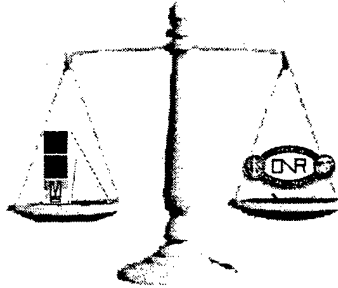


***A Comprehensive, Robust Design Simulation  
Approach to the Evaluation/Selection of Affordable  
Technologies and Systems***



Prepared By:

**Dr. Dimitri Mavris**

**Dr. Dan DeLaurentis**

Under Grant N00014-97-1-0783

**Aerospace Systems Design Laboratory**  
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Georgia Institute of Technology  
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## Presentation Outline

- 1. Introduction and Research Setting/Summary***
- 2. Overall Technical Approach for Affordable Systems Design***
- 3. Methods Implementation and Testbed Applications***
- 4. Key Advancements in Method Components***
- 5. Conclusions/Summary***

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## Section 1

- 1. Introduction and Research Setting/Summary*
- 2. Overall Technical Approach for Affordable Systems Design*
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## ONR-AMPP Goals and ASDL Objectives

### Overall ONR Goal (AMPP program)

Develop methods for measuring and predicting affordability during S&T investment decision making for optimal resource allocation

### Results of Georgia Tech ASDL Research Grant

- A comprehensive, structured, and transparent decision making **methodology** has been developed to guide S&T investment and resource allocation, with the capability for risk reduction, total ownership cost reduction, and performance improvement.
- The baseline tool created to implement this process is called TIES: the *Technology Identification, Evaluation, and Selection* tool  
TIES is the research testbed as well as research product !

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# REPORT DOCUMENTATION PAGE

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14. ABSTRACT  This annual report documents the results of basic research in the area of affordability measurement and prediction science. A key result has been the formulation of a comprehensive, rational approach to technology identification, evaluation, and selection, to aid Navy decision-makers in developing new and more affordable systems.					
15. SUBJECT TERMS  Affordability, Technologies, Robust Design, Requirements					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 92	19a. NAME OF RESPONSIBLE PERSON Dimitri Mavris
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## ASDL-ONR Objective Mapping

### AMPP Objectives:

- ☛ Facilitate S&T Resource Allocation Decisions ✓
- ☛ Enable Early Definition/ Assessment of Weapon System Design Trade Spaces ✓
- ☛ Assess Impact of Technology Insertion ✓
- ☛ Perform Total Cost of Ownership Prediction and reduction for Navy Weapon Systems ✓
- ☛ Define Affordability Metrics ✓
- ☛ Predict System Affordability ✓

### ASDL Research Thrusts:

- ☛ Multi-Attribute Decision Making
- ☛ Technology Impact Forecasting
- ☛ Technology Identification, Evaluation, and Selection
- ☛ Joint Multivariate Probabilistic Modeling
- ☛ Advances in Soft Computing

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## ONR Grant: ASDL Ph.D. Student/Staff Support

Number of Ph.D. Students Supported: 8

- |                            |                            |
|----------------------------|----------------------------|
| Ms. Debora Daberkow (ASDL) | Mr. Oliver Bandte (ASDL)   |
| Ms. Danielle Soban (ASDL)  | Mr. Andy Baker (ASDL)      |
| Ms. Elena Garcia (ASDL)    | Ms. Linda Wang (ASDL)      |
| Ms. Shobana Murali (Math)  | Mr. Noppadon Khiripet (EE) |

Number of Masters Students Supported: 8

Multidisciplinary Professional Team: 4

- |                              |                              |
|------------------------------|------------------------------|
| Dr. Dimitri Mavris (AE)      | Dr. Daniel DeLaurentis (AE)  |
| Dr. Dan Schrage (AE)         | Dr. Mark Hale (AE)           |
| Dr. Leonid Bunimovich (Math) | Dr. George Vachtsevanos (EE) |
| Dr. Jimmy Tai (AE)           | Dr. Ivan Burdun (AE)         |

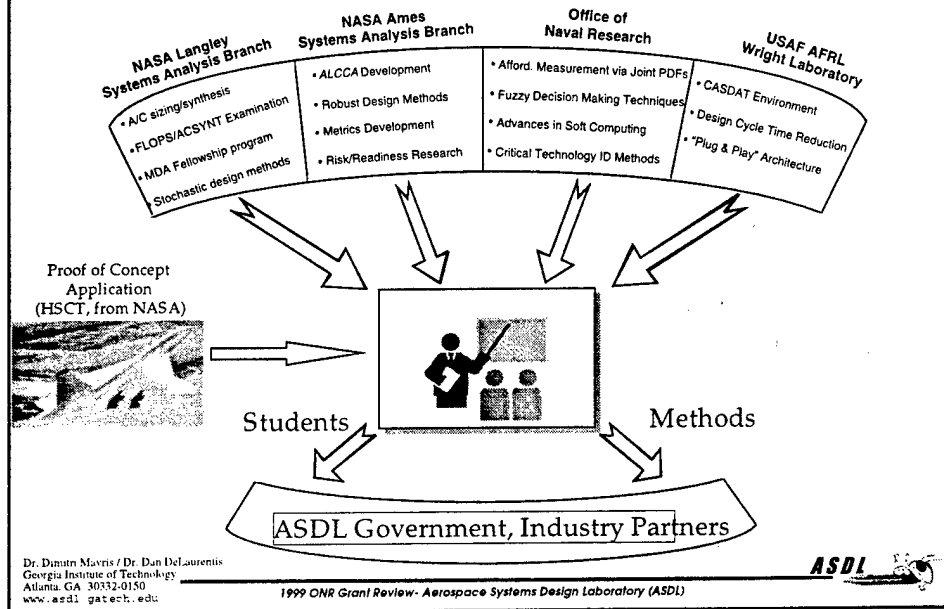
**+ Over 40 students exposed to methods in graduate design curriculum**

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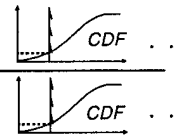
# Collaborative Research Sponsorship



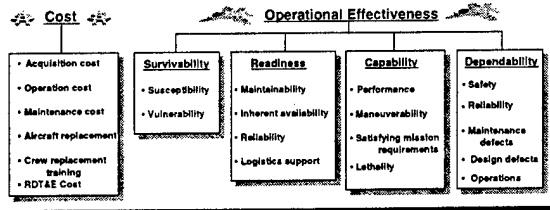
# Definition of Affordability

**Affordability:** The ratio of benefits provided or gained from the system over the cost of achieving those benefits  
*In a probabilistic, Modeling & Simulation approach, Risk is inherent in these estimates*

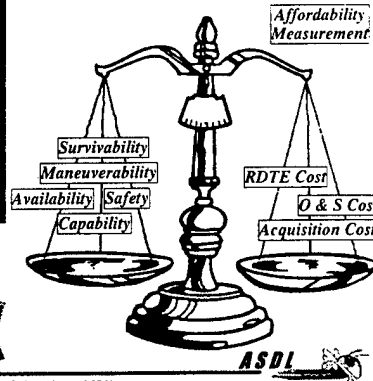
$$S \ \& \ T \ \text{Affordability} = \frac{\text{Weapon System Effectiveness}}{\text{Investment to Achieve This Effectiveness}}$$



## Weapon System Effectiveness- Aircraft Example



$$\text{Effectiveness} = k_1(\text{Capability}) + k_2(\text{Survivability}) + k_3(\text{Readiness}) + k_4(\text{Dependability}) + k_5(\text{Life Cycle Cost})$$



