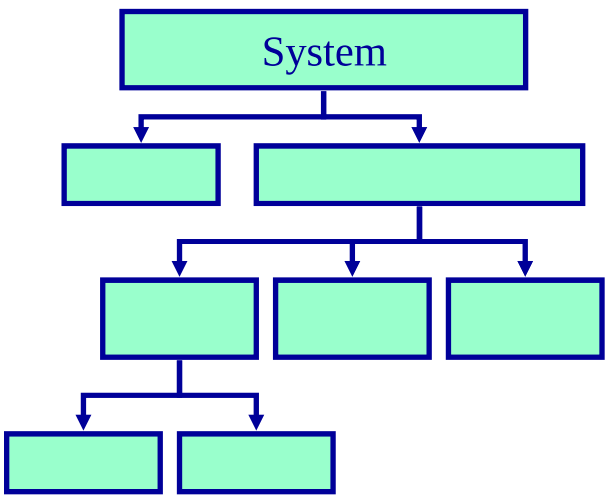
Visualize

Building the Model

Source:
(J. Merenich, 2007)

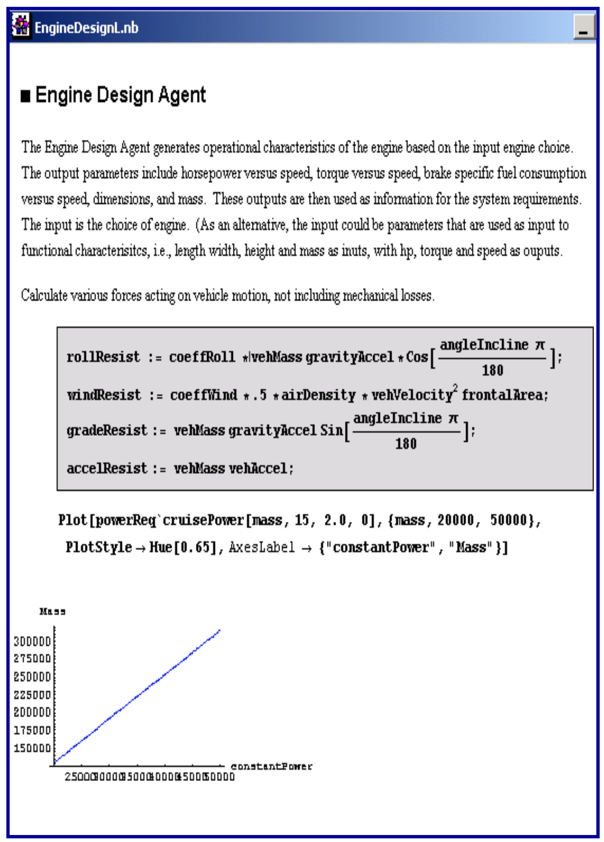
System Decomposition

- Define subsystems and their interfaces
- Identify critical independent and dependent design parameters
- Physical and functional



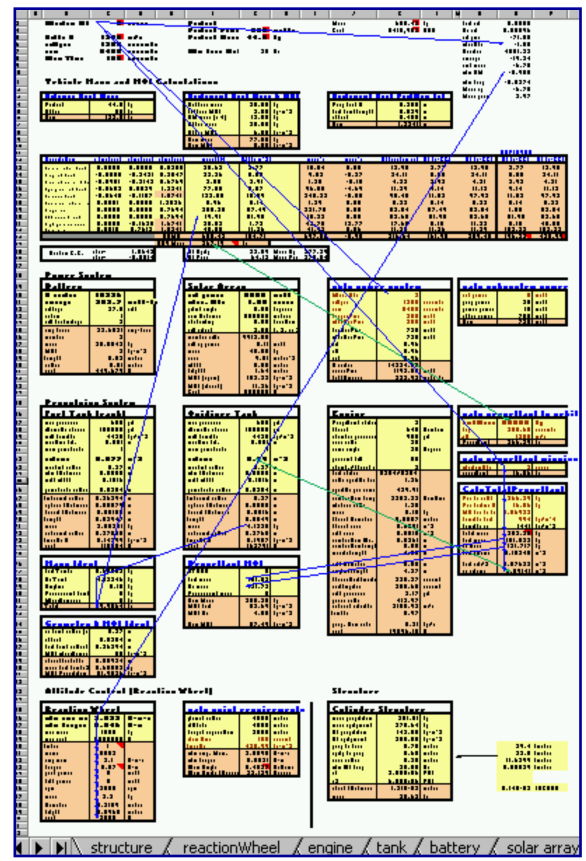
Rule Capture

- Subsystems and their disciplines
- System level rules to integrate subsystems
- Mathematica, Matlab, Excel, etc.



System Models

- Compose model to evaluate a single design configuration at a time
- Generate hundreds or thousands of designs in minutes to hours



Rule Capture

Source:
(J. Merenich, 2007)

- Physics-based rules
- Analytic equations
- First principles
- Simulation models
  - Discrete event
  - System dynamics
- Empirical data
  - Regression models
  - Parametric models
- Design “lookup” tables
  - Determine required motor size and weight given power requirements and technology options using a database of existing motors each with specific features

Rules/models can be at different levels of fidelity, adding fidelity as more info/data becomes available

Rules/models must capture the trades of interest

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Explore

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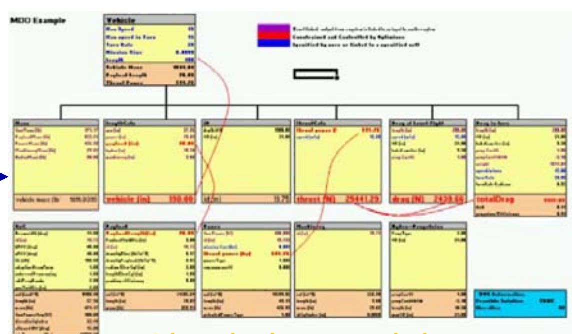

Simulation Model

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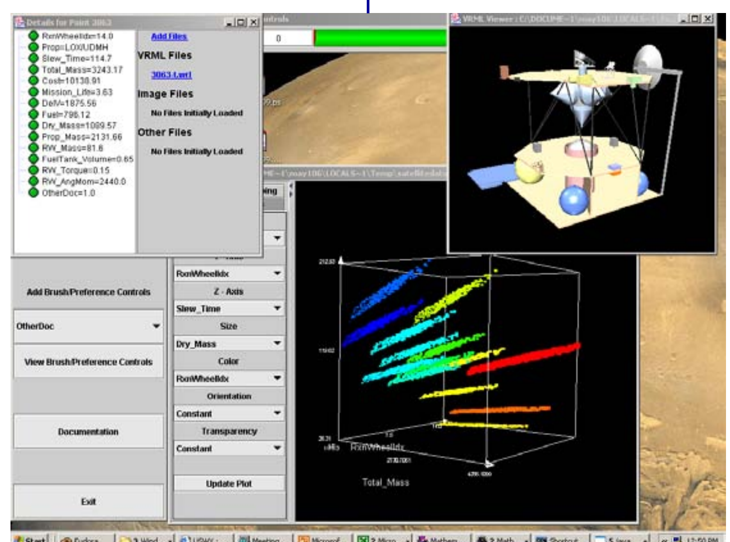


Repeat 1000+ times

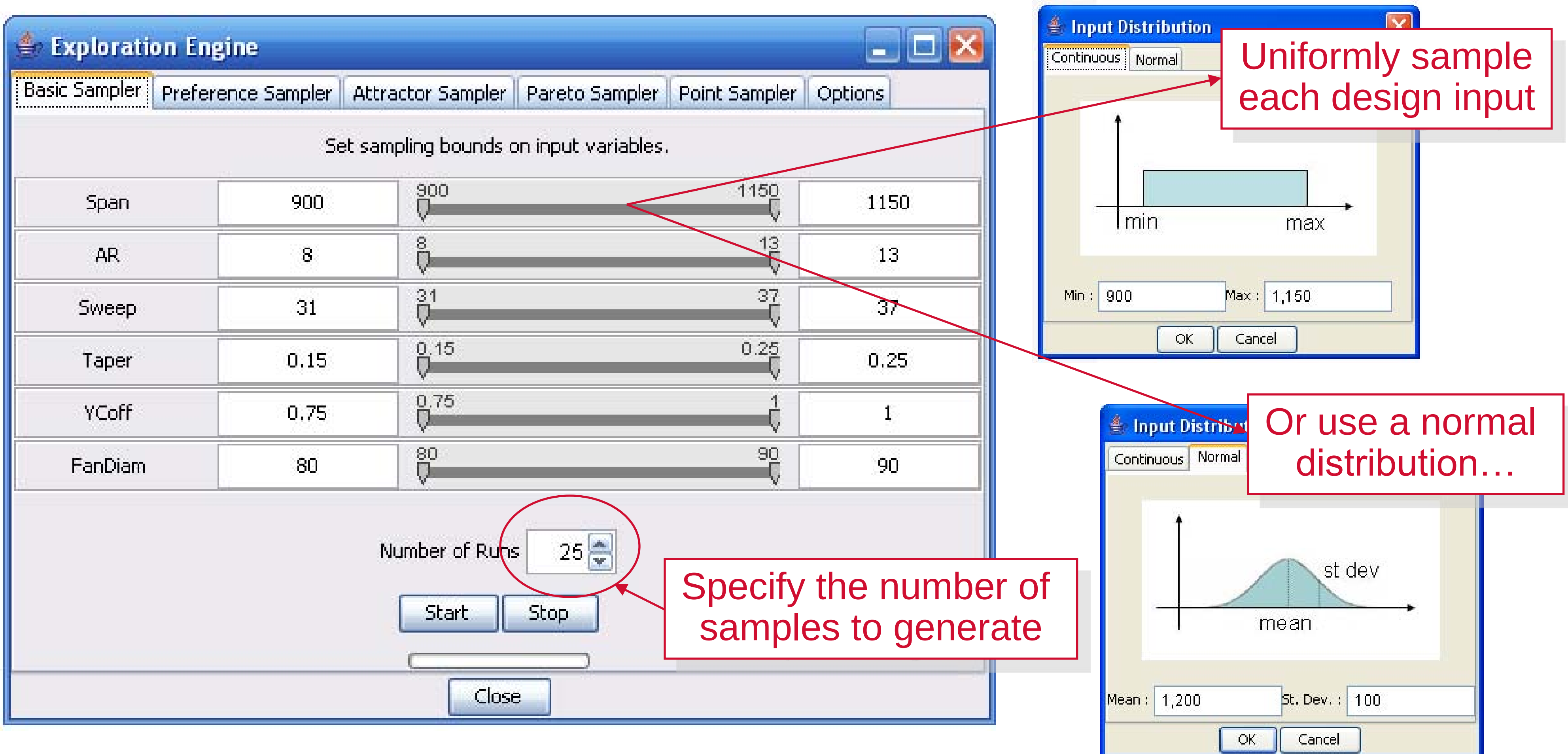
Iterate until feasible design is calculated

Design Database

Visualize

Generating Data

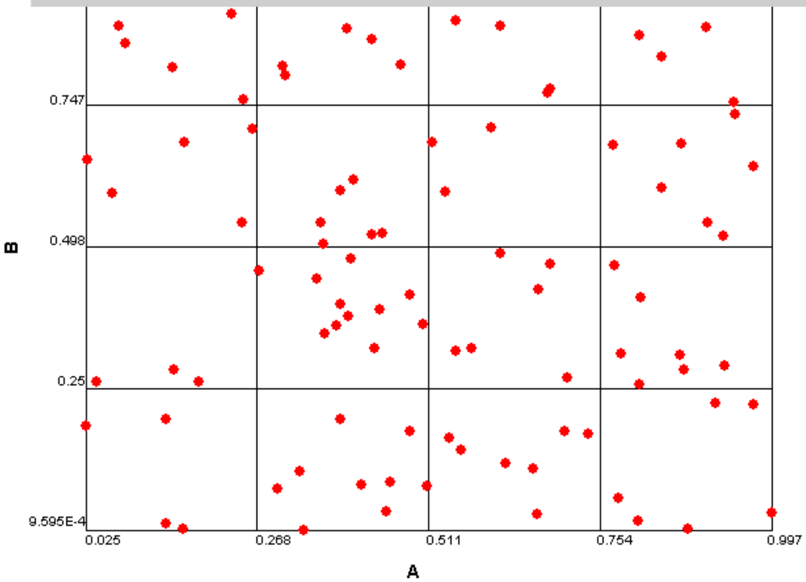
- Once rules/model can be executed in "batch" mode:
  - Define initial region of interest, i.e., bounds of input space
  - Use Design of Experiments (DoE) or Monte Carlo simulation to generate hundreds or thousands of design alternatives



