Decision Making Methods in Space Economics and Systems Engineering

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Decision Methods Outline

A. **A Catalog of DM Methods**
- Business Case Analysis / Financial Techniques
- Systems Engineering / Trade Studies Techniques

B. **Summary and Observations**

A. A Catalog of Decision Making Methods

A Catalog of Decision Making Methods in Space Economics and Systems Engineering

- Present Value and IRR
- Cost-Benefit Analysis
- Real Options

} Business Case Analysis/Financial Techniques

- Cost-Effectiveness Analysis
- Cost-Utility Analysis
- Multi-Attribute Utility Theory (MAUT)
- Analytic Hierarchy Process (AHP)

} SE/Trade Study Techniques

Note: Decision processes may use decision analysis (trees), Monte Carlo simulation techniques, and game theory (e.g., Nash equilibrium) as an overlaid framework for handling uncertainty.

Present Value and IRR

- Primary application in business case analysis for commercial and some government investments

- Requires estimation of the stream of costs, *C*, and revenues, *R* (or savings)

  - PV calculation $$PV(r,T) = \sum_{t=0}^{t=T} (R_t - C_t)(1+r)^{-t}$$
  - IRR calculation $$IRR = r^* \text{ such that } PV(r^*,T) = 0$$

- Treatment of uncertainty?

Cost-Benefit Analysis

- Given a market failure situation, should a particular (public) investment be made?
- The foundation of cost-benefit analysis is the *Kaldor-Hicks compensation principle*.
- Distributional (equity) issues are not addressed, and so-called "secondary" or "intangible" benefits are typically ignored.
- Benefit measures for public investment projects designed to ultimately benefit consumers are generally based on the concept of *willingness-to-pay*.
- Cost-benefit analysis is appropriate when there are market prices that can be used to infer the values of the goods or services produced by the public investment.

Real Options Analysis

- Real options valuation is a financial technique for evaluating investments under conditions of uncertainty, particularly uncertainty associated with market variables such as future product demand or the future value of an asset.
- Option pricing is a well-developed area of financial engineering, where it deals with the valuation of puts, calls, and more complex derivatives, but when applied to non-financial assets, the term "real options" is used.
- In real options valuation, the general ideas from financial options pricing theory are used along with some of the mathematics.

Basic Concepts of Real-Options Valuation

"The future is uncertain . . . and in an uncertain environment, having the flexibility to decide what to do after some of that uncertainty is resolved definitely has value. Option-pricing theory provides the means for assessing that value"

Robert C. Merton

Nobel Lecture, 1998

Would You Have Invested?

Microsoft Corporation, 1978

Basic Concepts of Real-Options Valuation

- The real-options approach captures the additional value of managerial flexibility inherent in any phased investment, which makes it more suitable than older methods.
  - Mathematical representation of flexibility to alter course
  - Bring market information to bear when its available
  - Powerful analytic techniques based on stochastic processes
- The value v of a real (non-income producing) option that pays off W(T) at future time T is given by the general formula:

$$v(t,T) = \exp(-r\,(T - t))\, E[\max(0, W(T))]$$

where t is current time, E denotes the risk-neutral expected value, and r is the riskless discount rate.

Space Applications of Real-Options Techniques

- Making commercial satellites compatible with on-orbit servicing

  Lamassoure, E., Saleh, J., and Hastings, D., "Space Systems Flexibility Provided by On-Orbit Servicing, Parts 1 and 2", *Journal of Spacecraft and Rockets*, Vol. 39, No. 4, pp. 551-570, July-August 2002

- NASA technology evaluation

  Shishko, R. Ebbeler, D., and Fox, G. "NASA Technology Assessment Using Real Options Valuation", *Systems Engineering*, Vol. 7, No. 1, pp. 1-12, February 2004

Cost-Effectiveness Analysis

- A general approach to the analysis of alternatives (trade studies) that attempts to quantify selected MoEs and LCC
  - Focus on choosing the best alternative from among competing alternatives, not on whether the project is worth doing
  - Should not be confused with Cost-Benefit Analysis

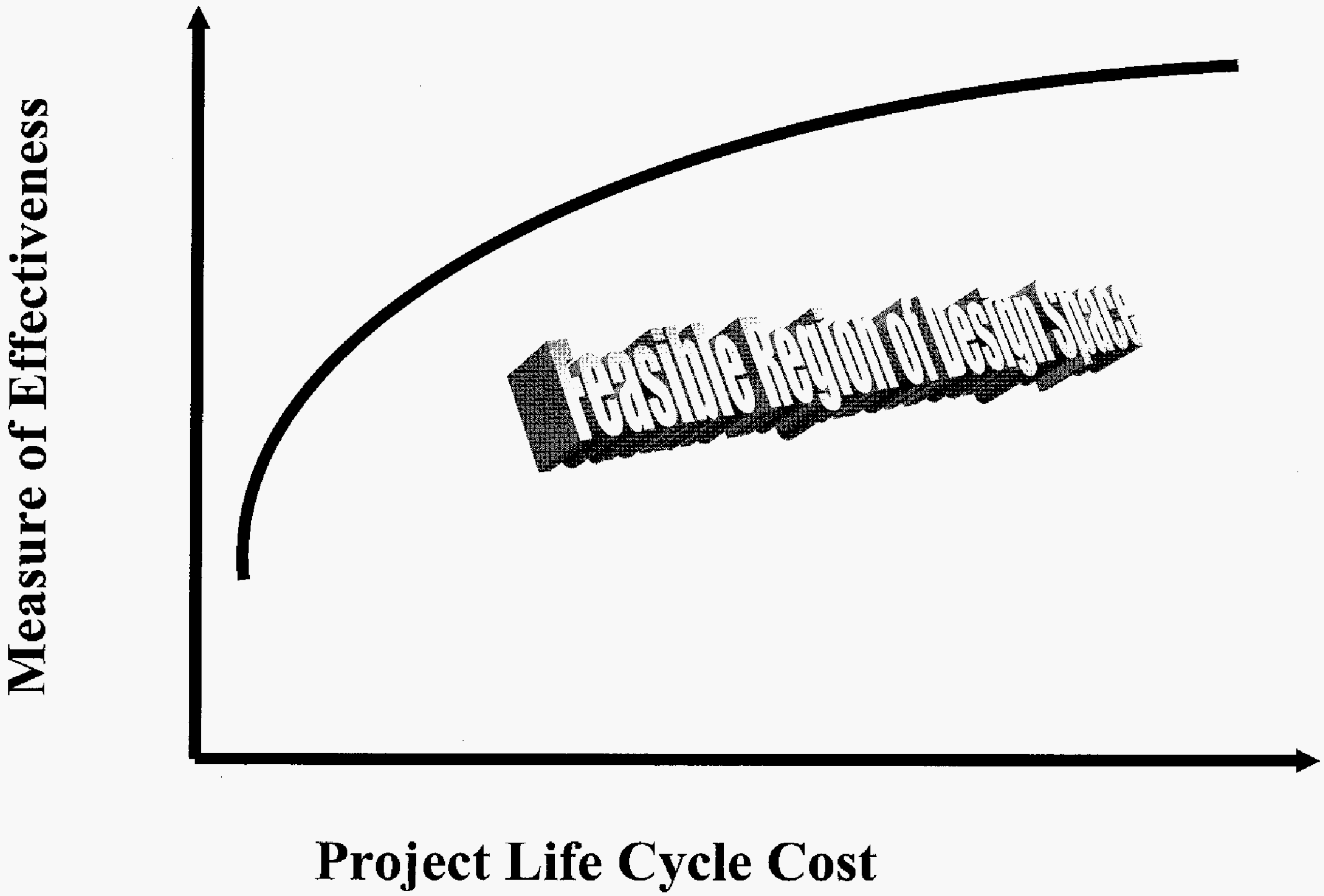
- Heavy reliance on engineering, operations, and cost models/simulations

- Permits exploration of the tradespace for design optimization (batch mode)

Measures of Effectiveness

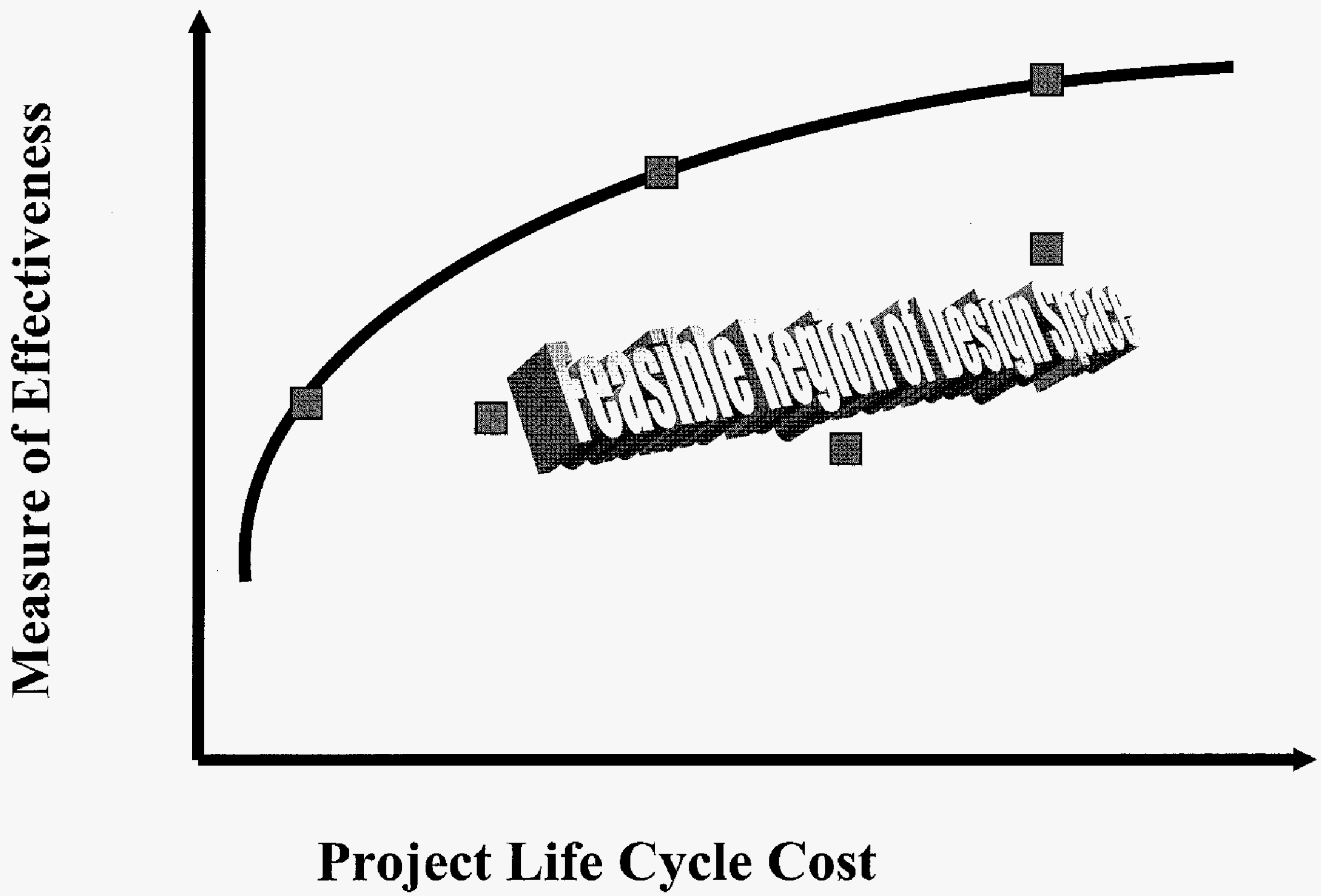
- A mission Measure of Effectiveness (MoE) is defined as a quantitative measure of the degree to which the mission's purpose is achieved.
  - For example, how much the mission returns in science data, and what the resolution and coverage are.
- It often depends on measures of performance (MoP), or size and quantity measures of several inputs. (A "Design Vector")
  - Launch vehicle probability of success and injected mass
  - EDL reliability
  - Instrument performance
  - Spacecraft subsystem (power, C&DH, telecomm, etc.) performance.
- Cost is NOT a Measure of Effectiveness; cost is a measure of the resources foregone.
- Cost-effectiveness is represented by a combination of both -- preferably as the whole Pareto frontier, but sometimes as points on that frontier.

Cost-Effectiveness Frontier (Pareto Optimal Frontier)



Level of effectiveness or level of cost usually is an external decision.

Cost-Effectiveness Frontier (Pareto Optimal Frontier)



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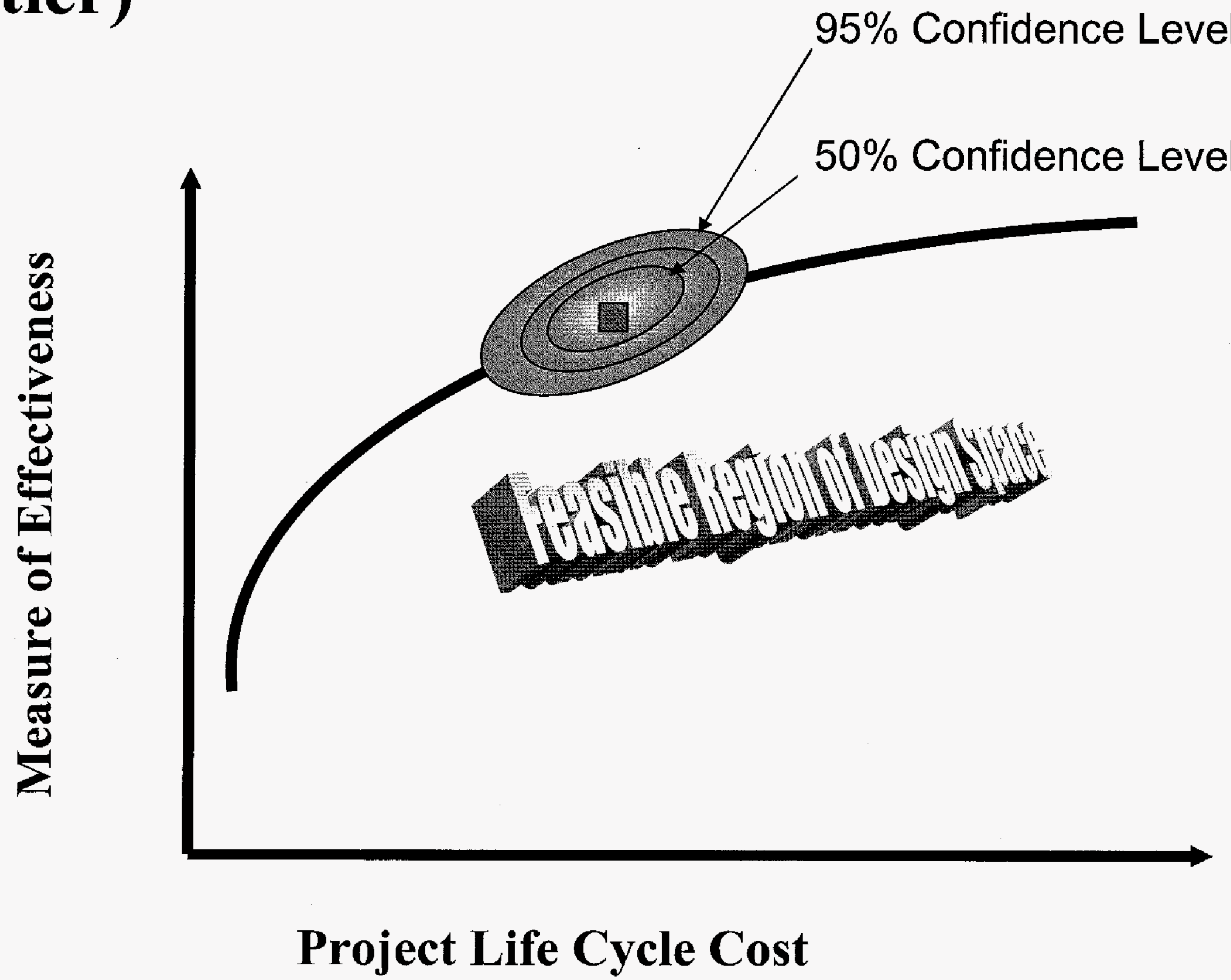

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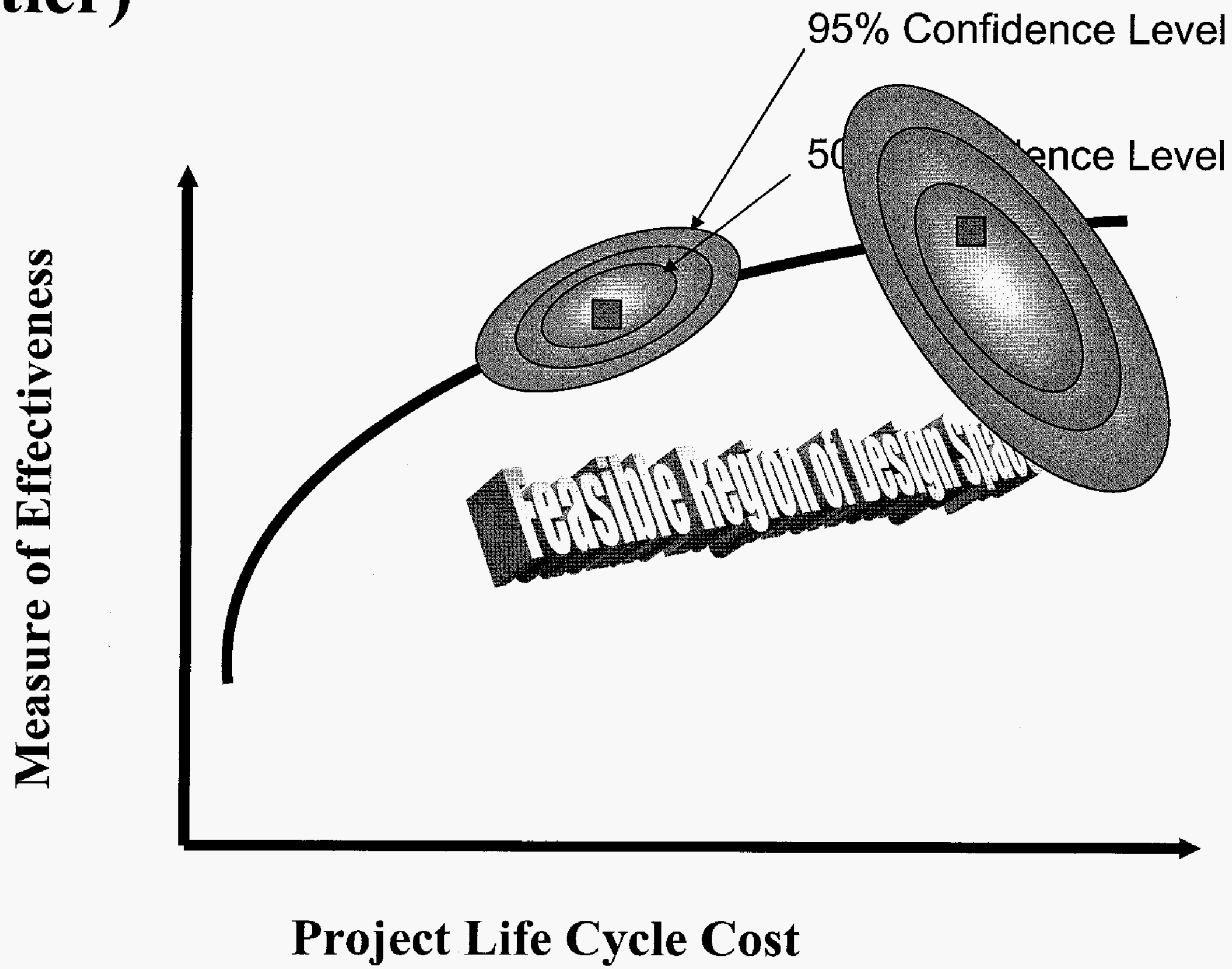

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Cost-Utility Analysis

- Similar in intention to cost-effectiveness, but uses a utility function to translate outcomes into a single decision variable
- Uses basic decision analysis concepts (vN-M utility theory) for decisions under risk.
- Decision analysis rests on 4 (sometimes 5) axioms requiring rationality when making decisions under risk.
- Useful when outcomes are uncertain and decision maker is not risk neutral

Cost-Utility Analysis: Technical Aspects

- Alternative with the highest expected utility is preferred

$$E(U) = \sum_i p_i U(X_i)$$

$$CE = X \text{ such that } U(X) = E(U)$$

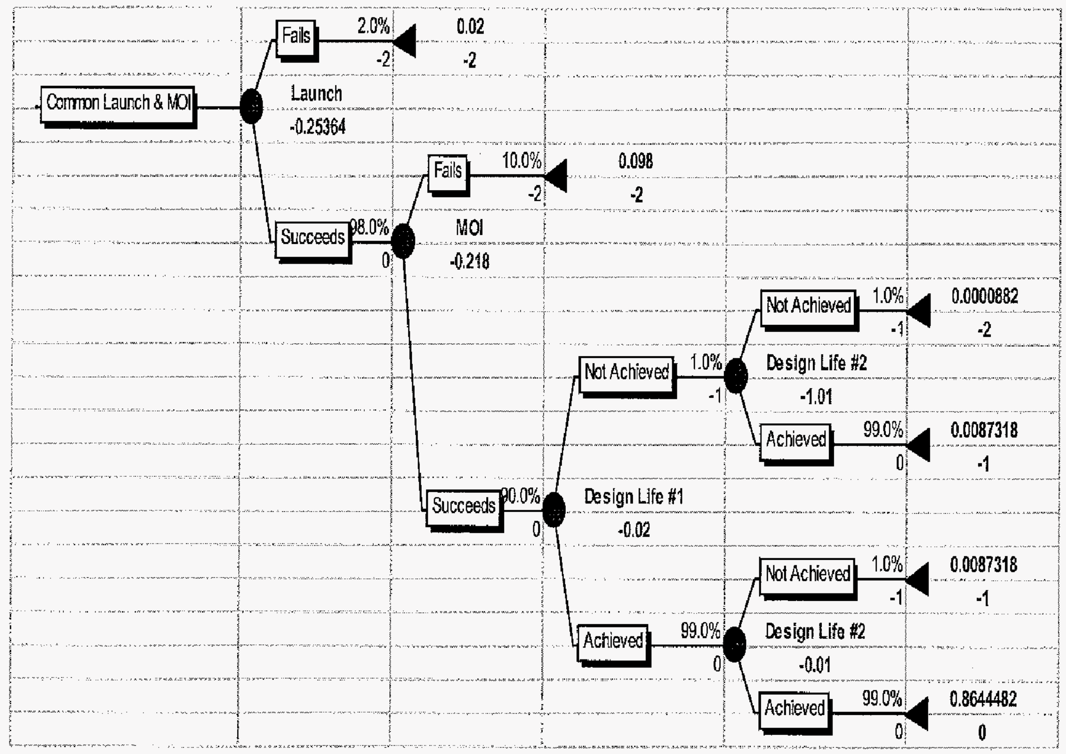
- Typically, decision trees are used to represent alternatives and probabilities of risk events
- Functional form selected for convenience
- Exponential form:

$$U(X) = a - be^{-rX} \quad r, b > 0$$

- Parameters are determined by asking decision maker to compare various "lotteries"

Mars Risk Model: Decision Tree

- Risk model building process involves (for each option):
  - Identify key risk events
  - Develop a decision tree
  - Solve tree
  - Calculate certainty equivalent (CE) as risk metric