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# Science & Technology Return on Investment (ROI)

## An Alternate Evaluation Criterion:

$$\frac{\partial \text{Benefit}}{\partial \text{S\&T Investment}} ; \frac{\partial \text{Cost Savings}}{\partial \text{S\&T Investment}} ; \frac{\partial \text{Risk Reduction}}{\partial \text{S\&T Investment}}$$

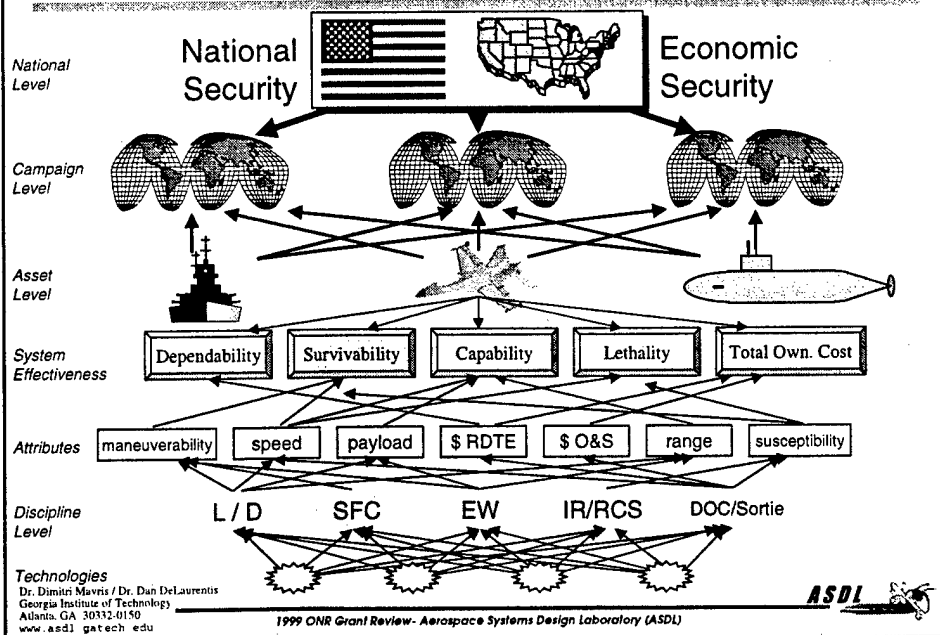
*ROI* Assesses the impact that the S&T investment made on the system performance, survivability, safety, ..., developmental, production, support life cycle cost and on averting or reducing risk or by improving the readiness associated with a given technology.

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## Problem Definition- Hierarchical Decomposition



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## Technical Areas of Research

ASDL's research for the ONR presented here falls in the following categories:

- ◆ Decision-Making methods for Affordability, with and without modeling and simulation capabilities. This area includes:
  - ◆ *analysis of alternative concepts and technologies*
  - ◆ *joint multivariate probability models for decision making*
  - ◆ *multi-attribute methods such as TOPSIS*
  - ◆ *decision tree networks with fuzzy inputs.*
- ◆ Affordability measurement and prediction (forecasting) of future technology options, in the presence of a variety of uncertainties. This area includes:
  - ◆ *Use of Response Surface Models of physics-based analyses*
  - ◆ *Uncertainty modeling and use of Fast Probability Integration (FPI)*
  - ◆ *Preliminary research into stochastic models and methods*
- ◆ Concurrent, physics-based modeling of system requirements and technologies
  - ◆ *Nonlinear, constrained equation solver for feasible solutions that trade requirements and technology levels*

*All three of these areas are encompassed in the overall TIES environment*

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## Review of Year 1 Results

An innovative, comprehensive method for engineering decision making was created, the Technology Identification, Evaluation, and Selection (TIES) method, populated by:

- ◆ *Problem Definition/Brainstorming Tools: QFD, Morphological Matrix, Pugh Matrix*
- ◆ *Intelligent Modeling & Simulation and Technology Impact Forecast through Response Surface Methods*
- ◆ *Method for rapid assessment of technical feasibility and economic viability*
- ◆ *Multi-attribute decision making methods (MADM)*
- ◆ *Initiation of a Joint Probability Decision Making (JPDM) model*

Investigation of Advanced Math and Soft Computing Techniques

- ◆ *Review and classification of nine emerging techniques*
- ◆ *Comparative study of Neural-Network and Response Surface approximations*
- ◆ *Employment of Fast Probability Integration (FPI) techniques to assist in probabilistic formulation*
- ◆ *Review of advanced tree-network formulations for decision-making under uncertainty and schedule constraints*

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## Summary of Year 2 Results

1. Significant enhancements to the TIES affordability environment est. in Year 1
  - ◆ *Pilot Studies: Environment prototype for Navy's F-18C, NASA's HSCT, a notional 150 pax transport, and a short-haul civil tiltrotor*
  - ◆ *JPDM incorporation and validation; n-variate math model constructed*
  - ◆ *Genetic Algorithm for technology combinatorial selection problems*
  - ◆ *Fuzzy Decision tree constructed to treat stochastic affordable technology selection problem, an evolution of TIES to include schedule/cost as well as performance*
2. Completion of the investigative research into mathematical and soft computing techniques and stochastics, resulting in:
  - ◆ *Web-based database of advanced math and soft computing techniques relevant to affordability measurement and prediction, including current investigators, computer codes, and transition status*
  - ◆ *Several implementations of methods (Fuzzy sets, GA's, Neural Networks)*
  - ◆ *Roadmap towards stochastic methods established, research goals prioritized*
3. A powerful mathematical tool to examine the simultaneous impact of vehicle requirements & technologies has been created and initially tested on a F/A-18C case, including carrier suitability constraints.
4. Methods have been integrated in Graduate level curriculum

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## Research Payoffs: Value Added to USN

- Tradeoff requirements vs. technologies *early in design and procurement* phases, with implications for Navy Total Cost of Ownership (TOC) reduction
  - Ability to identify and assess the impact of new technologies for *Resource allocation planning*
    - *Probabilistic assessment of design, technological, and operational uncertainty*
    - *Efficient system feasibility and economic viability assessment*
  - *Reduction in design cycle time and cost*
  - *Design for affordability* in an IPPD environment
  - Design for "cost as an independent variable" (CAIV) as a stochastic process
  - Initial implementation of affordability methods to F/A-18C and NASA's HSCT, with further validation on Navy systems proposed



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## Section 2

1. *Introduction and Research Setting/Summary*
2. *Overall Technical Approach for Affordable Systems Design  
- Feasibility/Viability Examination and the TIES  
Method for Affordable Technology Investment*
3. *Methods Implementation and Testbed Applications*
4. *Key Advancements in Method Components*
5. *Conclusions/Summary*

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## Decision Making:

### Two Avenues for Technology Assessment

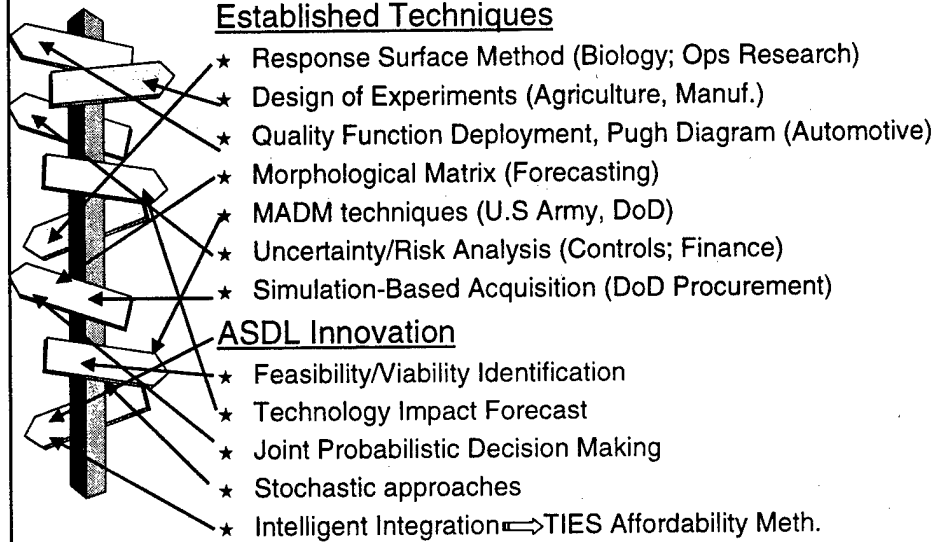
- 1) Subjective Rankings through QFD, Pugh Diagrams, and Multi-Attribute Decision Making (MADM)
  - DoD guiding documents (e.g. DTAPS) & expert opinion are used to establish a mapping of the Navy's warfighting structure
  - Through Quality Function Deployment (QFD) and Pugh Diagrams, this mapping is used to subjectively assign importance weights to various technologies accounting for joint warfighting needs
  - Multi-Attribute Decision Making (MADM) techniques use results to guide the decision maker to the best solutions
- 2) Modeling & Simulation (M&S) and Joint Probabilistic Decision Making (JPDM)
  - Engineering analyses and physics-based models of technologies are employed in order to obtain objective estimates of technology impacts
  - Probabilistic analysis techniques captures uncertainty and risk among multiple, inter-related decision criteria

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Established Techniques + Innovative Methods = *The TIES Affordability Approach*

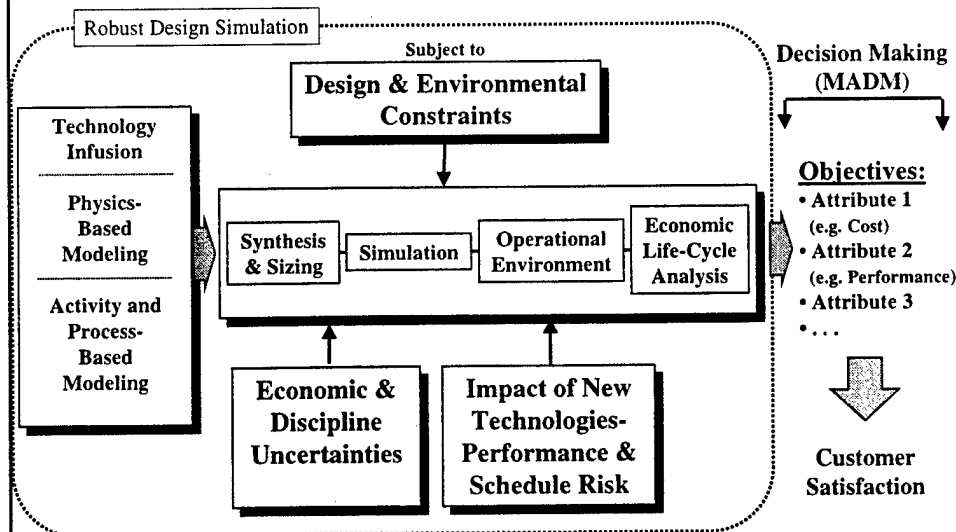


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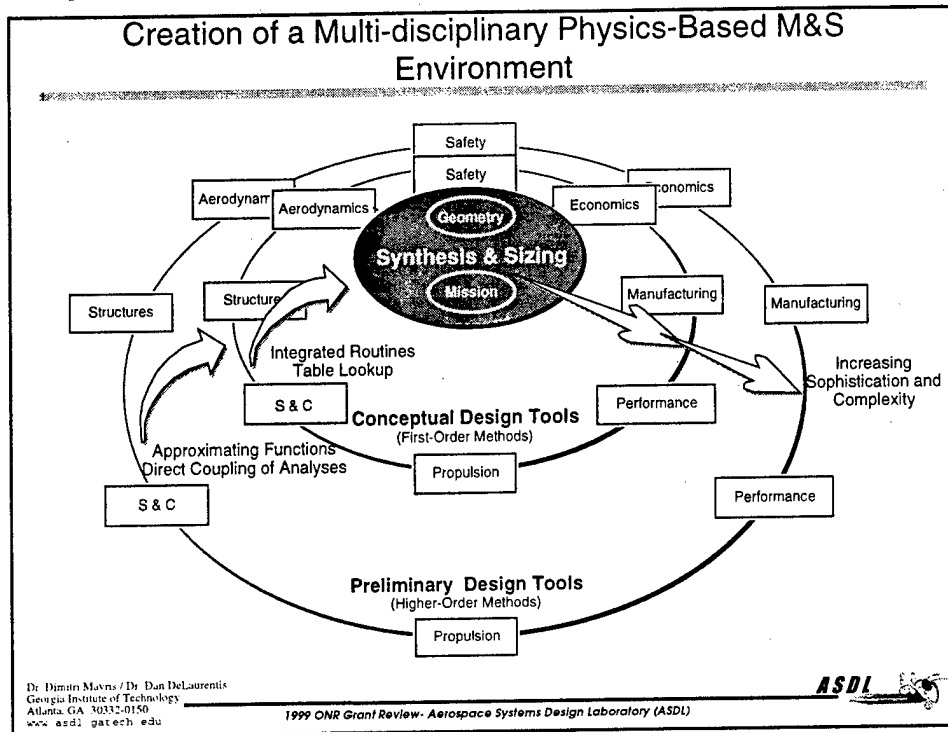
Physics-Based Modeling and Simulation Environment



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## Response Surface Methodology (RSM)

- RSM is a multivariate regression technique developed to model the response of a complex system using a simplified equation
- RSM is based on the design of experiments methodology which gives the maximum power for a given amount of experimental effort
- Typically, the response is modeled using a second order quadratic equation of the form:

$$R = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} x_i x_j$$

Where,

- $b_i$  are regression coefficients for the first degree terms
- $b_{ii}$  are coefficients for the pure quadratic terms
- $b_{ij}$  are the coefficients for the cross-product terms

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# Robust Design

**Robust Design** is the systematic approach to finding *optimum values of design factors* which results in economical designs which *maximize the probability of success*.

A Robust Design is characterized by:

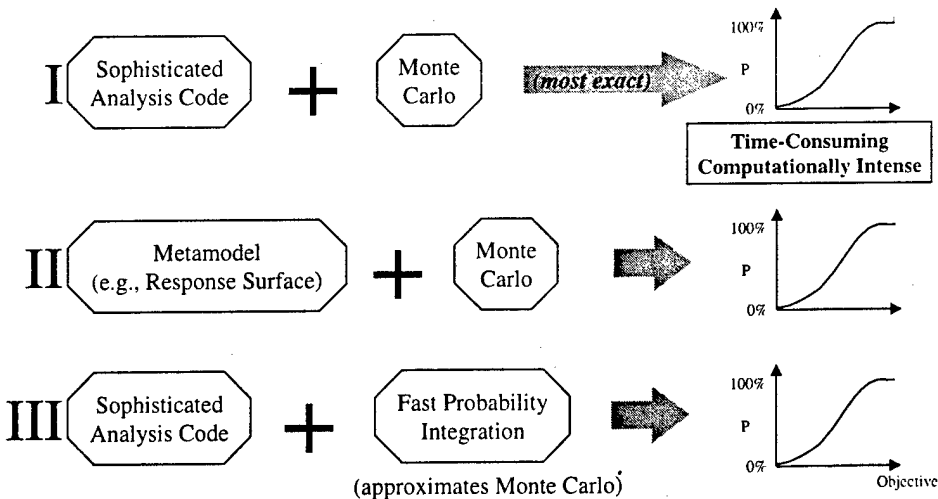
- Technical Feasibility** → satisfies all technical constraints for a given confidence level,
- Viability** → customer's economic targets are also met