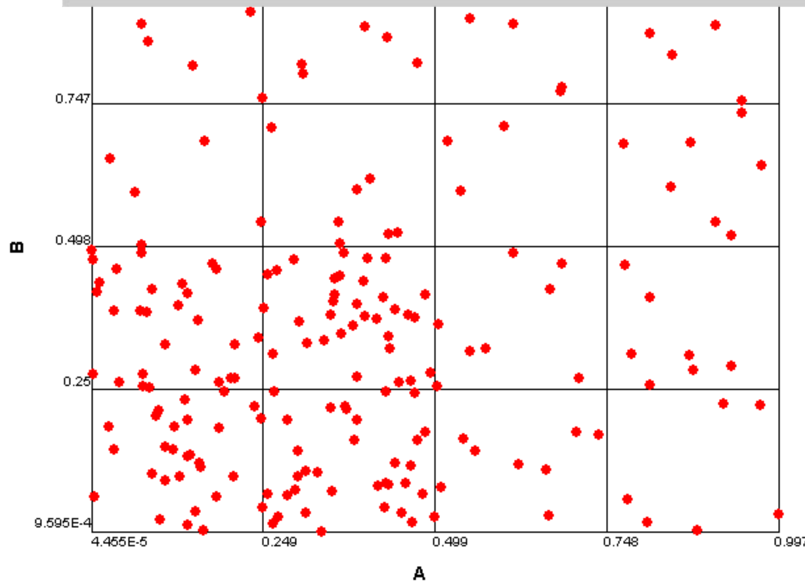
Basic Sampler

- Basic sampler randomly samples the design variables (inputs), *X*, using Monte Carlo simulation
  - ❑ Sampling range on any input variable can be reduced by brushing to "zoom in" on regions of interest

100 Random Samples in A,B ∈ [0,1]

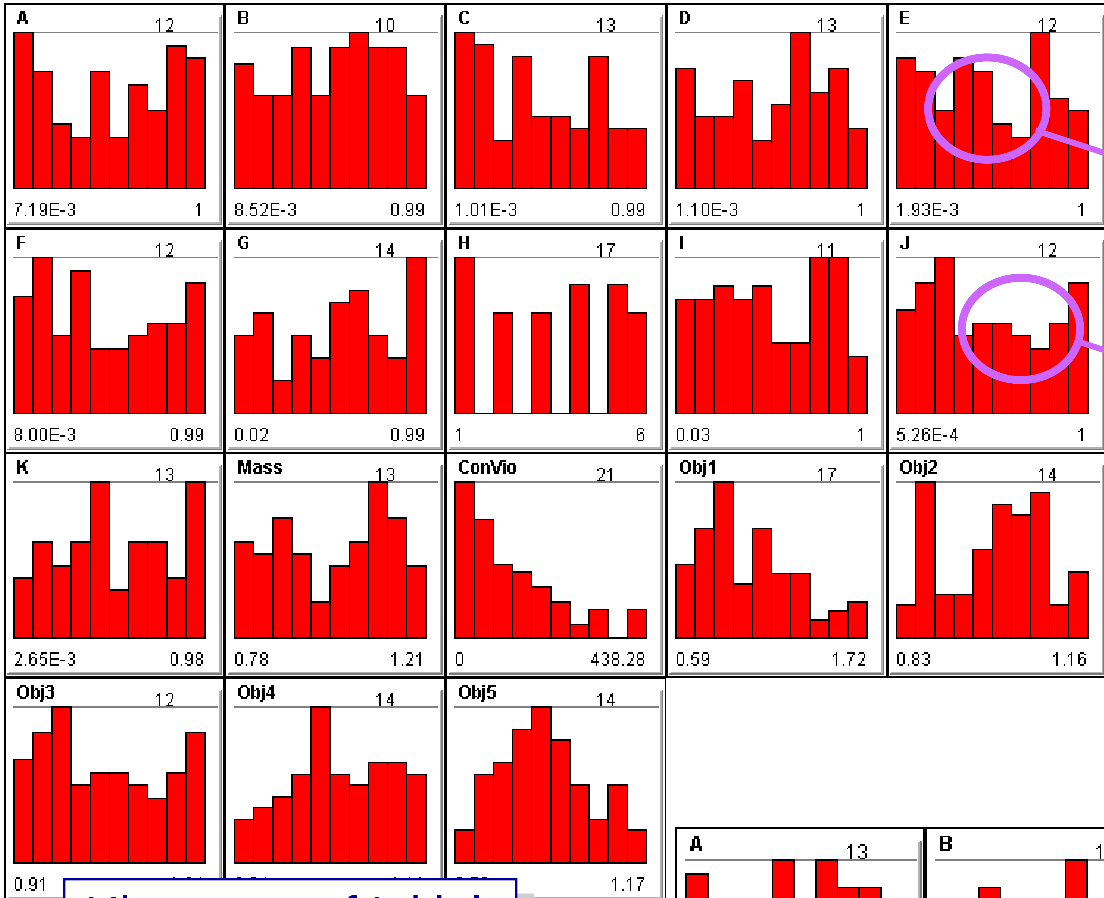


100 New Samples in A,B ∈ [0,0.5]

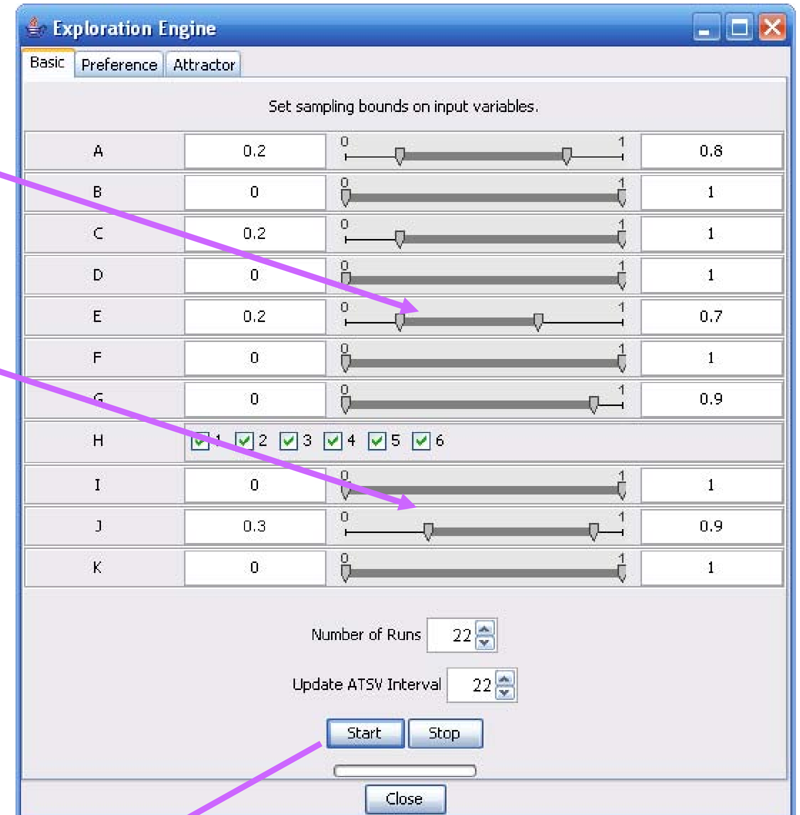


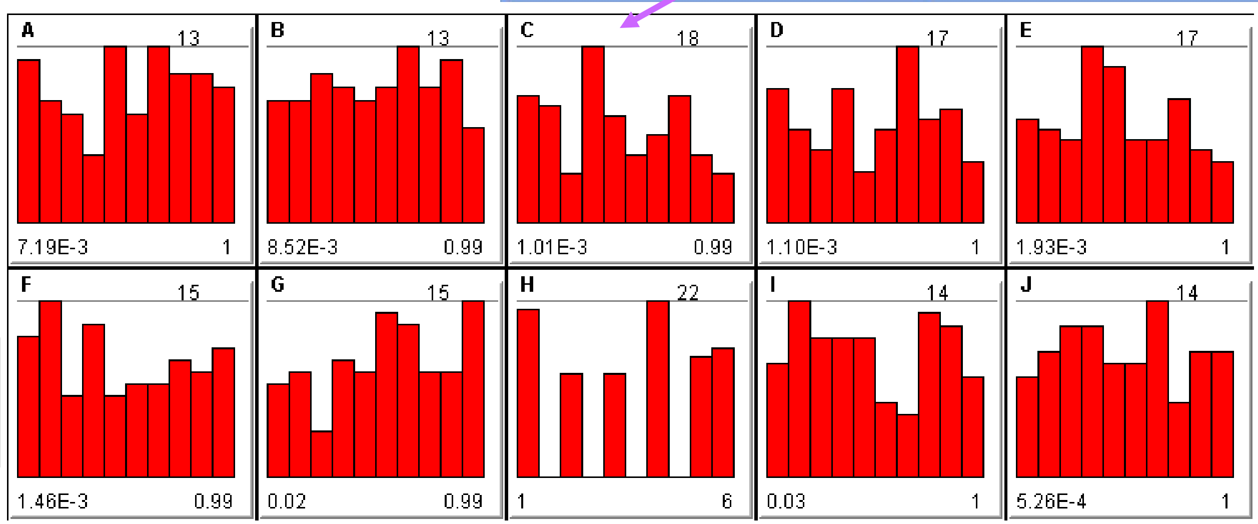
- ❑ Random sampling is more advantageous to trade space exploration since any structure occurring in the data is natural, and not induced by the sampling process (e.g., a grid)

Example of Basic Sampler



Histogram of Initial
78 Configurations





Updated Histograms
(22 additional points)

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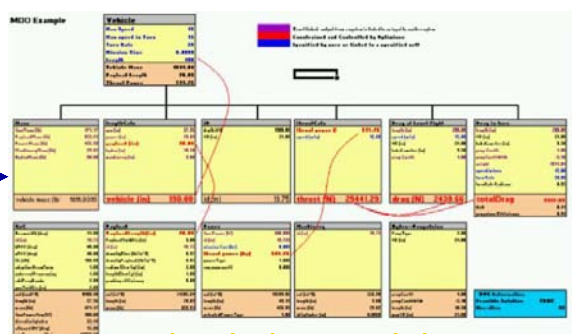

Simulation Model

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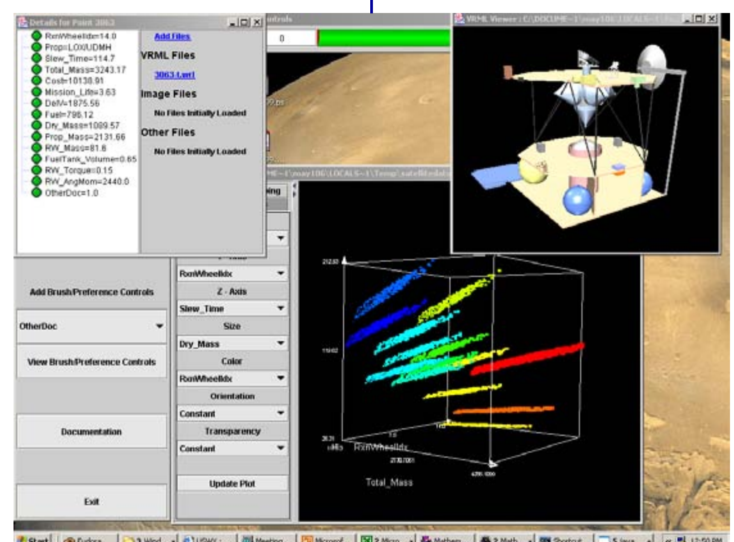


