Visual Steering Commands and Test Problems to Support Research in Trade Space Exploration*

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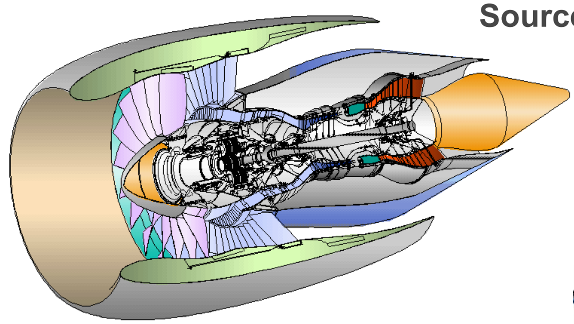
Overview of Presentation

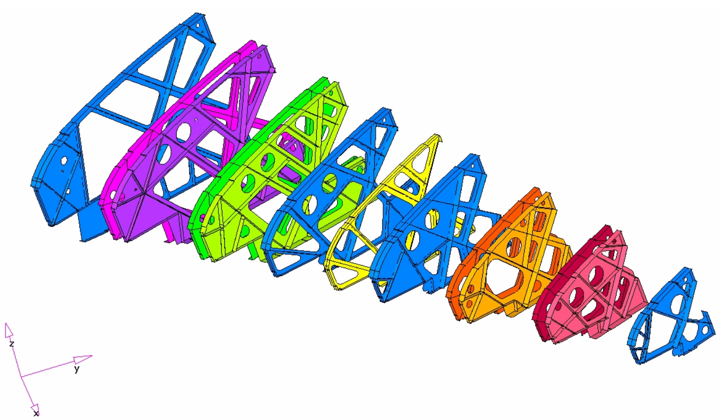
- Trade Space Exploration
  - Motivation for the work
  - Optimization vs. exploration
- ARL Trade Space Visualizer (ATSV)
  - Multidimensional data visualization
  - Visual Steering Commands
- Suite of Test Problems
  - Complex engineered systems for land, sea, air, and space
- Sample Results
- Closing Remarks

Modeling, Analysis, and Simulation

- 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: Trevor Bailey, UTRC



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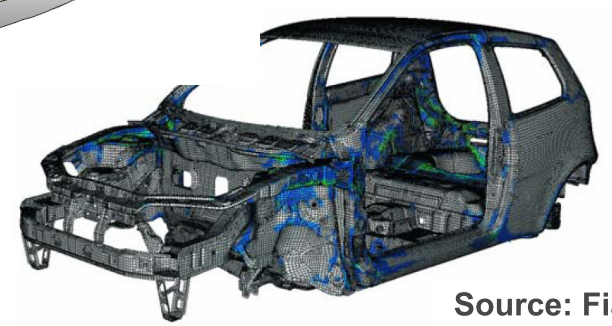
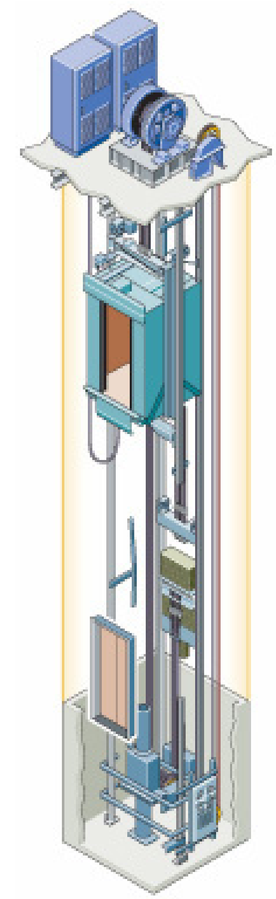


Source: Fiat

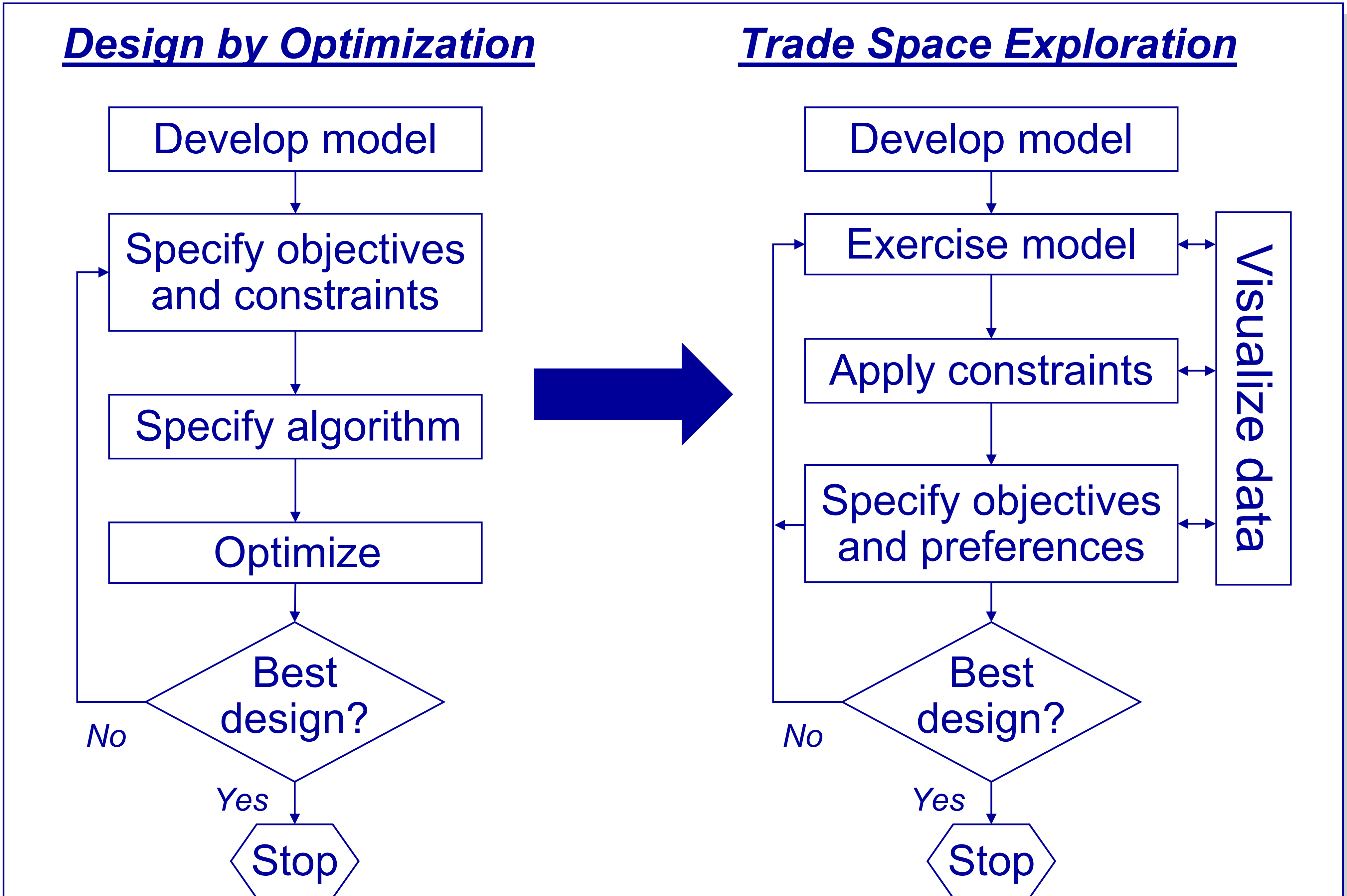


Source: www.otis.com

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

Shifting to a Better Paradigm?