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# Options for Probabilistic Design

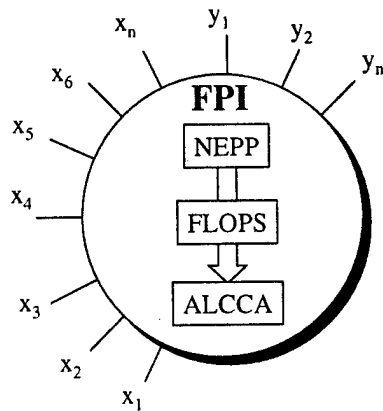


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## Fast Probability Integration (FPI)



- FPI manages program execution while handling up to 100 deterministic ( $x_i$ ) or probabilistic ( $y_i$ ) variables, with capability for expansion
- Establishes design feasibility
- Identification of most critical constraints
- Creates probabilistic sensitivity derivatives and CDFs for each objective & constraint
- Assessment of new technologies impact deterministically or probabilistically
- Probabilistic solutions for a set of design variables subject to uncertainty
- Identification of feasible and/or robust solutions, by assigning random distributions to each design variable, within the range of applicability, and allowing for operational and manufacturing uncertainty

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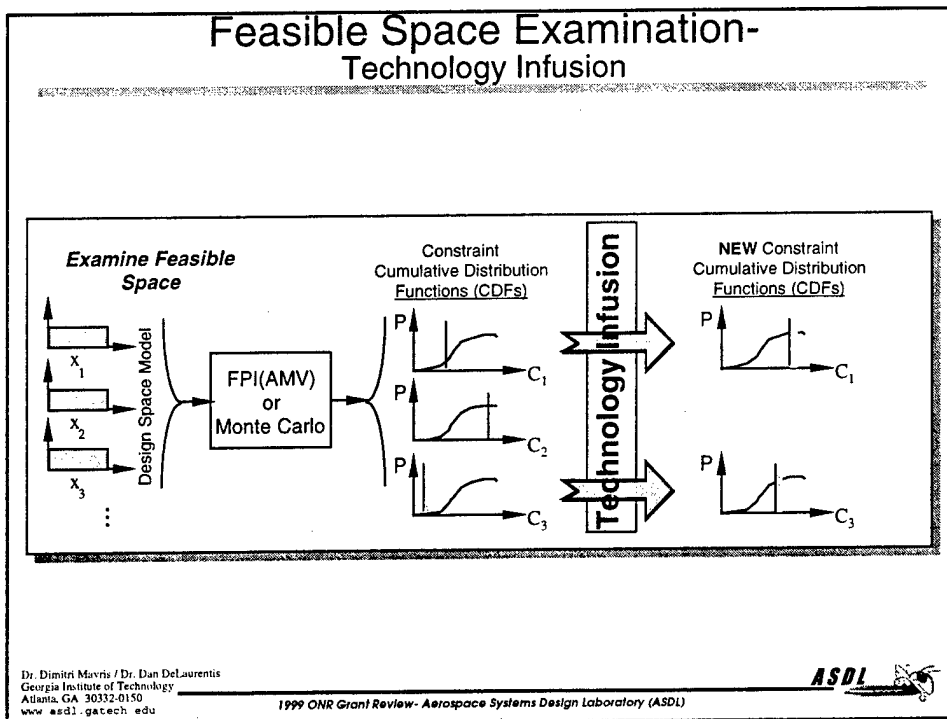
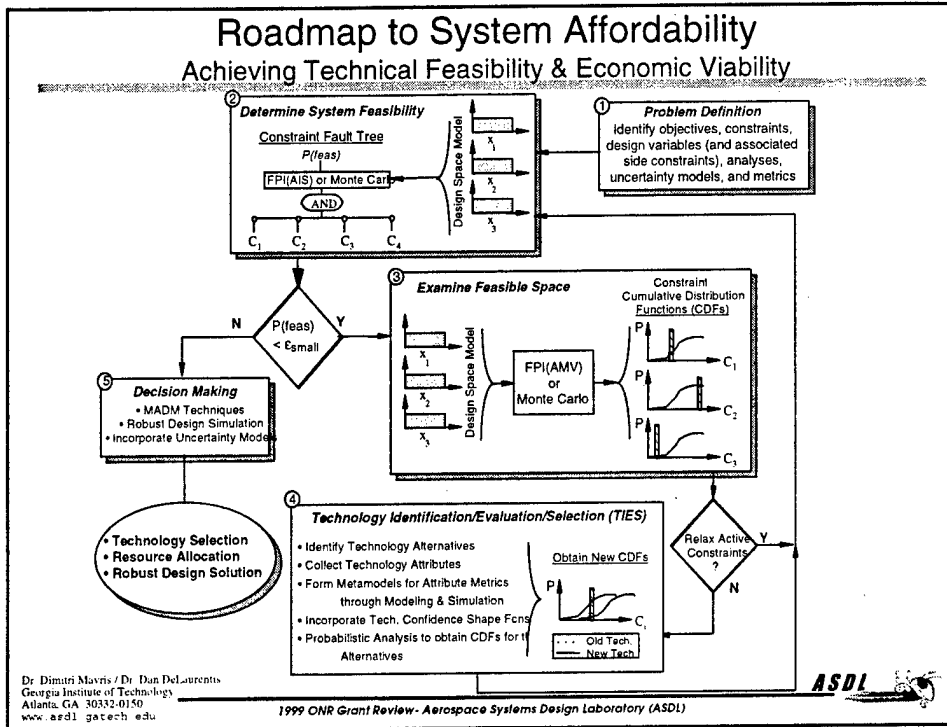
## Characterizing the Feasibility/Viability Method

- Q1: What are the measures of success ?
- Q2: Is a new technology needed ? i.e. Can optimization satisfy the requirements ?
- Q3a: What constraints are being violated ?
- Q3b: Can constraints be relaxed ?
- Q3c: Can requirements be relaxed? Can they be manipulated/examined simultaneously ?
- Q3d: What discipline metric is responsible for this violation ?
- Q4a: What is the mapping between technologies and metrics, including adverse effects ?
- Q4b: What is the confidence associated with a technology estimate ?
- Q4c: What is the optimal resource allocation (including combinations of technologies) ?
- Q4d: Multi-Attribute Decision Making methods (MADM) yields best mix of technologies ?
- Q5: With technologies and confidence estimates chosen, return to full analysis. Can final design space exploration and robust design optimization improve the result ?