Visualize

Visualizing Multi-Dimensional Data

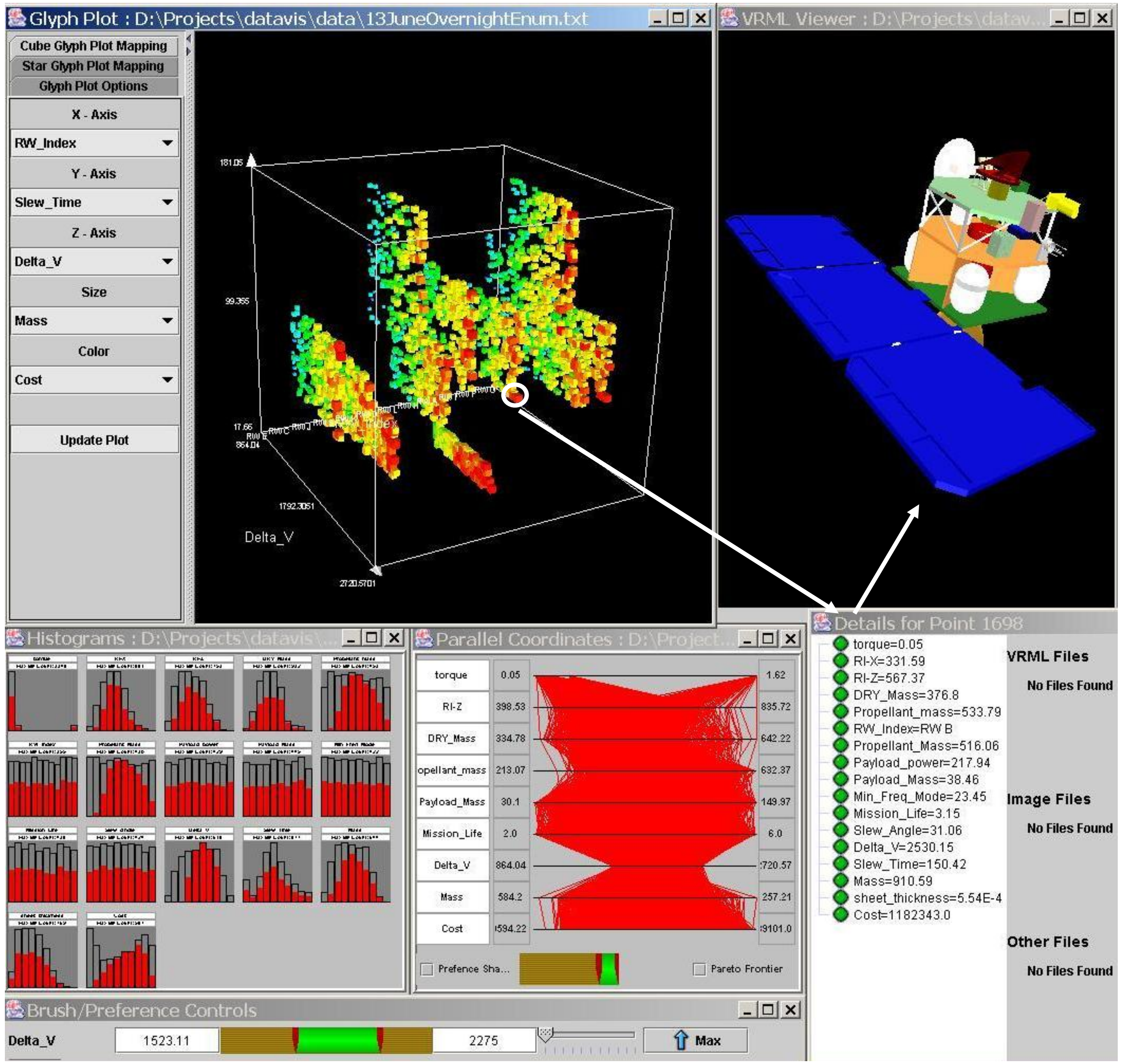
Multi-dimensional data visualization:

- Glyph plots
- Histogram plots
- Parallel coordinates
- Scatter matrices
- Brushing
- Linked views