ARL Trade Space Visualizer (ATSV)

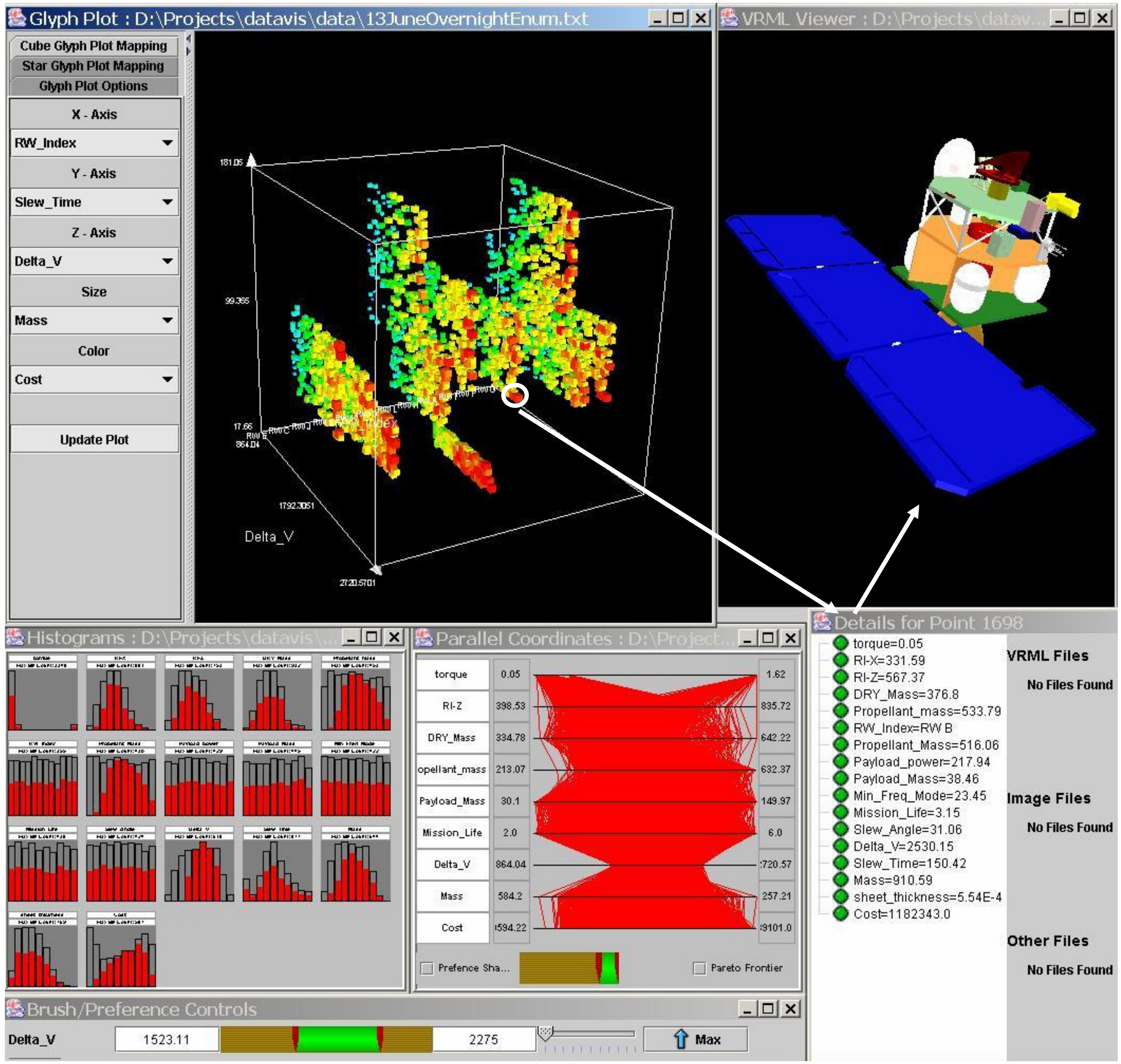
Multi-dimensional data visualization:

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

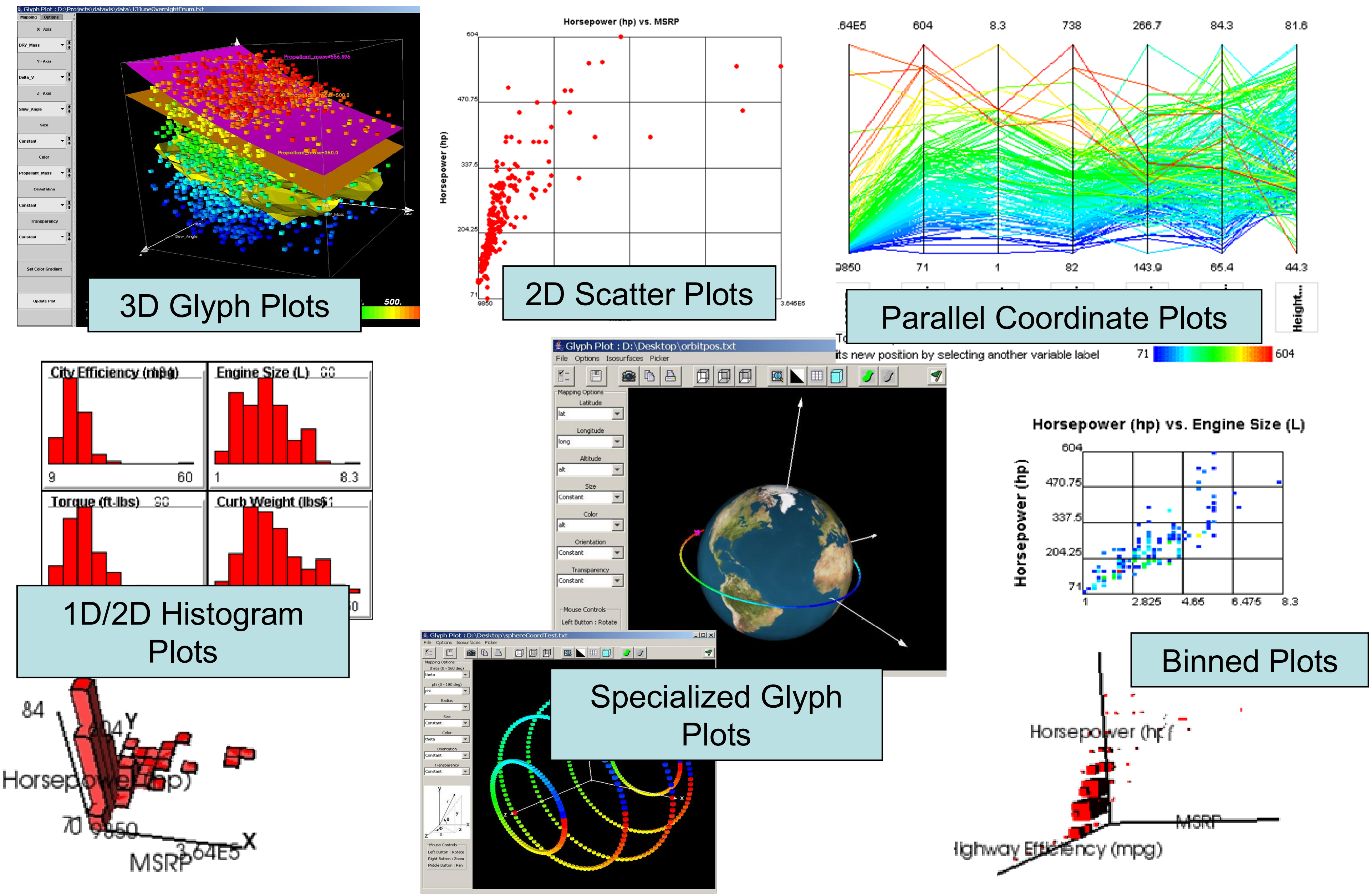
Display multiple plots simultaneously

Interrogate specific design points

Interactively apply preferences and constraints

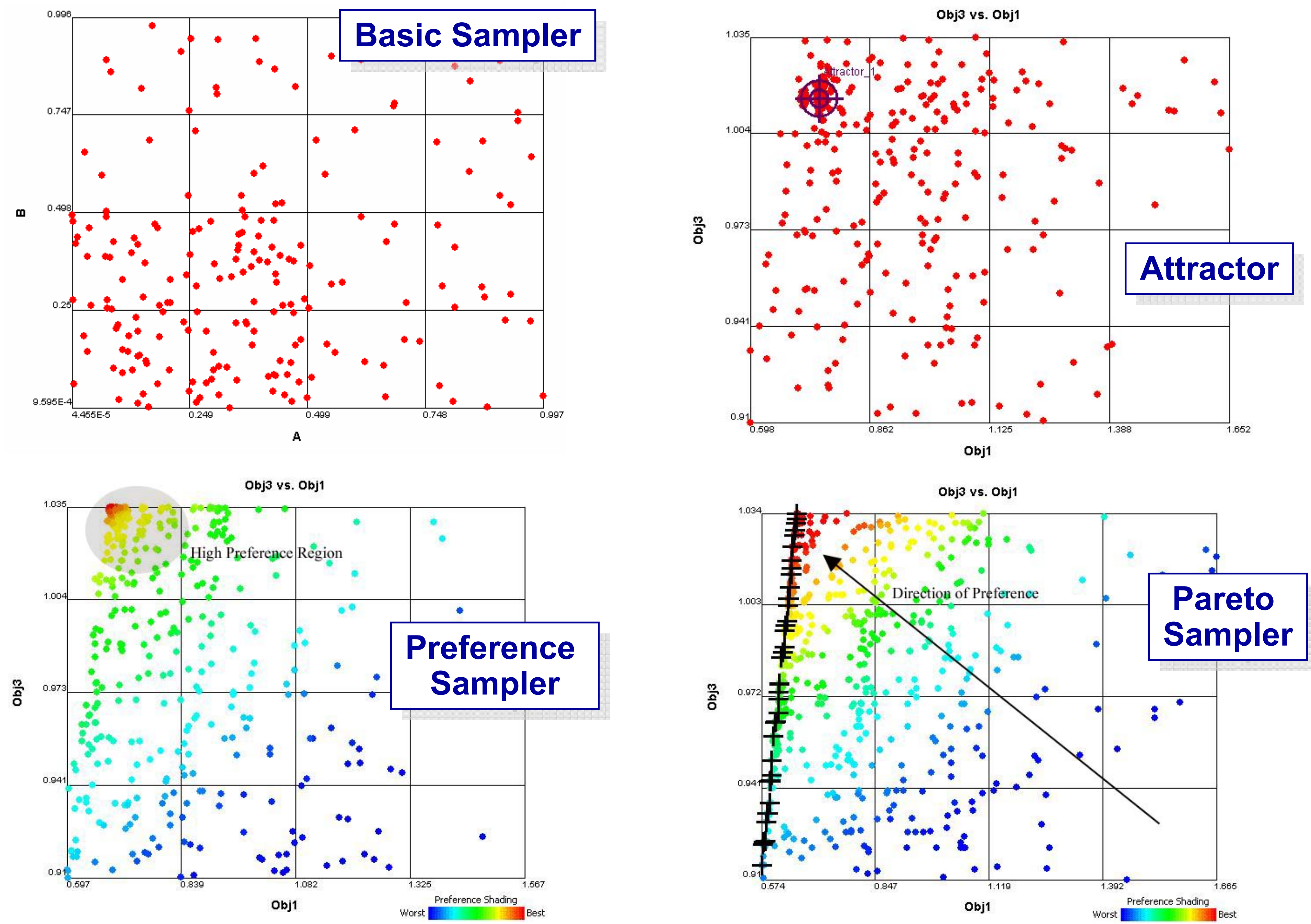


Multi-Dimensional Data Visualization

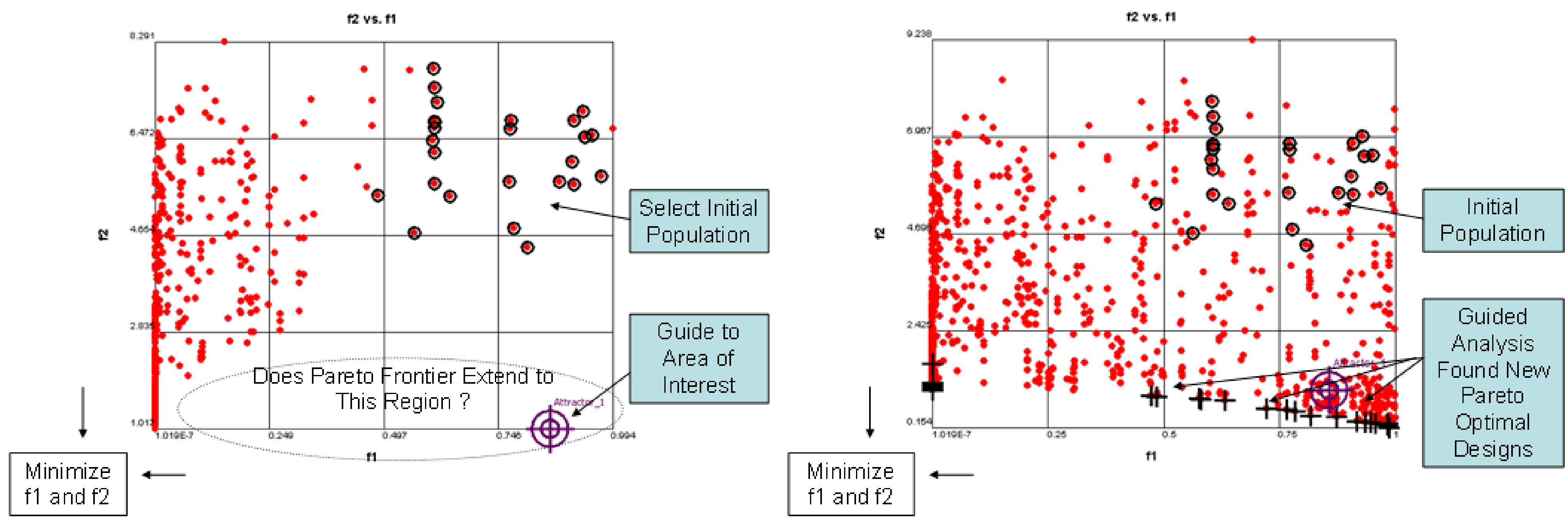


Visual Steering Commands

Refer to: (ASME DETC2007-34684)

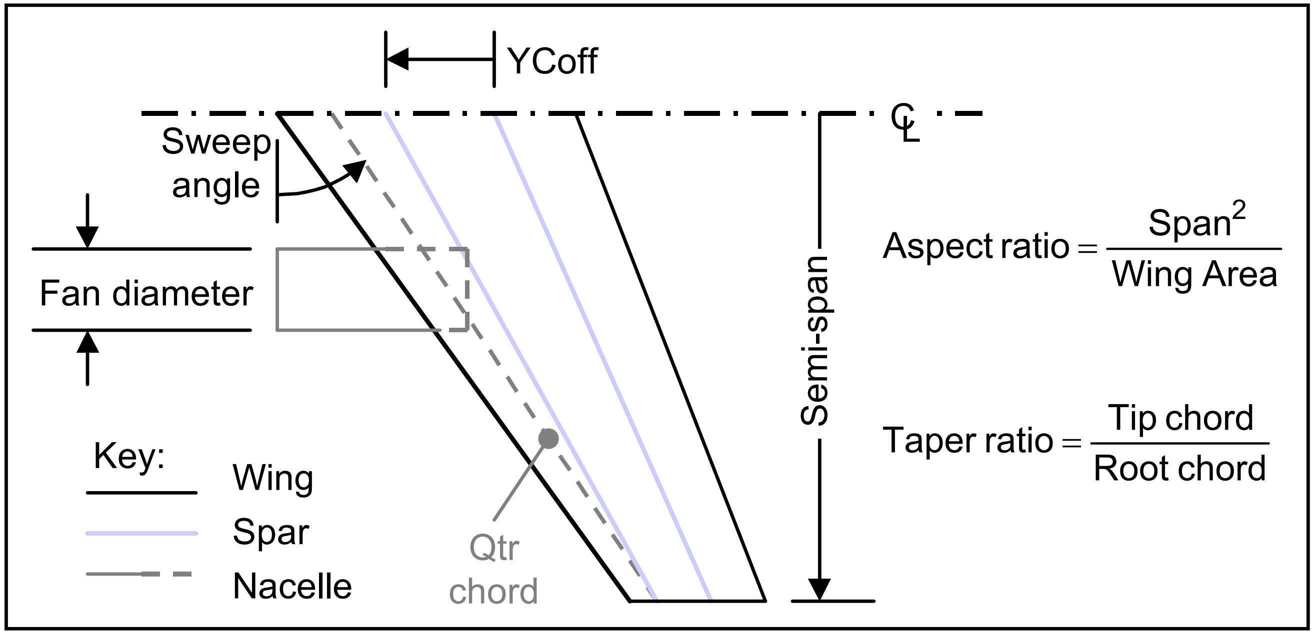


Guided Pareto Sampling



- 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.