Mars Risk Model: Spreadsheet Version

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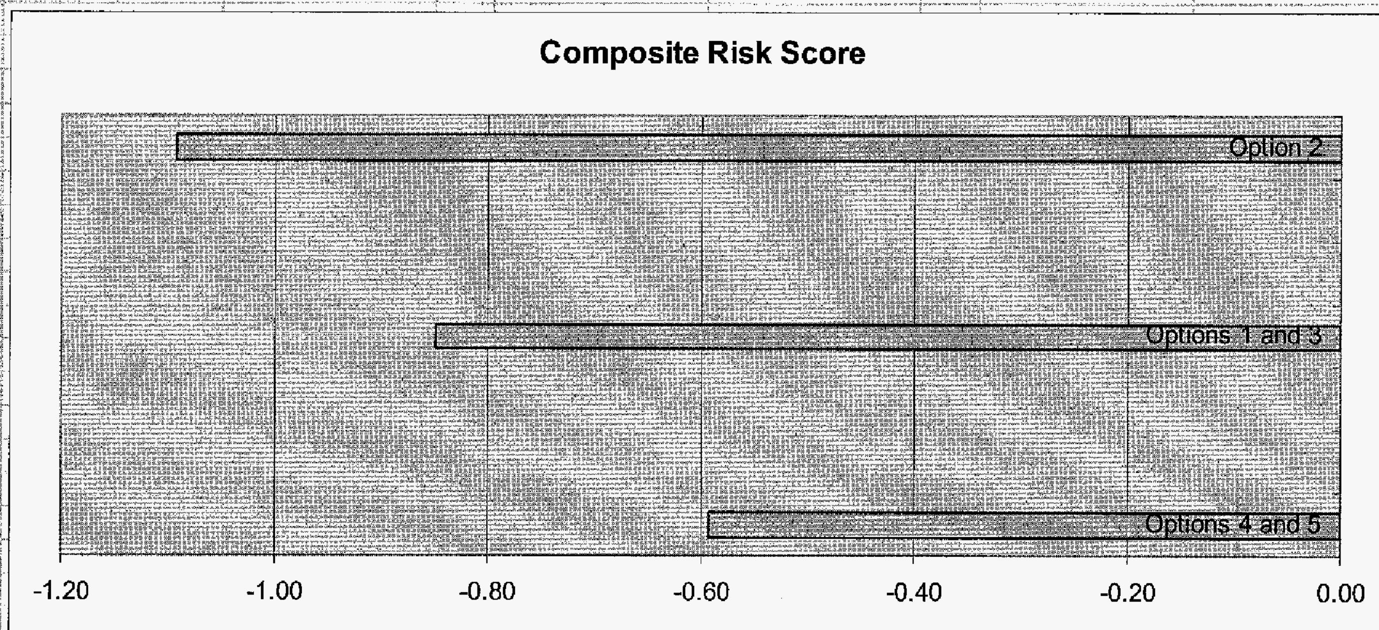
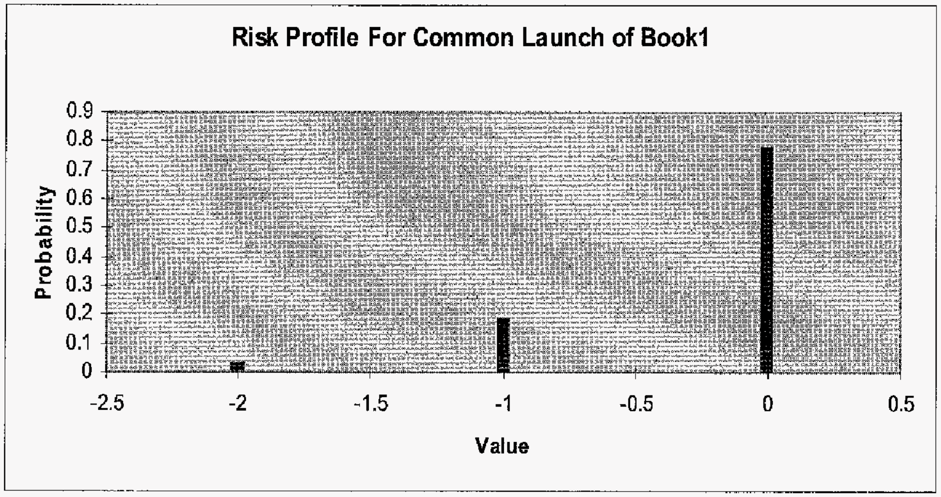
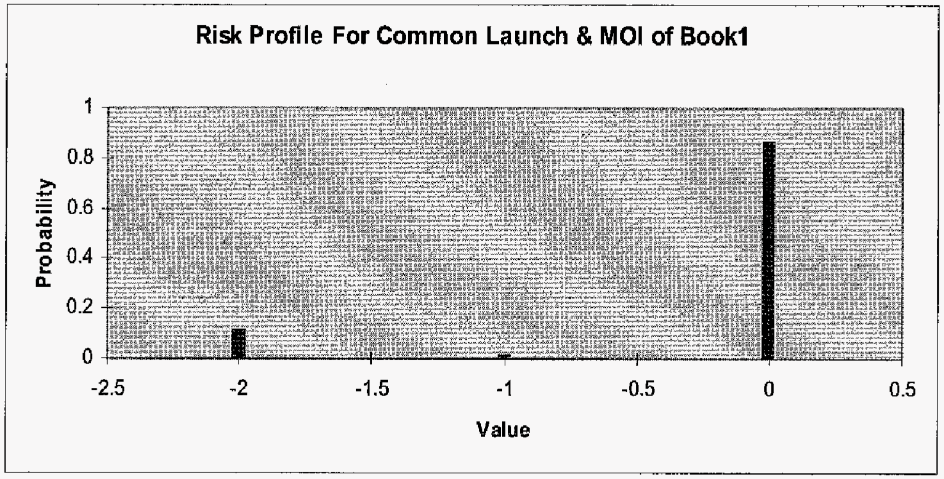
Project:	Mars '03		Risk Assessment		Risk Aversion	2.00
Option Name:	Options 4 and 5		Options 1 and 3		Option 2	
Option Description:		2 Delta launches; 2 separate S/C		1 launch; 2 separate S/C		1 launch; 1 S/C thru MOI
Events	Likelihood of Occurrence	Severity of Consequences	Likelihood of Occurrence	Severity of Consequences	Likelihood of Occurrence	Severity of Consequences
S/C #1 Launch Failure	2.00%	Lose one S/C	5.00%	Lose two S/C	5.00%	Lose two S/C
S/C #1 MOI Failure	10.00%	Lose one S/C	10.00%	Lose one S/C	10.00%	Lose two S/C
S/C #1 Design Life Failure	1.00%	Lose one S/C	1.00%	Lose one S/C	1.00%	Lose one S/C
S/C #2 Launch Failure	2.00%	Lose one S/C				
S/C #2 MOI Failure	10.00%	Lose one S/C	10.00%	Lose one S/C		
S/C #2 Design Life Failure	1.00%	Lose one S/C	1.00%	Lose one S/C	1.00%	Lose one S/C
		Options 4 and 5		Options 1 and 3		Option 2
Composite Risk Score		-0.59		-0.85		-1.09



Mars Risk Model: What is the Risk Metric?

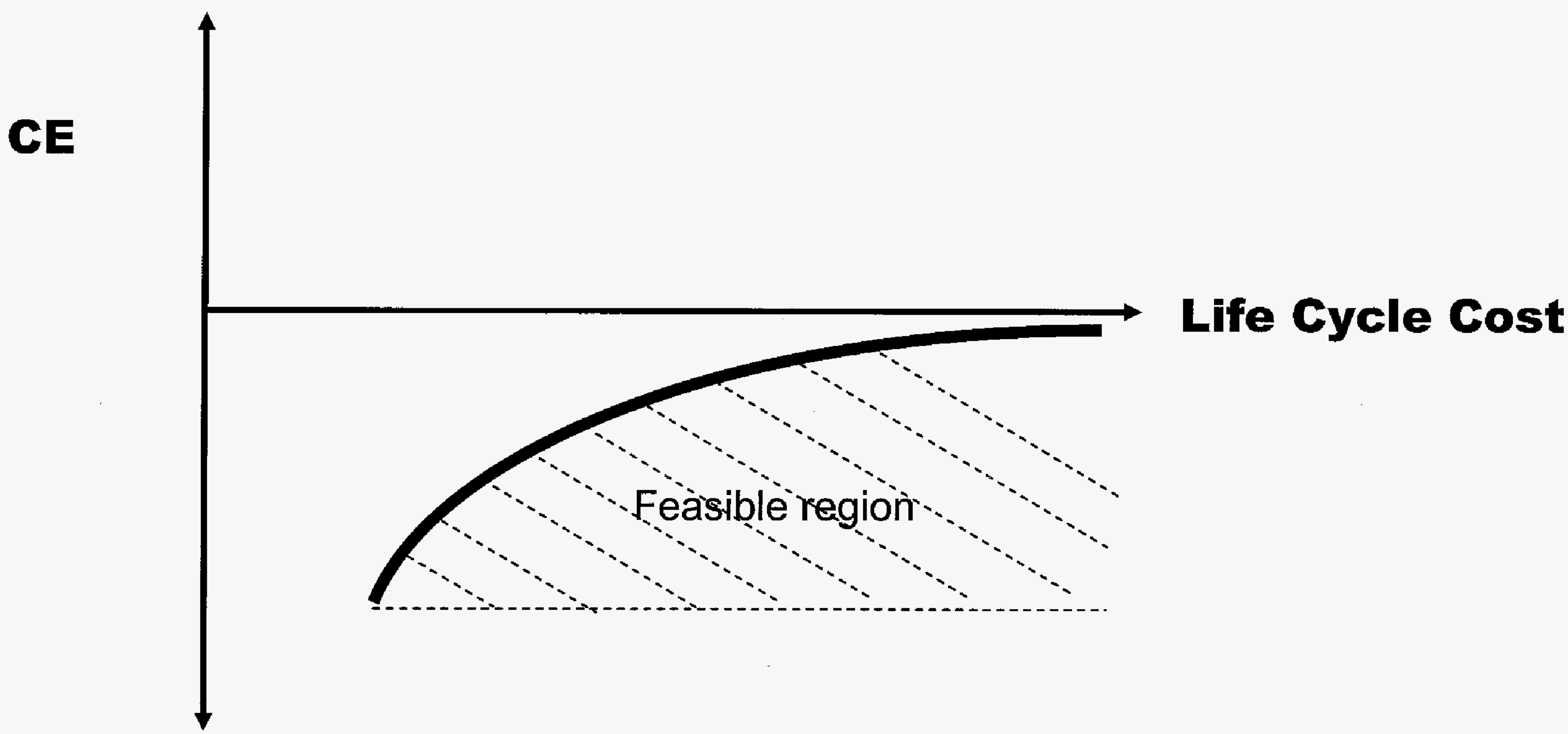
- **Risk metric is "certainty equivalent" (CE)**
  - Amount (outcome) that makes the decision-maker indifferent between accepting the "gamble" (shown at right) or taking with certainty
  - Comparing CEs provides a rational way of selecting alternatives; the higher CE option is always preferred
  - Mathematically related to the concepts of "risk aversion" and "risk premium"
- **In Mars Risk Model spreadsheet, CE units are "spacecraft lost", hence a less negative number is preferred**





Mars Risk Model: Adding Costs

Add costs to develop the Pareto optimal frontier

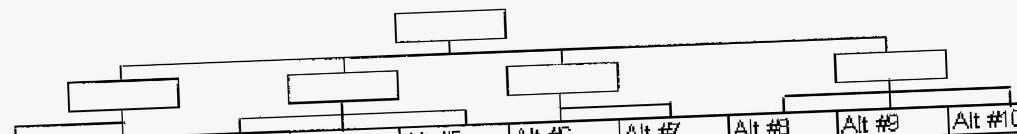


Multi-Attribute Utility Theory

- Extends utility concept to situations with multiple, usually conflicting, decision attributes
- Select a set of decision attributes (criteria)
  - Recommend between 3 and 10
  - Attributes can be quantitative or qualitative
  - Getting the right ones can be difficult; need to distinguish among alternatives and should be orthogonal
- Create weights; different groups might disagree on weights
- Develop individual utility functions for each attribute
  - u(best) = 1.0; u(worst) = 0.0
- Calculate total rating (score) for each alternative

Multi-Attribute Utility Theory: Mars Exploration Rovers Example

Trade Tree



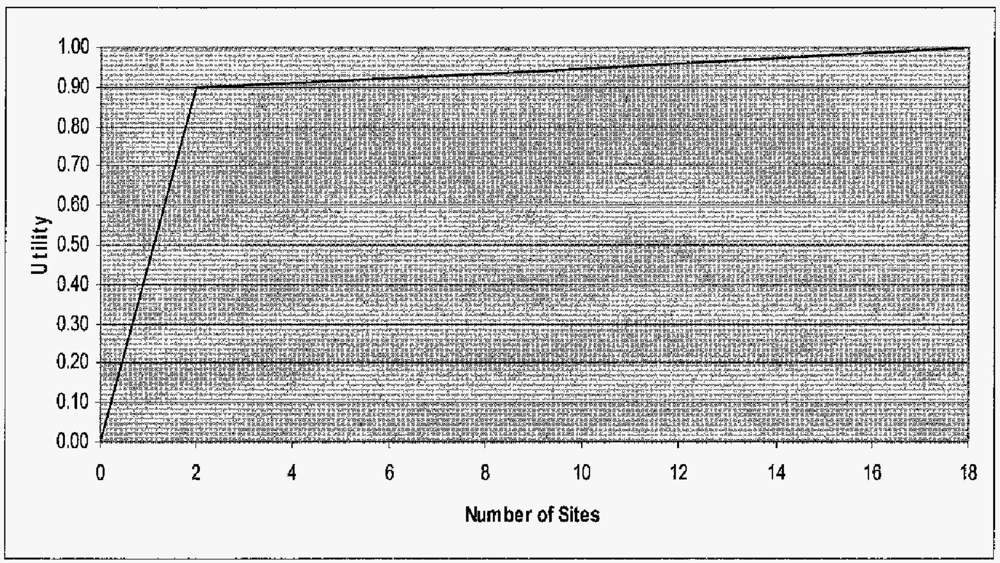
Decision Attributes

Major Criteria	Weight	Sub-criteria	Weight	Alt #1	Alt #2	Alt #3	Alt #4	Alt #5	Alt #6	Alt #7	Alt #8	Alt #9	Alt #10
Mission Reliability/Survivability	40%	Launch Reliability	30%										
		EDL Survivability	35%										
		Surface Reliability	35%										
Science Diversity	30%	E[Mission Duration]	20%										
		Num of Sites	50%										
		Mission Distance	30%										
Affordability	10%		100%										
Operability	20%	Downlink Thruput @3db	50%										
		Decision Cycle Time	25%										
		Command Complexity	25%										
			Rating										

$$Rating_j = \sum_i w_i u_{i,j}$$

Mars Exploration Rovers Example

Attribute	Max	Min	Value	Utility
Experiment 1				
Number of Sites	18	0	0	0.00
			2	0.90
			9	0.94
			15	0.98
			18	1.00
Experiment 3				
Number of Sols	1000	10	10	0.00
			90	0.70
			180	0.80
			500	0.90
Experiment 4				
Distance Traversed	80	0	0	0.00
			10	0.80
			40	0.96
			60	0.98
			80	1.00



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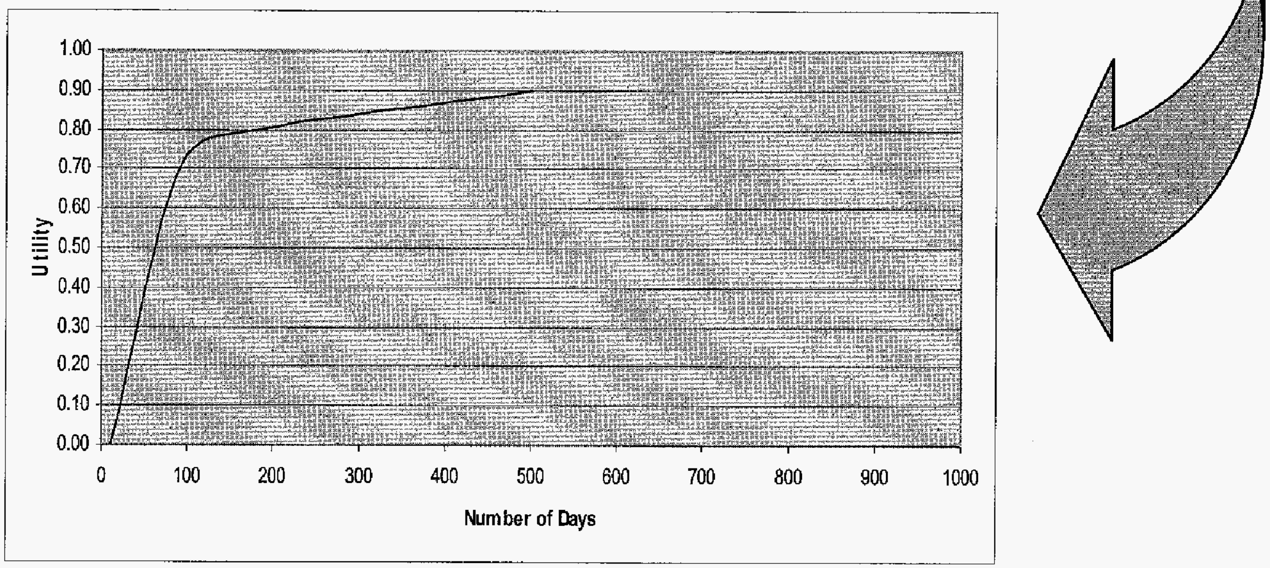

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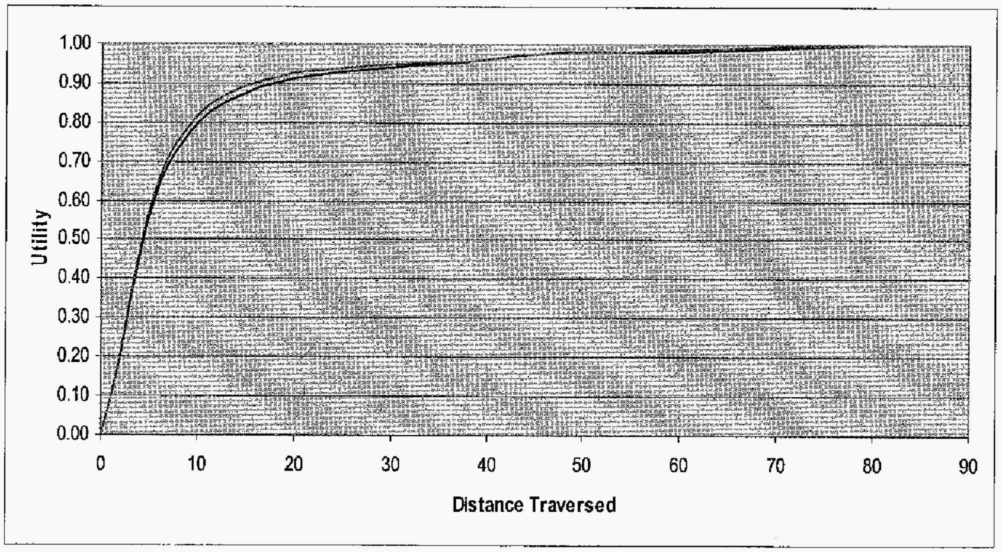
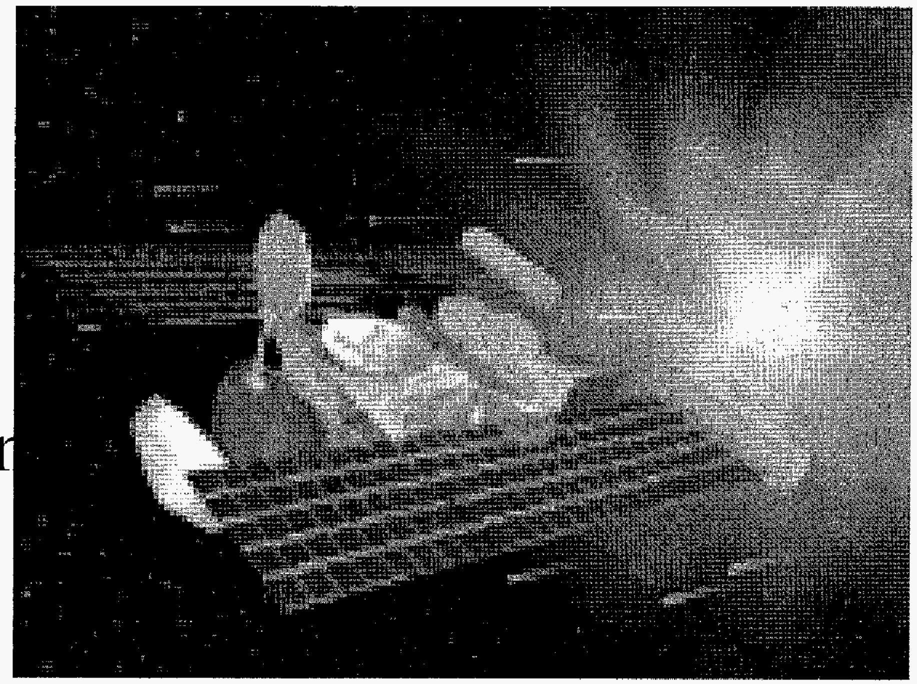


Comet Flyby Example

- Scientists want to get close to obtain better samples, but are aware of the risks.
- Engineers are concerned about losing the s/c, so they want to stand-off.
- Assume a flyby closest approach between 100 km an 1,000 km of the nucleus are acceptable to both Project Engineers and Project Scientists.



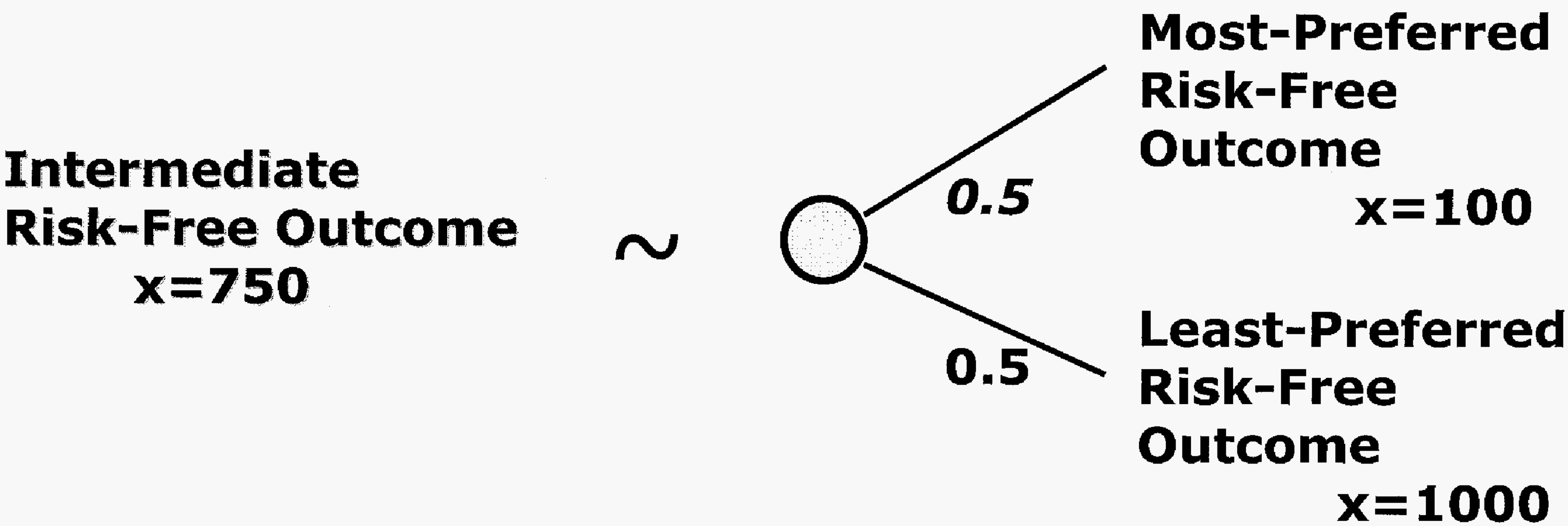
Project Manager's Decision Dilemma

- Different decisions favor different groups
- Individual utility functions need to quantified
- Need to combine the individual utility functions into a single (SW) function to be "optimized."
- Largely a "political" decision

Comet Flyby Example: Scientist's Utility Function

Hypothetical Example to Illustrate the Theory

u(x=1000) = 0.0 u(x=100) = 1.0



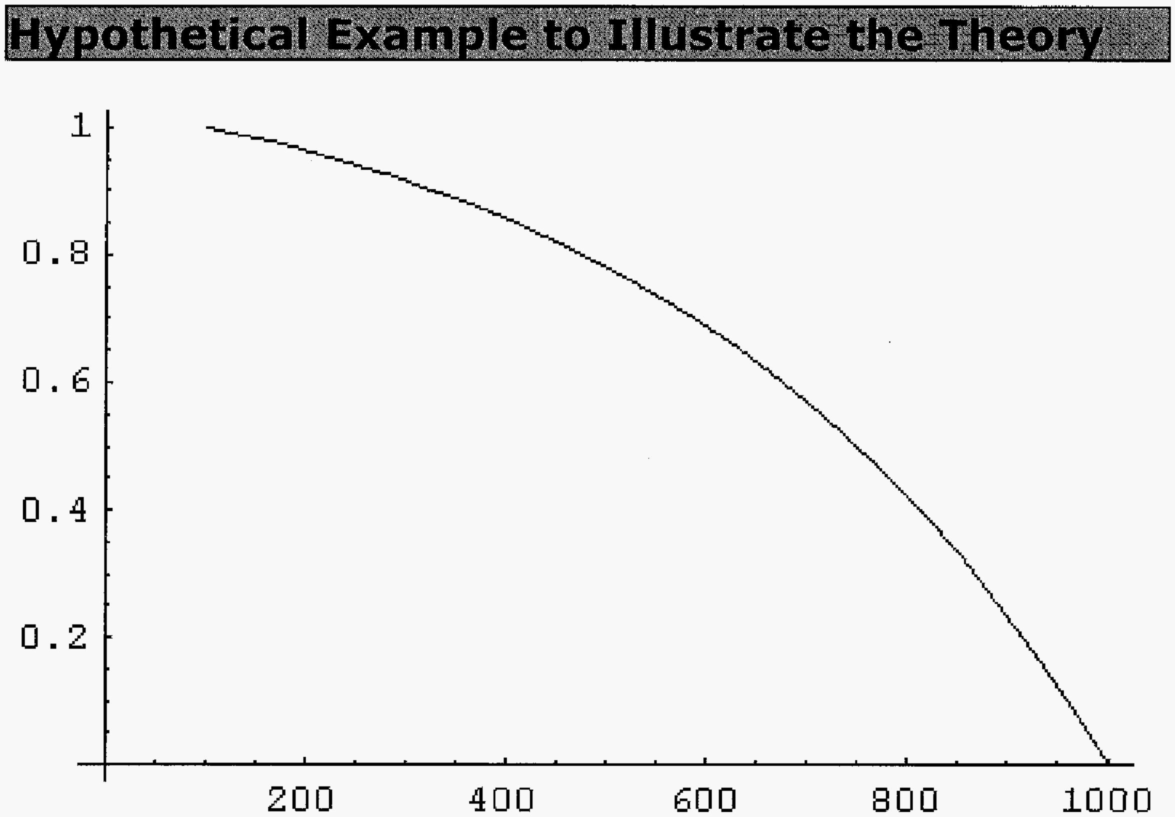
Then u(x=750) = 0.5, from above indifference relationship