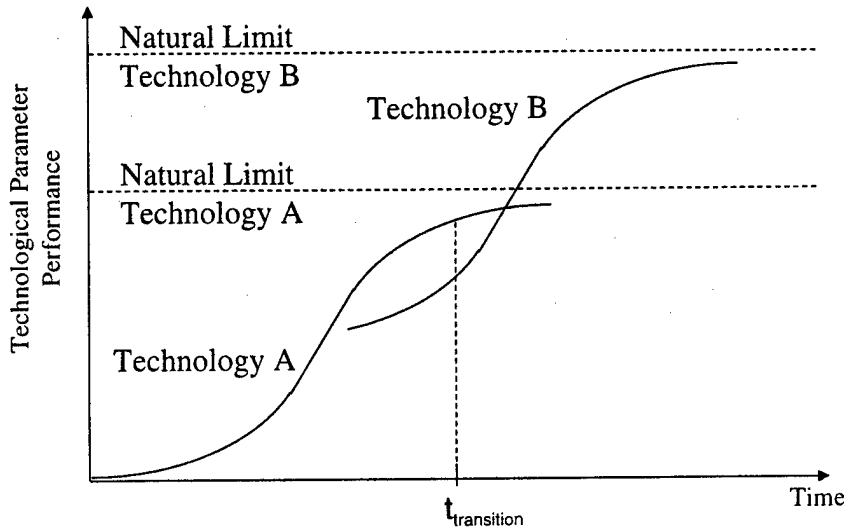
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# Technology Substitution



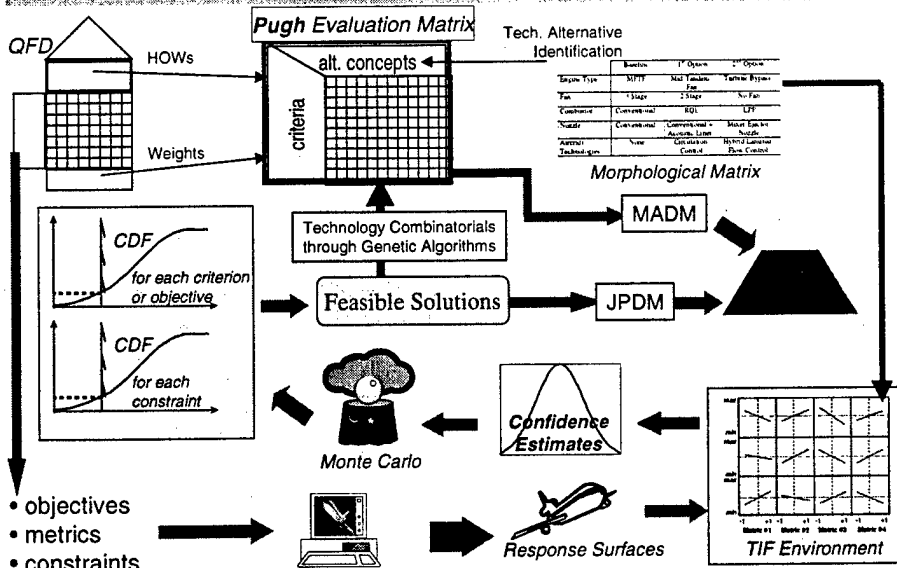
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Reference: Twiss, 1992



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# Technology Identification Evaluation Selection (TIES)

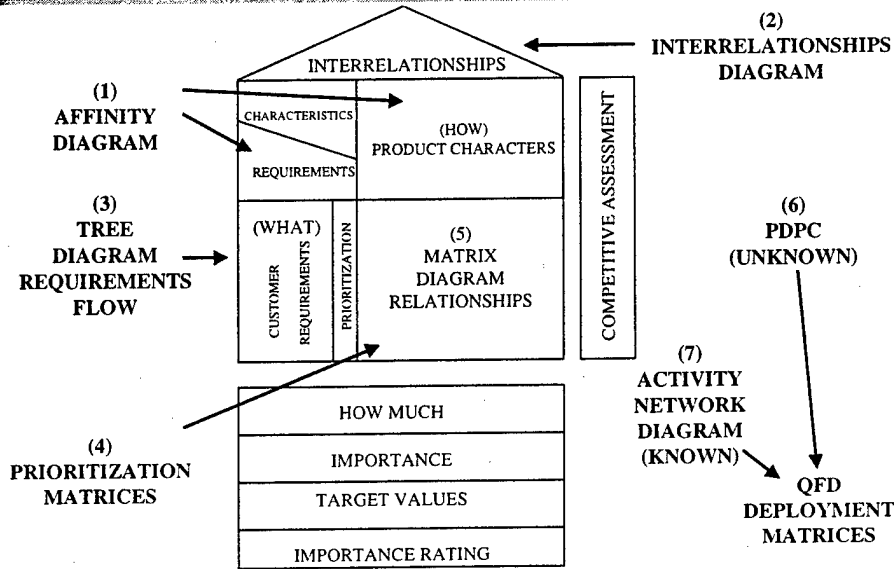


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## How the Seven Management and Planning Tools Relate to Quality Function Deployment



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## Morphological Matrix

Alternatives	1	2	3	4
Vehicle	Wing & Tail	Wing & Canard	Wing, Tail & Canard	Wing
Fuselage	Cylindrical	Area Ruled	Oval	
Pilot Visibility	Synthetic Vision	Conventional	Conventional & Nose Droop	
Range (nmi)	5000	6000	6500	
Passengers	250	300	320	
Mach Number	2	2.2	2.4	2.7
Type	MFTF	Turbine Bypass	Mid Tandem Fan	Flade
Fan	None	1 Stage	2 Stage	3 Stage
Combustor	Conventional	RQL	LPP	
Nozzle	Conventional	Conventional & Acoustic Liner	Mixed Ejector	Mixer Ejector & Acoustic Liner
Low Speed	Conventional Flaps	Conventional Flaps & Slots	CC	
High Speed	Conventional	LFC	NLFC	HLFC
Materials	Aluminum	Titanium	High Temp. Composite	
Process	Chordwise Stiffened	Spanwise Stiffened	Monocoque	Hybrid

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## Pugh Evaluation Matrix

Qualitative Example		Alternative Concept					
	Evaluation Criteria	1	2	3	4	...	n
Airline Economics	\$/RPM	+	-	-	+		
	Acquisition Price	+	-	+	S		
	Engine Price	-	+	-	-		
	DOC/trip	S	+	+	-		
Manufacturer Economics	Sunk Cost	+	-	-	S		
	Break Even Unit	+	-	-	+		
Environmental	EPNLdB $SL_n$	+	+	-	-		
	EPNLdB $TO_n$	-	+	-	-		
	EPNLdB $FO_n$	+	+	-	-		
Reliability Maintainability	MTBF	+	+	-	+		
	MTTR	+	-	S	+		
	MMH/FH	S	S	+	S		
	Risk	+	S	-	-		
	$\Sigma+$	9	6	3	4	...	
	$\Sigma-$	2	5	9	6	...	
	$\Sigma S$	2	2	1	3	...	

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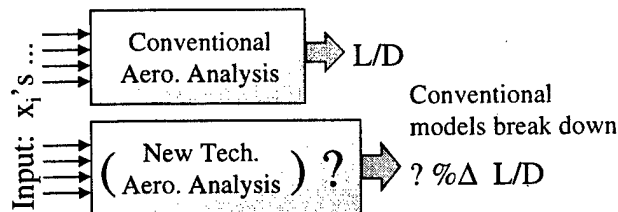
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## Mapping Responses to Discipline Metrics via Physics-Based M&S

**Purpose: To Open Feasible Space**

- ♦ Formulation in terms of elementary variables does not lend itself to disciplinary or multidisciplinary technology assessment



- ♦ The assessment of new technologies must be addressed through the disciplinary metrics (or technology "k" factors) since a mathematical formulation is not yet available

*constraints/objectives* =  $f(k_{L/D_{sub}}, k_{L/D_{sup}}, k_{C_{Lmax}}, k_{TI}, k_{SFC_{sub}}, \dots)$

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## Technology Impact on Metrics