Display multiple plots simultaneously

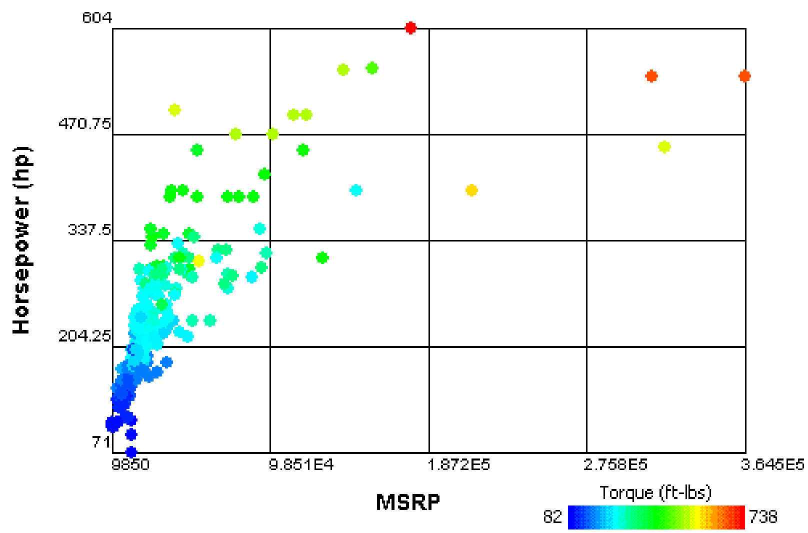
Interrogate specific design points

Interactively apply preferences and constraints

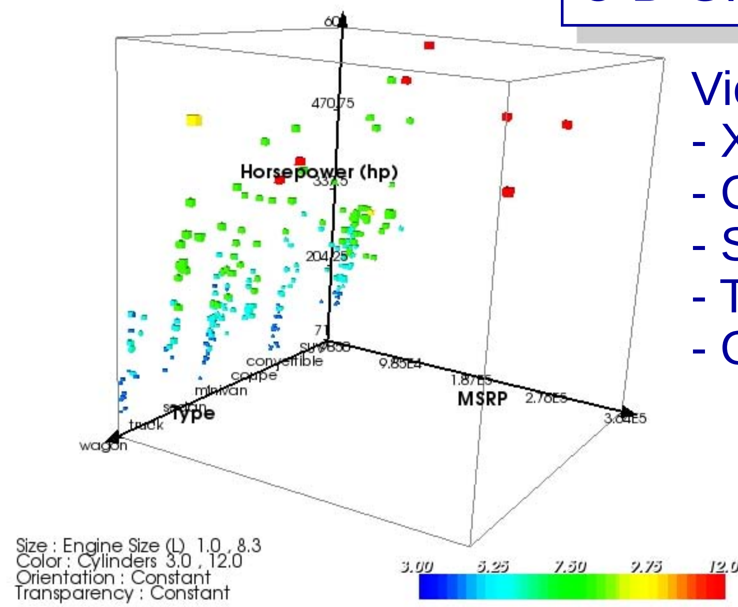


Examples of Multi-Dimensional Visualization

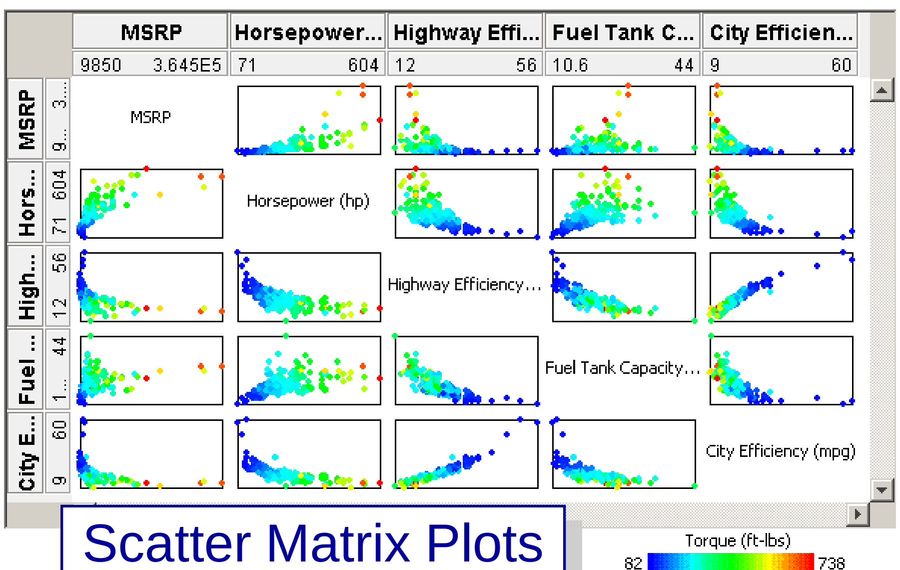
2-D Scatter Plots



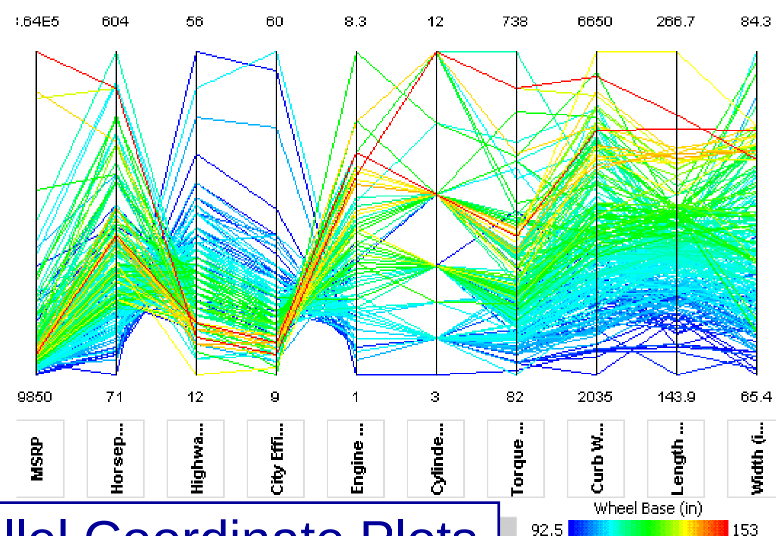
3-D Glyph Plots



View up to 7D:
- X, Y, Z axes
- Color
- Size
- Transparency
- Orientation



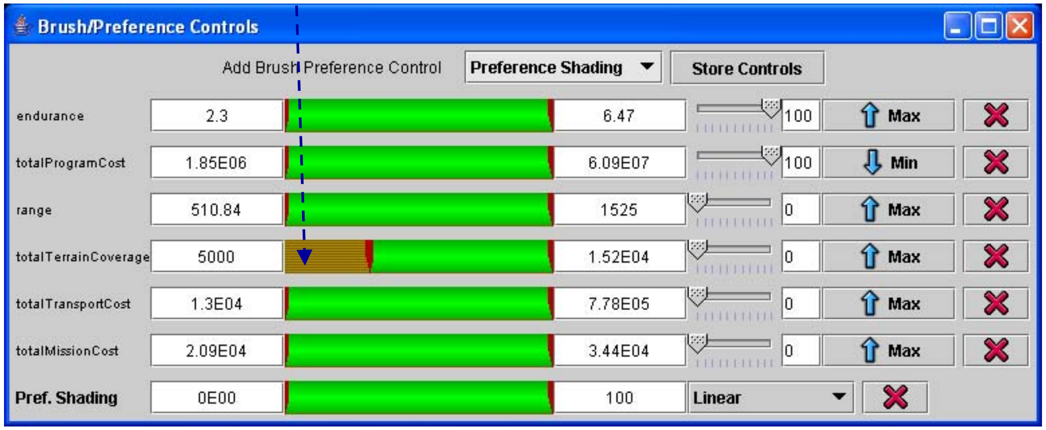
Scatter Matrix Plots

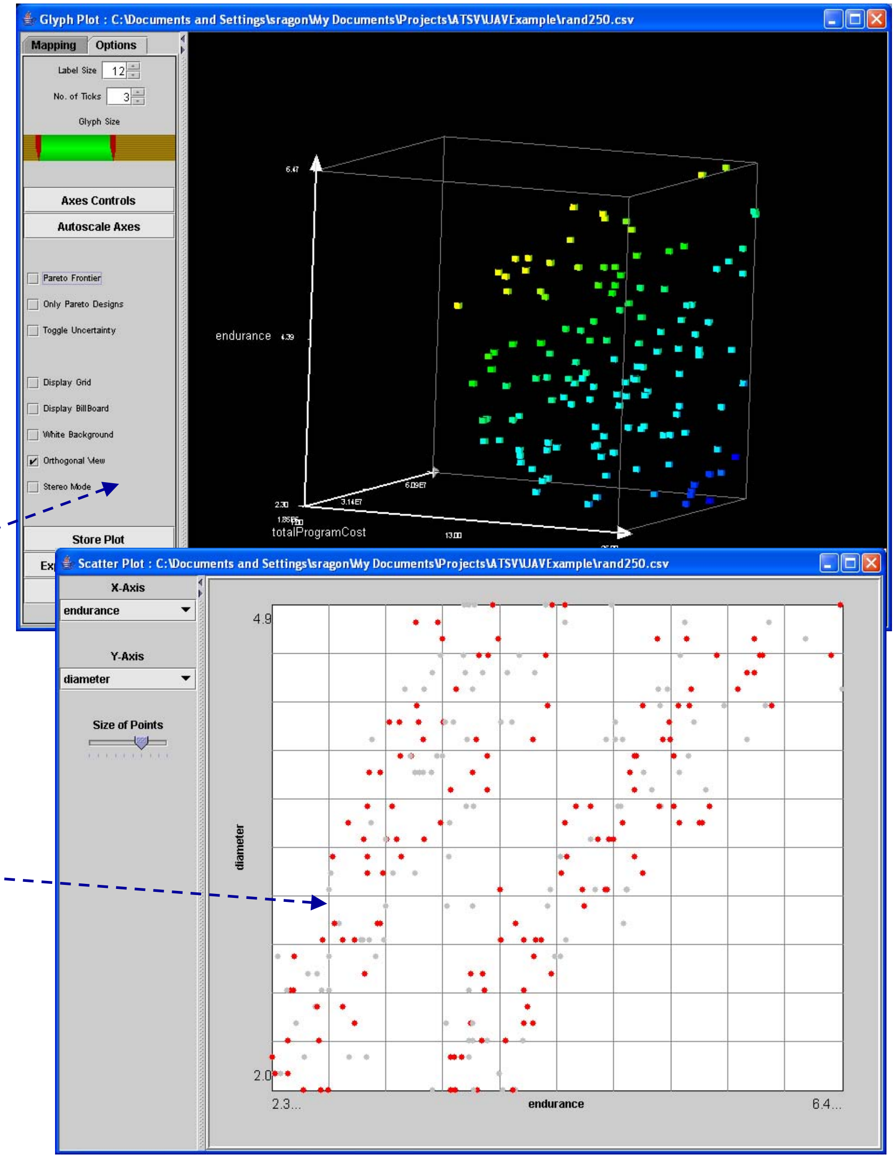


Parallel Coordinate Plots

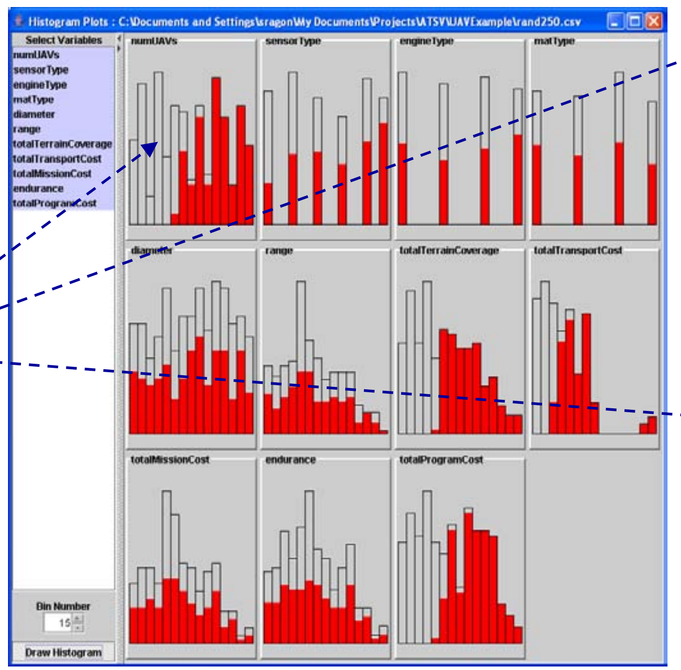
Interactive Brushing and Linking

- For example, interactively apply constraints with brushing





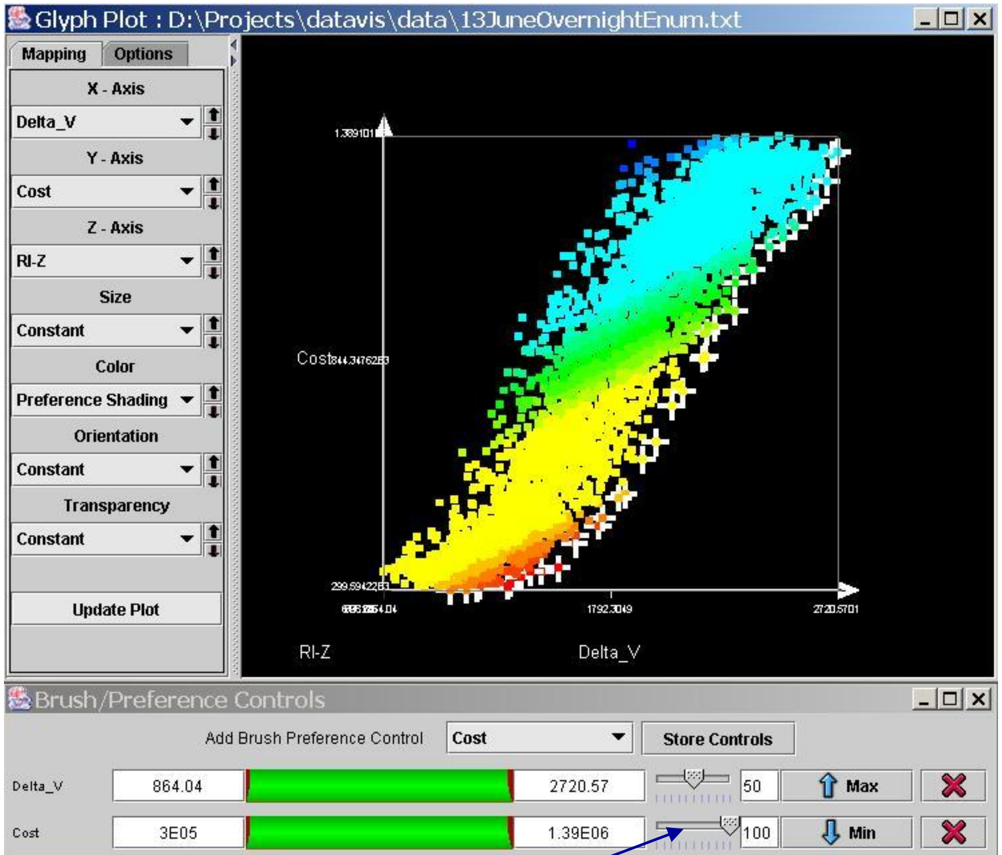
Infeasible designs are grayed out/disappear



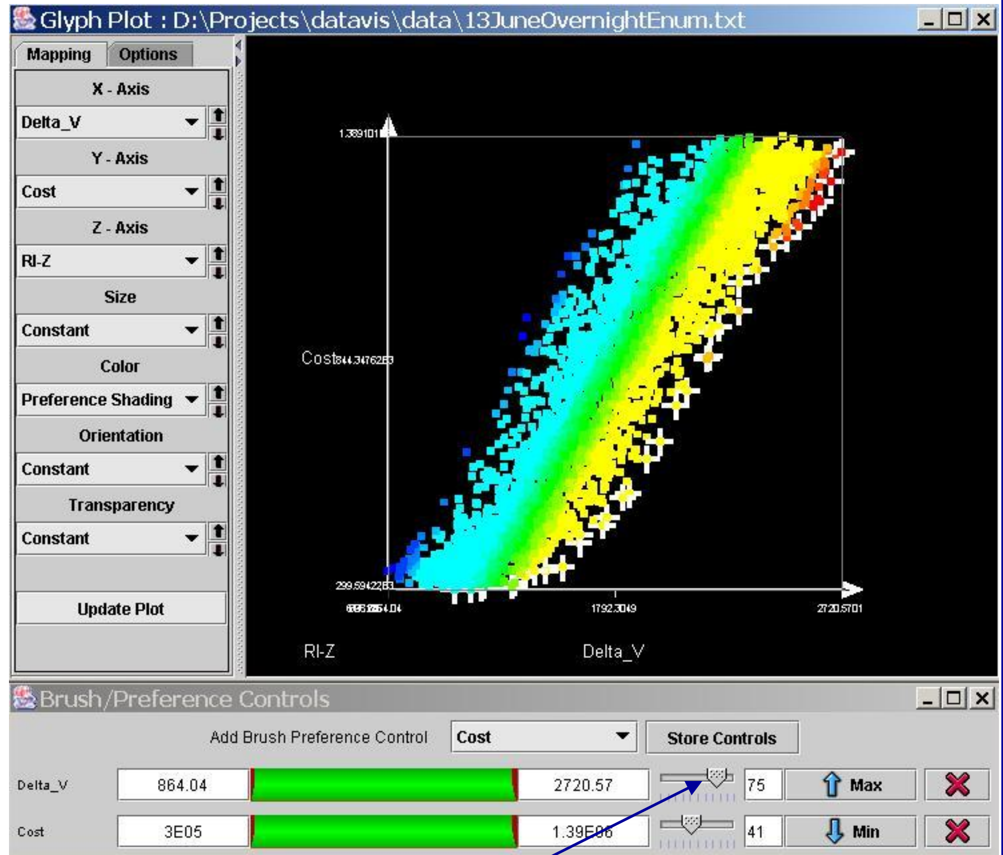
All displays are linked and interactively updated in real-time

Preference Structures and Pareto Frontiers

- Interactively visualize preference structures and Pareto frontiers with preference shading and a fast Pareto sorting algorithm