Using the constant risk aversion utility function:

$$u(x) = 1.145(1 - e^{-0.0023(1000-x)})$$

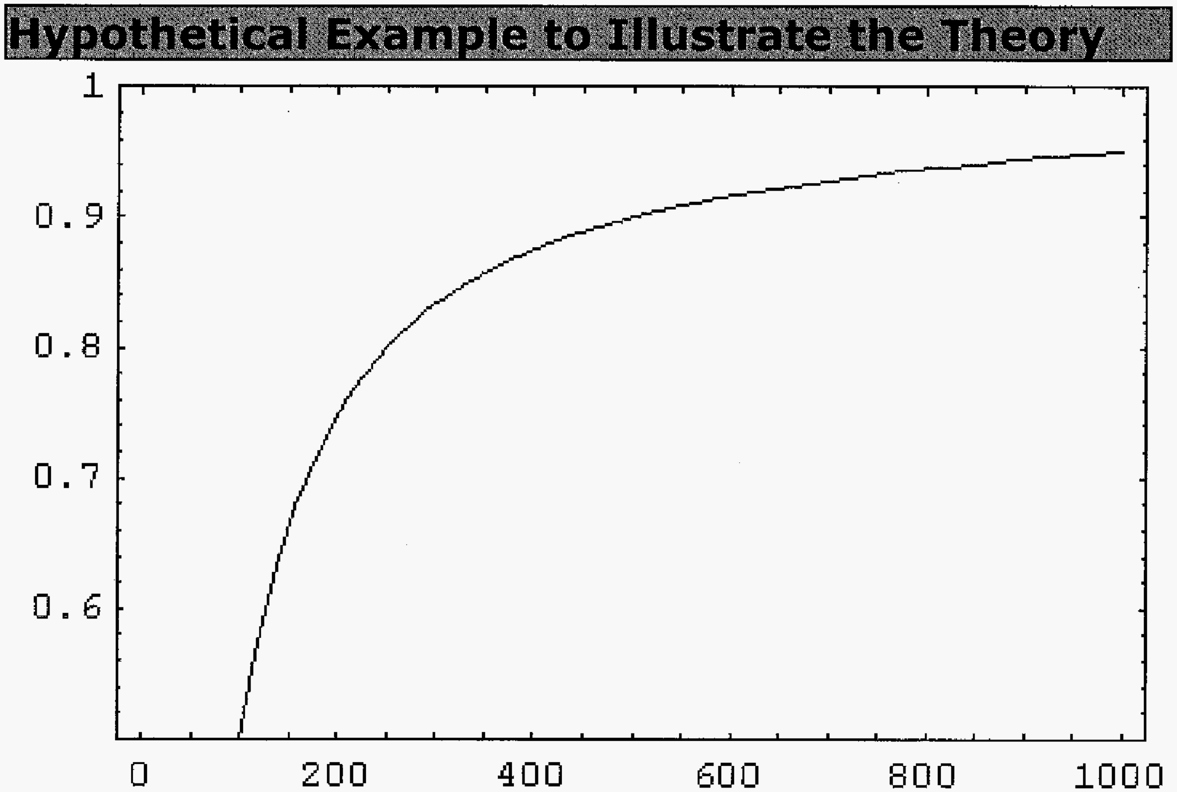
Science Value for Comet Flyby

Assume indifference between science at 750 km and a 50/50 gamble between 100 km and 1,000 km. This yields the curve for *v(x)*.



Mission Failure Risk for Comet Flyby

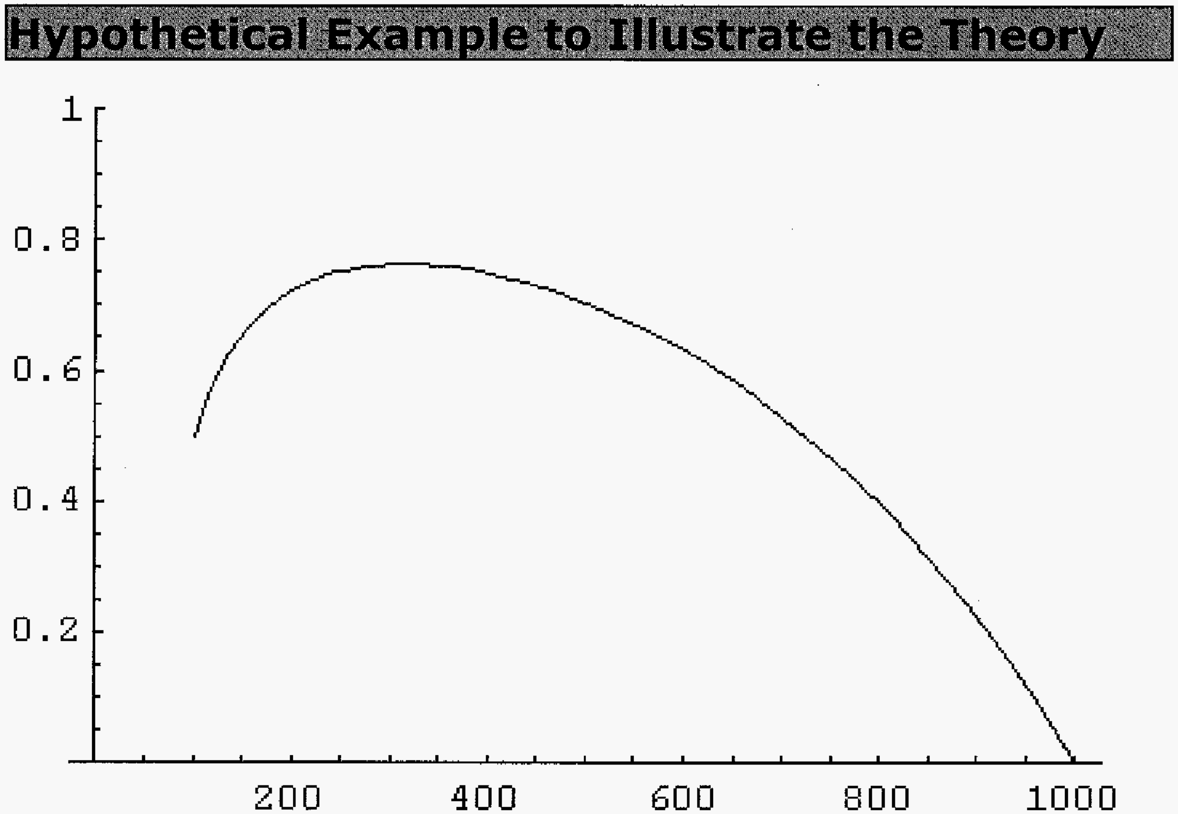
Assume risk increases as (a + b/x), where x is the flyby closest-approach distance.



In this figure, $p(x) = 0.5$ @ 100 km and 0.95 @ 1,000 km.

Utility Function for Comet Scientists

Expected Science Value= $p(x)\ v(x)$



The maximum Expected Science Value is at 315 km.

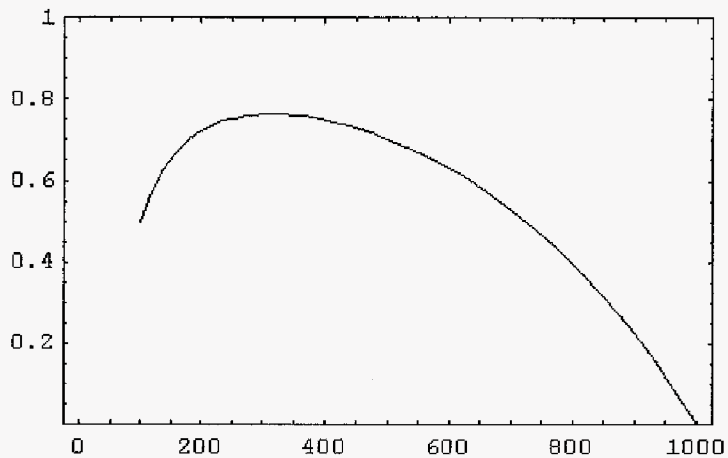
Assume the Following Social Welfare Function

$$SW(U_{Scientists}, U_{Engineers}) = kU_{Scientists} + (1-k)U_{Engineers}$$
$$= kp(x)v(x) + (1-k)p(x)$$
$$0 \le k \le 1$$

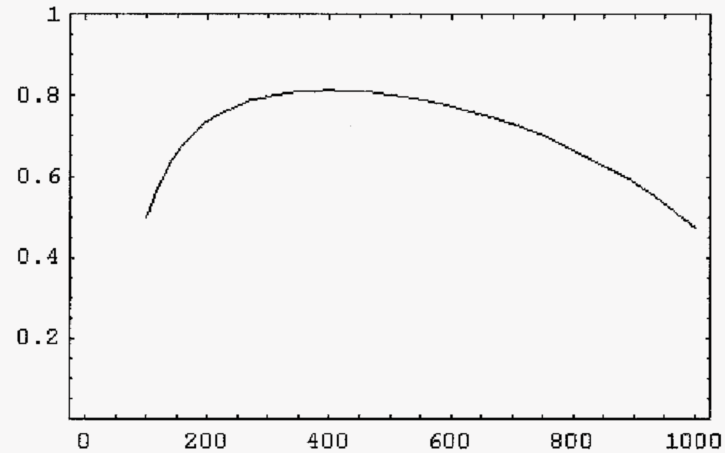
A high value of k favors the project scientists; a low value favors the project engineers in the social welfare function

Different Social Welfare Curves for Comet Flyby

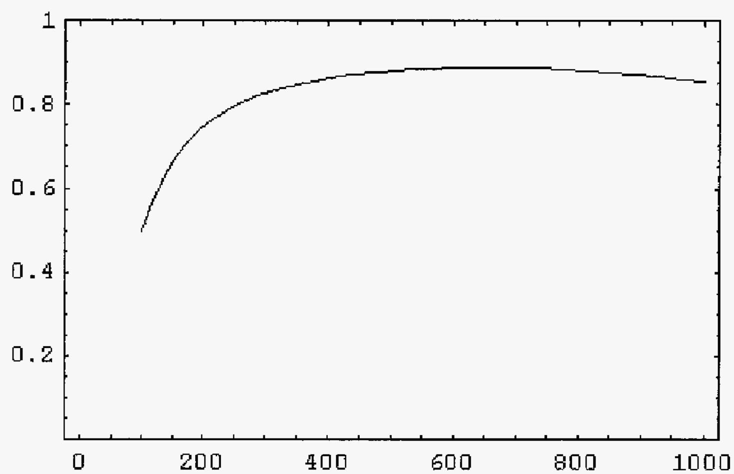
Hypothetical Example to Illustrate the Theory



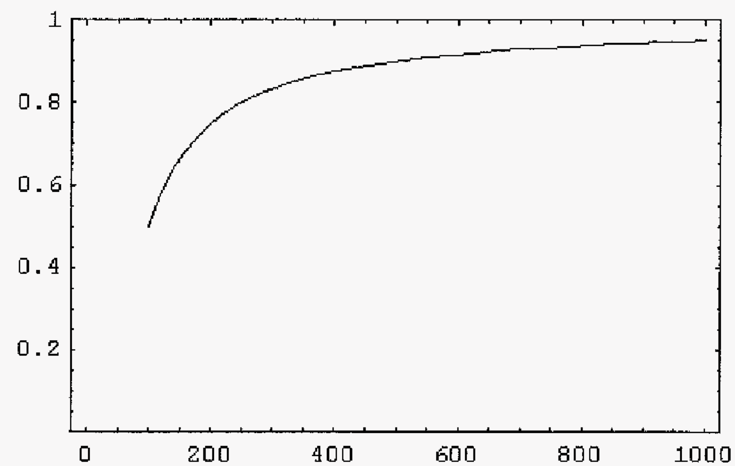
For *k* = 0.0, SW Max @ 315 km. Risk = 0.16



For *k* = 0.5, SW Max @ 400 km. Risk = 0.13



For *k* = 0.9, SW Max @ 658 km. Risk = 0.08

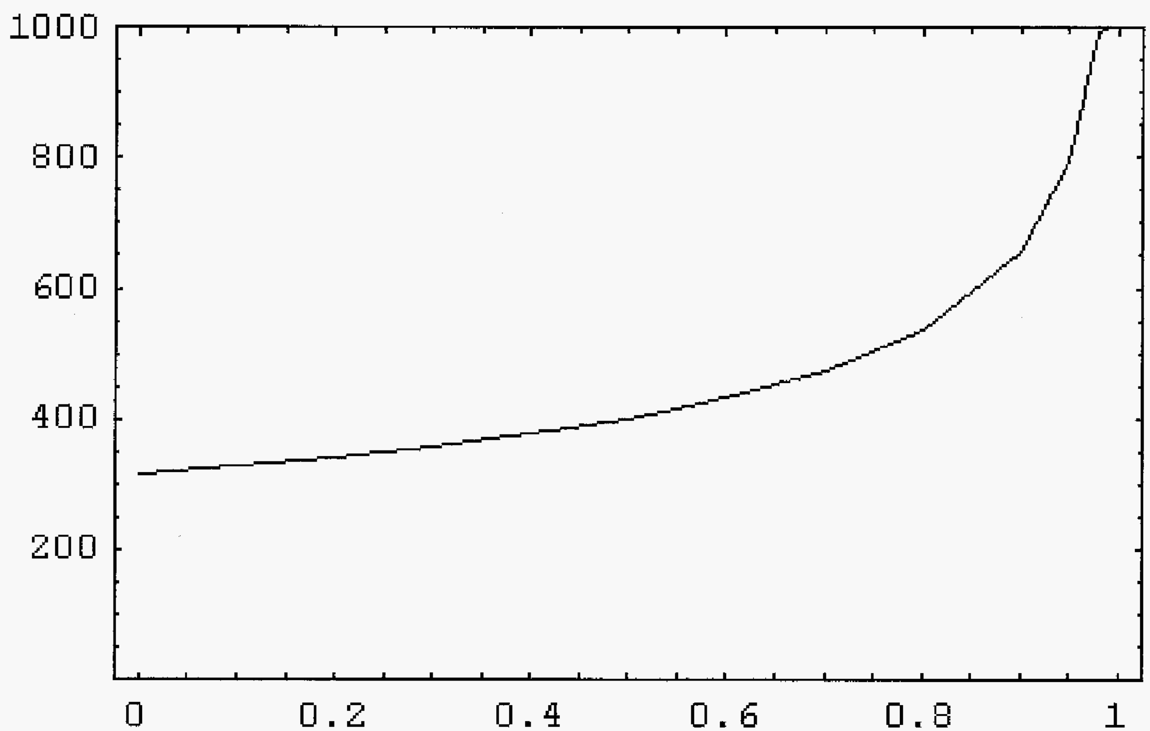


For *k* = 1.0, SW Max @ 1,000 km. Risk = 0.05

Optimum Flyby Altitude vs. Risk Factor *r*

As the Risk Factor *k* varies from 0 to 1, the optimum flyby altitude varies from 315 km to 1,000 km.

Hypothetical Example to Illustrate the Theory



Analytic Hierarchy Process (AHP)

- In AHP as in MAUT, a rating (score) is determined for each alternative.
- As in MAUT, a hierarchy of decision attributes is developed.
  - Decision attributes are evaluated in a series of pair-wise comparisons
  - Comparisons are usually on a qualitative scale, which is then converted to a quantitative one
- Multiple experts make separate pair-wise comparisons of the alternatives with respect to each decision attribute.
- An AHP software program then computes the rating.
- Consensus may take several iterations, or may not achieve consistency.

B. Summary and Observations

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Summary and Observations

- Variety of DM available; apply the one that best fits the decision problem
- Have the right mix of skills as part of the analysis team
- Physics-based models are fairly reliable; costs of alternatives are the hardest to estimate
- Treatment of uncertainty is an important part of most decision problems in space SE and BCA
- Document analysis assumptions, alternatives, data, methods, models, and decision results to avoid unnecessary replication

Tradespace Exploration: Some Fundamental Concepts and Models

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California Institute of Technology

Tradespace Exploration Outline

A. **Introduction and Fundamental Concepts**
- What is a Tradespace?
- Project tradespace modeling
- Pareto optimality and Pareto frontiers
- Iso-effectiveness curves
- Issues in building a Project Tradespace Model

B. **Building a Project Tradespace Model for Mars Science Laboratory**

C. **Tradespace Visualization**

D. **Tradespace Mini-Workshop**

A. Introduction and Fundamental Concepts

Old Problem, New Solution

Traditional Approach

- Create/adopt stand-alone models
- Tradeoffs made sequentially
- Assumptions change over time

tradeoff → tradeoff → Result: Point design

time

< 5 designs

Tradespace Modeling Approach

Trade relationships identified → Result: Tradespace frontier

- Create/adapt models addressing system issues
- Tradeoffs deferred until systemic impacts examined
- Assumptions consistent at decision time

100-1000 designs

What is a Tradespace?

- A ***project tradespace*** is a complete, quantitative description of the alternatives available to a project based on potentially available technologies, in terms of design and operational inputs, and project outcomes.
  - **Inputs:**
    - System and subsystem (e.g., spacecraft and instrument) performance ratings, sizes, quantities, etc.
    - Operational scenario parameters, orbits, launch dates, etc.
  - **Outputs:**
    - Project/mission Measures of Effectiveness, including mission risks (chances of mission success),
    - Life-cycle costs, including cost risk

- A project tradespace model (PTM) has been used in previous projects/programs to integrate these considerations.
  - Space Station Freedom
  - Pluto Flyby
  - Europa Orbiter
  - Mars Science Laboratory

Project Tradespace Model (PTM)

- Captures project/system design relationships and associated *life-cycle cost* information
- Calculates project-level implications of design changes for trade studies (sensitivities)
- Permits rapid exploration of the tradespace neighborhood for design optimization (batch mode)

Measures of Effectiveness

- A mission Measure of Effectiveness (MoE) is defined as a quantitative measure of the degree to which the mission's purpose is achieved.
  - For example, how much the mission returns in science data, and what the resolution, and coverage are.

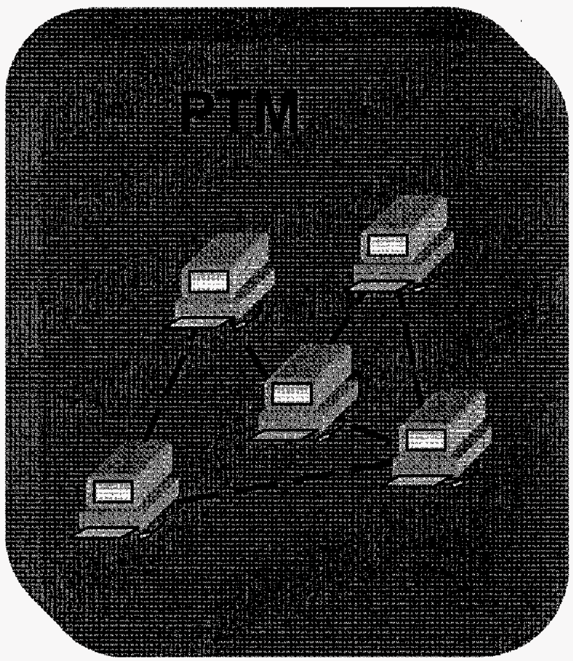
- It often depends on measures of performance (MoP), or size and quantity measures of several inputs. (A "Design Vector")
  - Launch vehicle probability of success
  - Injection, cruise, and EDL reliability
  - Navigation accuracy
  - Instrument performance
  - Spacecraft subsystem (power, C&DH, telecomm, etc.) performance.

- Cost is NOT a Measure of Effectiveness; cost is a measure of the resources foregone.

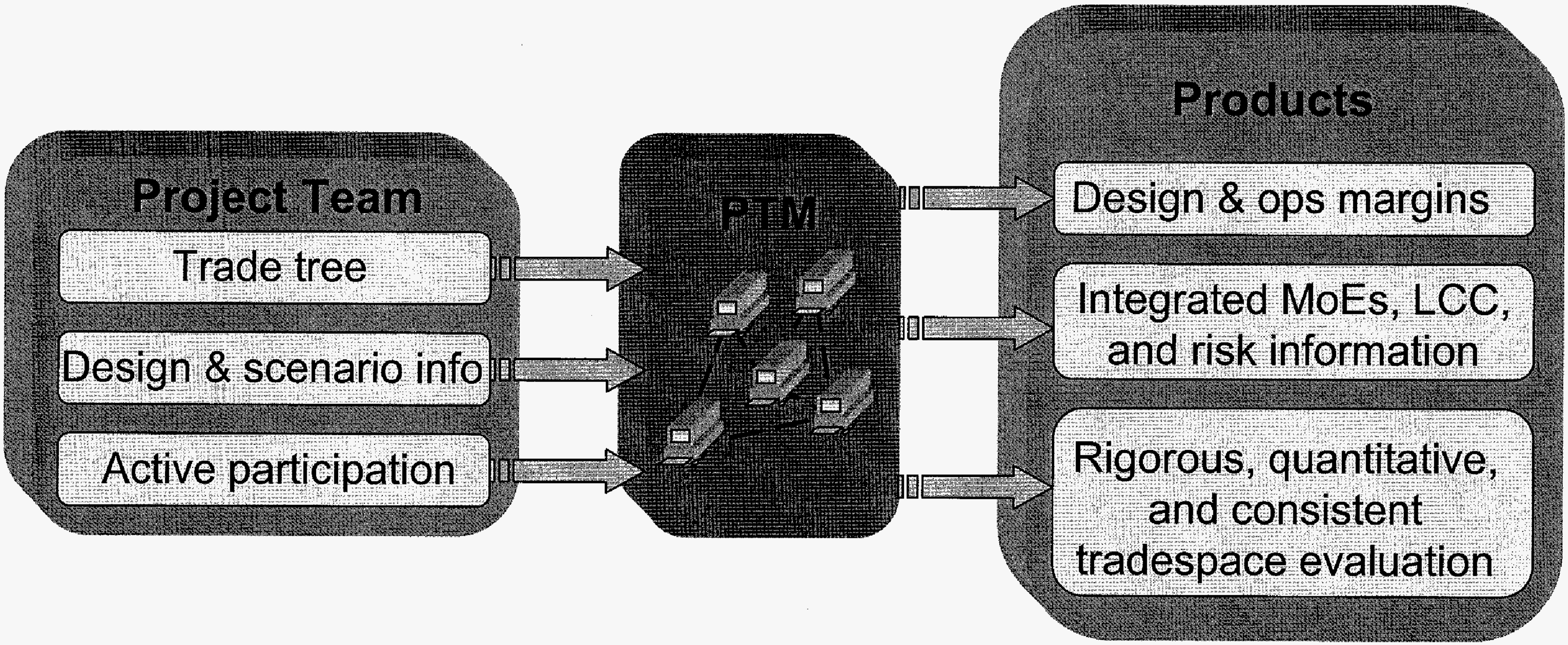
- Cost-effectiveness is represented by a combination of both -- preferably as the whole Pareto frontier, but sometimes as a point on that frontier.