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

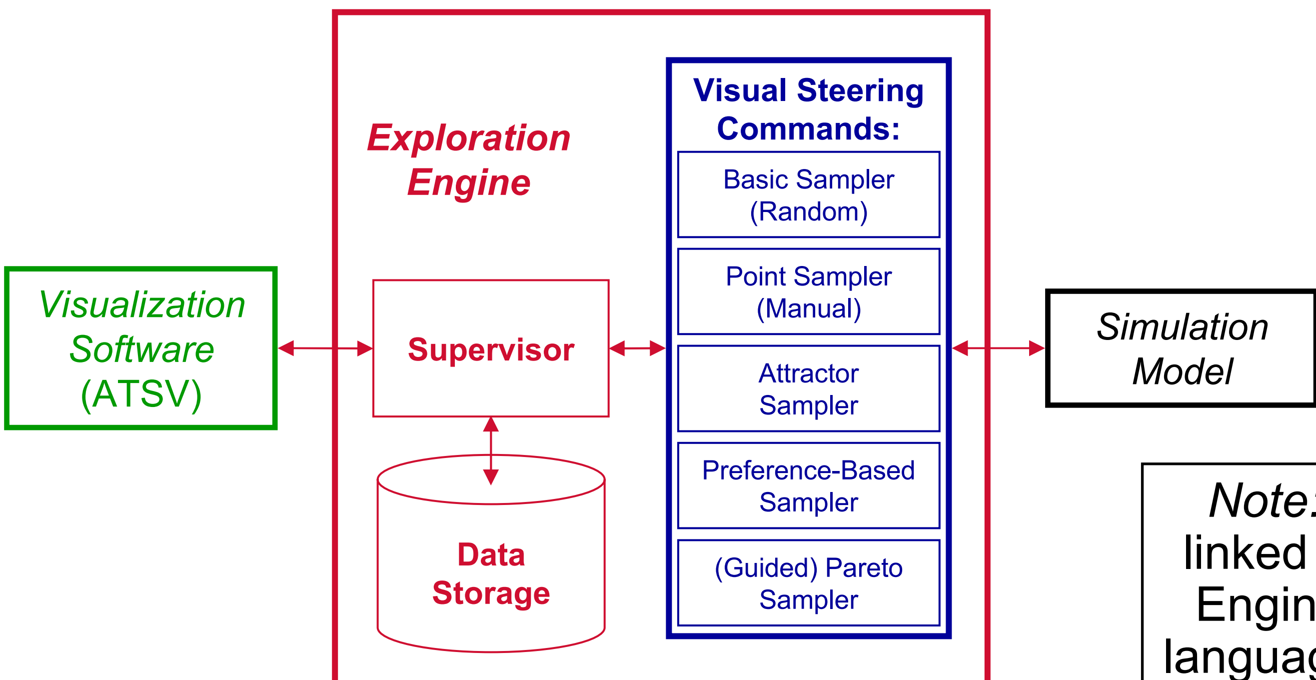
Buffet altitude $\geq$ 0.603

Takeoff field length $\leq$ 0.377

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

Implementation with 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++)

Problem Test Suite

- In order to test algorithmic developments and perform experimental user studies, we have created a suite a test problems that vary in size, complexity, etc.

Domain	Problem	Inputs	Objectives	Constraints
Land	Vehicle Configuration Model	11	5	2
Sea	Conceptual Ship Design	6	3	9
Air	Aircraft Wing Sizing	6	2	3
Space	Space Shuttle External Fuel Tank	5	1 System & 4 Subsystem	4

- Problems are representative of conceptual design of complex engineered systems in the four domains

Vehicle Configuration Model

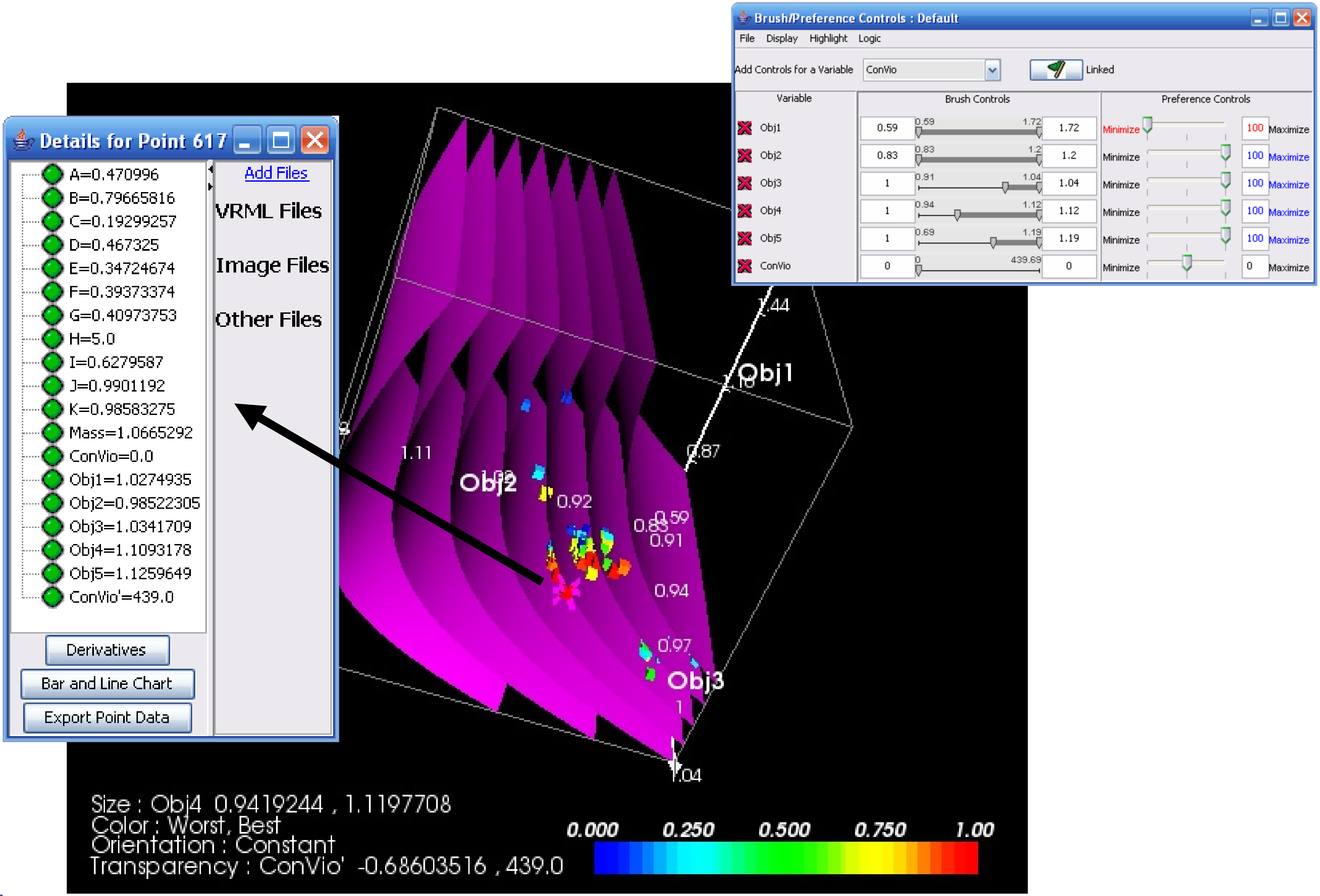
Refer to: (ASME DETC2007-34684)