Greater importance on minimizing cost



Greater importance on maximizing ΔV

ATSV DEMO

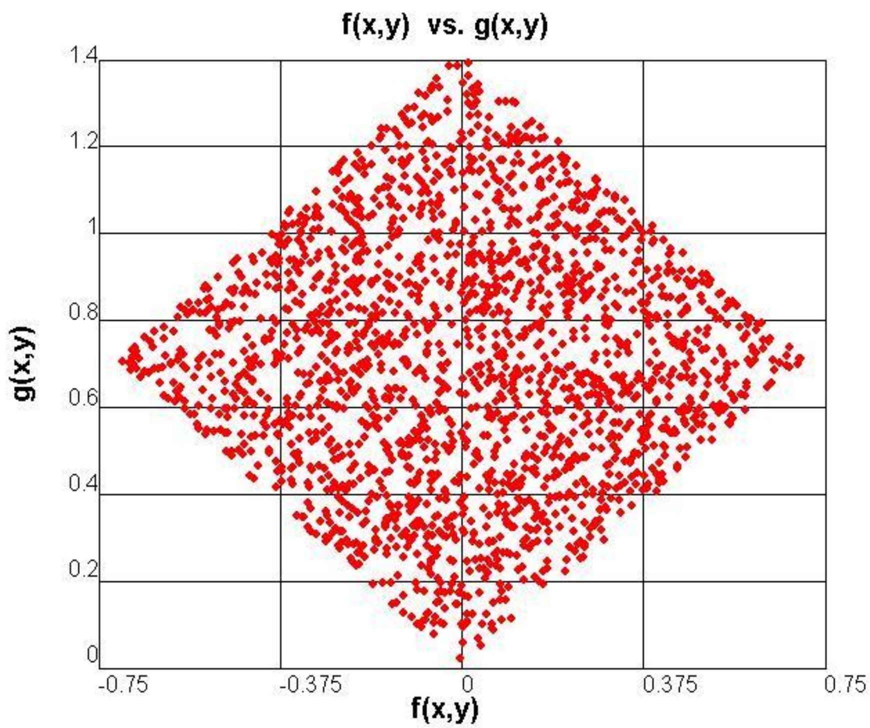
(Static Dataset)

Visual Steering for Trade Space Exploration

- Visual steering generates data “on the fly” to facilitate multi-attribute trade space exploration and navigation

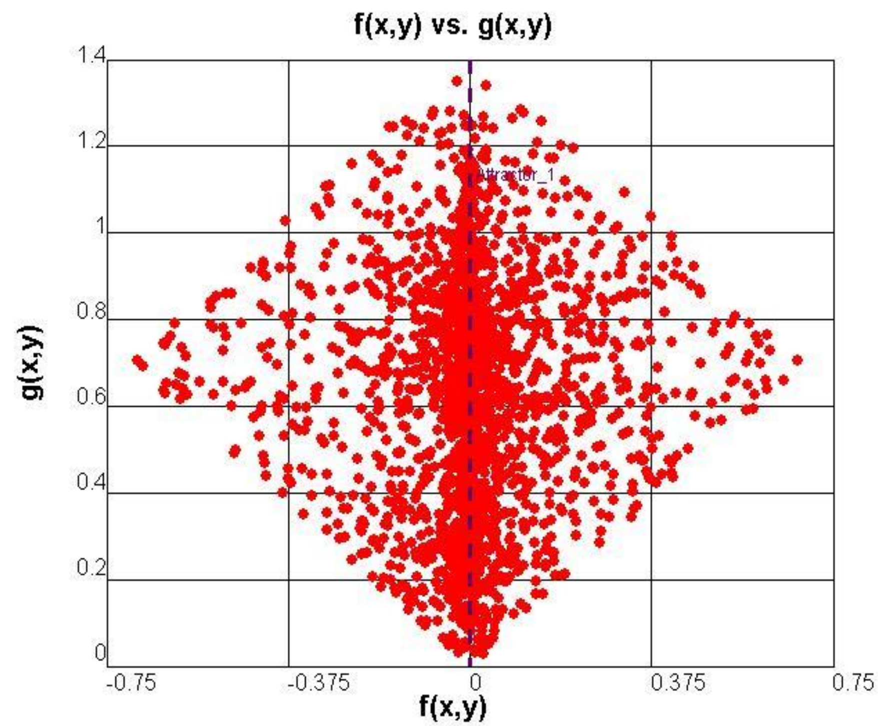
(1) Use to Explore

- Sample new points uniformly over entire region of interest



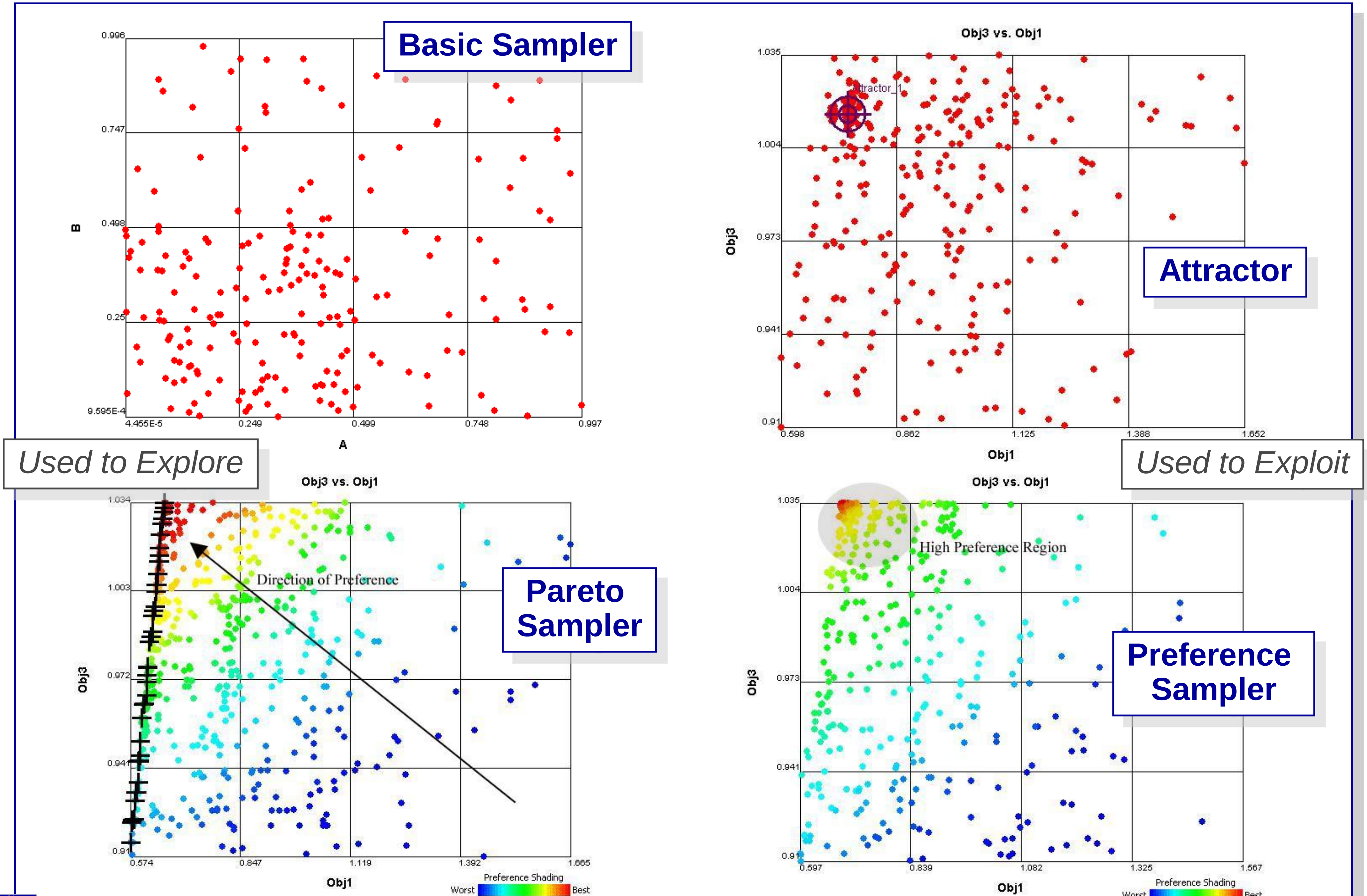
(2) Use to Exploit

- Bias sampling near a point or specified region of interest



Visual Steering Commands

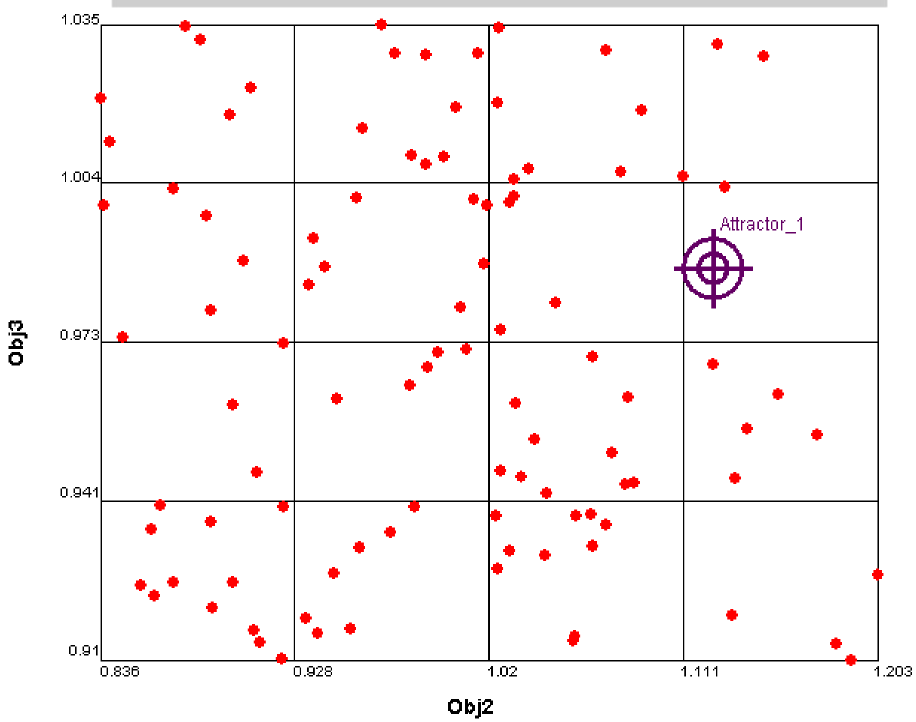
Refer to:
(Stump, et al., 2007)



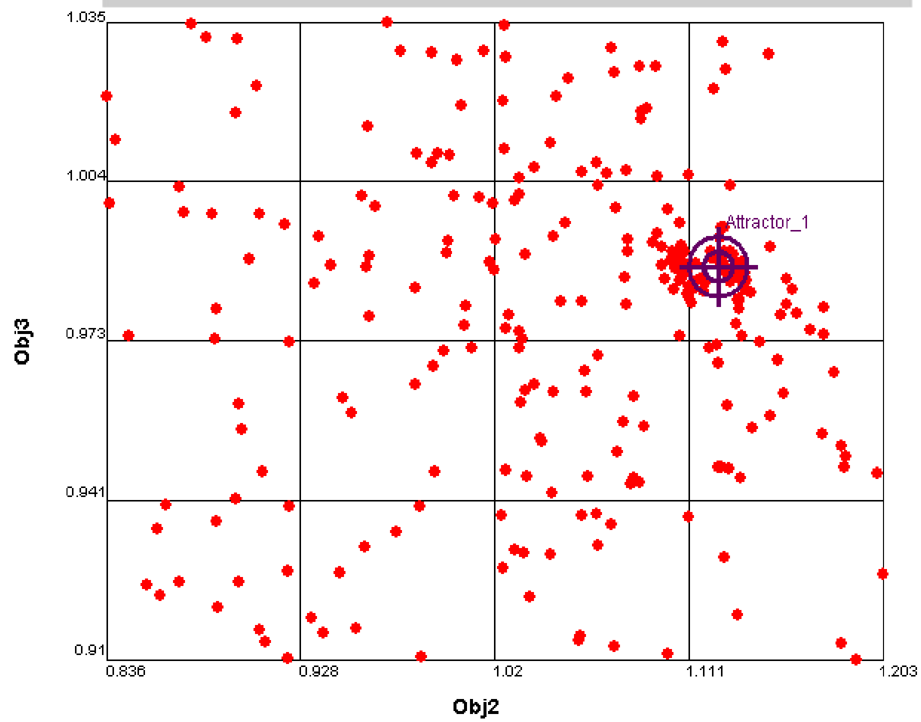
Point Sampler (Attractor)