Building a Project Tradespace Model (PTM)

- Identify the project/system MoEs and MoPs
- Identify Life-Cycle Cost (LCC) drivers
- Determine the "threads of calculation" needed to quantify these
- Implement the calculations by integrating appropriate space system design, cost, and operations models / simulations

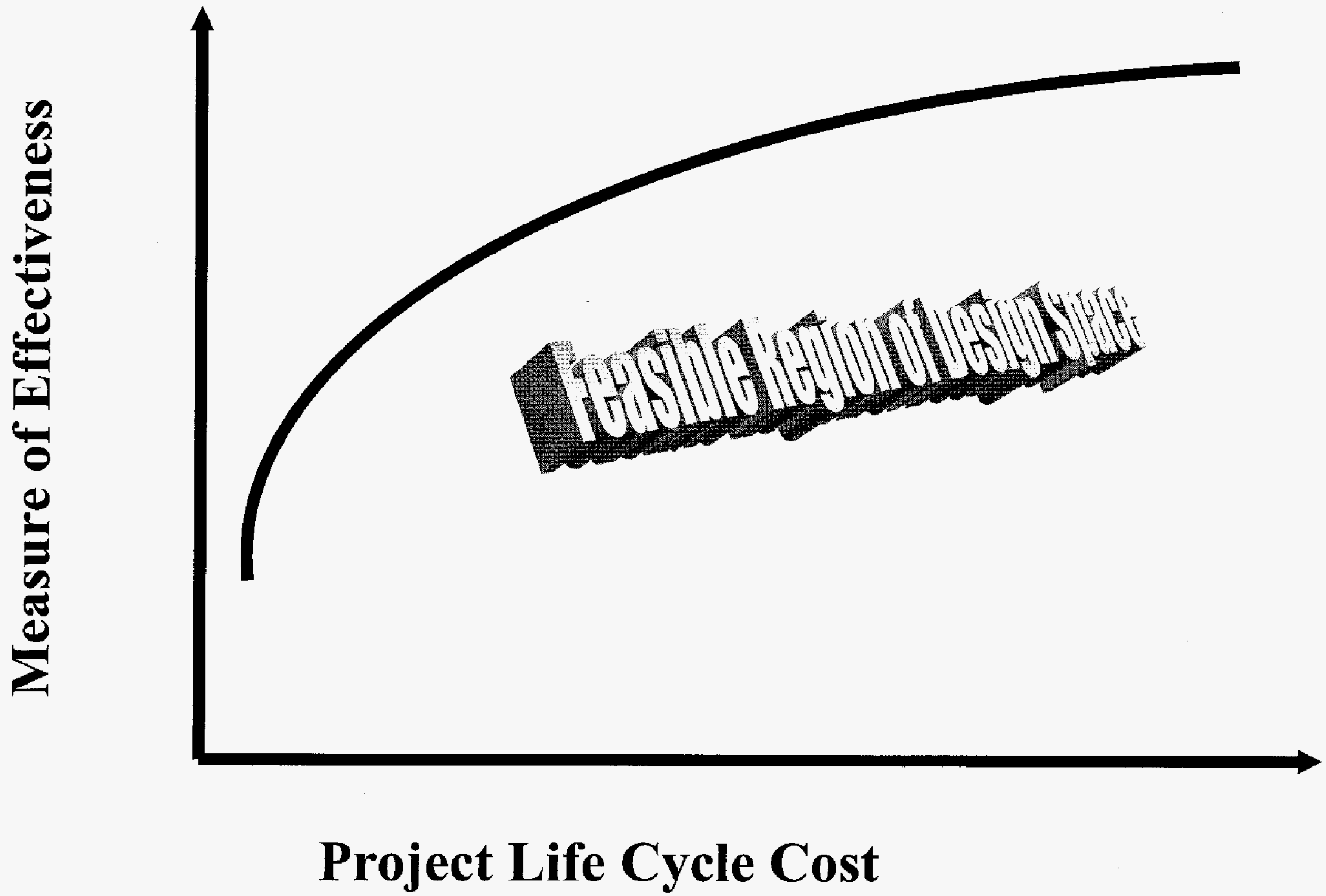


PTM: Inputs and Outputs



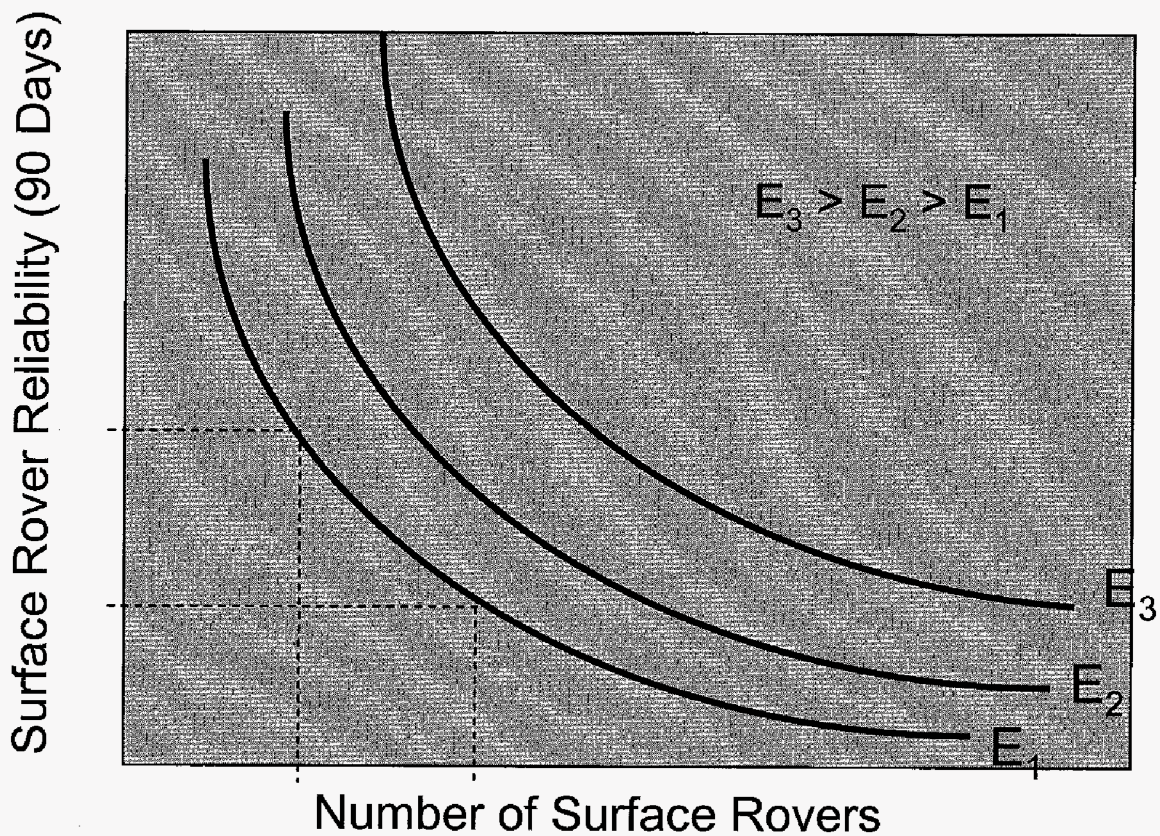
Each PTM is custom-built to a project, but contains many reusable elements

Cost-Effectiveness Frontier (Pareto Optimal Frontier)



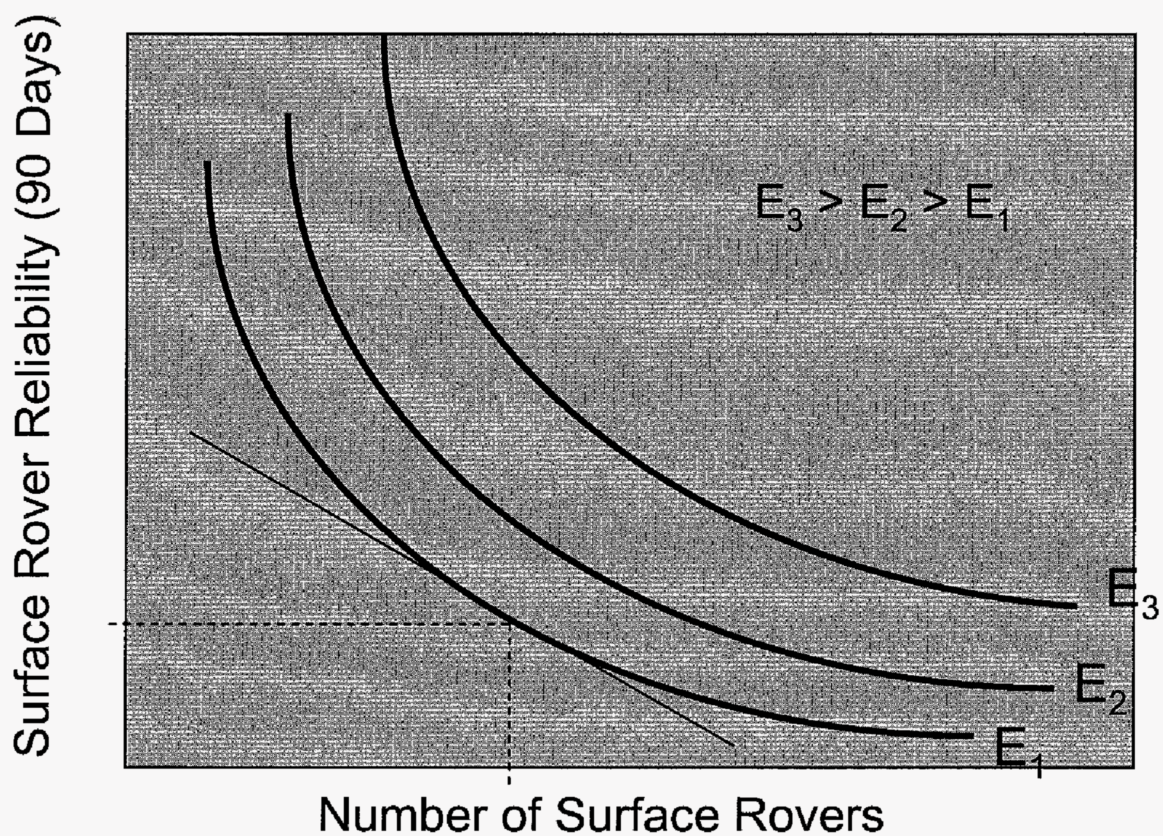
Iso-Effectiveness Curves

Iso-effectiveness curves represent combinations of the input variables that yield the identical value for a Measure of Effectiveness. For illustration:



Iso-Effectiveness Curves

Generally each iso-effectiveness curve has only one point that's Pareto optimal.



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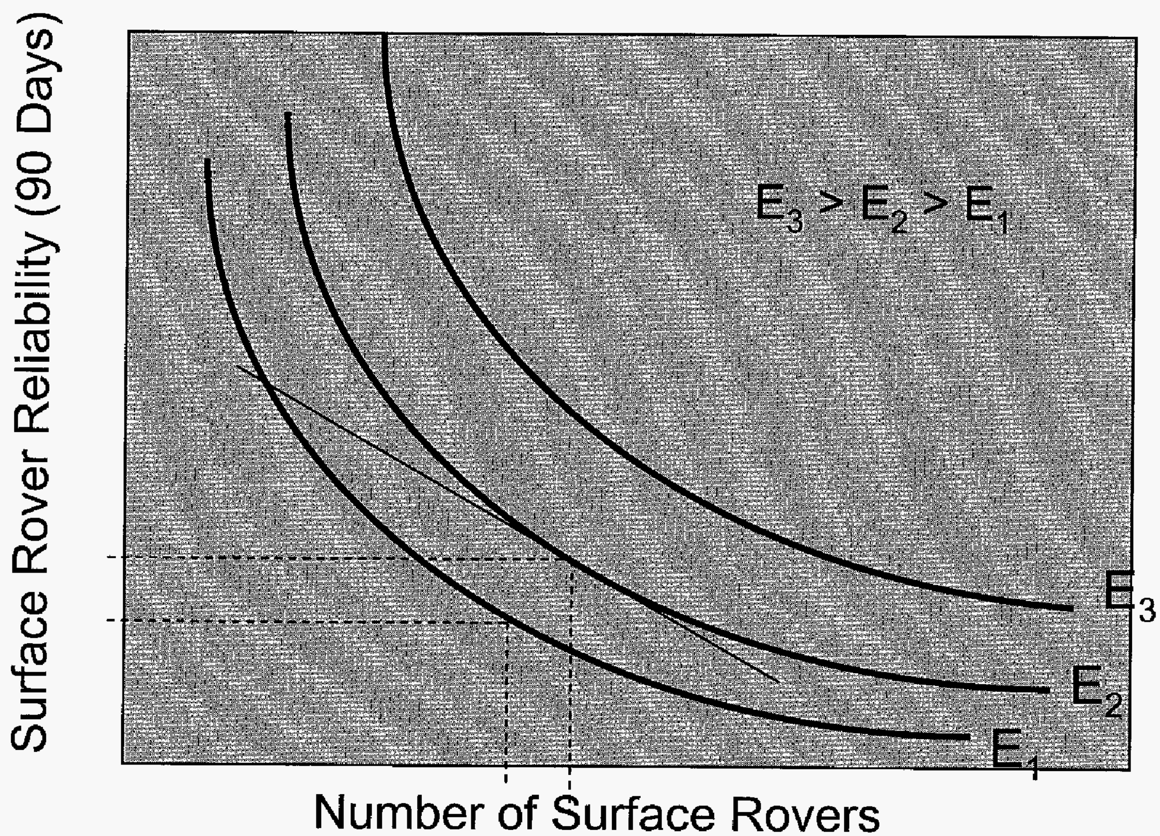
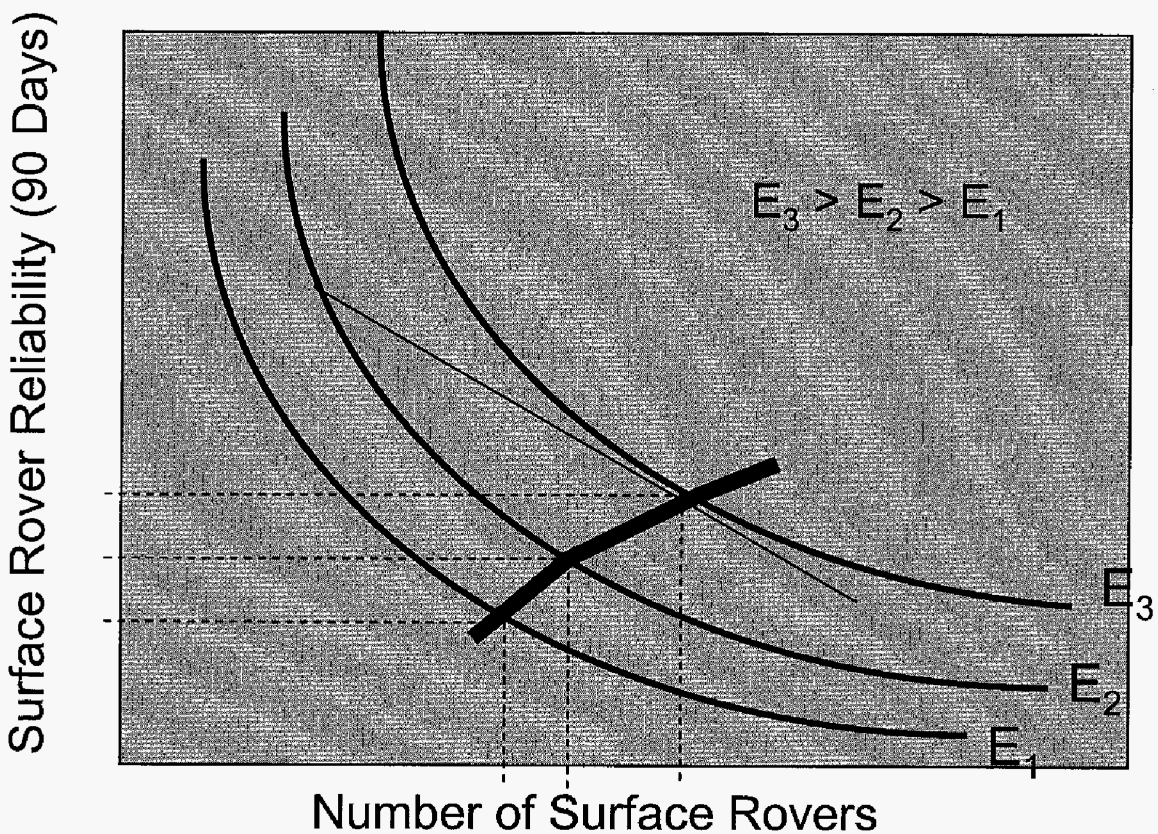
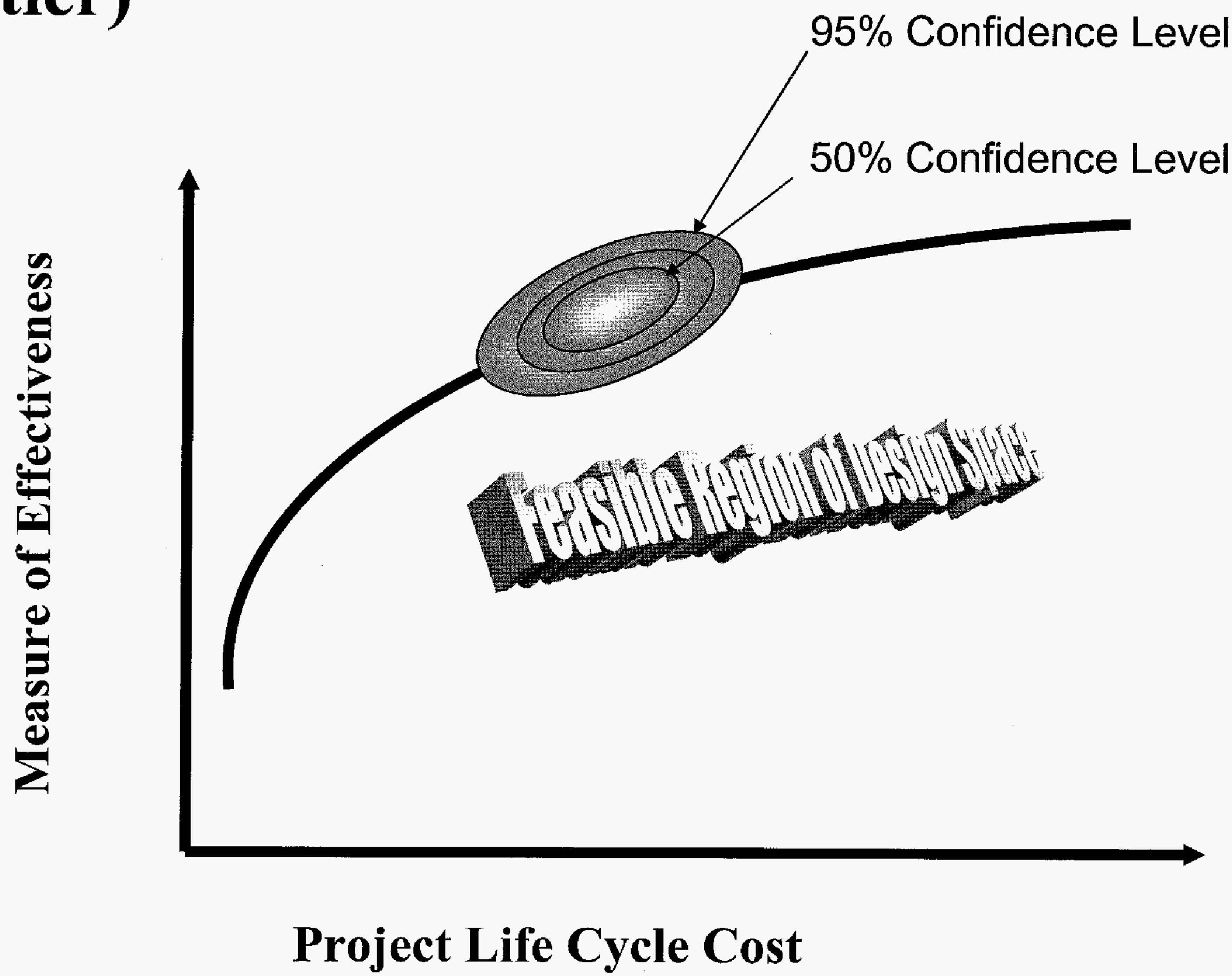


Iso-Effectiveness Curves

Generally each iso-effectiveness curve has only one point that's Pareto optimal. Connecting these points produces the optimal expansion path



Cost-Effectiveness Frontier (Pareto Optimal Frontier)



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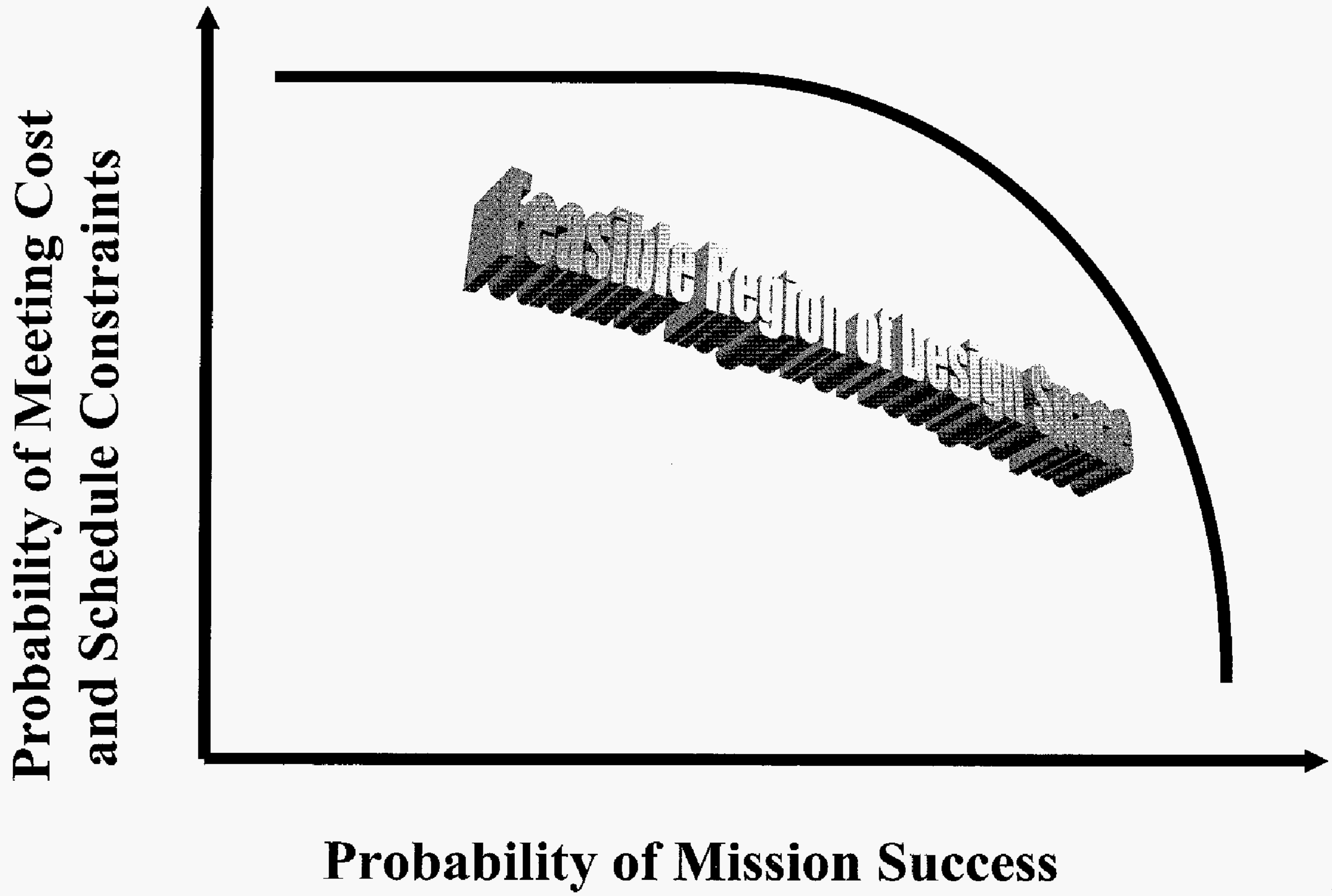
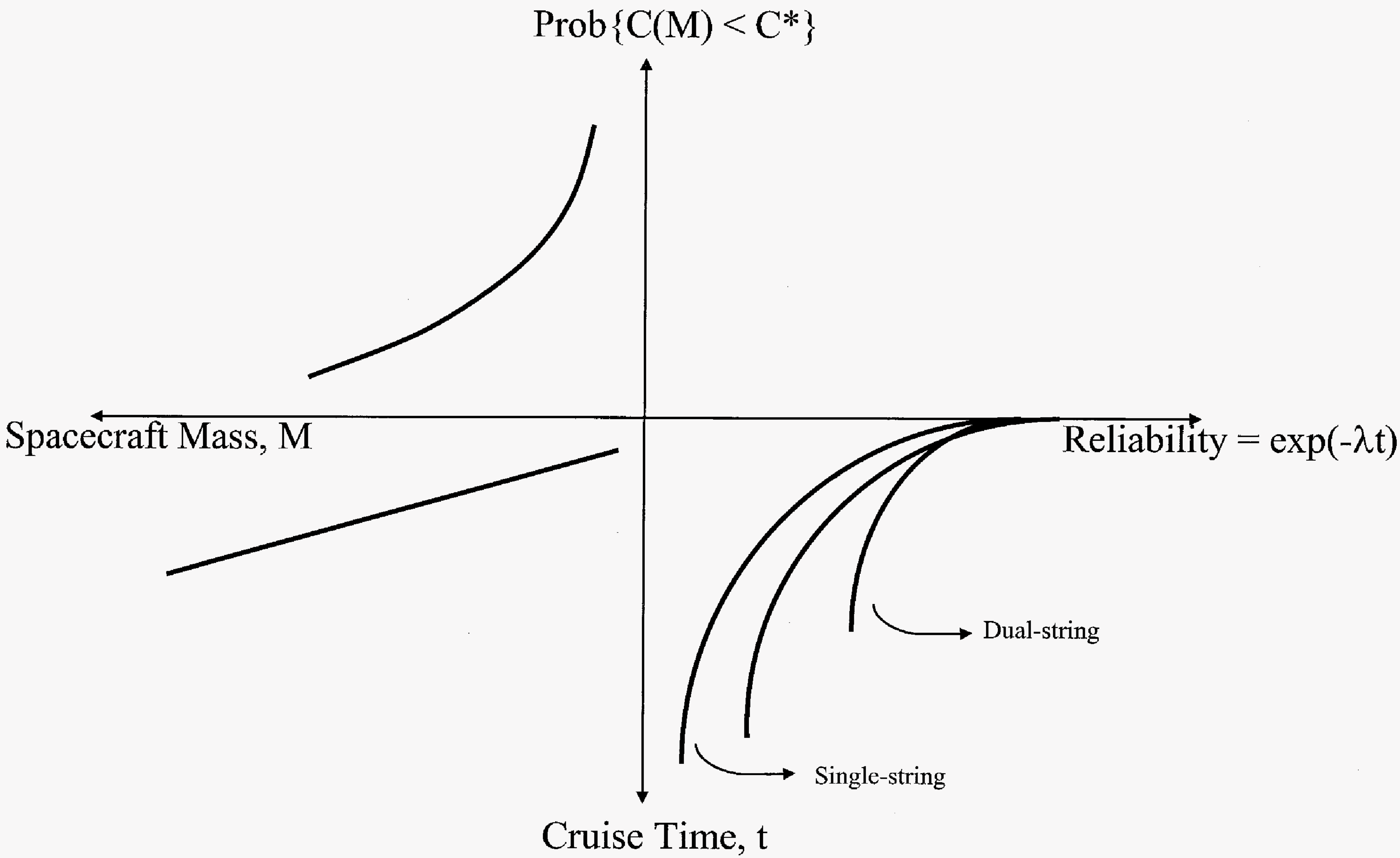
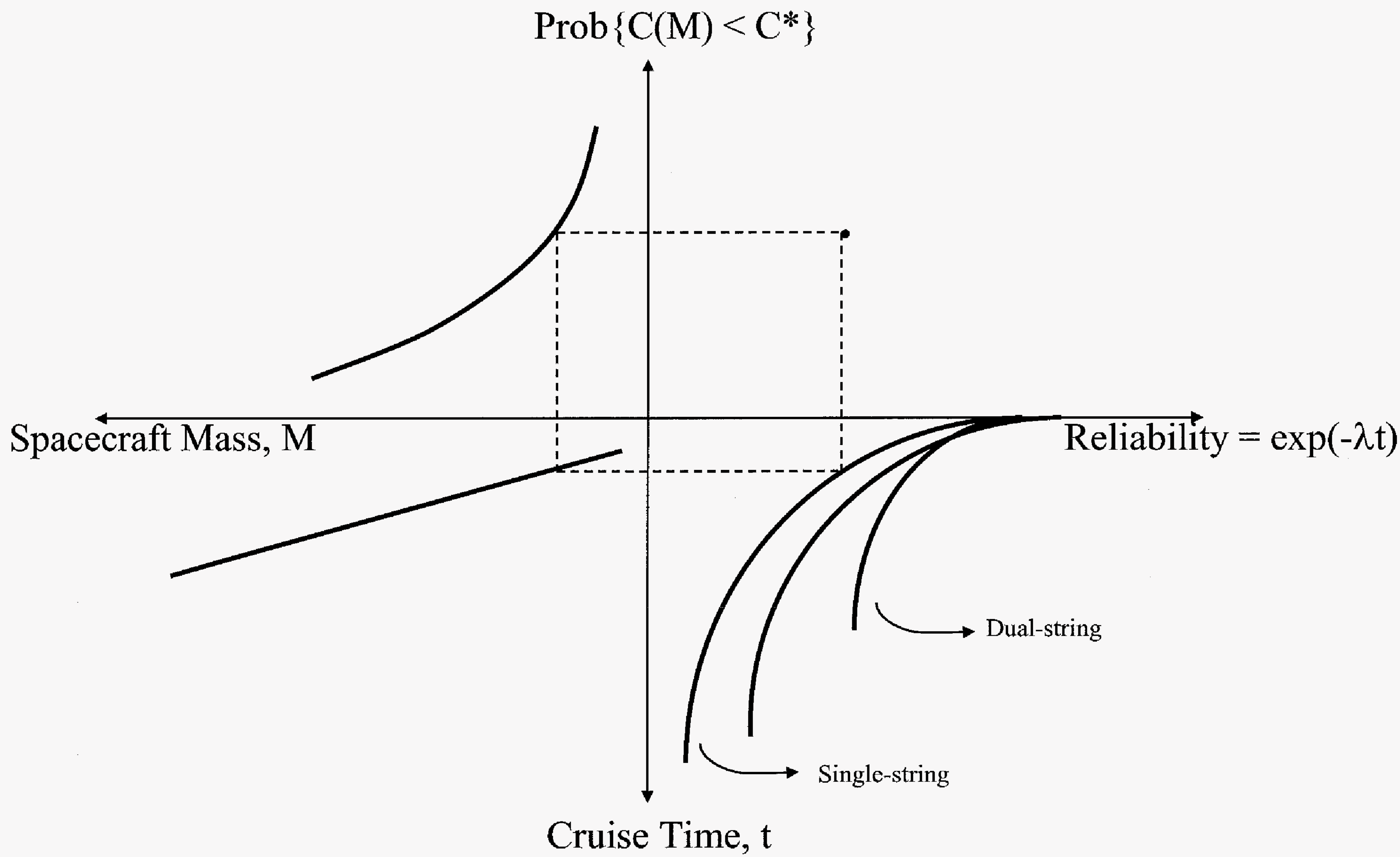
Cost-Effectiveness Frontier (Pareto Optimal Frontier) in Terms of Probabilities