- 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

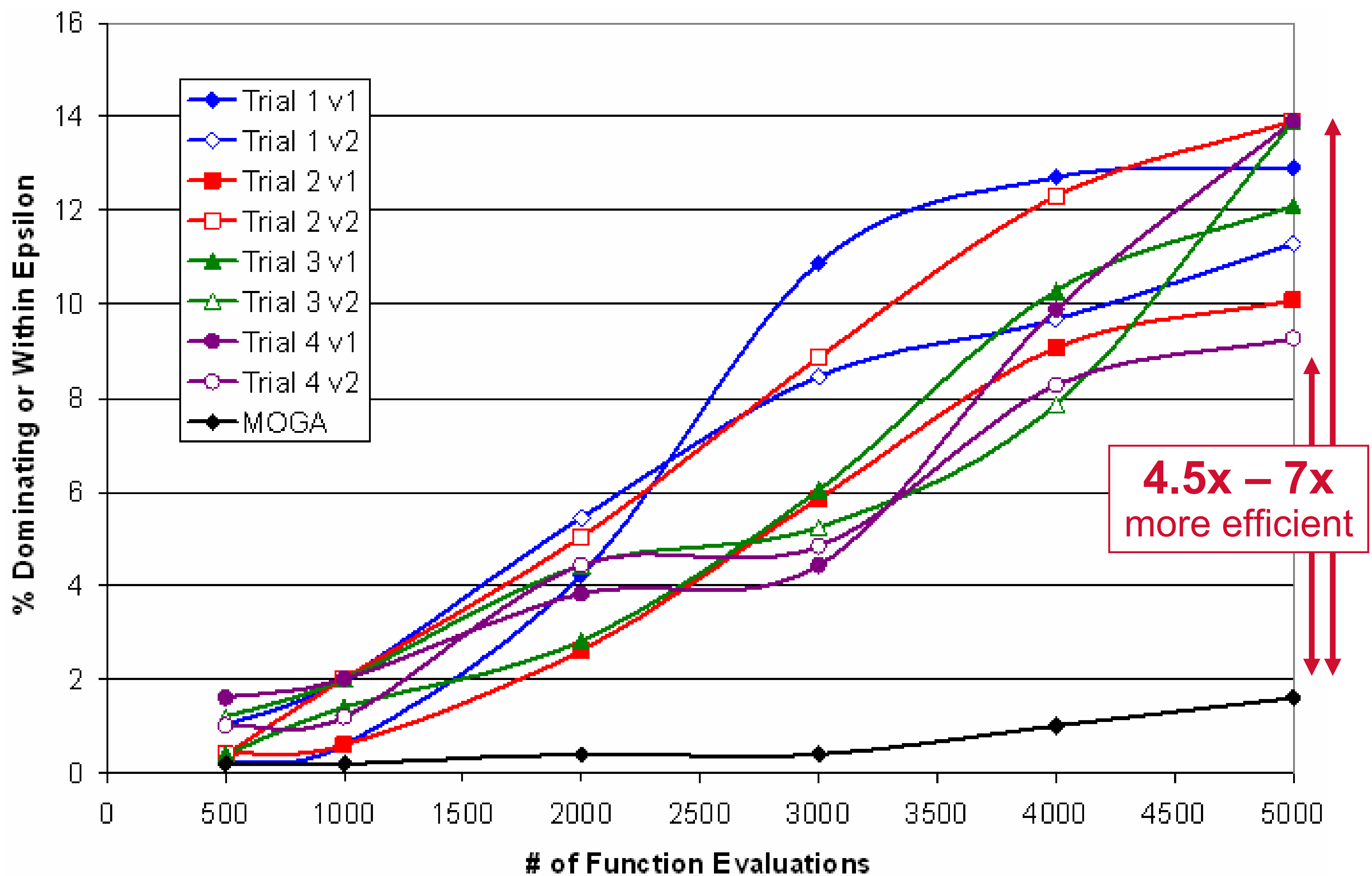


Quantifying Benefits of Our Approach

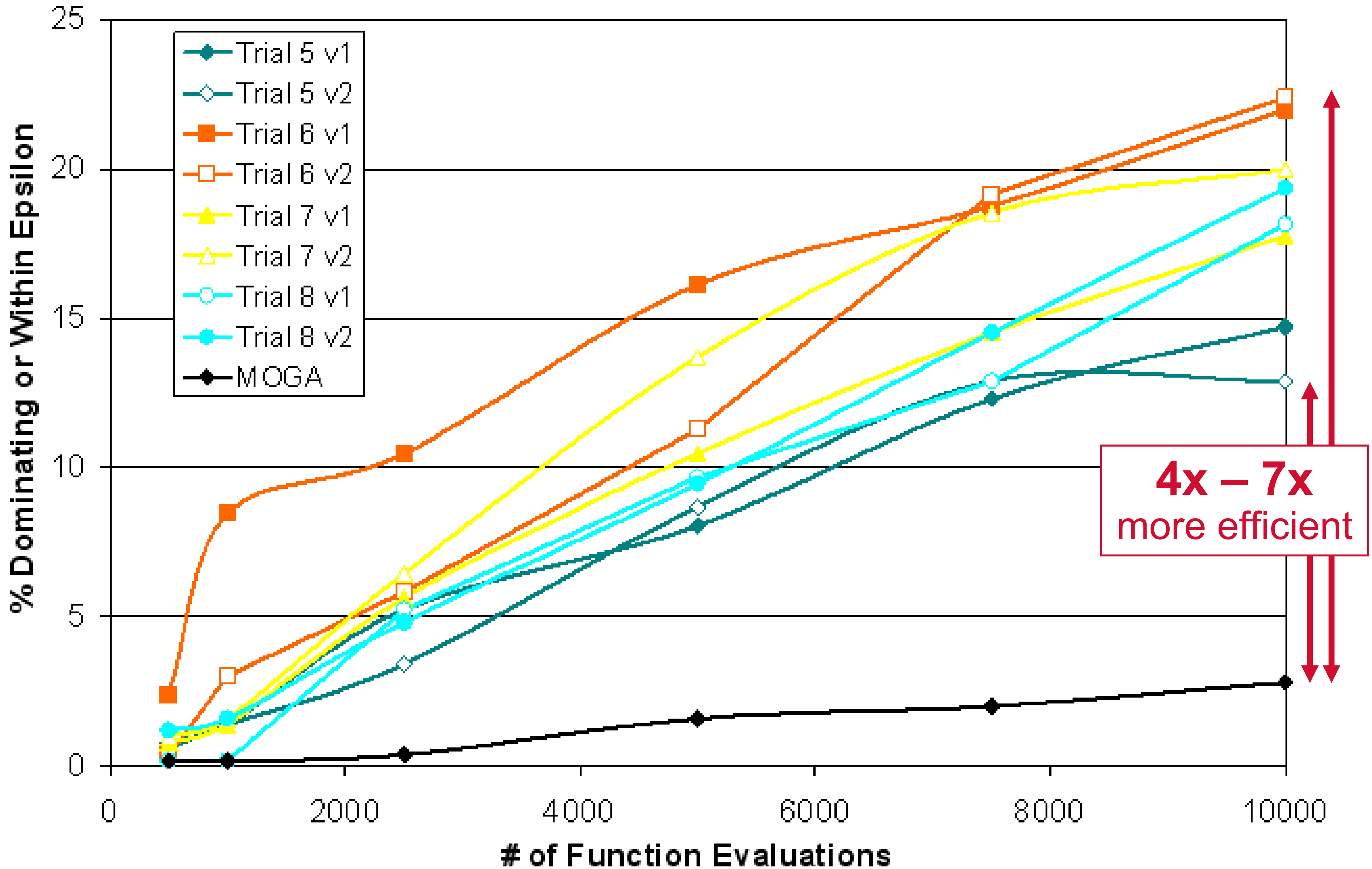
Refer to: (ASME DETC2008-49681)

- 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 1-4 (5,000 pts)

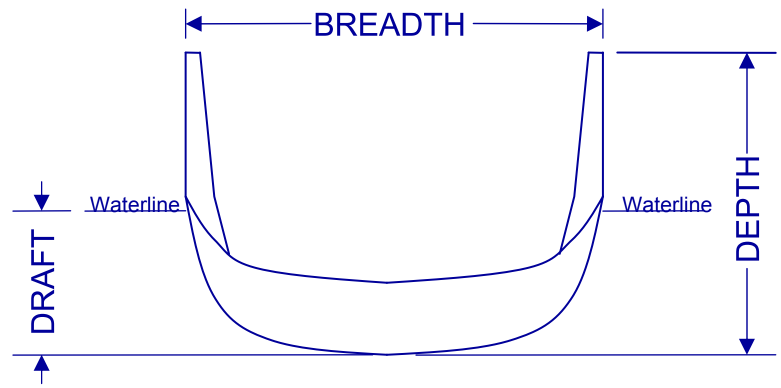


Evolution of Solutions for Trials 5-8 (10,000 pts)



Conceptual Ship Design

Analytical model* approximates a family of bulk carriers with deadweight between 3,000-50,000 tons and speeds of 14-18 knots



<u>Design Variables</u>:

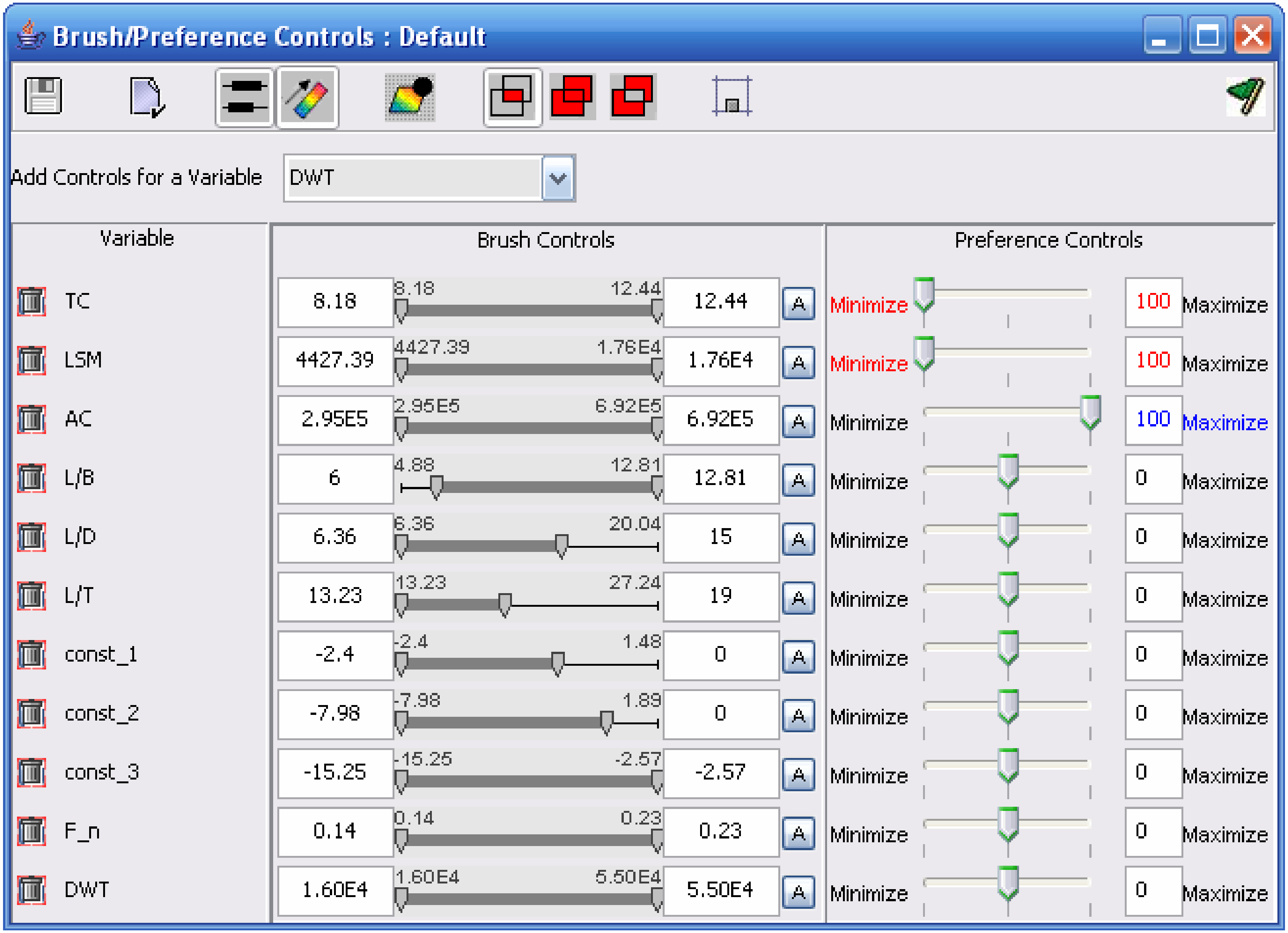
1. Length, $150 \leq L \leq 274.32$
2. Beam, $21 \leq B \leq 32.31$
3. Depth, $12 \leq D \leq 25$
4. Draft, $9.5 \leq T \leq 11.71$
5. Block Coefficient, $0.63 \leq C_B \leq 0.75$
6. Speed, $14 \leq V_k \leq 18$

<u>Problem Statement</u>:

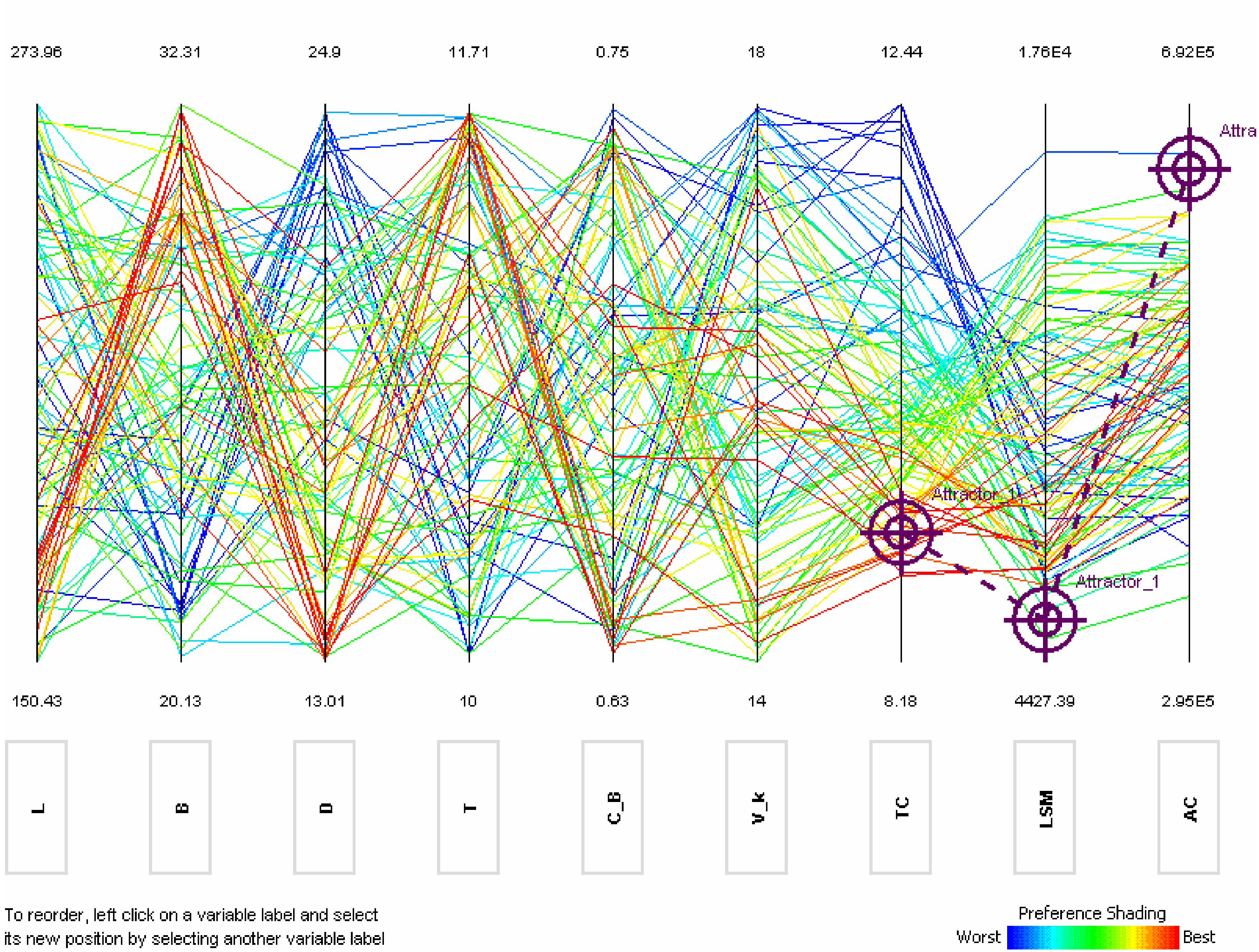
Minimize:	Transportation Cost
Minimize:	Light Ship Weight
Maximize:	Annual Cargo
subject to:	Nine (9) constraints

* Parsons and Scott (2004) & Sen and Yang (1998)