- New technology opens the range of the affected metric through a k-factor:  

$$L/D_{\text{new}} = k_{L/D} L/D_{\text{old}} ; \text{ where } k_{L/D} = 0.9 \dots 1.2 \text{ is based on Question 10.}$$
- Select ranges for all metrics affected by new technologies
- The technology is applied to a fixed baseline configuration
- Create a DoE to establish .... for each new technology considered

$k_{L/D\text{sub}}$	$k_{L/D\text{sup}}$	$k_{\text{SFC}}$	$k_n$	\$/RPM	TOGW	$V_{\text{app}}$	$R_n$
.9	1.05	0.95		0.125	809,781	119	
.9	1.05	0.85		0.129	825,432	121	
.9	0.85	0.95		0.137	755,593	117	
.95	0.85	0.85		0.133	791,024	122	
:	:	:	:	:	:	:	:

- Create RSE based on uncorrelated metrics, since configuration is fixed and metric improvements ( $k_m$ 's) are selected independently

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## Technology Estimates

### Addressing Technology Benefits, Penalties and Confidence

1. Create functional relationships between Objectives/Constraints and technology metrics

	<u>Objective</u> = $f(L/D_{\text{cruise}}, L/D_{\text{TO}}, C_{L\text{max}}, W_{\text{wing}}, \text{SFC}, \text{MMH/FH}, \dots)$
	<u>Constraint</u> = $f(L/D_{\text{cruise}}, L/D_{\text{TO}}, C_{L\text{max}}, W_{\text{wing}}, \text{SFC}, \text{MMH/FH}, \dots)$

2. Model technology benefits and penalties through metric "k-factors"

(Step Change in Mean)	+10%	+5%	+7%	-3%	+5%	-5%
-----------------------	------	-----	-----	-----	-----	-----

3. Assign probability distributions to the technology metrics to develop confidence estimates and CDFs

(Variability)

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# A MADM Choice: TOPSIS

## Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

- compensatory and compromising method utilizing preference in the form of weights  $w_j$  for each criterion
- best alternative has shortest distance to ideal solution and farthest away from negative-ideal solution

### Advantages:

- simplicity
- indisputable ranking obtained

### Disadvantages:

- dependent on cardinal information, such as weights
- solution highly dependent on values
- criteria have to have a monotonically increasing or decreasing utility to the decision-maker

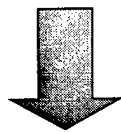
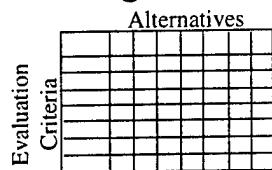
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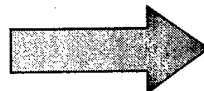
# Multi-Attribute Decision Making (MADM)

## Pugh Matrix

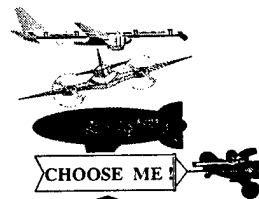


**+/- Ideal Solution**

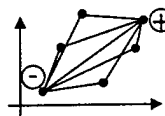
Based on best criteria values



## Ranked Alternatives



**Euclidean Differences**

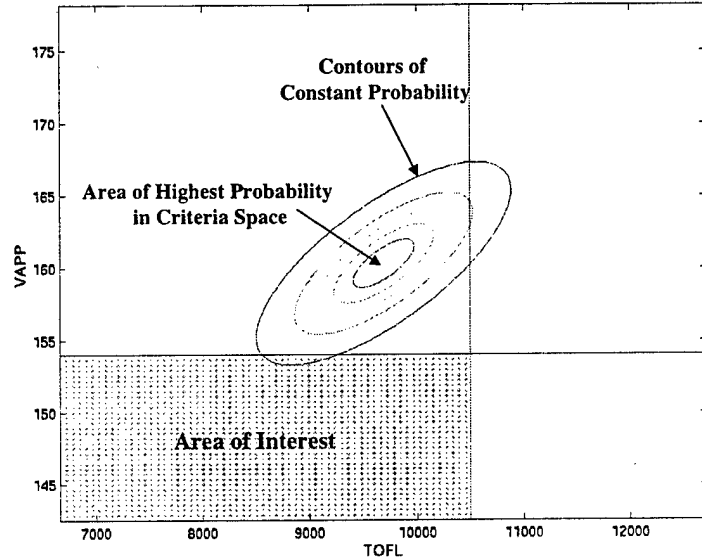


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## Joint Probability Density Function - 2D



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## Section 3

### *1. Introduction and Research Setting/Summary*

### *2. Overall Technical Approach for Affordable Systems Design*

### *3. Methods Implementation and Testbed Applications*

- *Design Space Exploration (Feasibility Determination for a High Speed Civil Transport)*
- *TIES Implementation (Technology Selection for an Advanced 150pax Transport)*
- *Joint Probabilistic Decision Making (JPDM)*
- *Simultaneous Examination of Requirements and Technologies (F/A-18C Testbed)*

### *4. Key Advancements in Method Components*

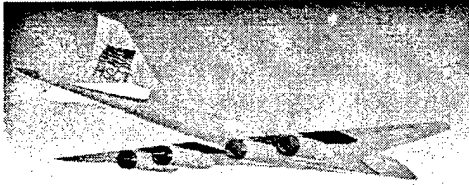
### *5. Conclusions/Summary*

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## High Speed Civil Transport (HSCT)



- Cruise Mach Number of 2.4
- Range of 5000 nm.
- Carry 300 passengers
- Powered by four engines capable of cruising supersonically without afterburner
- Able to make two round trips to Europe or Pacific Rim in the same amount of time as one trip for a subsonic transport

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## HSCT Challenges

- Environmental Constraints
  - Engine that is sized to cruise violates FAA noise regulations
  - Nitrogen Oxide emissions harm the ozone layer
- Performance Constraints
  - Poor takeoff and landing characteristics
  - High Mach numbers require special heat-resistant materials
- Economic Constraints
  - Will require a fare premium
  - Will have a high acquisition cost
  - Will require a large initial investment

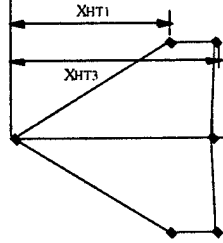
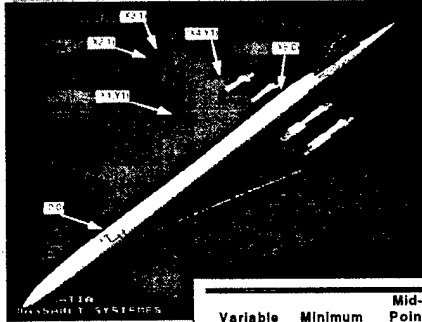


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# High Speed Civil Transport (HSCT)