Deriving the Cost-Effectiveness Frontier (Pareto Optimal Frontier)



Deriving the Cost-Effectiveness Frontier (Pareto Optimal Frontier)



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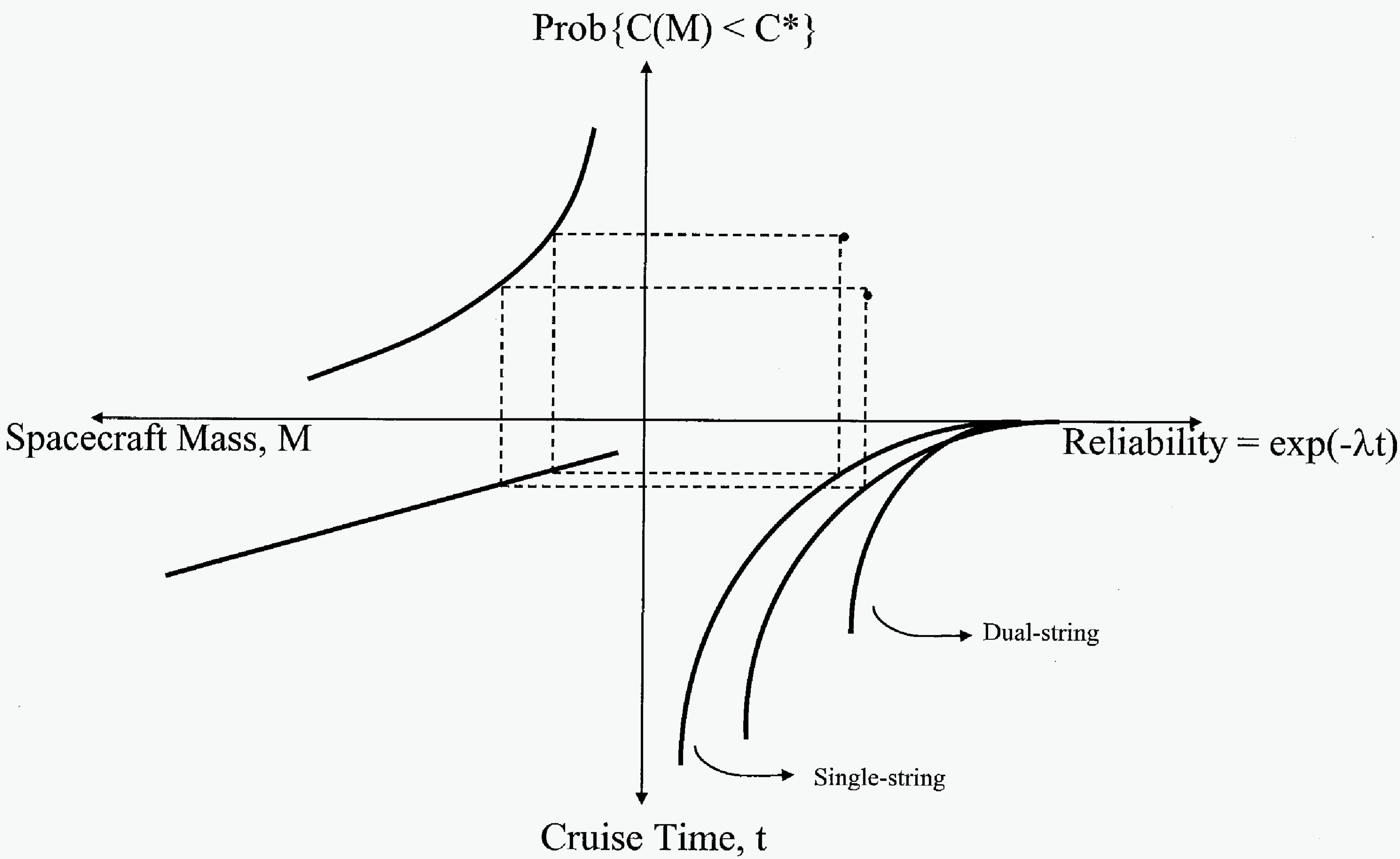
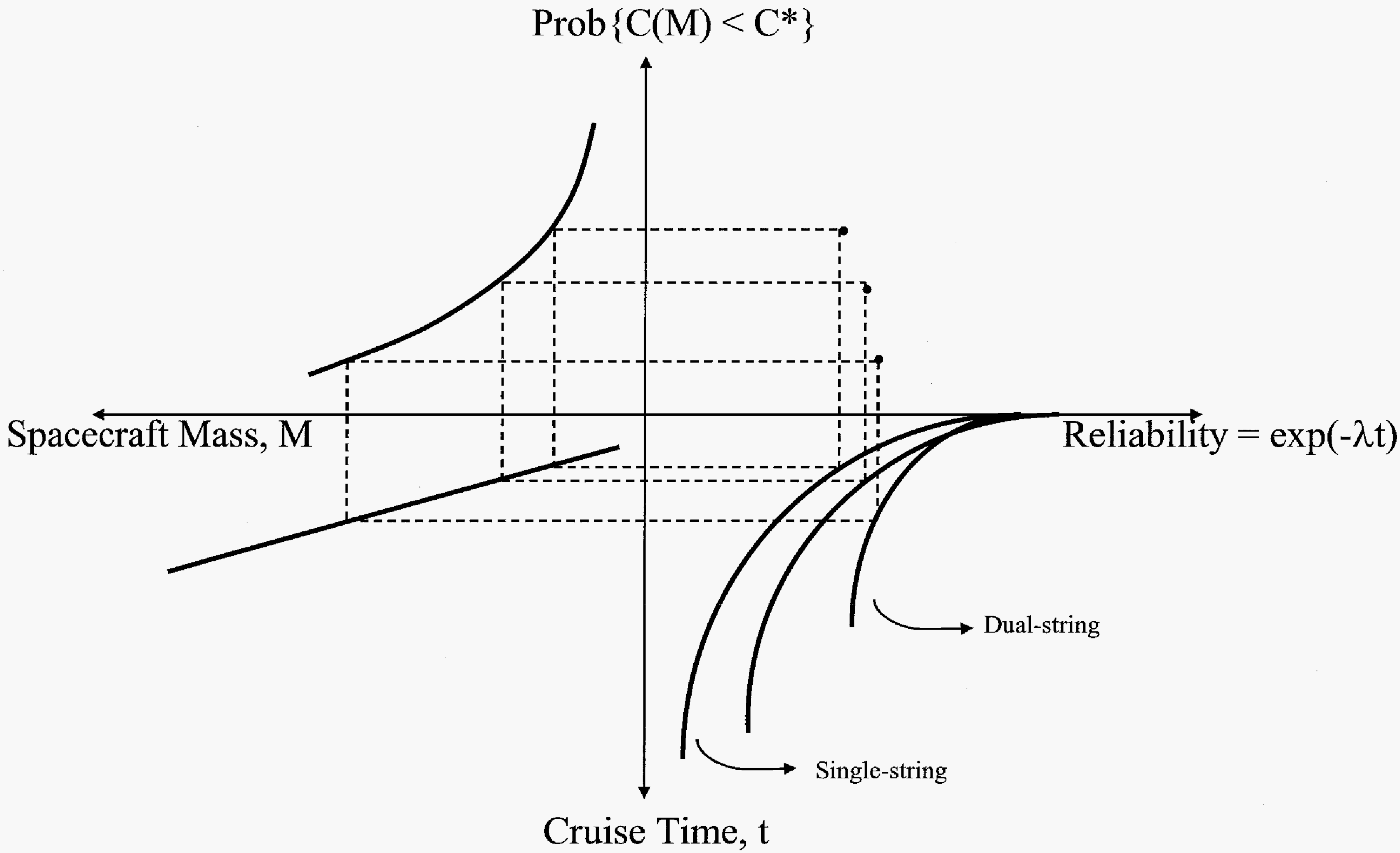
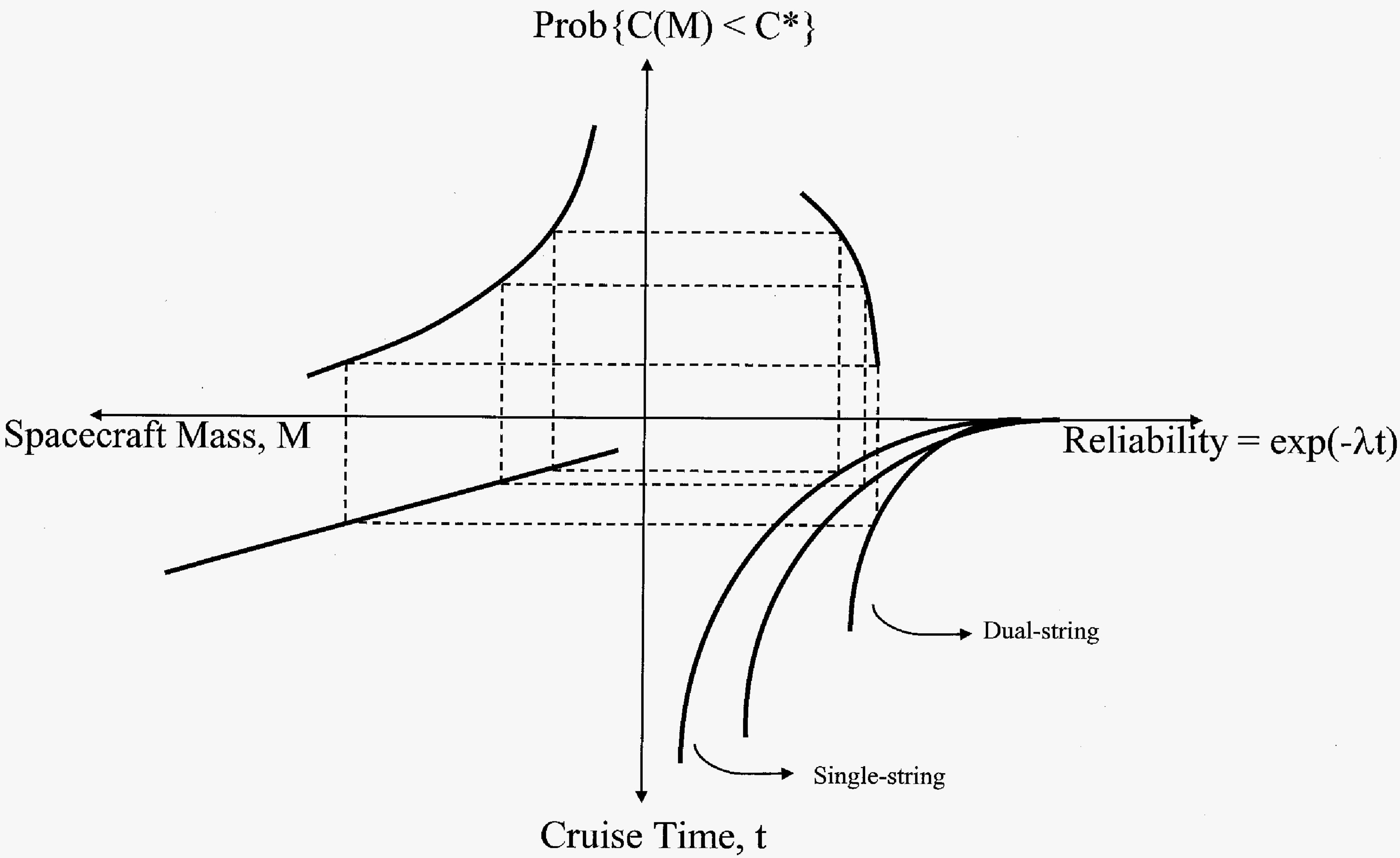


Deriving the Cost-Effectiveness Frontier (Pareto Optimal Frontier)



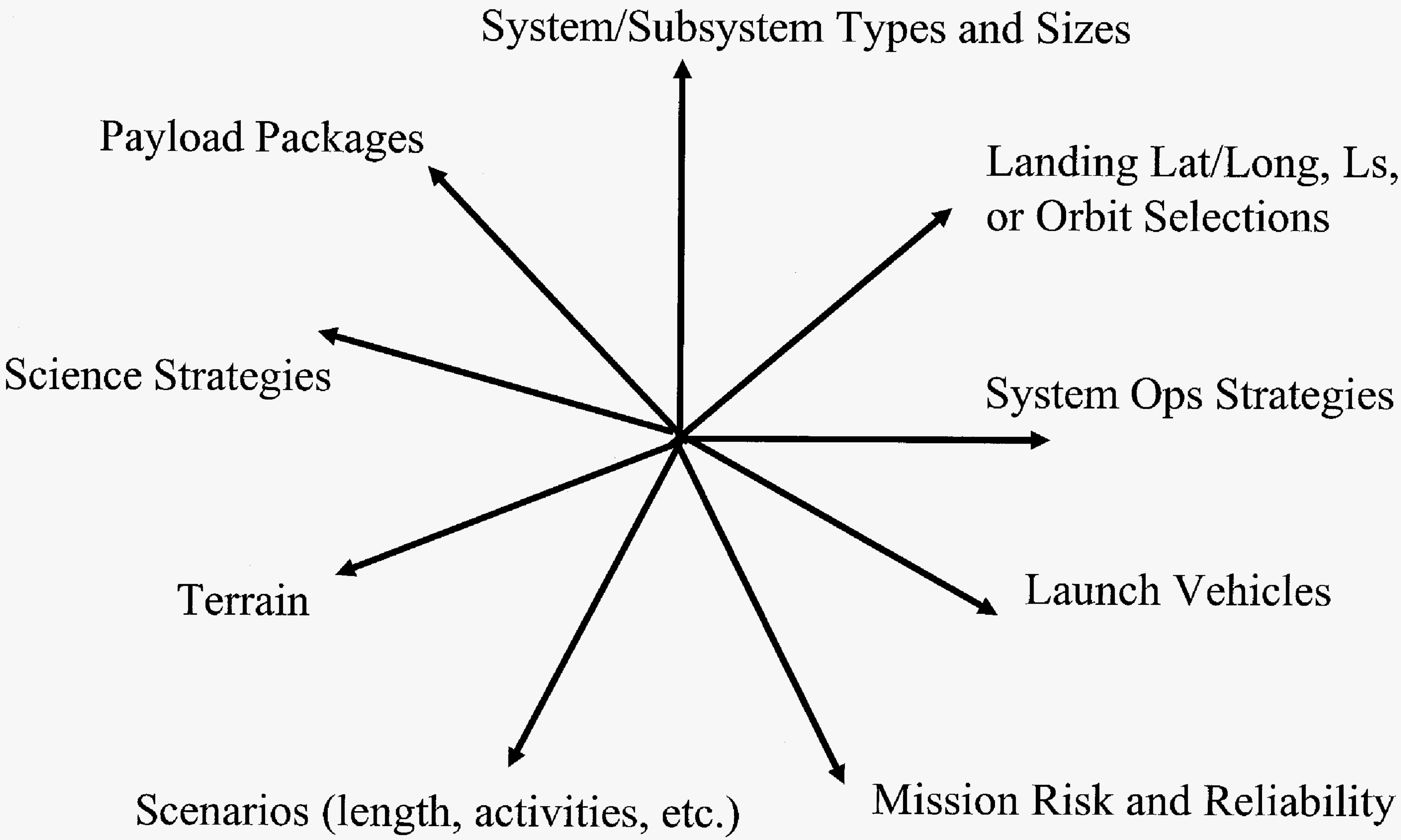
Deriving the Cost-Effectiveness Frontier (Pareto Optimal Frontier)



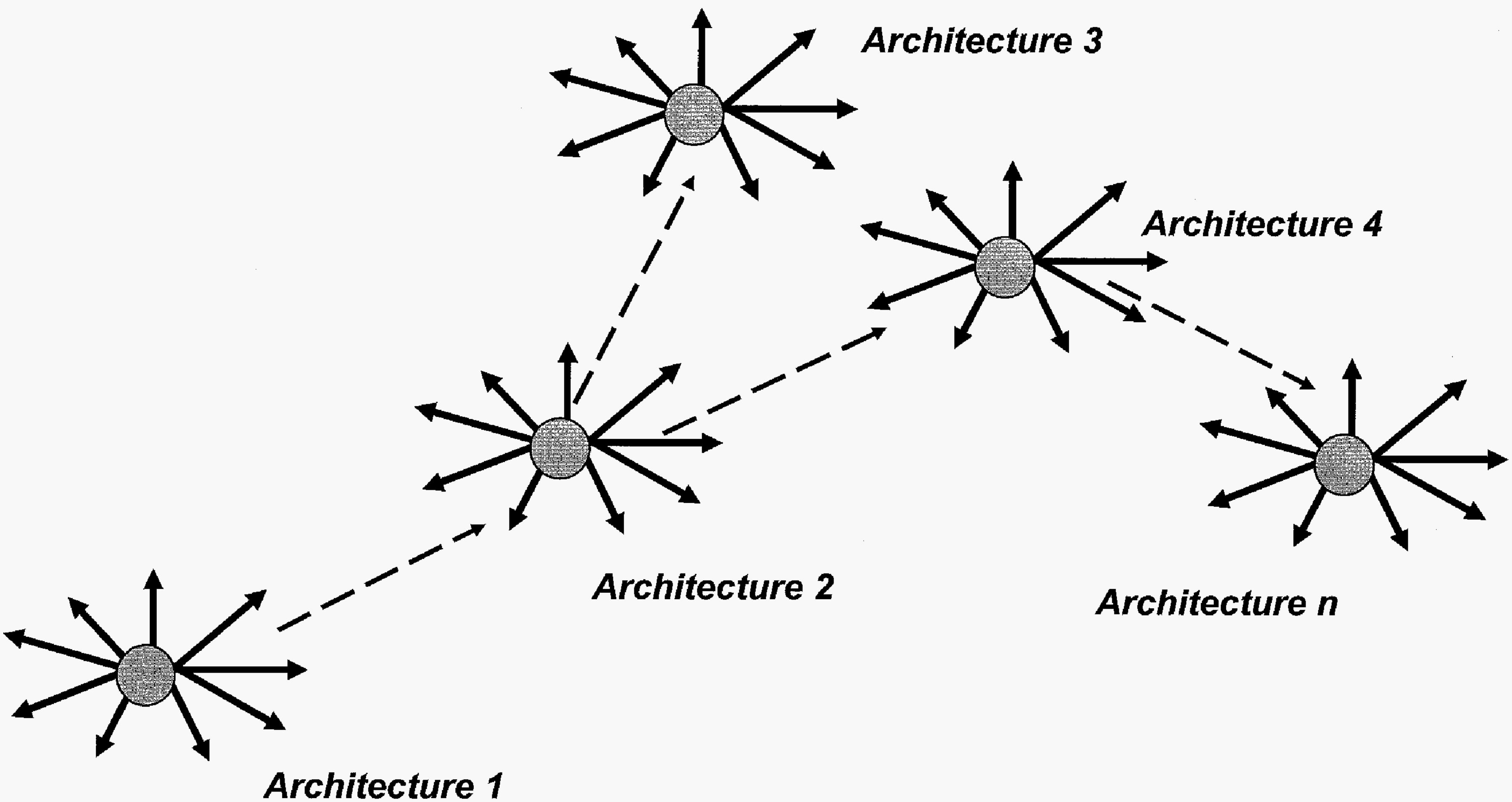
Issues in Building a PTM

- The PTM can involve analytic models, geometry-based models, Monte Carlo, and deterministic simulations.
  - Models are abstractions or representations of real-world processes or structures. In systems analysis, finding reliable relationships between the system's inputs (design vector) and effectiveness (or cost) is never easy.
  - Useful models may not exist, or if they do (from previous work), they come in various states of integration readiness
- Identifying appropriate Measure of Effectiveness can be difficult
- Tradespace dimensionality challenge

Tradespace Dimensionality Challenge



Explorations made possible



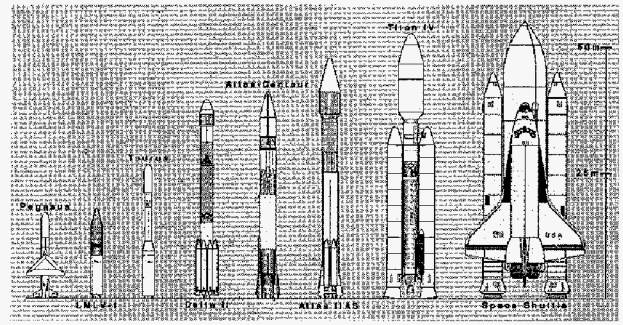
Project Tradespace Model Summary

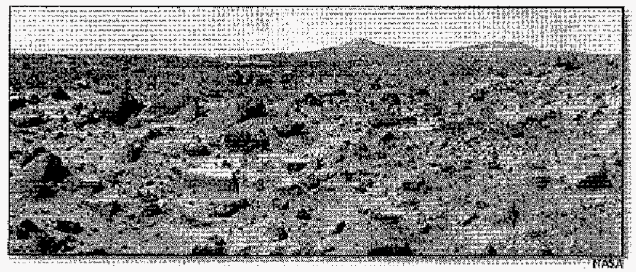
- The PTM is a package of linked models used for analyzing trades among different project/system architectures/designs and operations concepts/scenarios, i.e., exploring the tradespace.
- The PTM captures the relationships between the project's "design vector" (inputs) and the MoEs, life-cycle cost, and risk-metrics (outputs).
- Helps to define the Pareto frontier.