- Point sampler populates new sample points near a user-defined point (⊕) in the trade space
  - ❑ Useful for filling in "gaps" in the trade space and exploring new regions of interest
  - ❑ Can be any n-dimensional point *Z* in the trade space

100 Initial Samples in Obj2 & Obj3



New Points Near Specified Attractor



How the Attractor Works

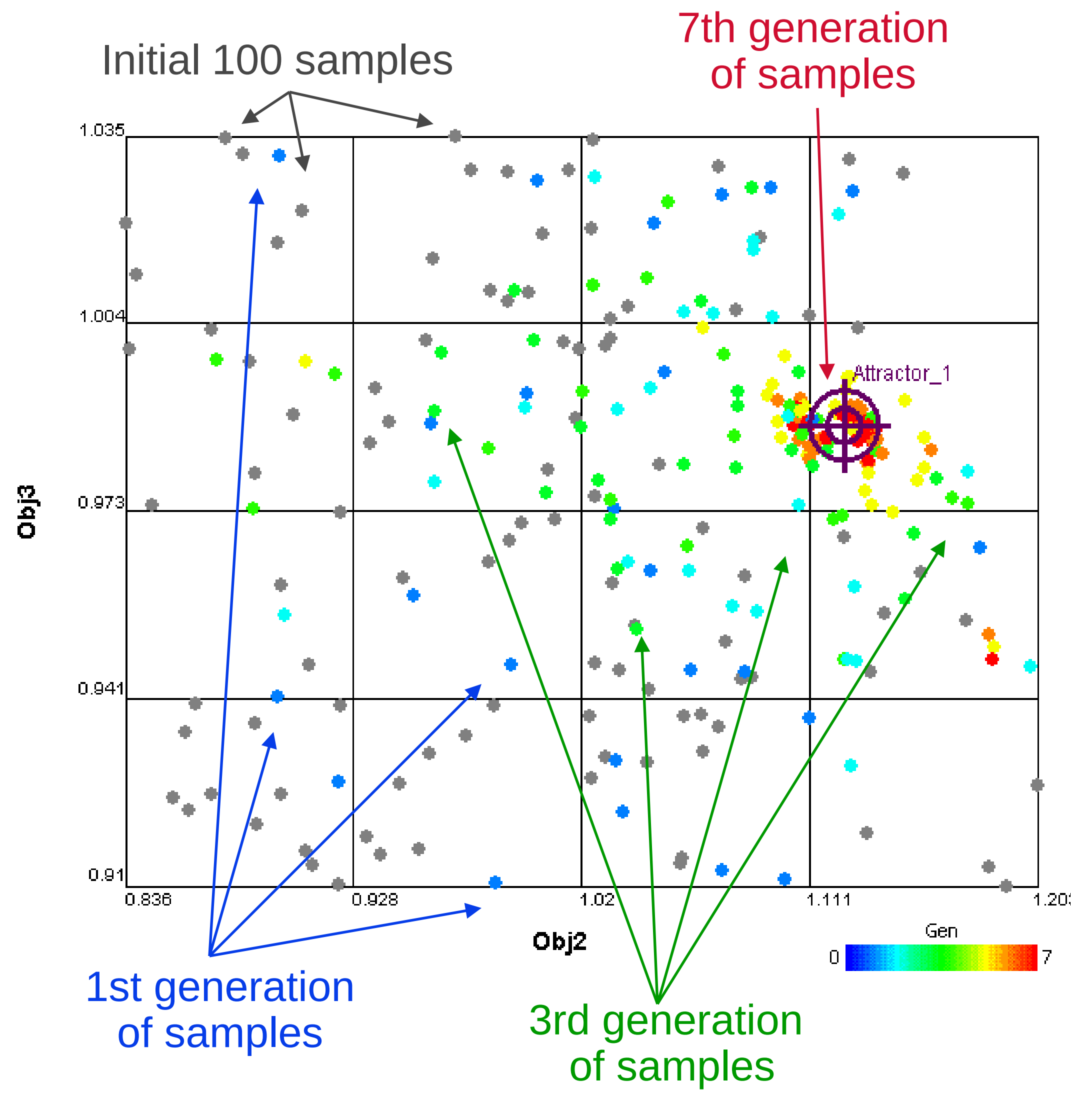
- We use the Differential Evolution algorithm of Price, Storn, and Lampinen (2005) to “evolve” samples toward the attractor

Fitness function =

$$\sqrt{\sum_{i=1}^{n}\left(\frac{Z_{i\_sample}-Z_{i\_attractor}}{Z_{i\_attrator}}\right)^{2}}$$

where Z_{i_sample} is location of new sample point and $Z_{i\_attractor}$ is location of the user-specified attractor

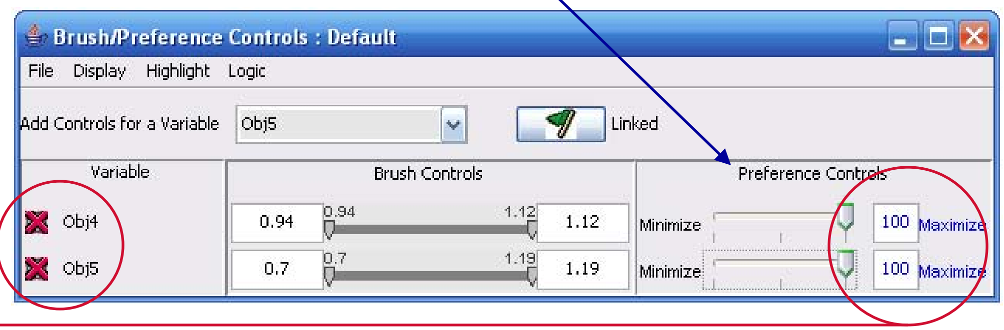
❑ Works well even with small populations and just a few generations



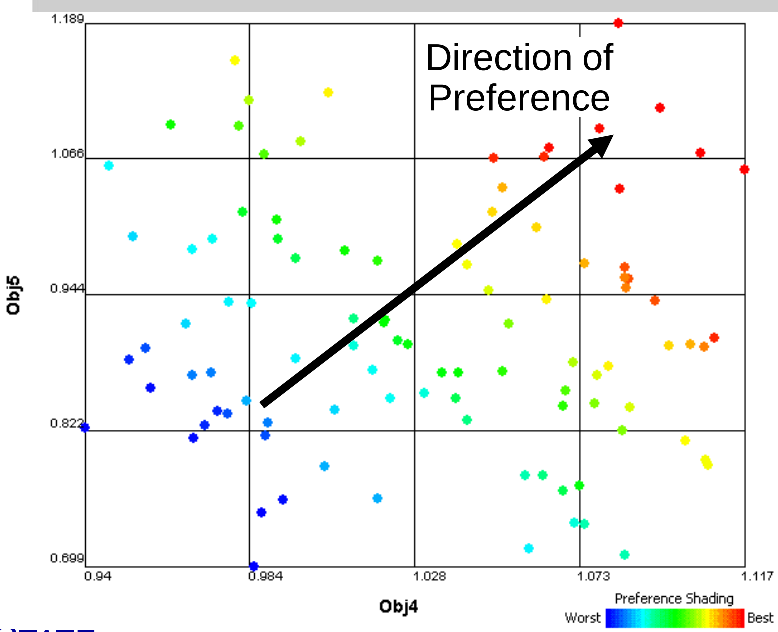
Preference-Based Sampler

- Preference-based sampler populates the trade space in regions that perform well with respect to a user-defined preference function (via preference controls):
  - Uses Differential Evolution with:

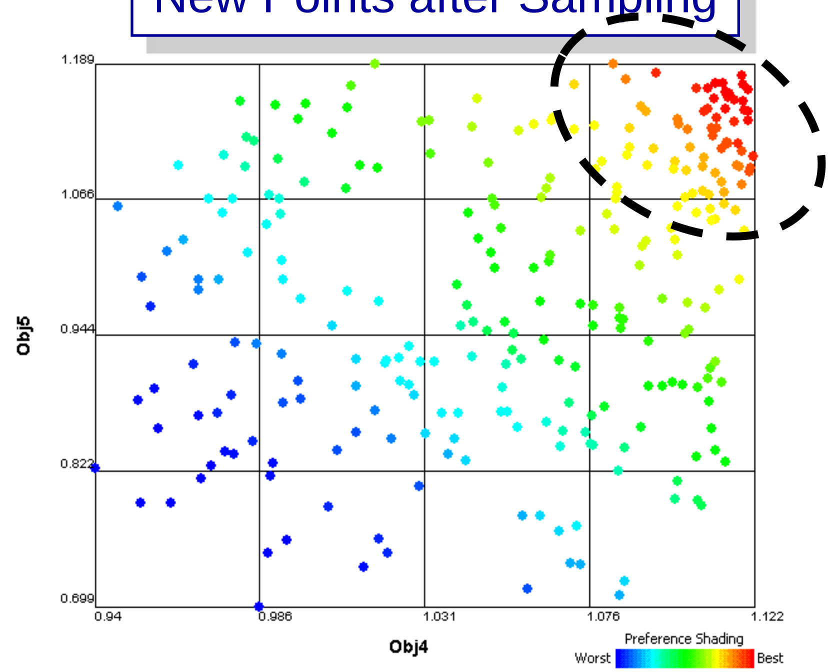
$$\text{Fitness} = \sum_{j=1}^{n_{pref}} w_j Z_j$$