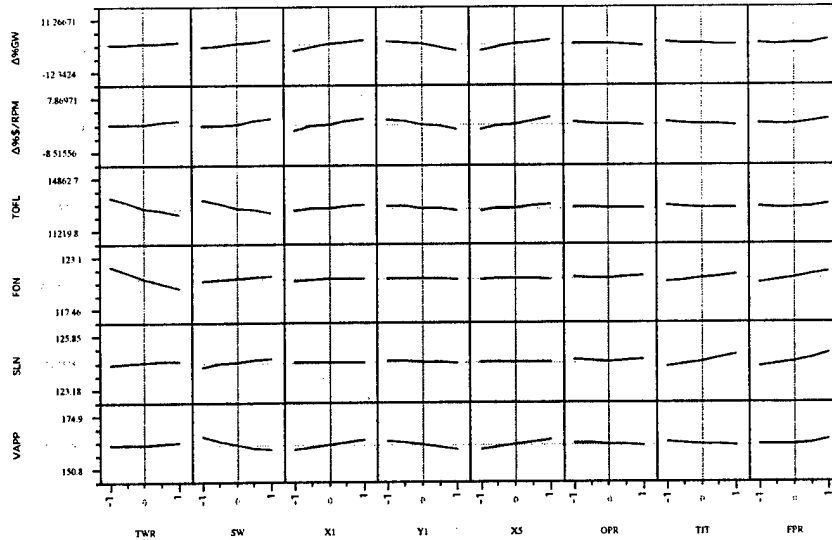
Variable	Minimum	Mid-Point	Maximum	Remarks
X1	1.54	1.615	1.69	Kink LE x-location, normalized by wing semi-span
Y1	0.44	0.51	0.58	Kink LE y-location, normalized by wing semi-span
X2	2.10	2.23	2.36	Tip LE x-location, normalized by wing semi-span
X3	2.40	2.49	2.58	Tip TE x-location, normalized by wing semi-span
X4	2.19	2.275	2.36	Kink TE x-location, normalized by wing semi-span
X5	2.19	2.345	2.50	Root Chord, normalized by wing semi-span
XWING	26%	28%	31%	wing position, % fuselage length
SW	8500	9000	9500	wing ref. area, square feet
XTAIL	82%	84.7%	87.4%	horizontal tail position, % fuselage length
ST	875	922.5	970	horizontal tail ref. area, square feet
XHT1	0.95	1.18	1.20	normalized by HT semi-span
XHT3	1.90	2.00	2.10	normalized by HT semi-span
CG	56%	57.5%	59%	CG, %fuselage

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## Prediction Profiles for the HSCT System Level Constraints

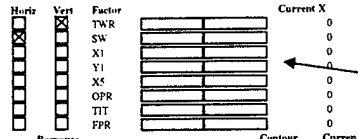


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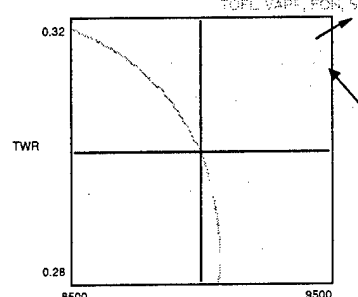
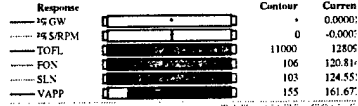
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## No Feasible Design Space Due to TOFL, VAPP, FON, and SLN



• The slide bars can be used to adjust the design variable settings, and the design plot is updated in real time.



• The design space plot shows no feasible space.

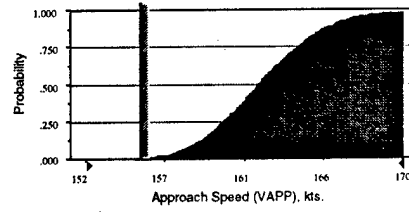
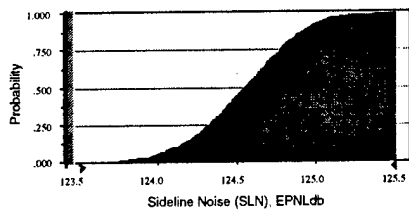
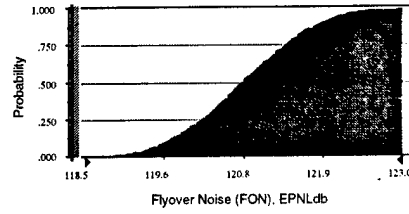
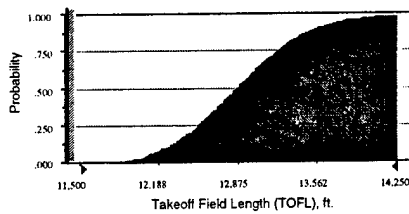
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## CDFs for the Four Constraints, from Monte Carlo Simulation (5,000 samples)

All constraints violated throughout initial design space



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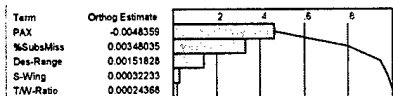
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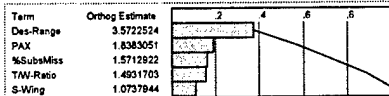
# Pareto Charts: Mission Requirements Sensitivities

## \$/RPM

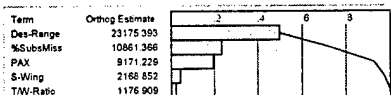
Average Required Yield per Revenue Passenger Mile



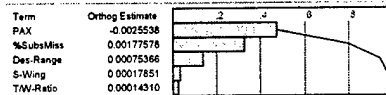
## -\$-Acquisition Price



## Gross Weight



## Direct Operating Costs

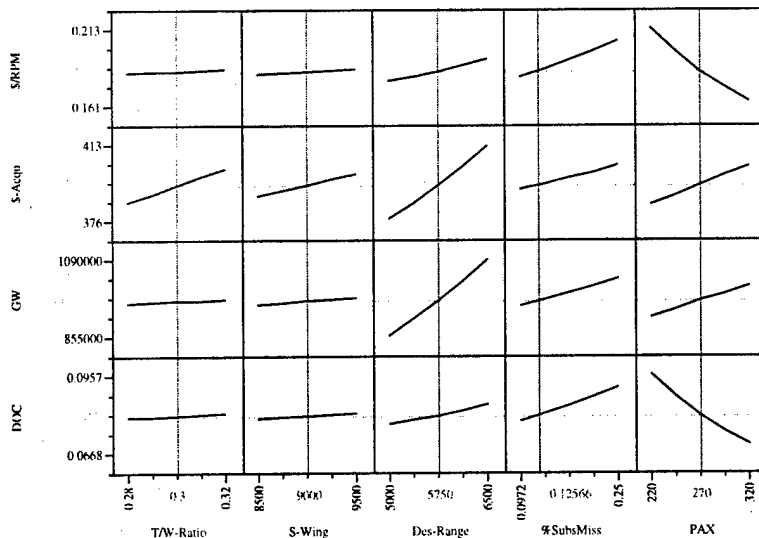


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# Mission Requirements Sensitivities



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# Feasibility and Viability Assessment

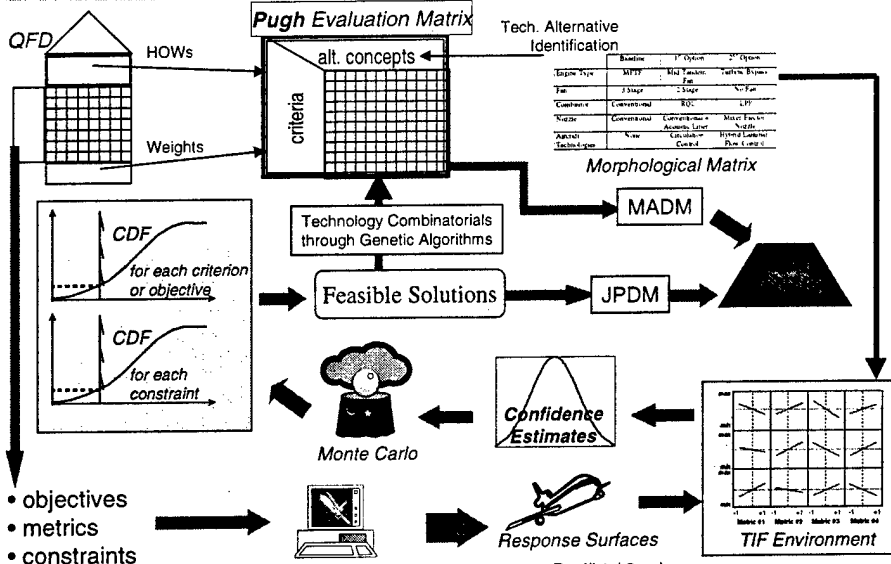
- If design space is not technically feasible or economically viable, the decision maker has 3 options:
  - 1) Open design variable ranges further
    - Design Space Exploration yielded no improvement
  - 2) Relax constraints
    - Non-negotiable in this case
  - 3) Infuse new technologies !!!