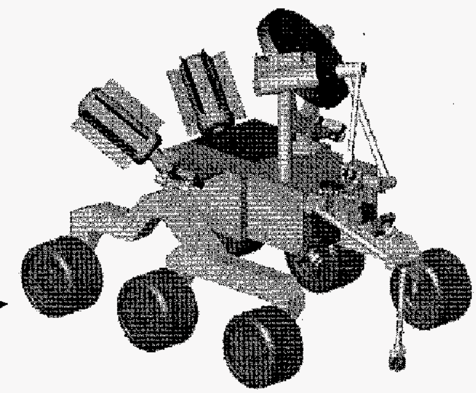
B. Building a Project Tradespace Model: MSL

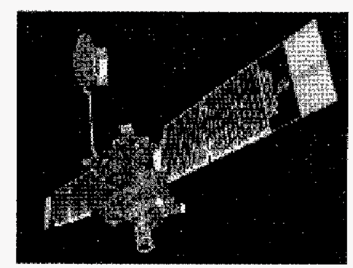
Mars Science Laboratory (MSL) Tradespace Model Design Vector

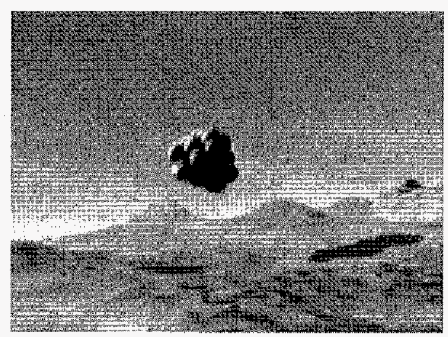
- Arrival date (L_s)
- Launch vehicle
- Mars location
- Inter-site distances
- Level of autonomy
- Power system type
- Telecomm strategy
- Reliability requirement
- Instrument suite
- EDL system type

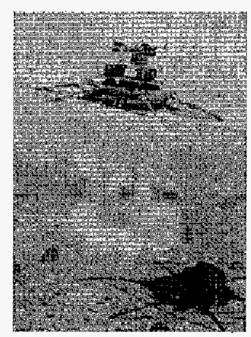




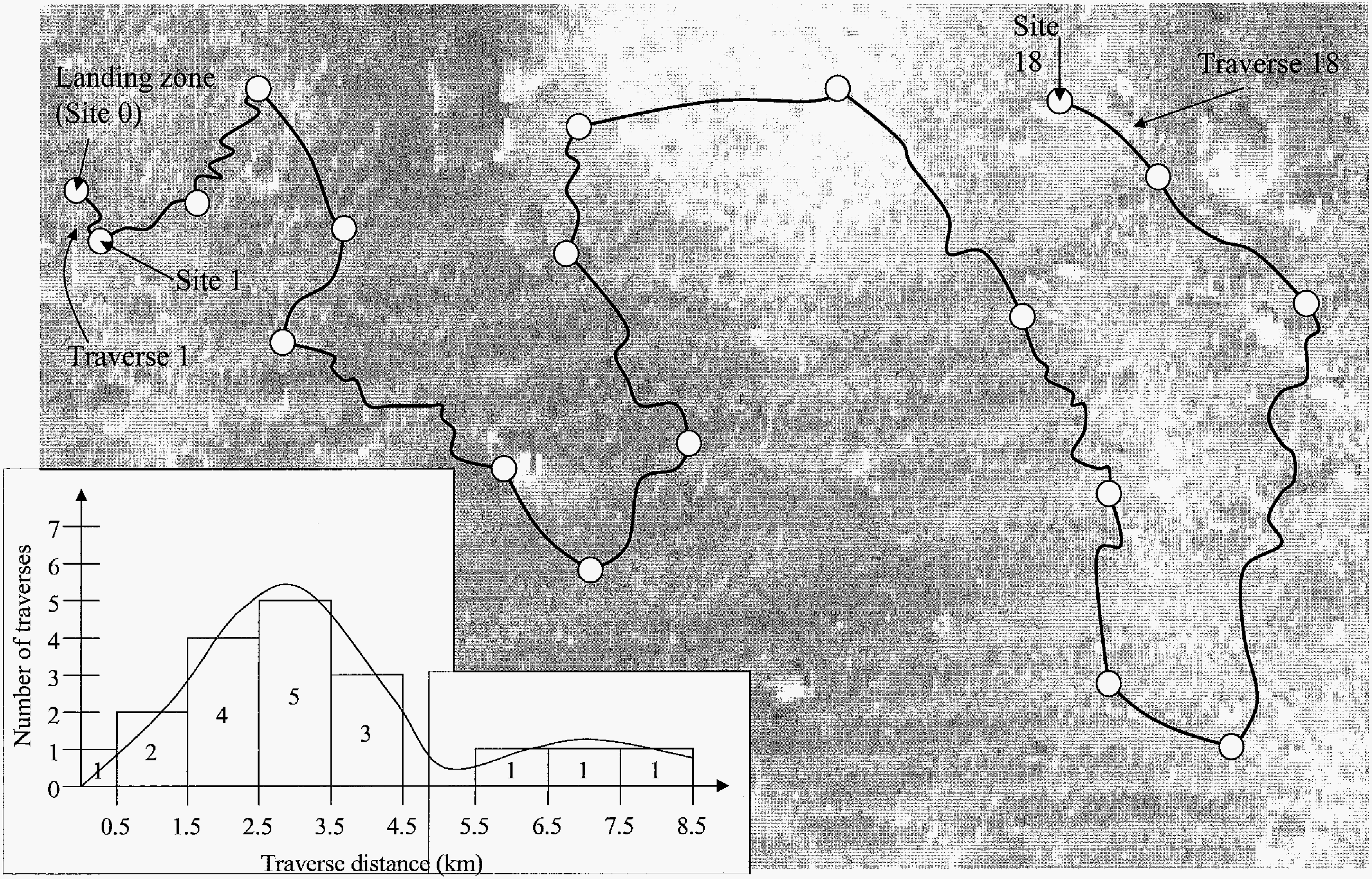








Traverse Lengths



Mars Science Laboratory (MSL) Tradespace Model Output Vector

- Achieved science data return (Mb/sol)
- Achieved site investigations

} Measures of Effectiveness

- Traverse distance margin (km)
- Flight system margin (kg)
- Surface system margin (kg)
- Launch vehicle excess capacity (kg)
- Power and energy margins (kW and kWh)
- EDL feasibility
- DSN availability (%)

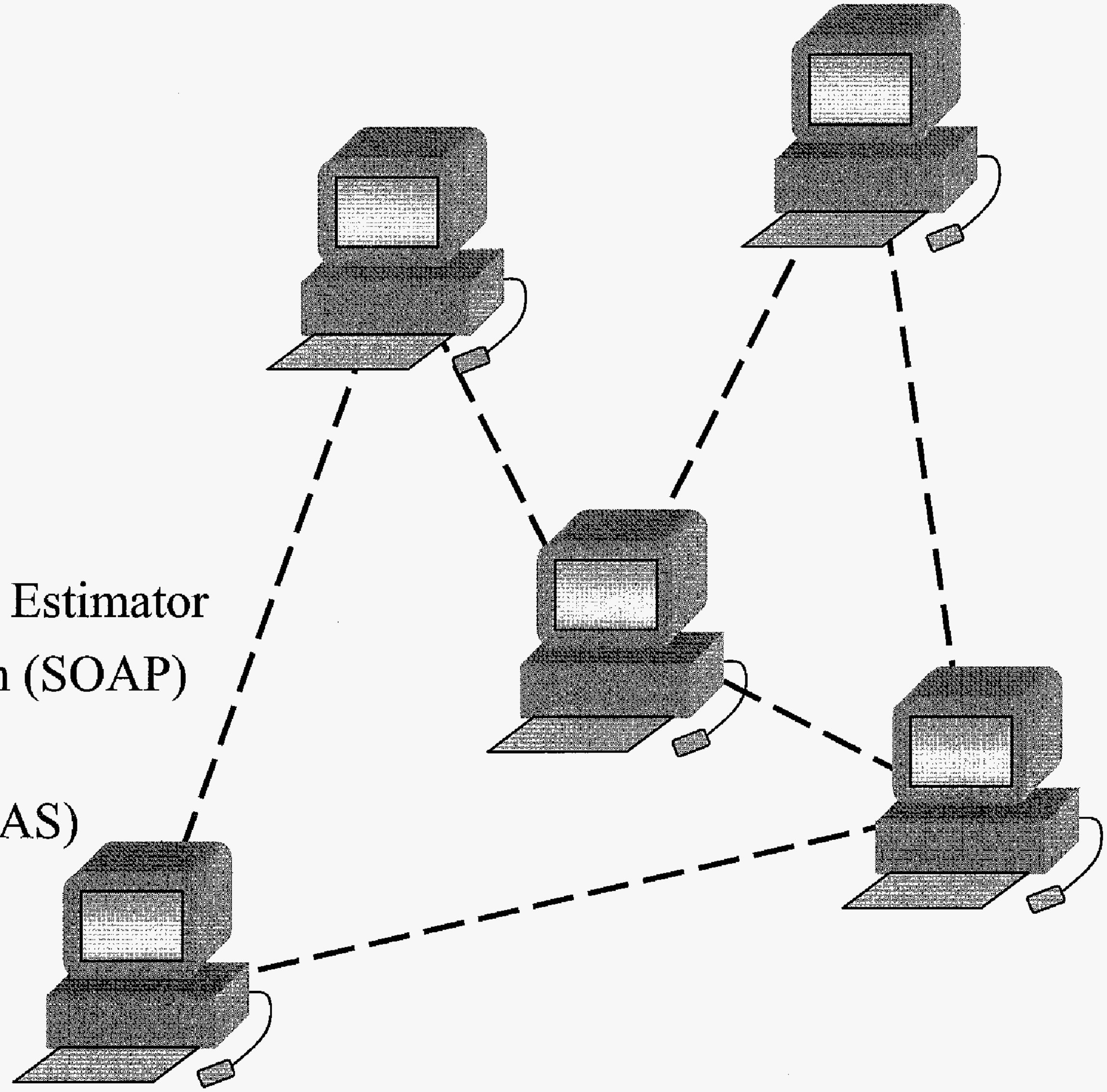
} Measures of Performance

- Estimated life cycle cost ($)
- Cost confidence (%)

} Measures of Cost

Linking Design and Output Vectors Requires Connecting Islands of Analytical Capability

APGEN
ROAMS
Terrain (Maker2)
Mobility & Structure
Launch Vehicle Database
Mars Data
MEL/PEL
Instrument Database
MER-based Phase E Workforce Estimator
Satellite Orbit Analysis Program (SOAP)
Telecom Link Analysis Tool
DSN Availability Model (TIGRAS)
Upper EDL Model
Developmental Cost Models
Team X Instrument Cost Model



MSL Tradespace Model Structure

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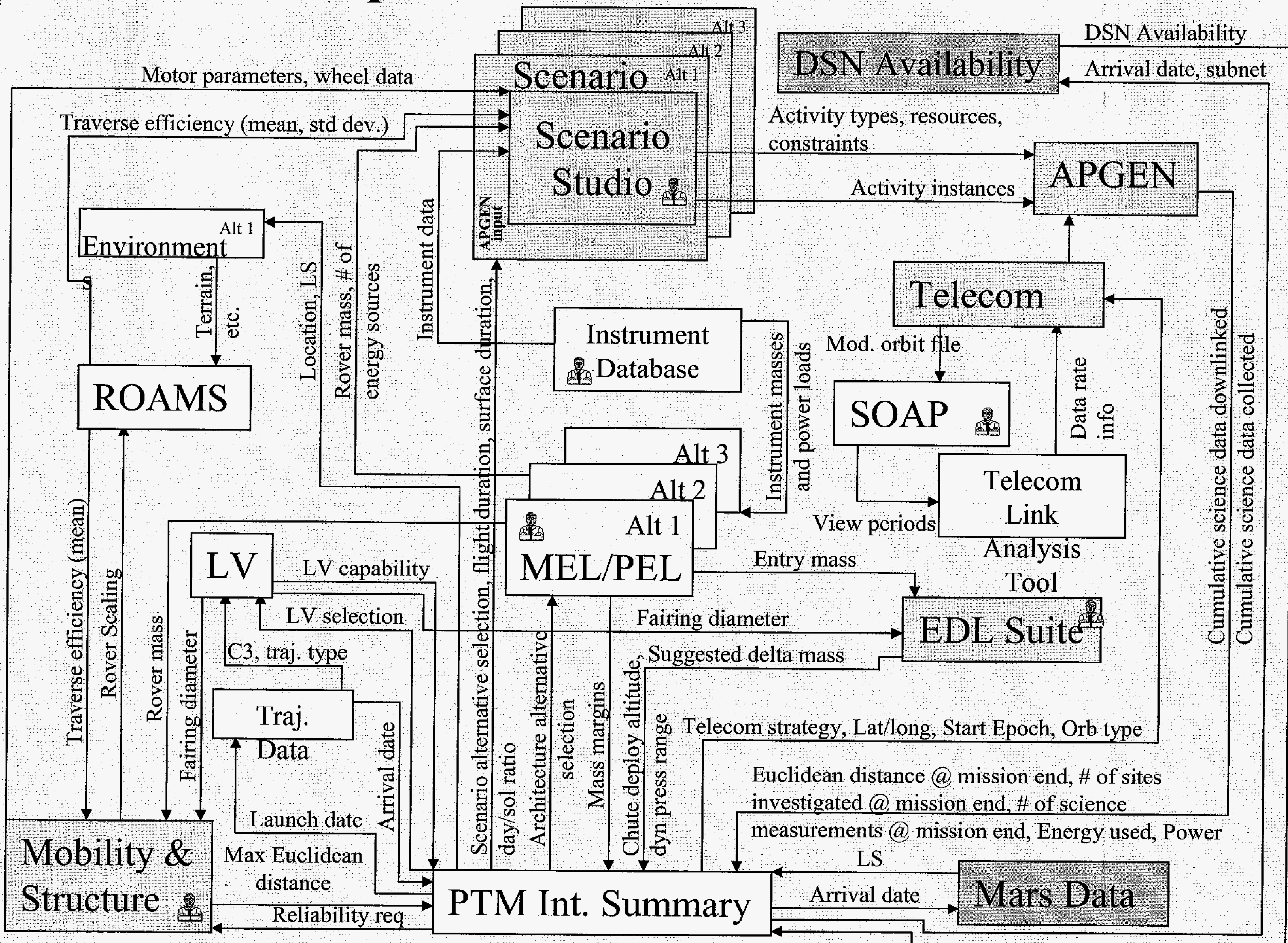
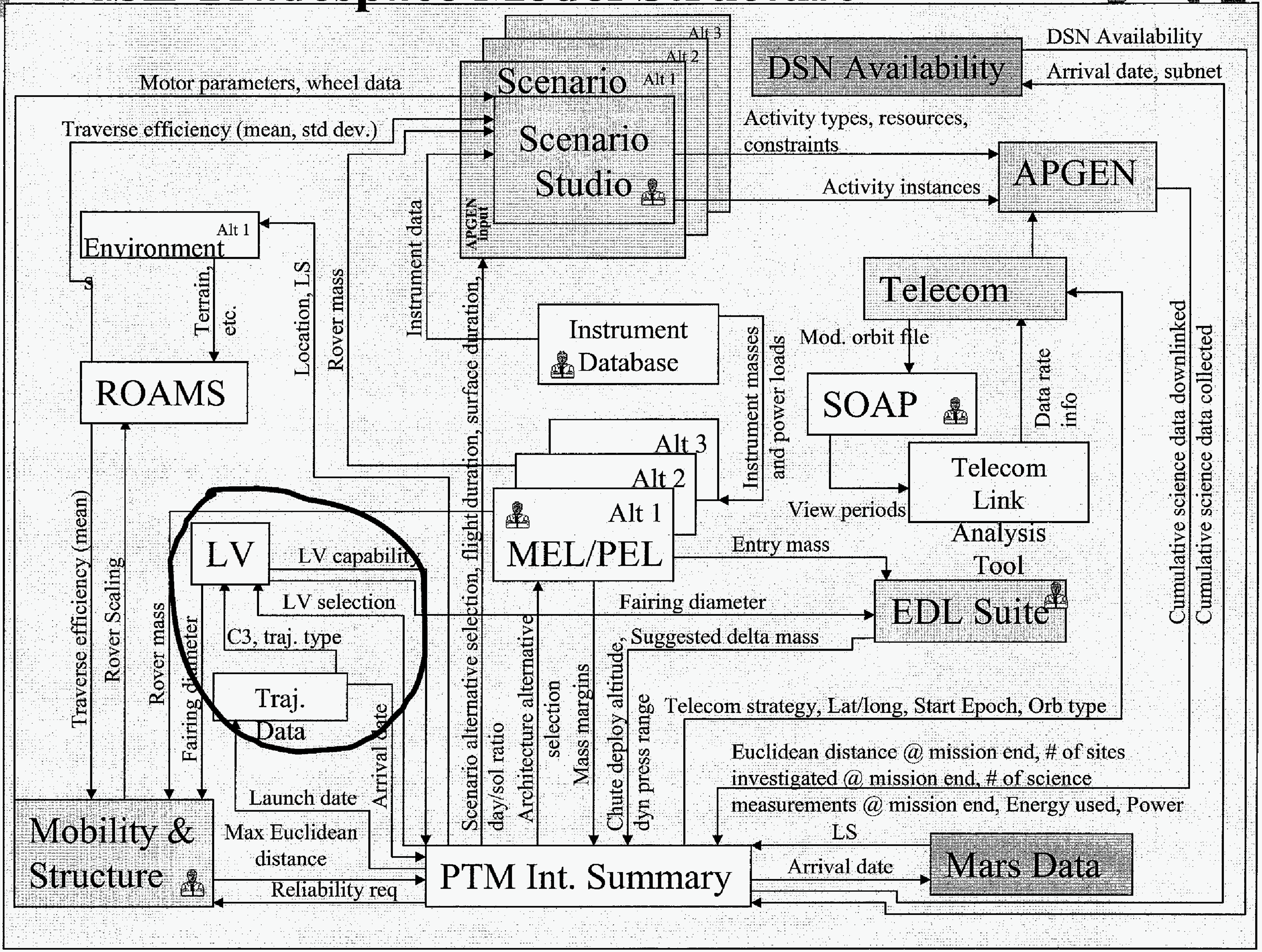


MSL Tradespace Model Structure



MSL Tradespace Model Structure

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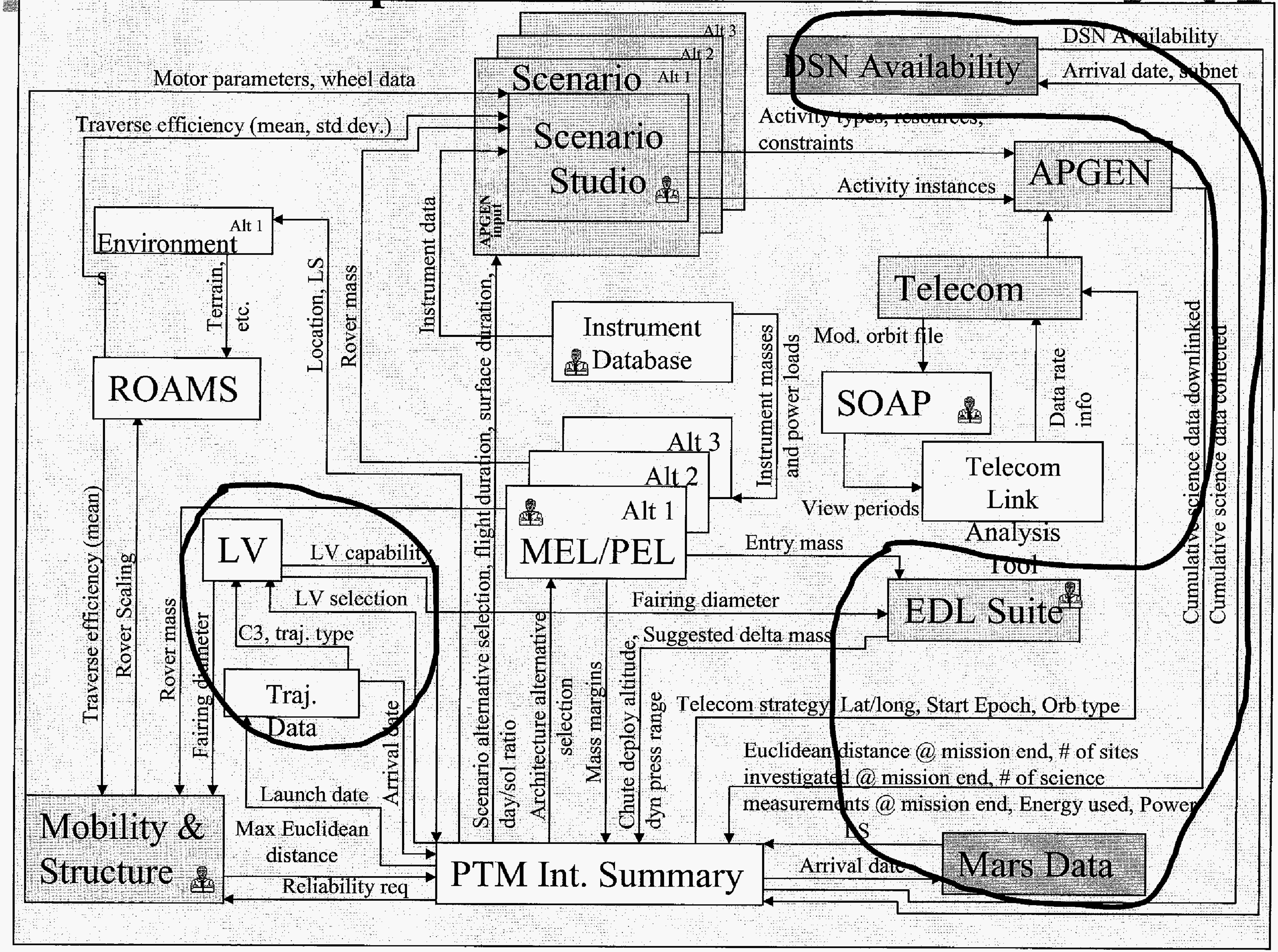

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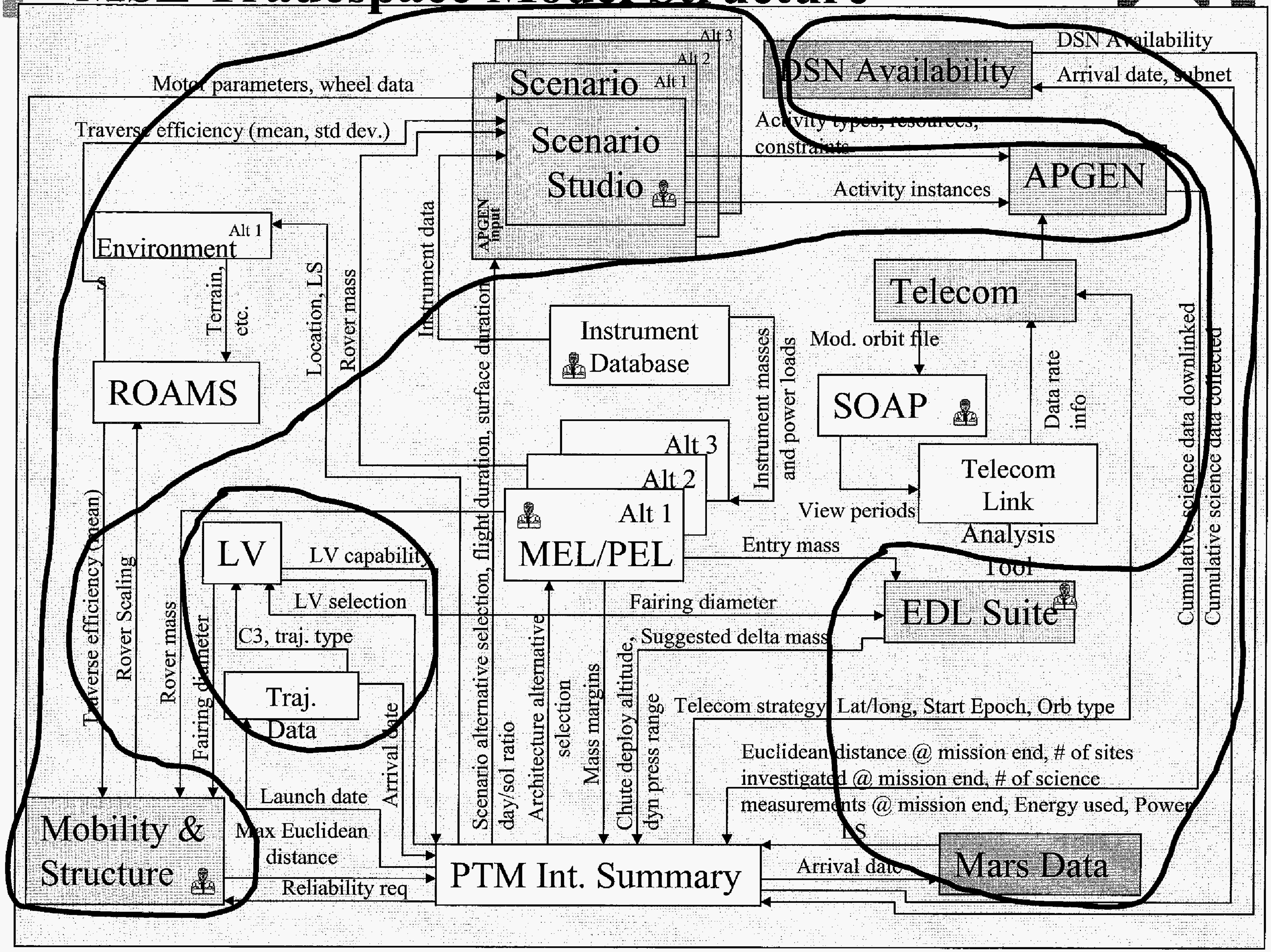