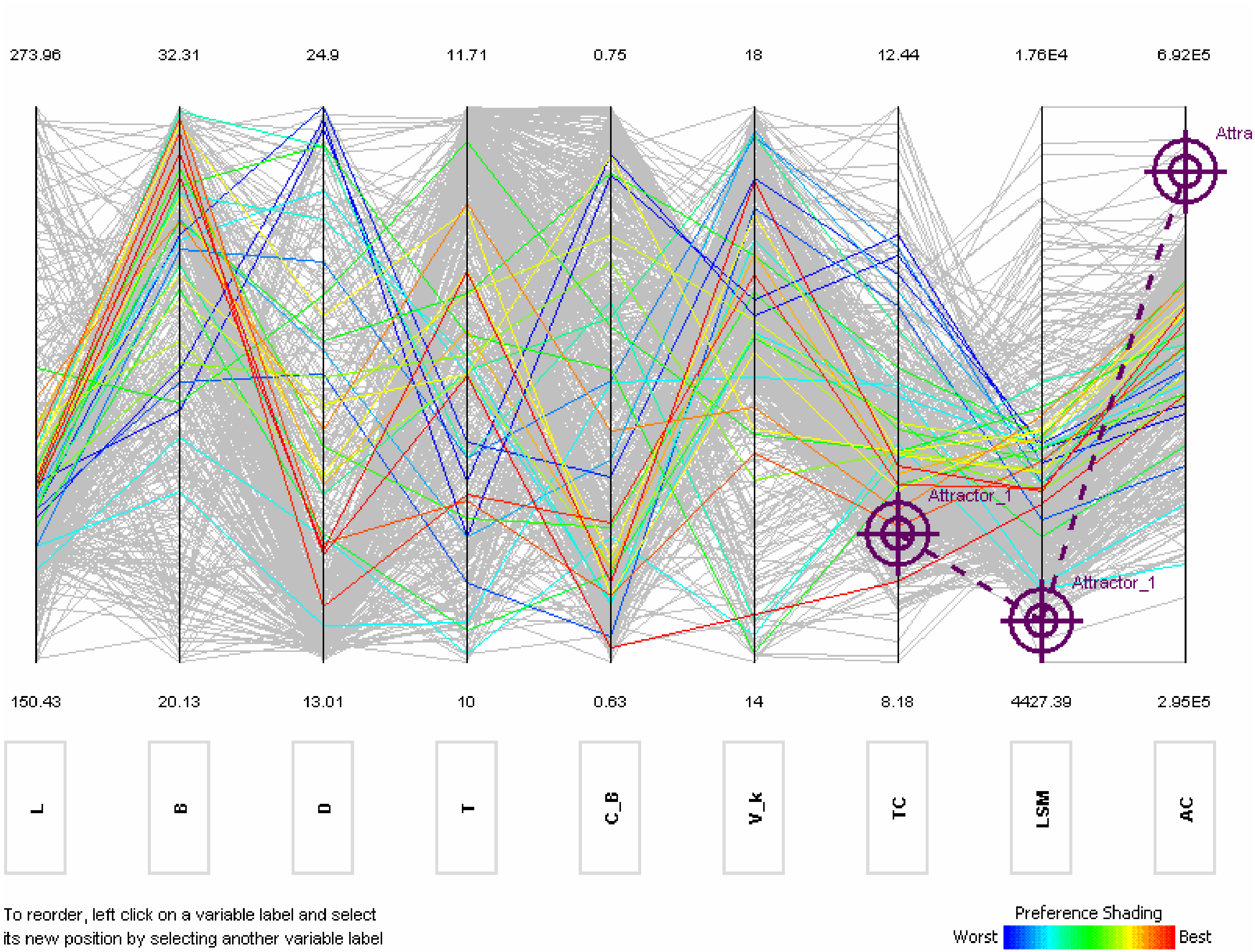
Problem Formulation in ATSV



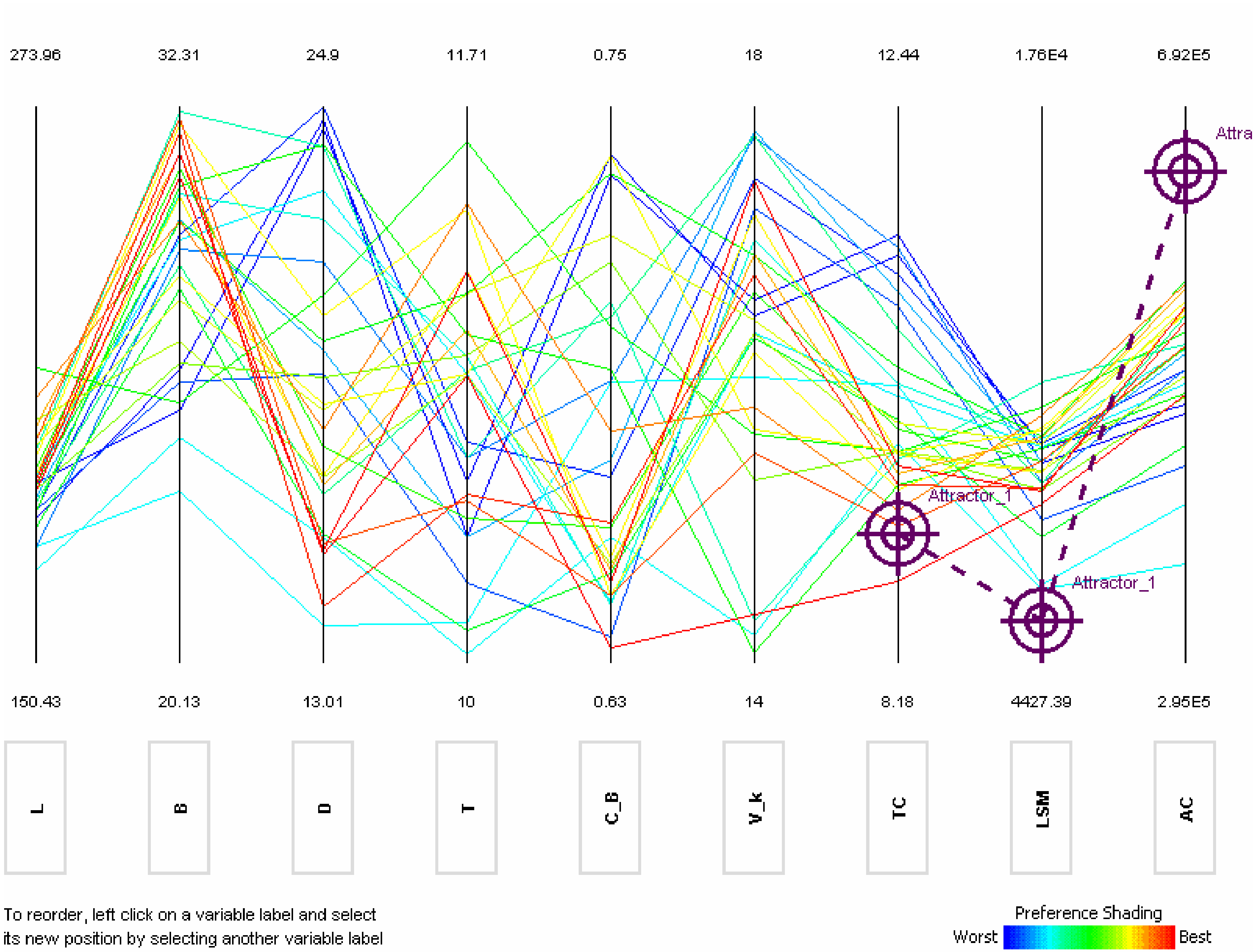
Using Attractors for Three Objectives



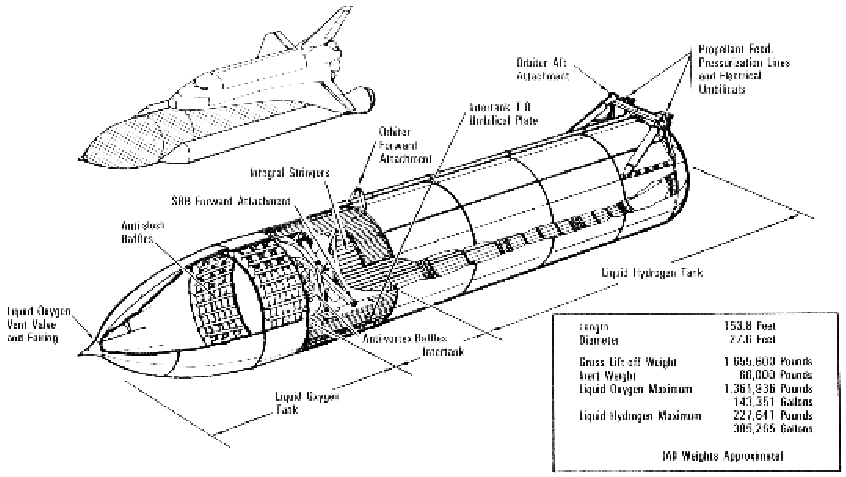
Visualization of Results



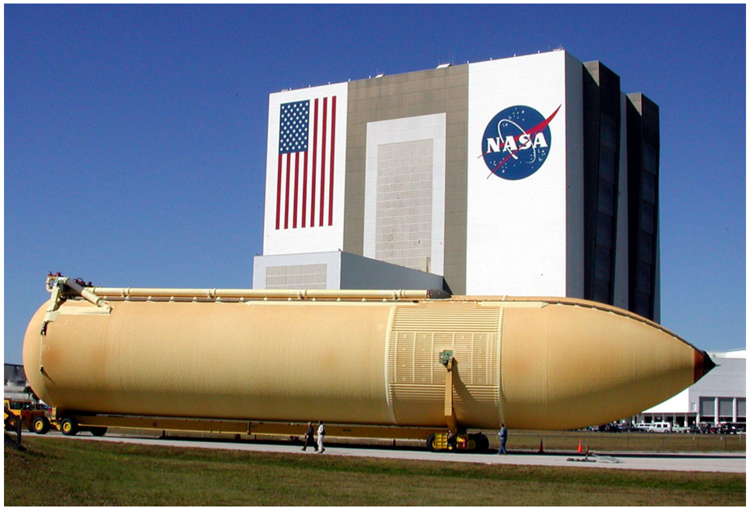
Visualization of Results

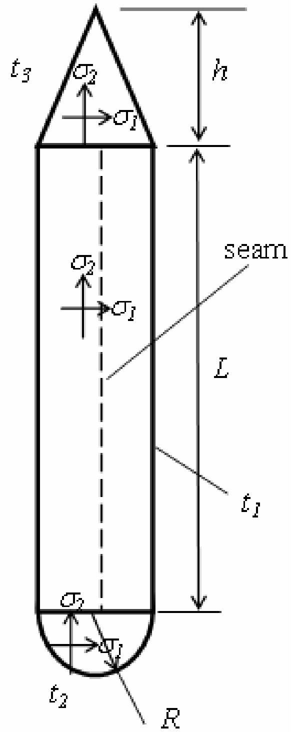


Space Shuttle External Fuel Tank



Lightweight External Tank





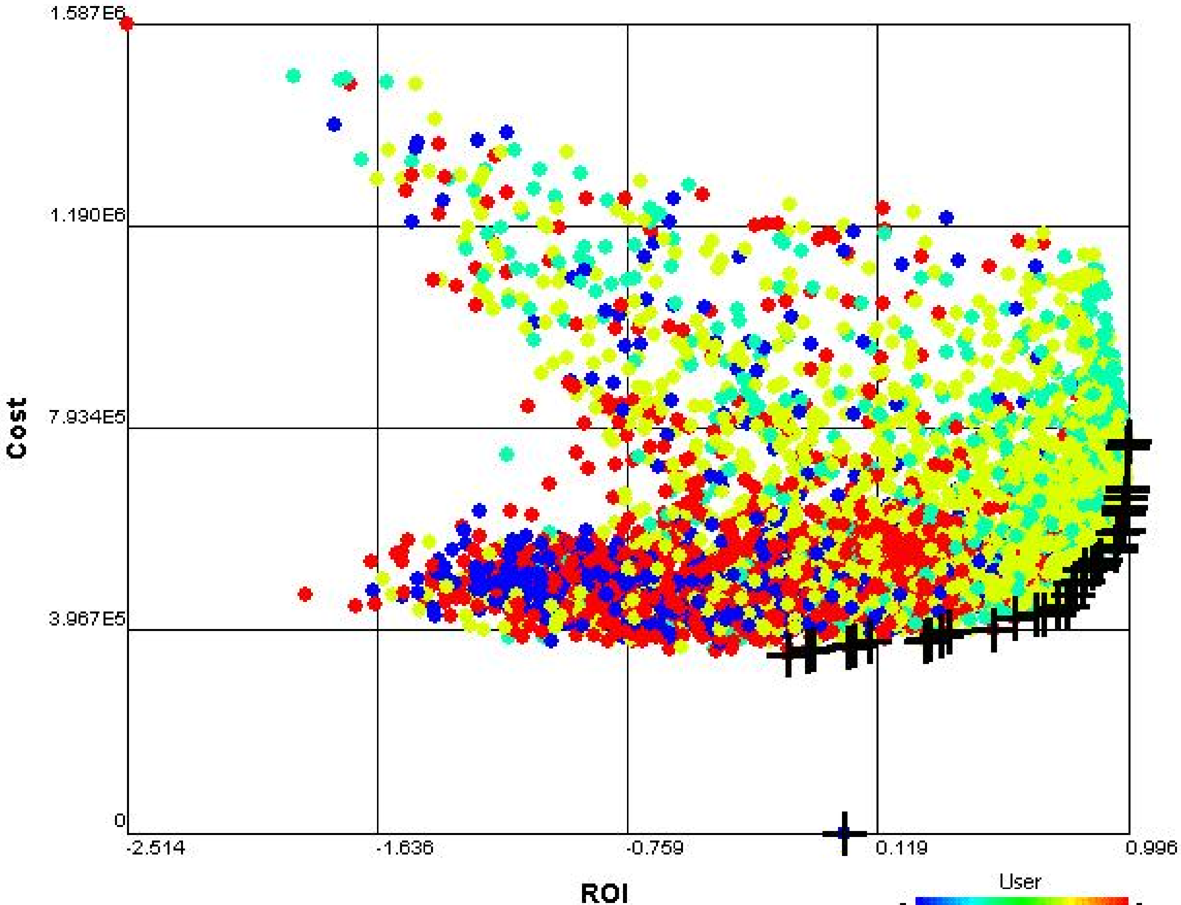
Originally developed by Dr. Jaroslaw Sobieski to illustrate how changes in a problem's objective function can influence the resulting optimal design

Minimize: ROI