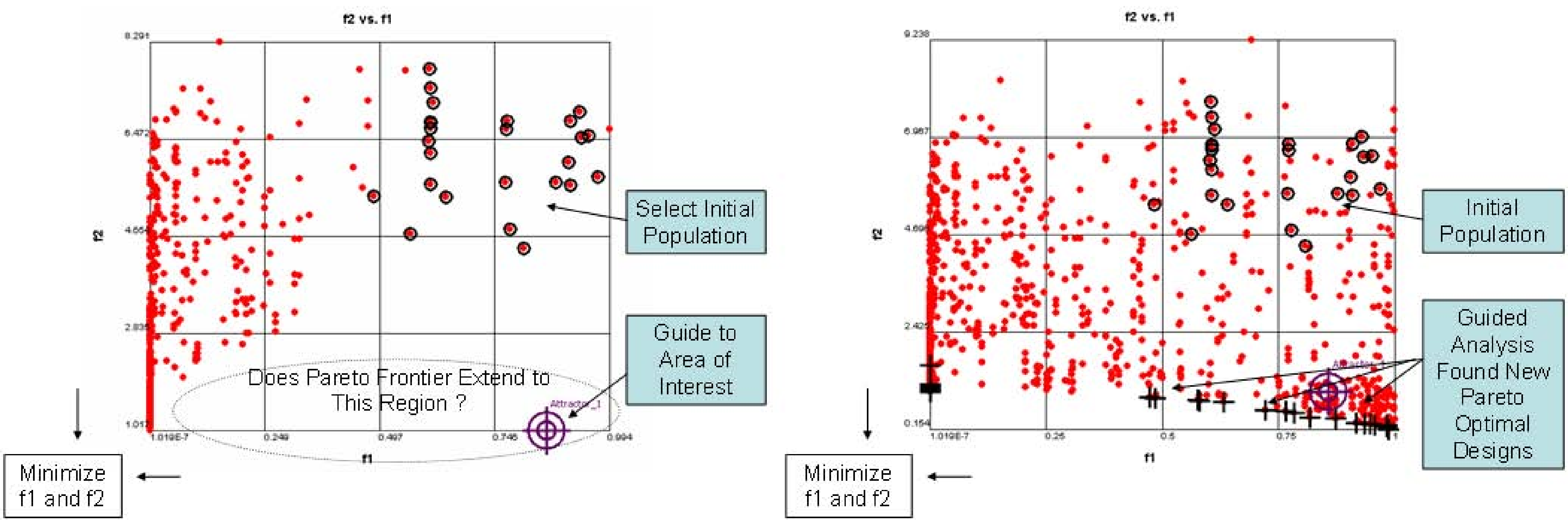
100 Initial Samples in Obj4 & Obj5



New Points after Sampling



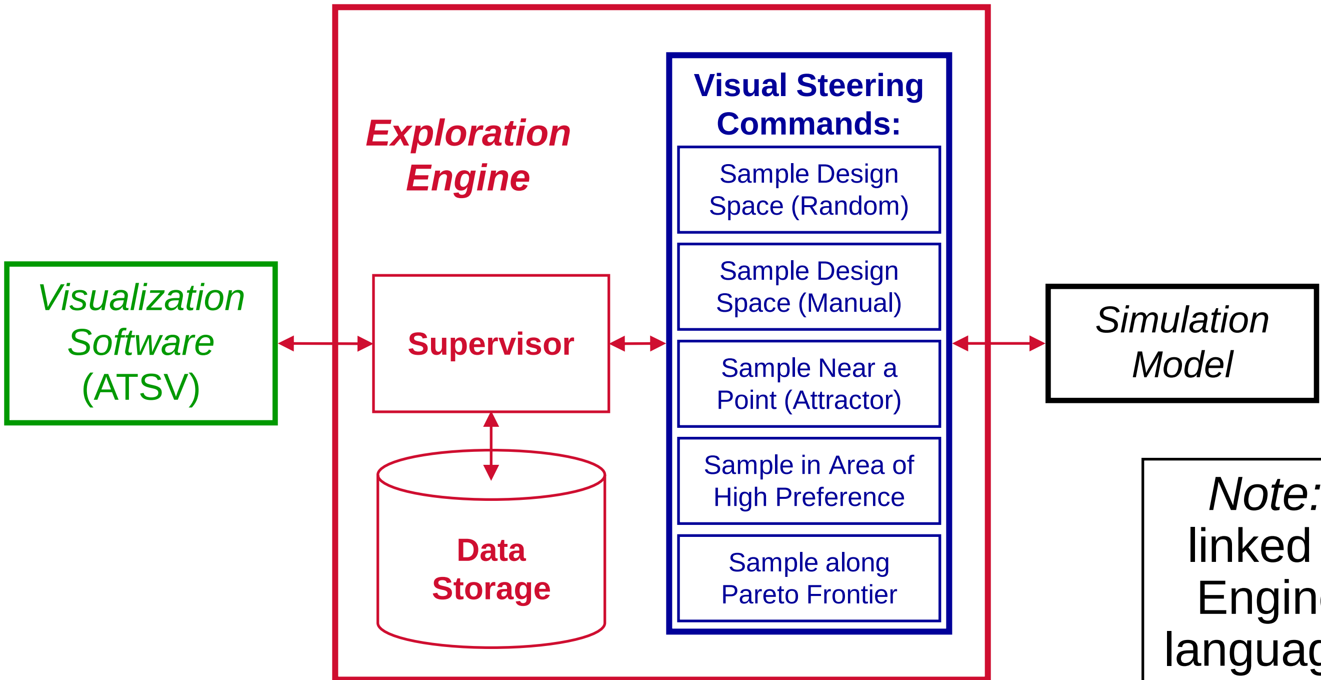
Guided Pareto Sampling



- Guided Pareto Sampler allows users to:
  - Select specific points within any data visualization window and use them to seed the initial generation for Pareto search
  - "Guide" Pareto search algorithms to regions of interest using Attractor icons
  - Start, pause, and stop the search at any time to change initial generation, guided search direction, modify formulation, etc.

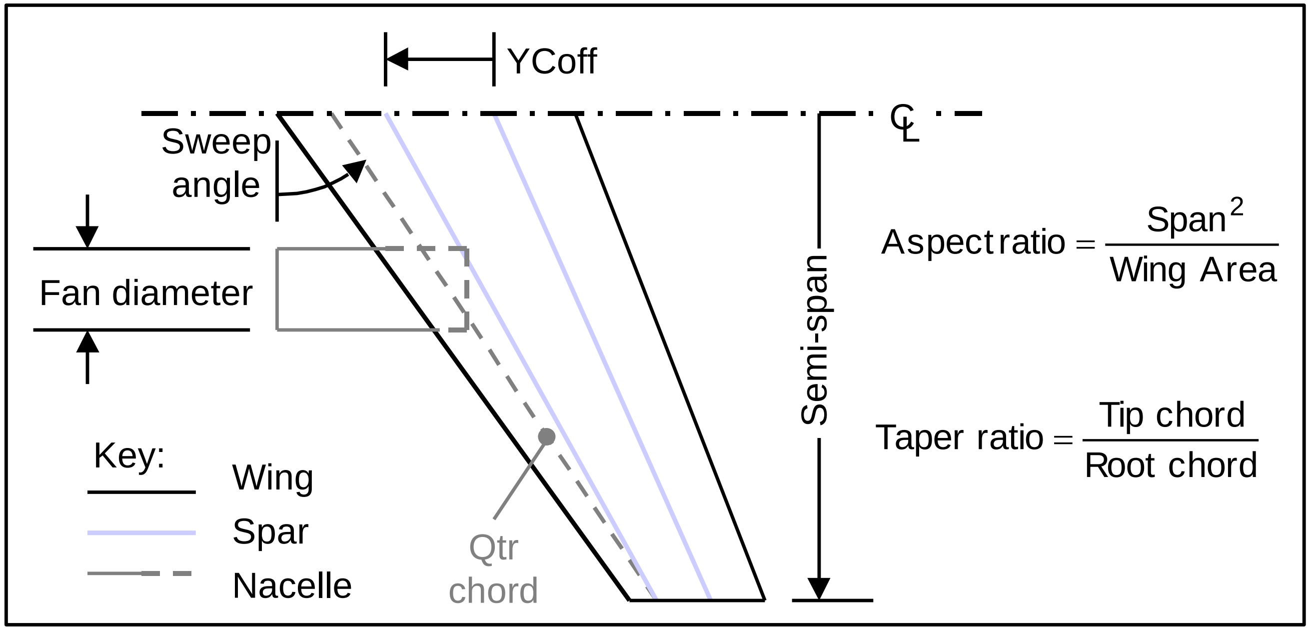
Implementation within ATSV

- Visual Steering Commands are handled independently of ATSV using an Exploration Engine:
  - user specifies Visual Steering Commands within ATSV
  - Exploration Engine invokes simulation model, stores new sample data, and updates ATSV displays
  - message passing protocol handles all communication



Note: Simulation models can be linked to ATSV via the Exploration Engine if they are in Excel or any language that is executable in batch mode (e.g., Java, Matlab, C, C++)

Aircraft Wing Sizing Problem



Design variables:
1. Semi-span
2. Aspect ratio
3. Sweep angle
4. Taper ratio
5. Sparbox root chord
6. Fan diameter

Bounds: $x_i^{lower} \leq x_i \leq x_i^{upper}$

Problem Statement:

Minimize: Cost
Maximize: Range
subject to: Range $\geq$ 0.589
Buffet altitude $\geq$ 0.603
Takeoff field length $\leq$ 0.377

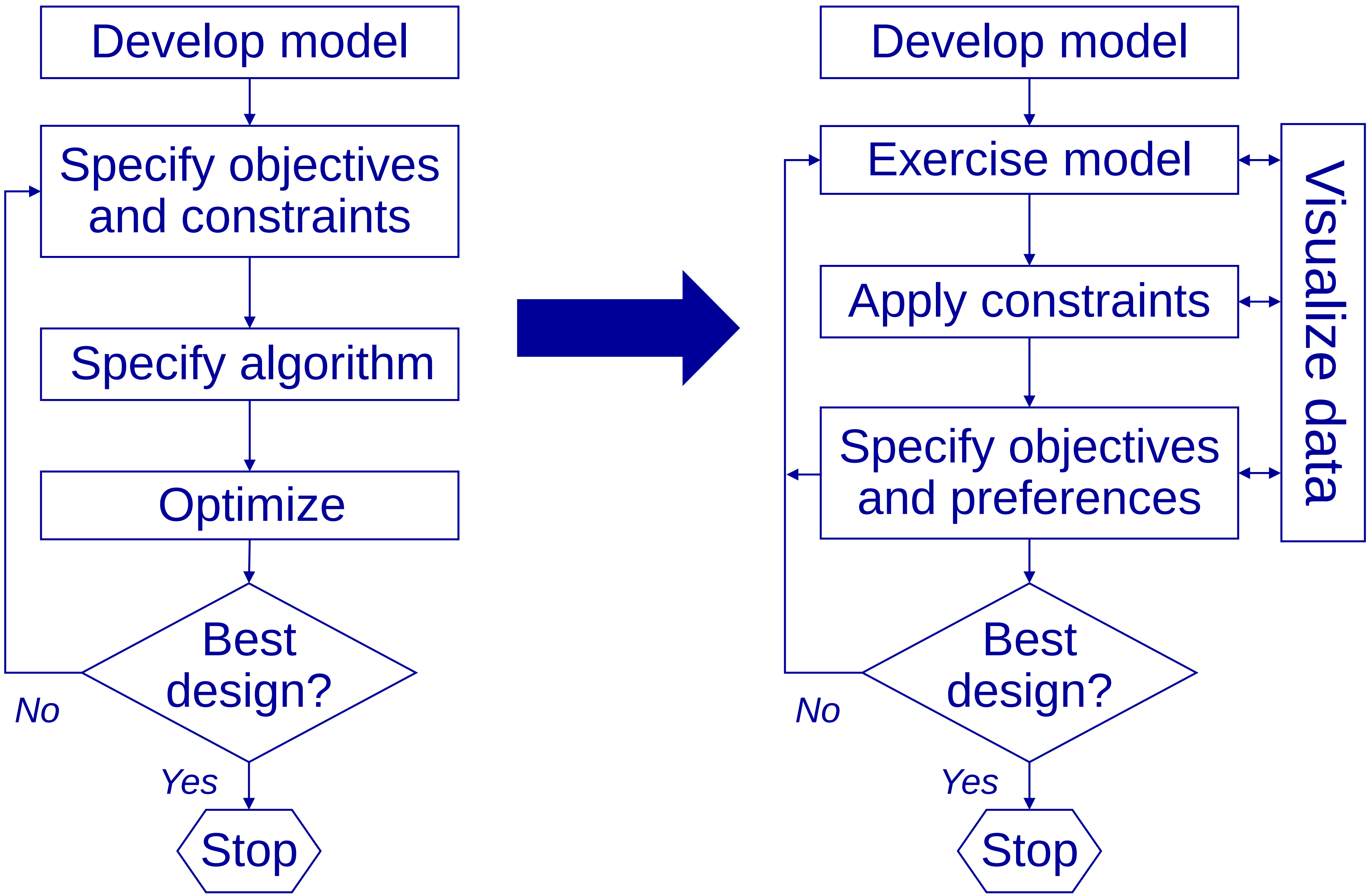
Values were obtained from 2nd-order response surface models developed from a 243 point orthogonal array

ATSV DEMO

(Visual Steering)

Shifting to a New Paradigm?