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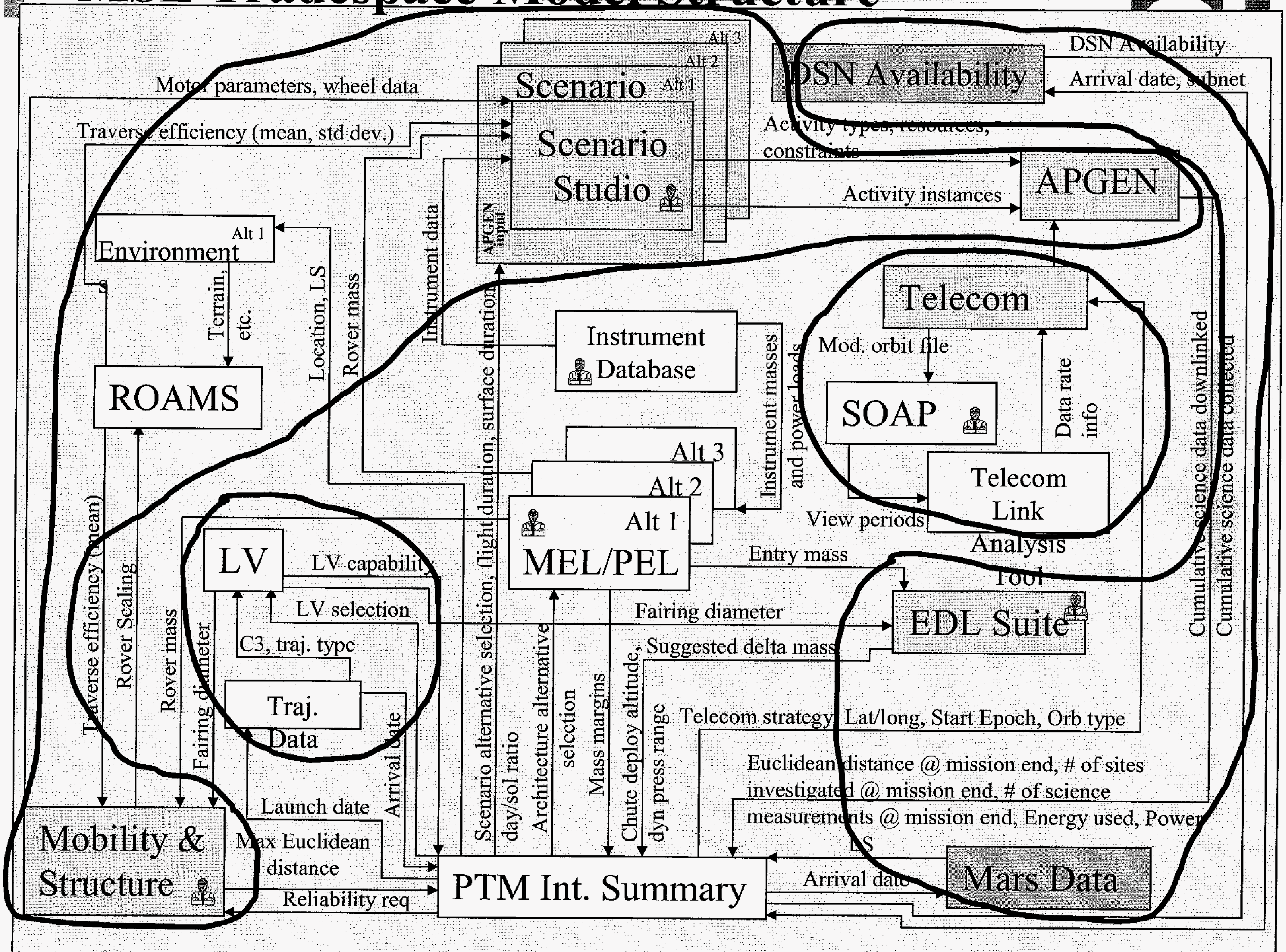

MSL Tradespace Model Structure

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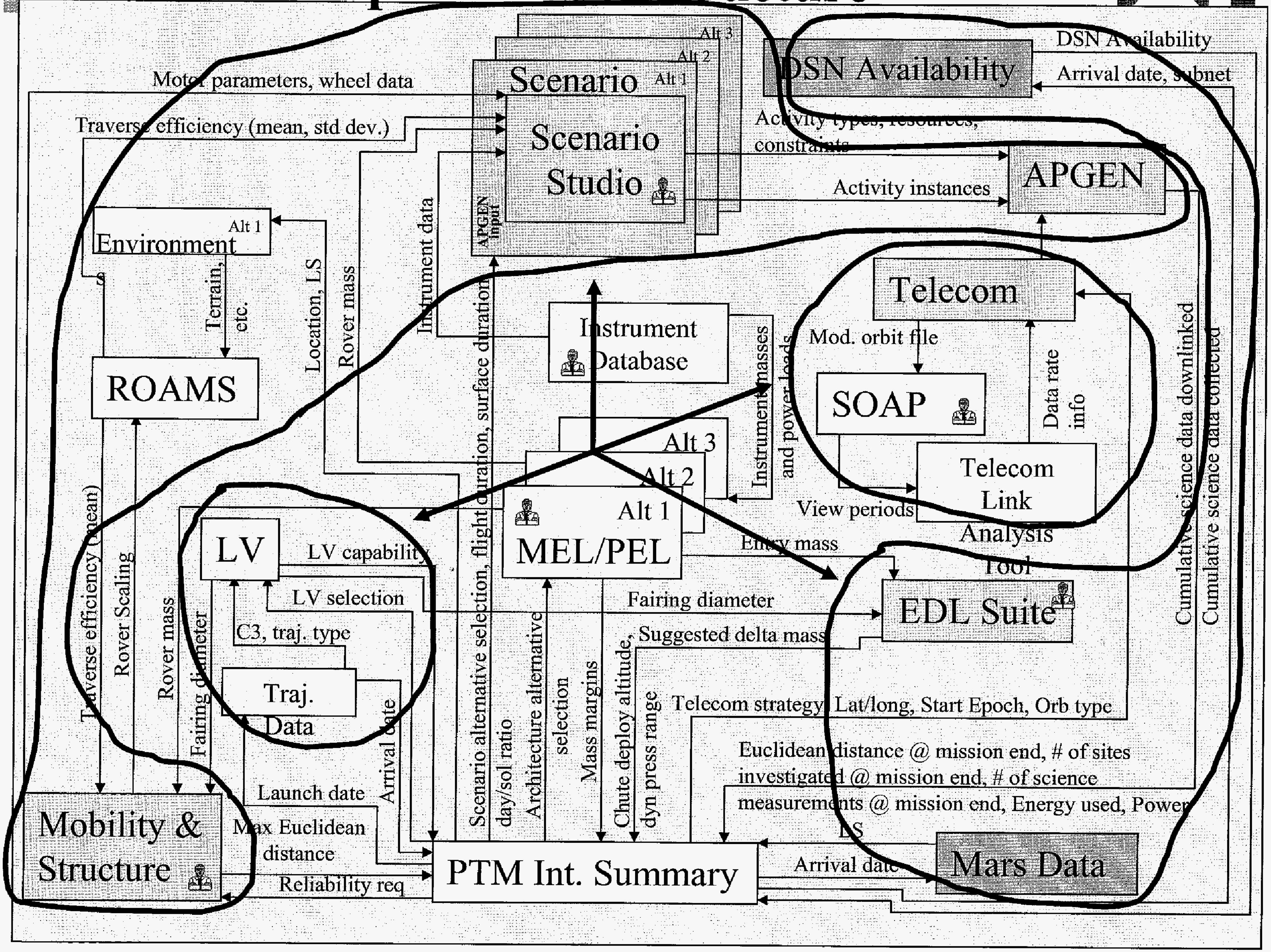
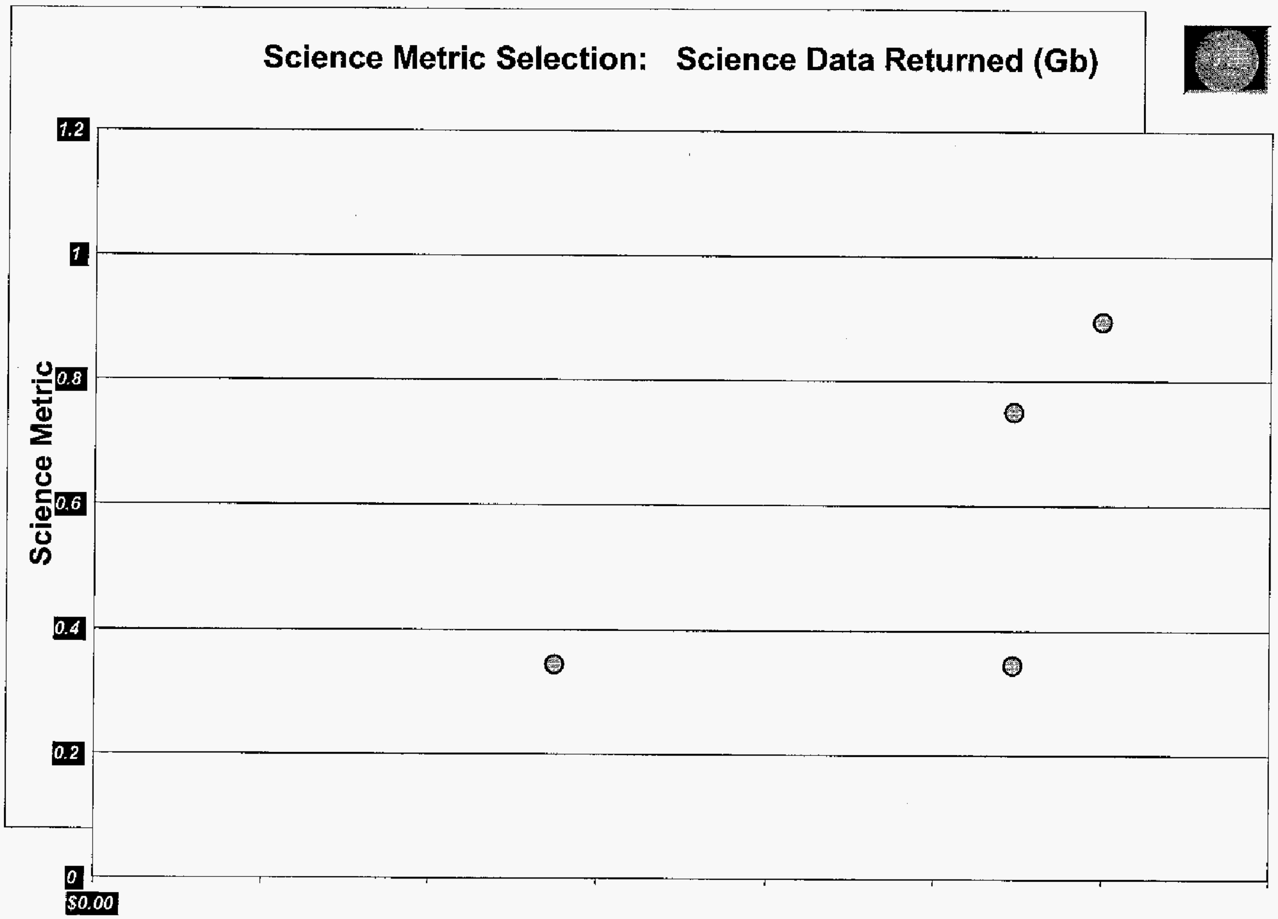


MSL Tradespace Exploration

- Enables team to more effectively explore the tradespace to find the best combination of life-cycle cost and mission effectiveness
- Shows HQ what is feasible with different funding levels



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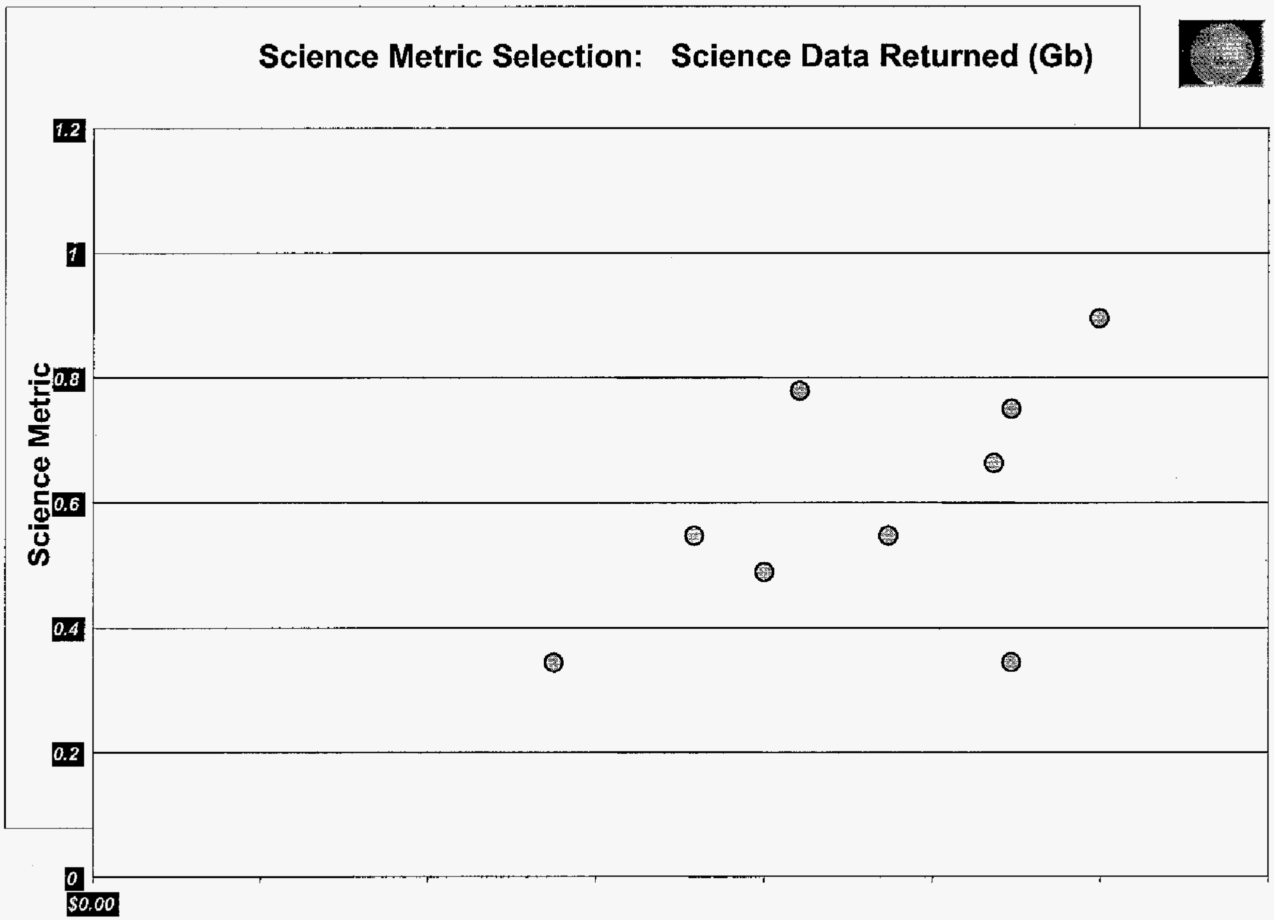

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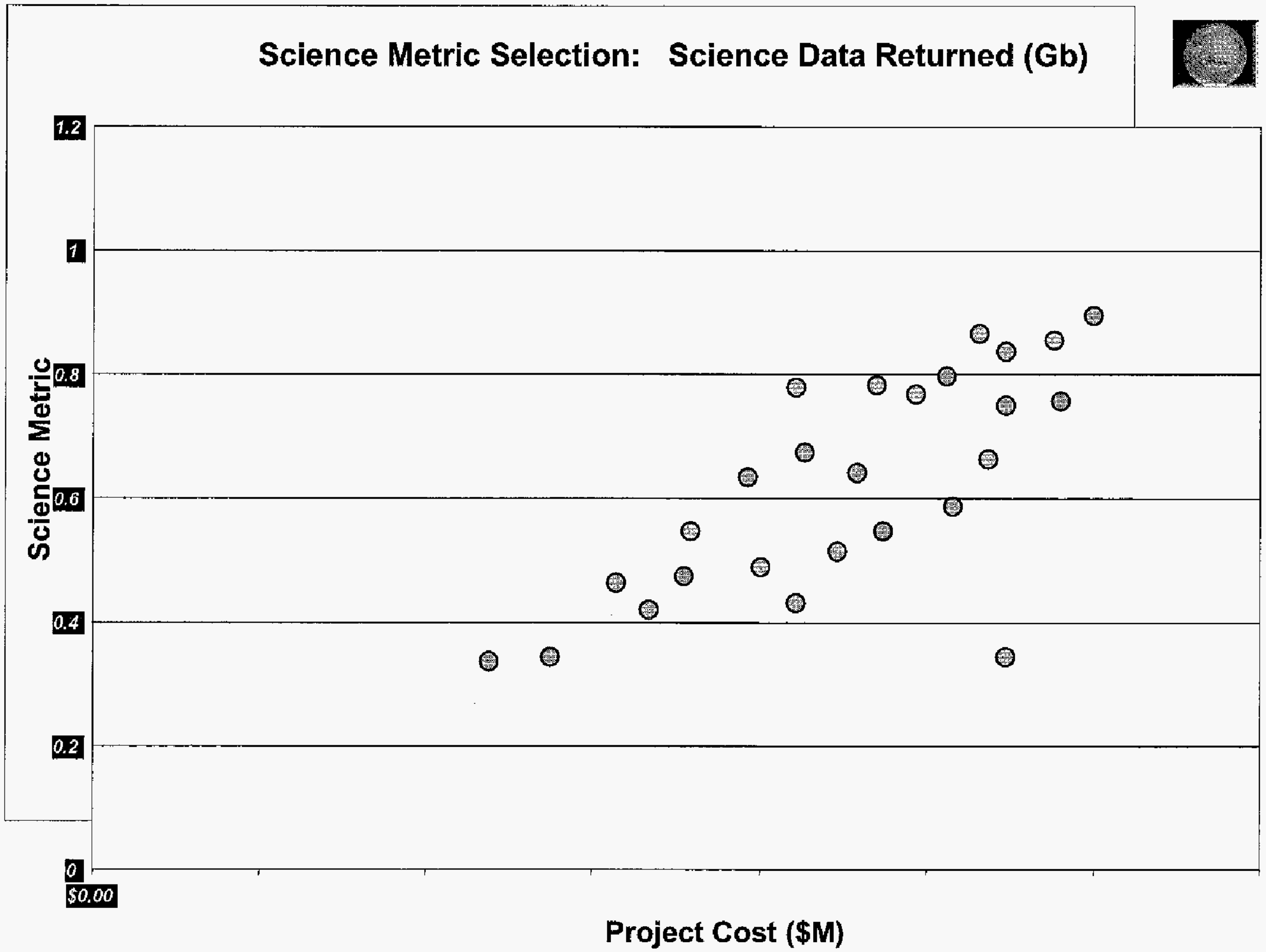

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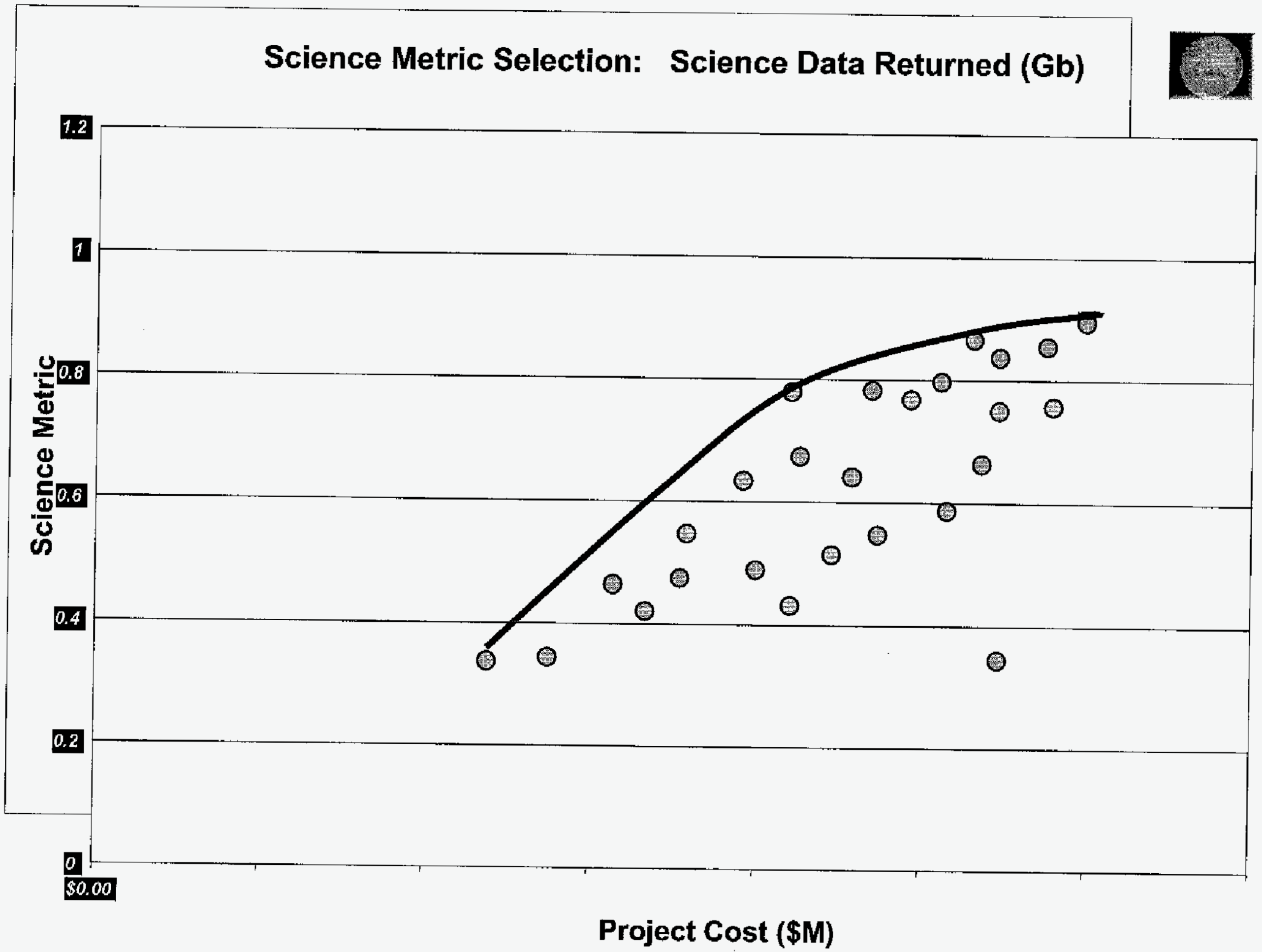
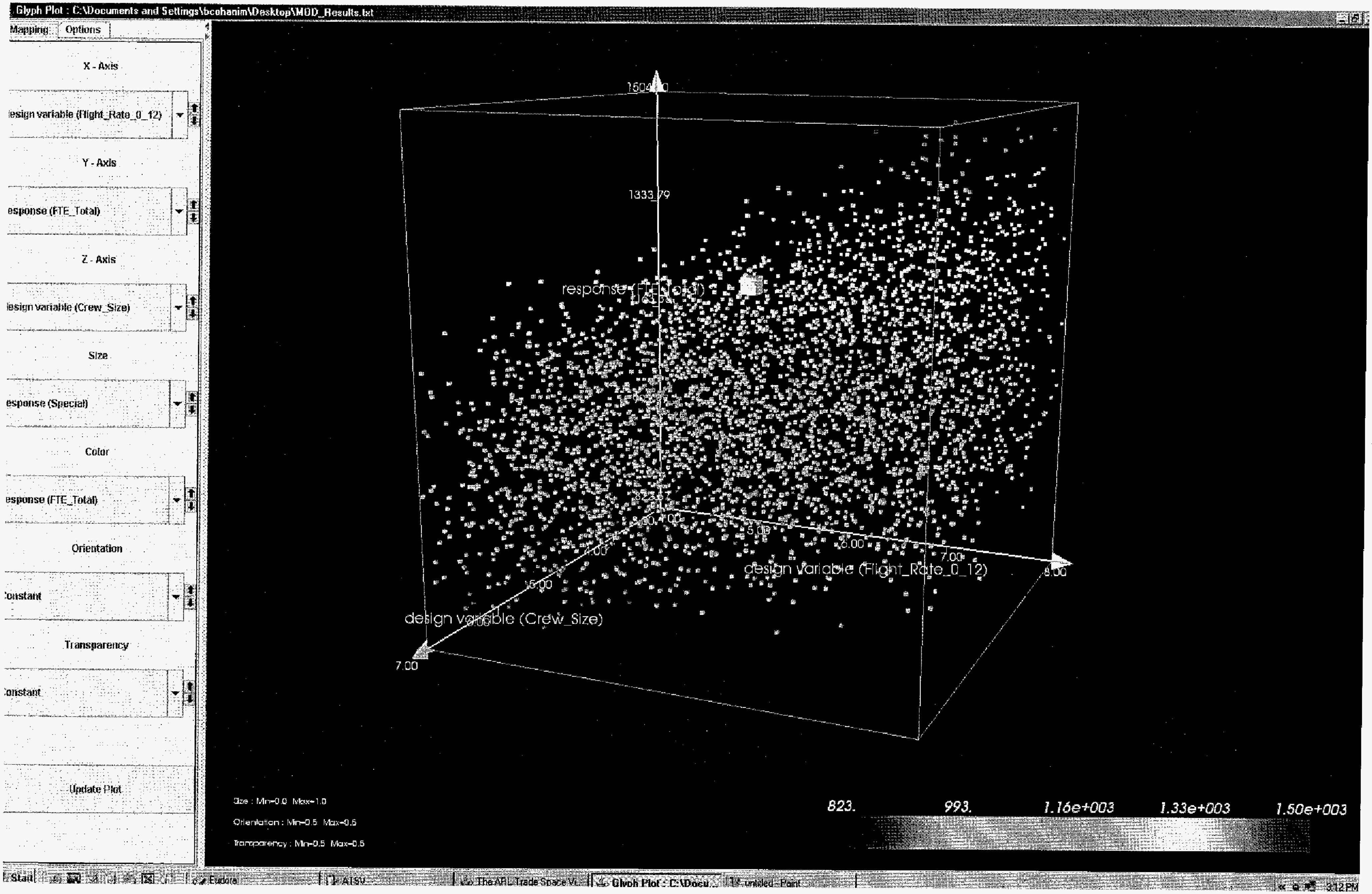