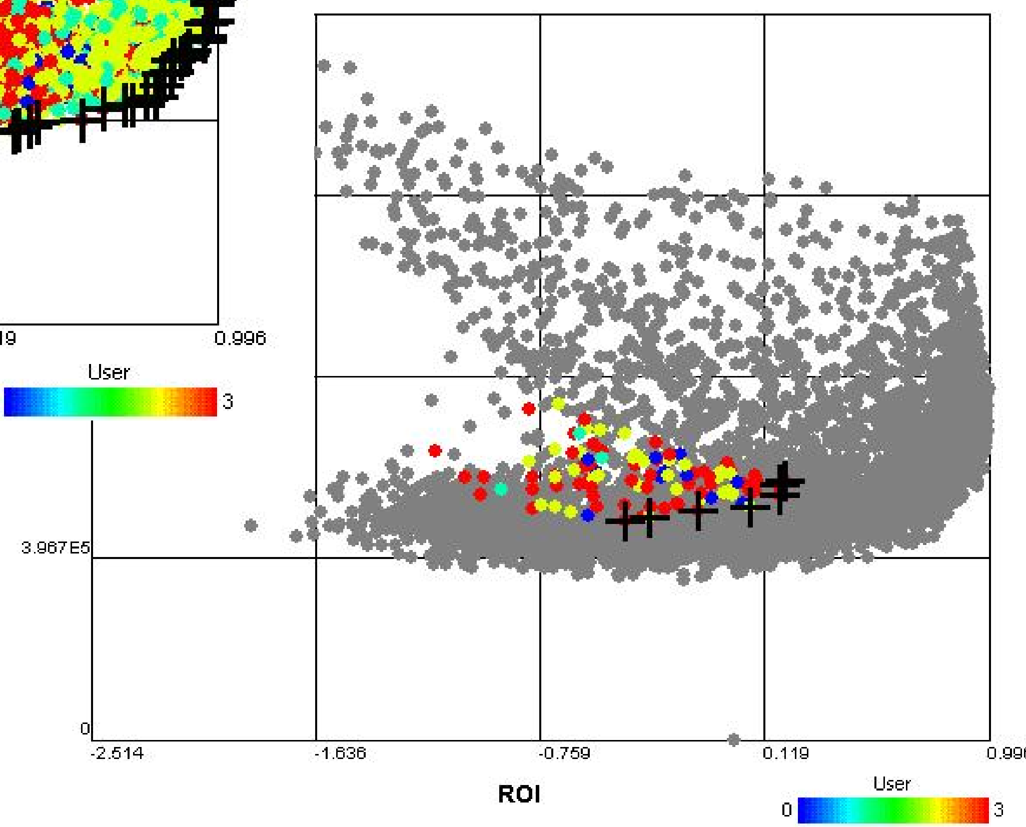
Subject to: volume, stress, and vibration constraints + bounds:

$0.01 \leq L_n \leq 5.0$	$0.25 \leq t2_n \leq 2.0$
$0.50 \leq R_n \leq 2.0$	$0.25 \leq t3_n \leq 2.0$
$0.25 \leq t1_n \leq 2.0$	$0.10 \leq h/R_n \leq 5.0$

Distributed Collaborative Design Experiments



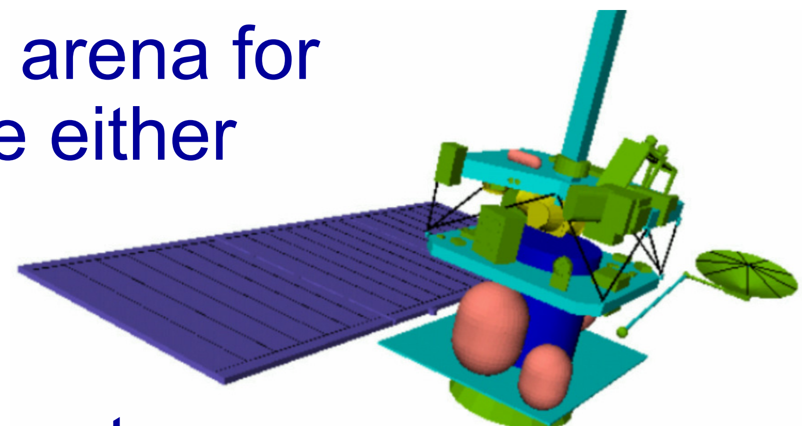
- Problem divided into:
  - System engineer
  - Cost engineer
  - Structural engineer
  - Aerodynamic engineer



- Each user steers own portion of the model
  - Colors indicate the designs they explored
  - Gray means infeasible

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