Design by Optimization ***Trade Space Exploration***



Vehicle Configuration Model

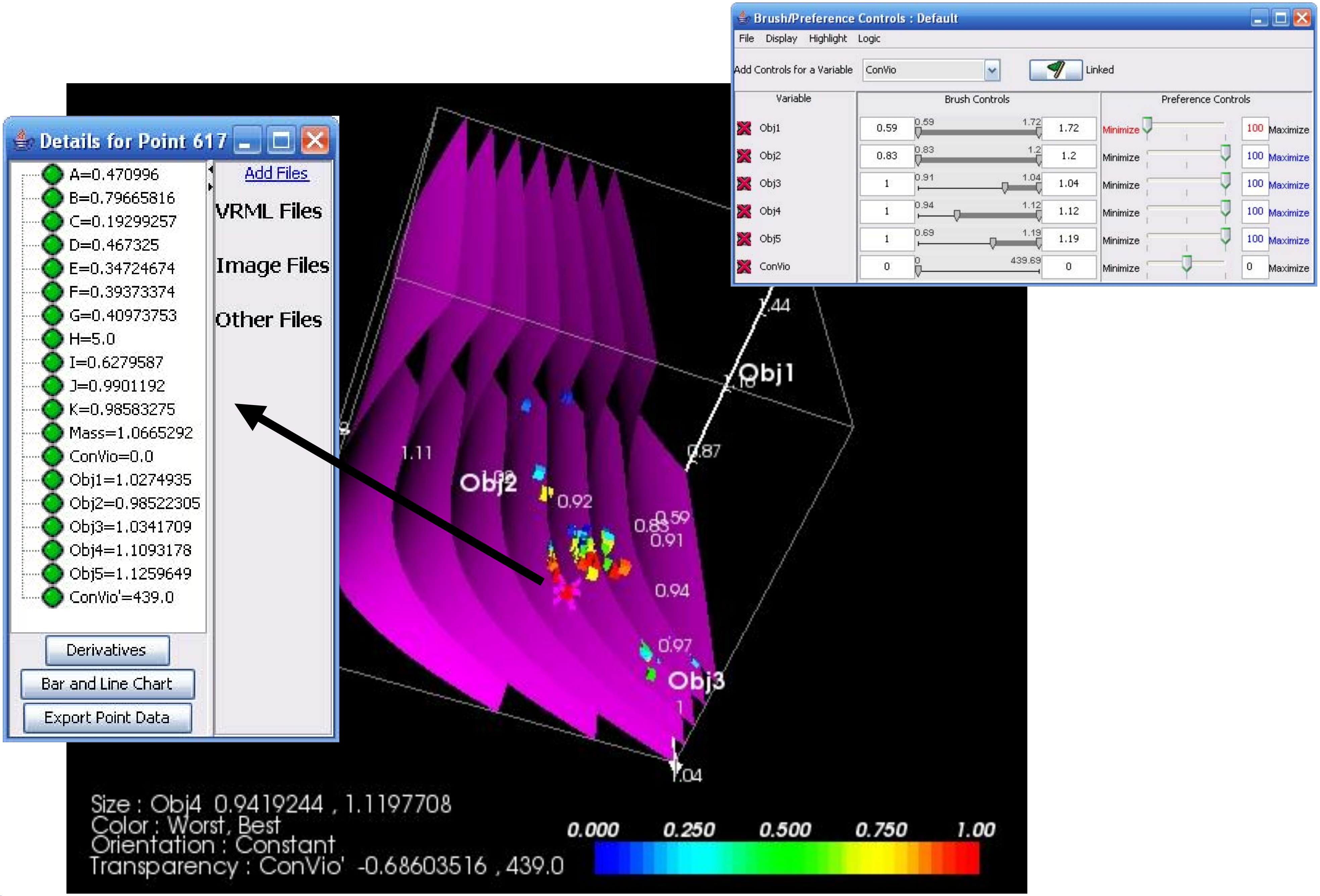
Refer to: (ASME DETC2007-34684)

- We used a vehicle configuration model that evaluates the technical feasibility of new vehicle concepts*
  - Inputs: 11
    - External dimensions
    - Occupant positions
    - Power train (discrete)
  - Objectives: 5
    - Acceleration
    - Fuel economy
    - Interior accommodation
  - Vehicle mass
  - Total constraint violation

Model Inputs		
Variable	**Lower Bound**	**Upper Bound**
A	0	1
B	0	1
C	0	1
D	0	1
E	0	1
F	0	1
G	0	1
H	1,2,3,4,5, or 6	
I	0	1
J	0	1
K	0	1
Model Outputs		
ConVio	0 → feasible	> 0 → infeasible
Mass	Baseline = 1	Defines weight class
Obj1	Baseline = 1	Smaller is better
Obj2	Baseline = 1	Larger is better
Obj3	Baseline = 1	Larger is better
Obj4	Baseline = 1	Larger is better
Obj5	Baseline = 1	Larger is better

* Ferguson, Lewis, and Donndelinger, et al. 2004, 2005 & 2006 MAO & DETC papers

Final Glyph Plot with Weight Classes

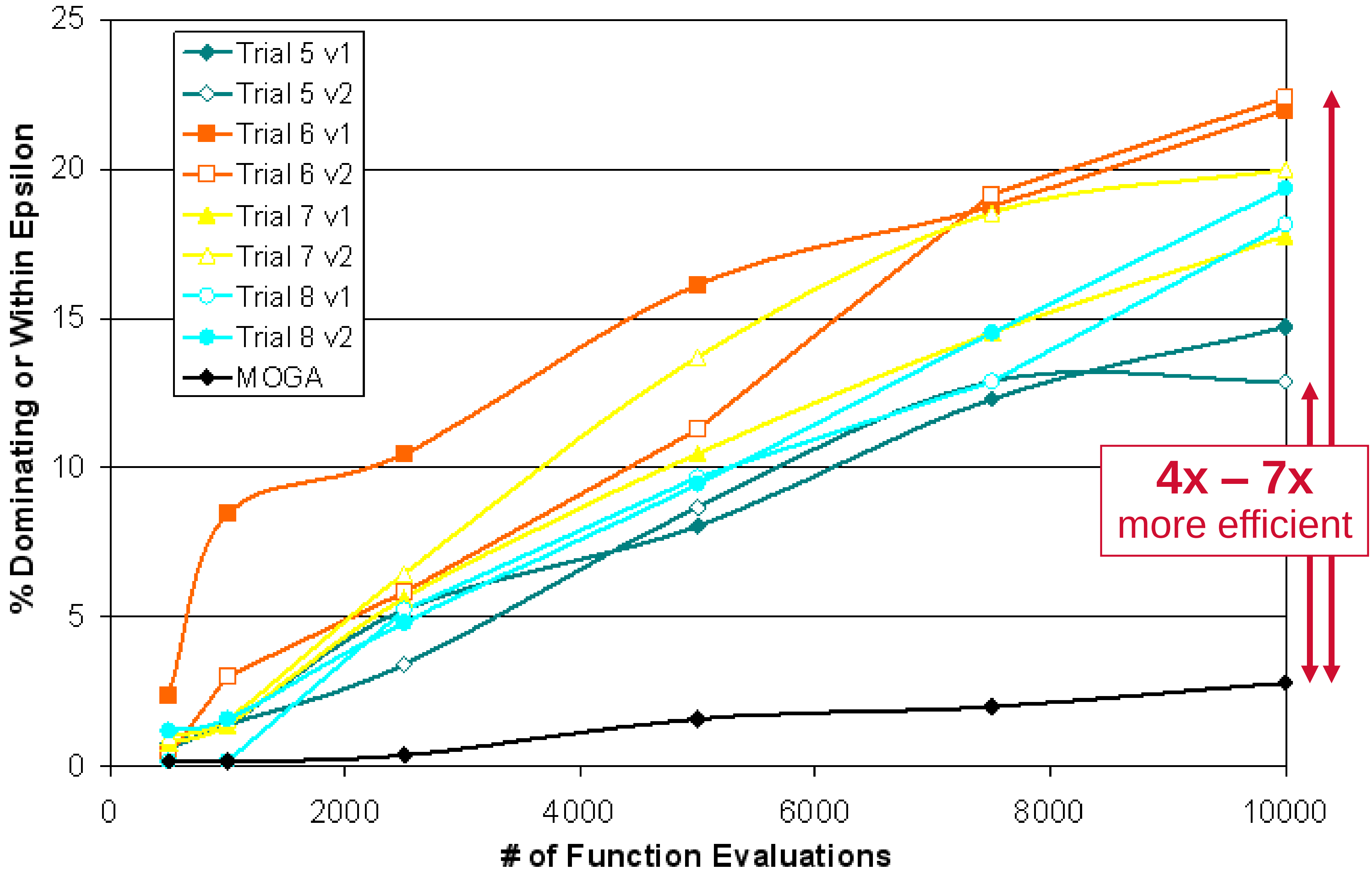


Quantifying Benefits of Our Approach

Refer to: (ASME DETC2008-49681)

- Research Objective:
  - Provide empirical evidence of the benefits of interactive visualization-based strategies that can support design optimization and decision-making
- Experimental Study:
  - Experimentally assess the effectiveness of user-guided visual steering in locating good (Pareto) solutions
- Experimental Set-Up:
  - Vehicle configuration model (11 inputs, 5 objectives)
  - Two users, 8 trials (4 w/5,000 fcn evals; 4 w/10,000 fcn evals)
  - Benchmark: 80,000 function evaluations in MOGA
  - Compare resulting Pareto fronts using ε-performance metric

Evolution of Solutions for Trials 5-8 (10,000 pts)

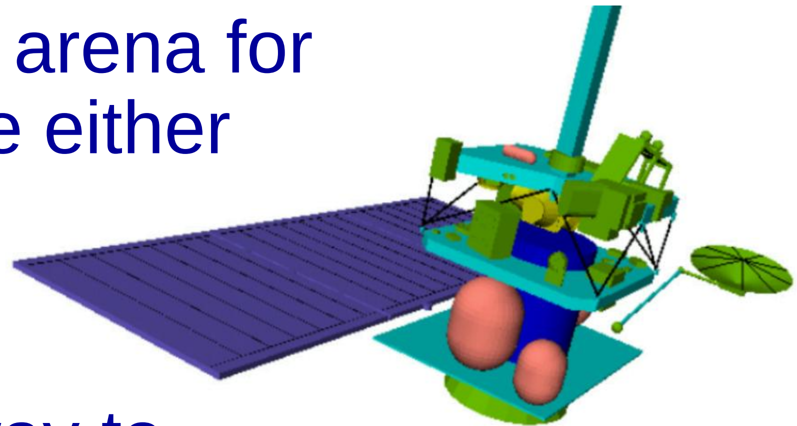


Useful Roles for Visualization

- Explaining
  - a.k.a. "Story telling"
  - Already know the data
  - Use the visualization to explain data to others
- Verifying
  - Expect a certain answer, verify the anticipated result
  - Debugging, fact checking
- Exploring
  - Not sure *a priori* hypothesis of what lies in the data
  - Looking for structure and relationships
- ***Deciding***
  - *A mixture of all three*

Closing Remarks

- Trade space exploration is a powerful alternative to optimization-based approaches to decision-making
  - Provides a visual and intuitive means to explore trade spaces
- ATSV combines multi-dimensional data visualization and visual steering commands to facilitate the trade space exploration process
- Trade space exploration is a rich arena for research in many areas that have either not been examined or have lain dormant for many years



- Experimental studies are underway to provide empirical evidence of the benefits of putting humans "back-in-the-loop" during design optimization

Users & Beta-Testers

- Companies
  - Aerospace Corporation
  - BAE
  - Boeing
  - GE
  - GM
  - Livermore Software Technology
  - NASA & JPL
  - Northrop Grumman
  - UTRC
    - Otis
    - Pratt & Whitney
    - Carrier
  - Vanderplaats R&D
  - Wyle
- Universities
  - Brigham Young University
  - Bucknell University
  - Clemson University
  - Georgia Tech
  - MIT
  - Northwestern University
  - Oregon State University
  - Penn State
    - Civil, IE, ME, IST
  - University at Buffalo-SUNY
  - University of Maryland
  - University of Michigan
  - UIUC
  - USC
- Phoenix Integration has a non-exclusive license to sell the visualization software and visual steering tools

Supporting Distributed/Collaborative Design

- ATSV is being used by JPL's Product Design Center
  - JPL does 50+ concept designs per year
  - Team-X does rapid conceptual design
  - Using ATSV to explore trade space

ESD.77 / 16.888 Multidisciplinary System Design Optimization
Spring 2010