Observations on Building the MSL PTM

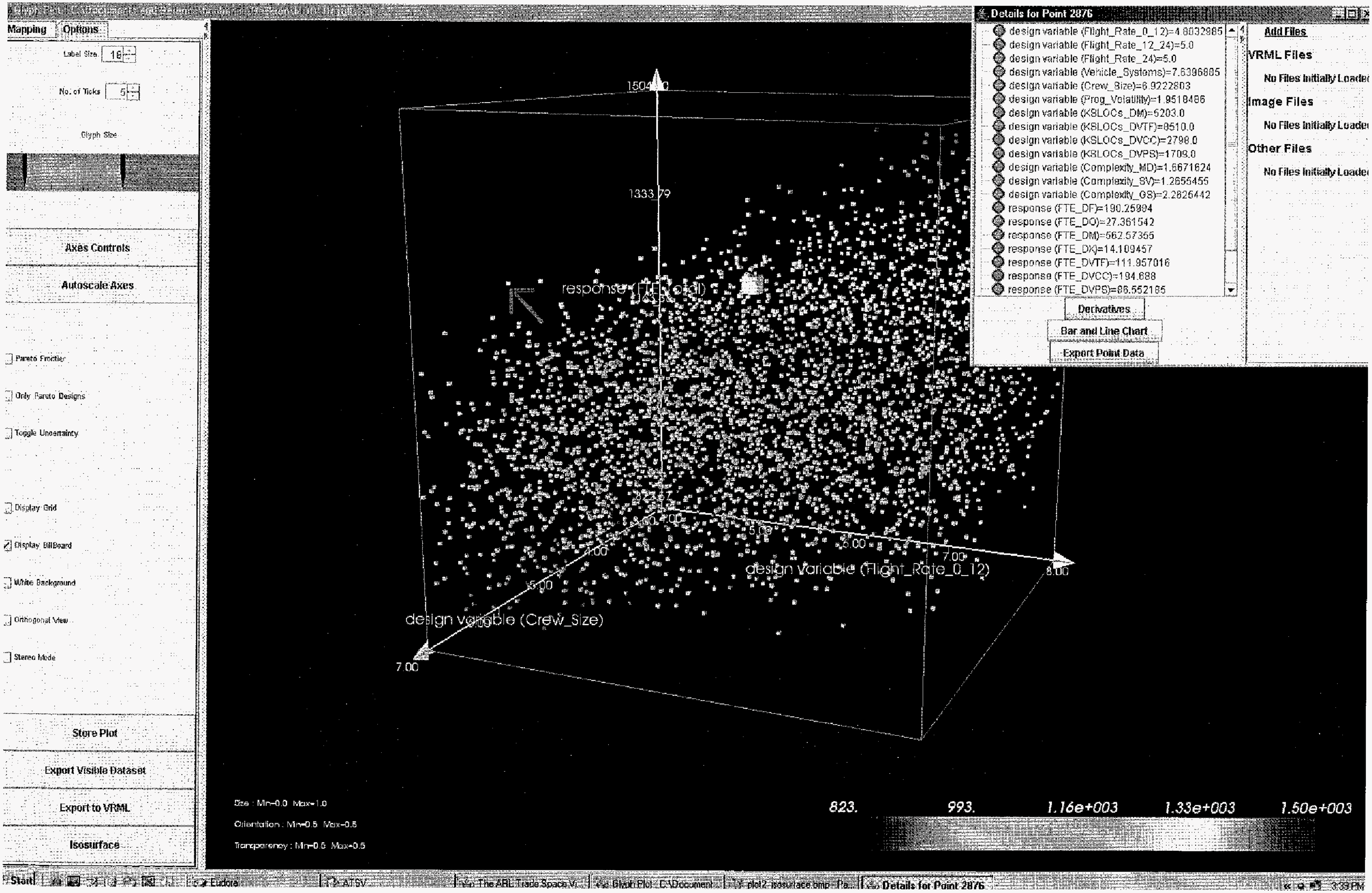
- PTM "components" may not be available inside or outside the organization
  - Develop, adapt, and standardize
  - Legacy models typically not "integration-ready"
  - Excellent cooperation from tool owners/originators allows fast progress
- Most successful application occurs when project tradespace modeling is a leadership priority
  - Design vectors are reasonably well-defined
  - Decision criteria (MoEs, LCC) are identified early
- Development increases system thinking and raises understanding of interrelationships
- Archives inputs/outputs, assumptions, and captures rationale
- Capability to pursue uncustomary trades

C. Tradespace Visualization

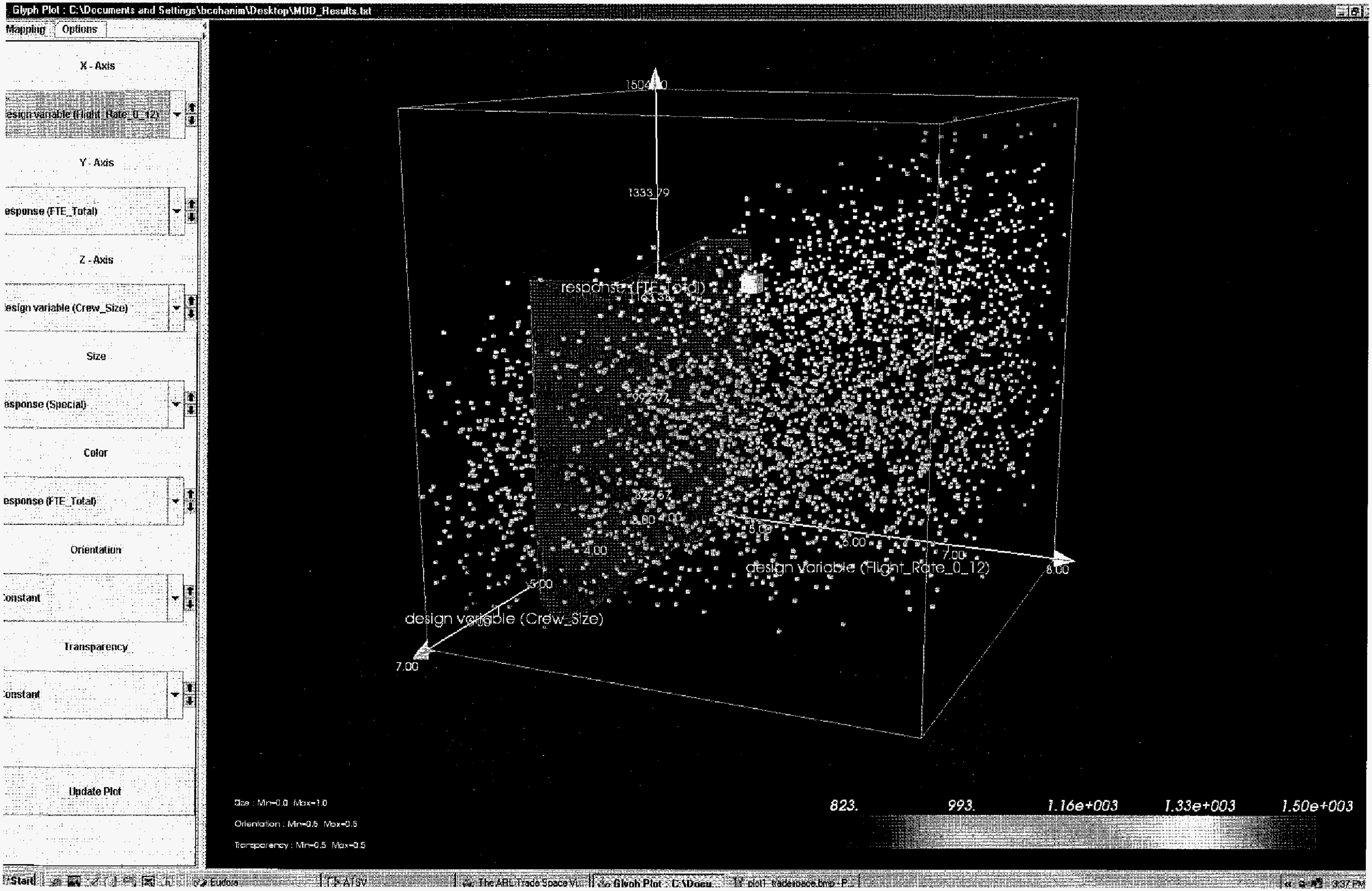
3D Tradespace



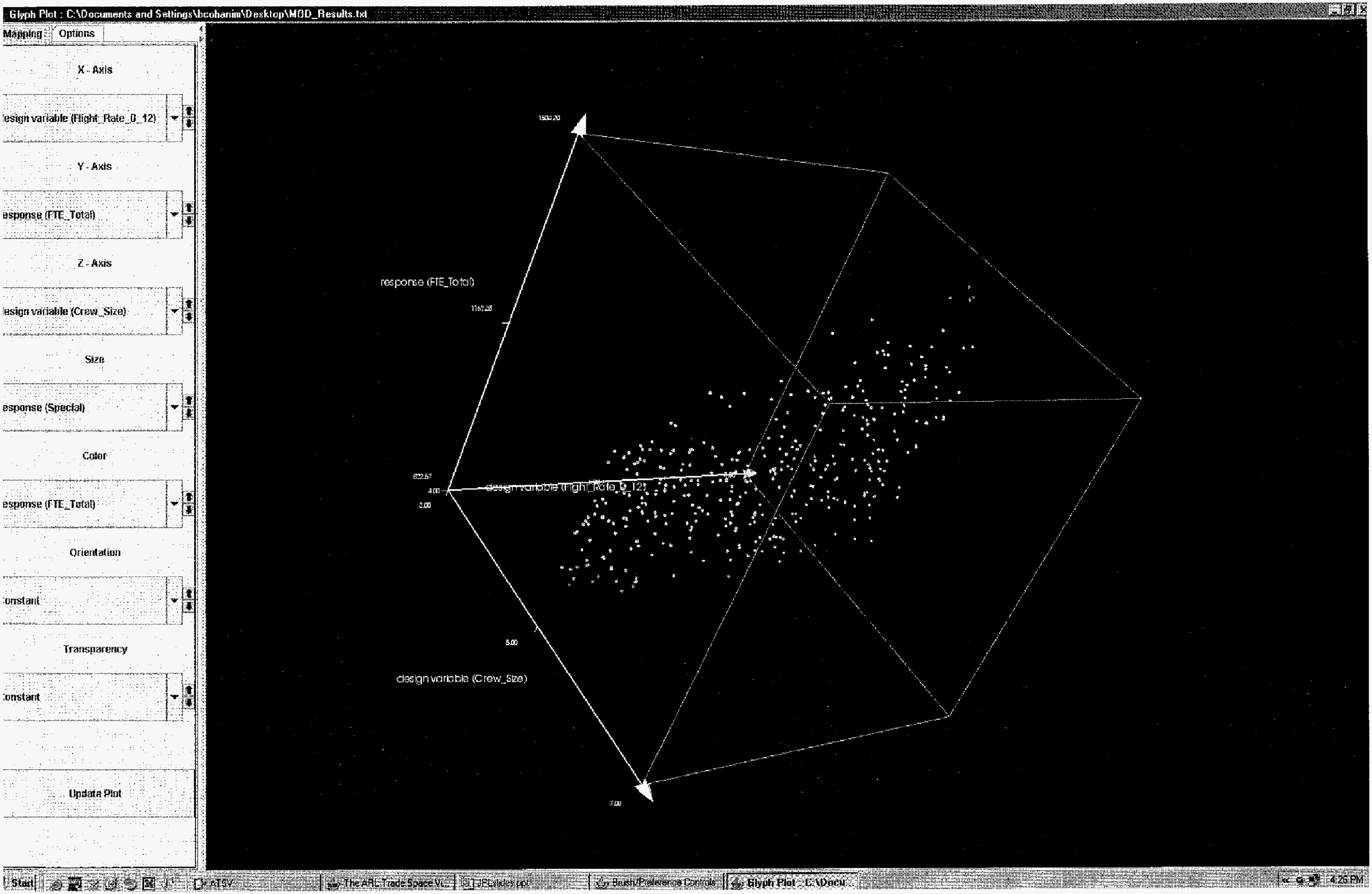
View Data on Selected Point



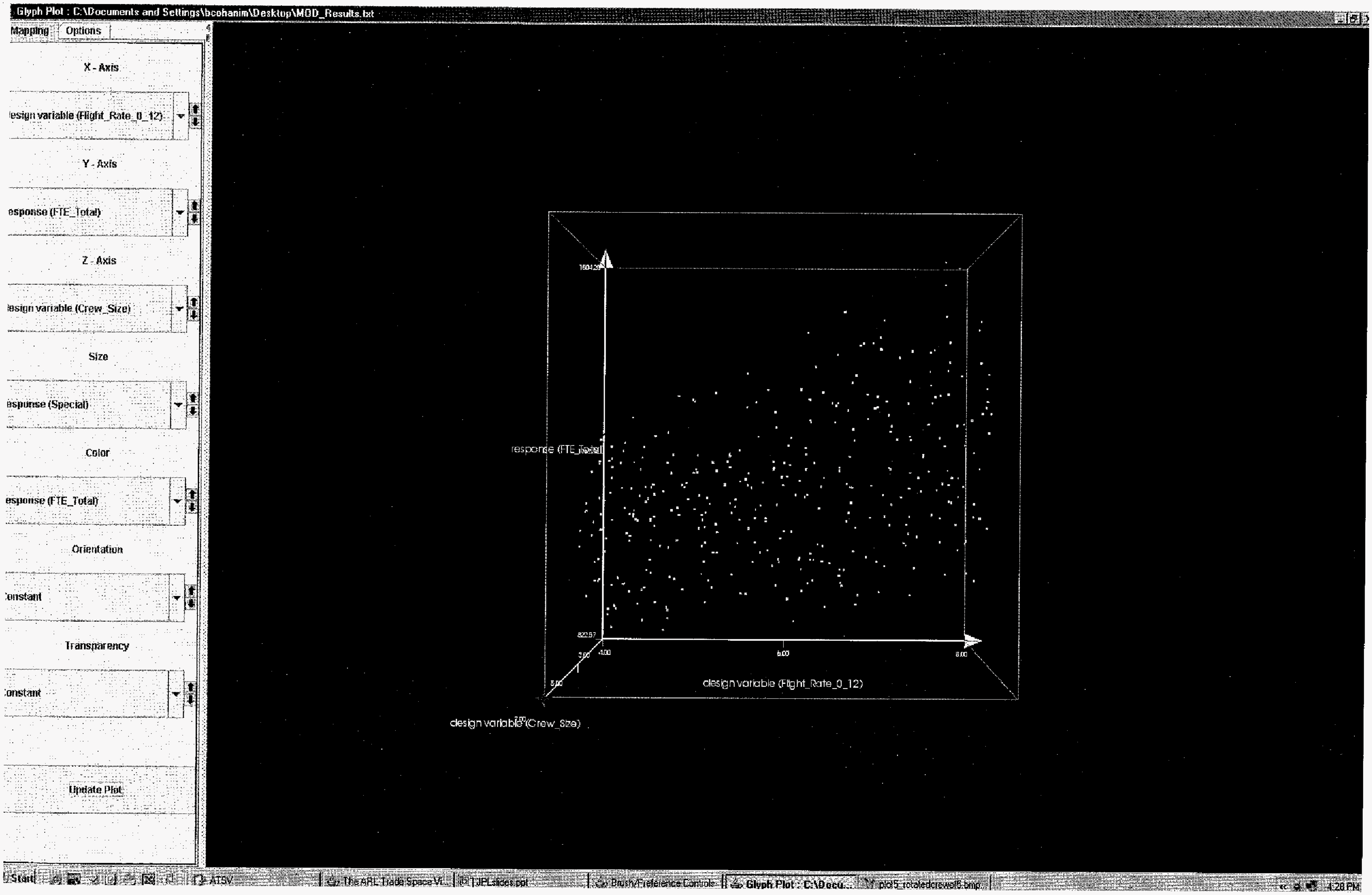
Surface of Constant Value



Filtered Slice



Pareto Surface (Two-Dimensional View)



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Summary

- Tradespace Exploration is part of the SE Process
- A Project Tradespace Model can help identify the Pareto frontier (i.e., those alternatives that are not dominated)
- Building a Project Tradespace Model requires more up-front effort, but
  - Results in a better understanding of the project-level effects of design changes
  - Helps to identify project disconnects earlier
  - Tends to produce more rigorous and consistent results so as to foster better decisions.

D. Tradespace Mini-Workshop

Tradespace Modeling Challenge for Exploration

- What flight rates would meet minimum lunar outpost operational needs over a variety of scenarios?
- Could lunar outpost concepts be changed to avoid sustainability issues?
- What kind of effort would be necessary to construct and maintain a viable lunar outpost?
- Is the architecture suitable for a given scientific, exploratory, or technology demonstration goal?
- How might Constellation architecture requirements be influenced by the revealed needs of a future outpost?

Lunar Outpost Design and Output Vectors

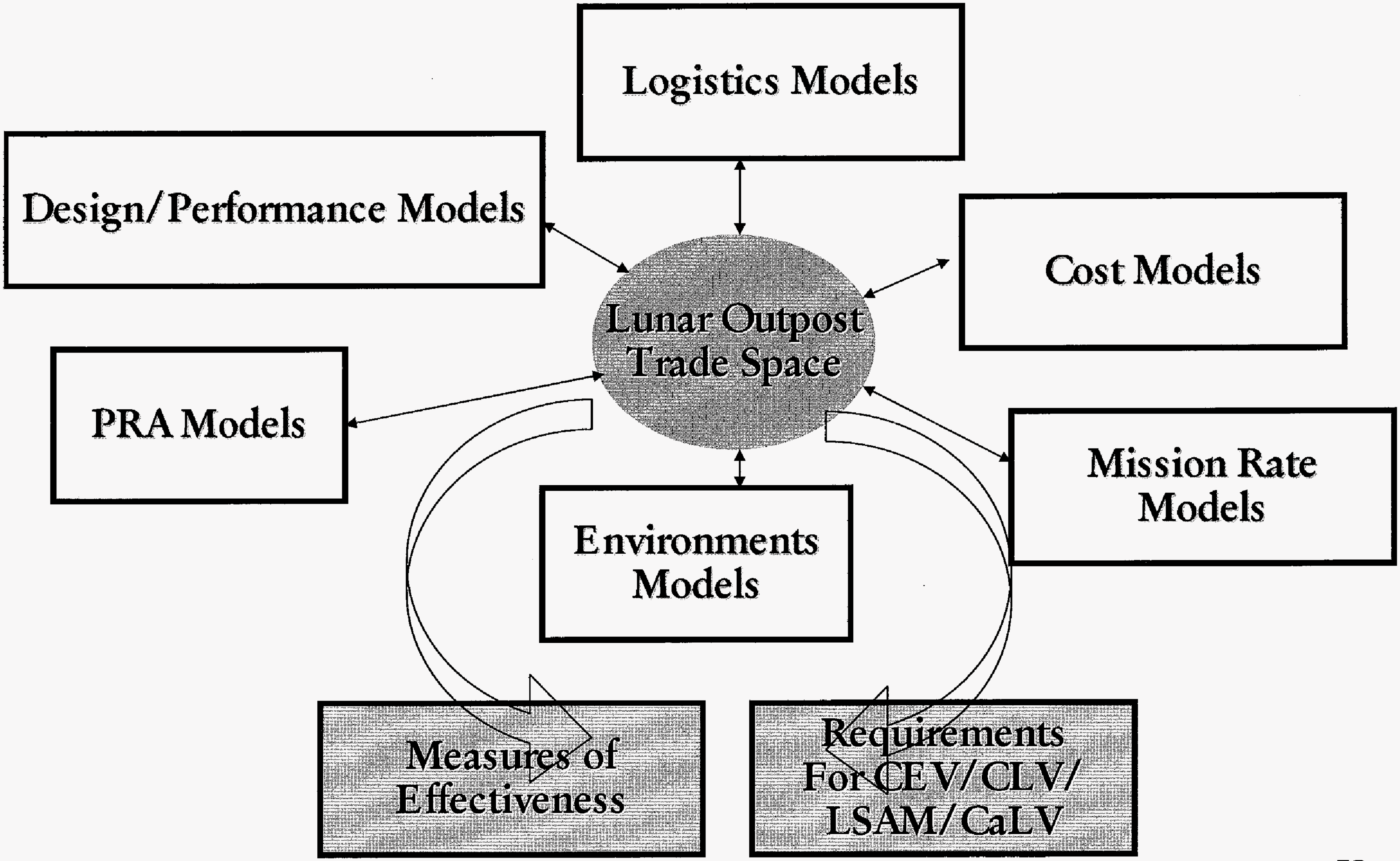
Inputs (Design Vector)

- ECLSS closure (%)
- Outpost location
- Power source type and output
- Level of repair (%)
- Surface crew size
- EVA frequency
- Surface stay duration
- Rover system type and performance
- Crew flight rate
- Cargo flight rate
- Infrastructure flight rate

Outputs (Output Vector)

- Lunar surface exploration footprint
- Outpost occupancy (%)
- Outpost EVA time
- Infrastructure mass
- Payload mass
- Logistics mass
- Sample return mass
- Outpost completion date

Lunar Outpost Systems Analysis



Lunar Outpost Trade Space Model

- Measures of Effectiveness
  - Exploration Mass Delivered (Sci/Engr)
  - Exploration Crewtime (EVA)
  - Exploration Footprint
- Major Inputs Affecting MoEs
  - CaLV cargo flights
  - ISRU
  - Surface mobility
  - ECLSS closure

Backup Material

How a Tradespace Model Fits Into the SE Process

- PTM development is a collaborative effort by the project team
  - Step 1: Determine the most important project design issues/trades
  - Step 2: Hold one-on-one meetings with cognizant engineers to develop or identify appropriate models
  - Step 3: Models are linked generally via WBS/PBS elements
  - Step 4: Review by team for completeness and consistency
- PTM development process often illuminates interface issues
- The PTM is not static! Ideally as project progresses:
  - Team augments scope and increases resolution of the models
  - User friendliness increases
  - Databases are improved and expanded
- PTM archives trade study results
- PTM evolves into a capability for future in-situ missions