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# Technology Identification Evaluation Selection (TIES)



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## Example Problem

- The implementation of the feasibility aspect of TIES has been performed on various vehicles
- The down-select of the specific technologies is the new dimension of the TIES method and will be applied for the example problem
- The proof of concept is performed on a 150 passenger, medium-range, intra-continental commercial transport and the technologies are evaluated deterministically
- See SAE Paper 98-5547 for the feasibility assessment, SAE Paper 98-5576 for the TIF, and AIAA 99-0183 for the joint probability decision making

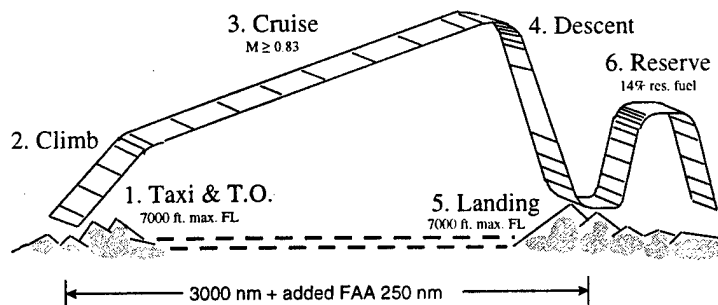
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## Problem Definition: 150 passenger concept

### Medium Range, Intra-continental Commercial Vehicle



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## Problem Definition: Quantitative System Level Metrics

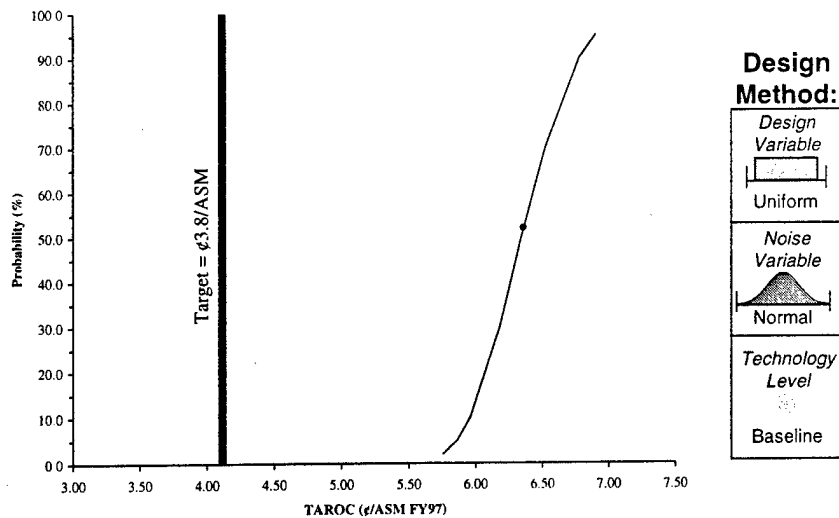
Parameter	Baseline Value	Target	Target Value	Units
<u>Weights and Performance</u>				
$V_{app}$	115.7	minimize	~	cts
Fuel Burn	44267	-48%	23019	lbs
Landing FL	4944	-21%	3906	ft
OEW	73850	-40%	44310	lbs
TOFL	5970	-21%	4706	ft
TOGW	149618	-31%	103236	lbs
<u>Economics</u>				
DOC-I	5.22	-42%	3.03	¢/ASM
TAROC	6.03	-37%	3.80	¢/ASM

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## Viability Assessment: TAROC



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# Technology Identification

## Compatibility Matrix

Compatibility Matrix  
(1: compatible, 0: incompatible)

	Composite Wing	Composite Fuselage	Aircraft Morphing	Natural Laminar Flow Control	Maneuver Load Alleviation	AST Engine Concept	Integrally Stiffened Aluminum Airframe Structures (wing)	HLFC	IHP/TET Engines
Composite Wing	1	1	1	1	1	1	0	0	1
Composite Fuselage	1	1	1	1	1	1	1	1	1
Aircraft Morphing	1	1	1	1	1	1	1	1	1
Natural Laminar Flow Control	1	1	1	1	1	1	0	1	1
Maneuver Load Alleviation	1	1	1	1	1	1	1	1	1
AST Engine Concept	1	1	1	1	1	1	1	0	1
Integrally Stiffened Aluminum Airframe Structures (wing)	1	1	1	1	1	1	1	0	1
HLFC	1	1	1	1	1	1	1	1	1
IHP/TET Engines	1	1	1	1	1	1	1	1	1

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# Technology Identification

## TIM: Technology Impact Matrix

	Composite Wing	Composite Fuselage	Aircraft Morphing	Natural Laminar Flow Control	Maneuver Load Alleviation	AST Engine Concept	Integrally Stiffened Aluminum Airframe Structures (wing)	HLFC	IHP/TET Engines
Technical K_Factor Vector									
Wing area	-	-	-	-	+18%	-	-	-	-
Vertical tail area	-	-	-	-	-40%	-	-	-	-
Horizontal tail area	-	-	-	-	-36%	-	-	-	-
Drag	-2%	-2%	-3%	-5%	-3%	-	-	-10%	-
Subsonic fuel flow	-	-0.5%	-1.5%	-	-	-10%	-	+1%	-5%
Wing weight	-15%	-	-3%	-	-	-	-15%	+4%	-
Fuselage weight	-	-25%	-2%	-	-	-	-	-	-
Electrical weight	-	-	-	-	+5%	+3%	-	+2%	-
Engine weight	-	-	-	-	-	-30%	-	+0.5%	-20%
Hydraulics weight	-	-	-	-	-10%	-	-	-	-
AL wing structure manufacturing costs	-	-	-	-	-	-	-2.5%	-	-
O&S	+2%	+2%	-	-	-3%	-2%	+3%	-3%	-
RDT&E	+2%	+2%	+2%	+2%	+3%	-4%	+4%	+3%	-
Production costs	+10%	+10%	-3%	+1%	-	-3%	-	+1%	-
Utilization	-2%	-2%	-	-	-	+3%	+2%	-2%	+2%

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## Technology Impact Matrix

- Potential system and subsystem level benefits and penalties associated with the technologies identified in the Morphological and Compatibility Matrices are established via expert questionnaires, physics-based modeling, or literature reviews
- In general, benefits and penalties are probabilistic (possibly stochastic) in nature
- Technology impact can be simulated in the TIF environment through technology "k\_factor" vectors and summarized in a TIM

where a technology can be represented as:

Technical "K" Factor Vector		T1	T2	T3
"K" Factor Elements	k factor 1	+4%	~	-10%
	k factor 2	~	-3%	~
	k factor 3	-1%	~	-2%
	k factor 4	-2%	-2%	+3%

$$T_i = \bar{k}_i = \left\{ \begin{matrix} \mu_{i,1}, \sigma_{i,1} \\ \mu_{i,2}, \sigma_{i,2} \\ \dots \\ \mu_{i,n}, \sigma_{i,n} \end{matrix} \right\}, TRL_i$$

where:  
 "i": specific technology  
 "n": number of k\_factors  
 "μ": mean of the k\_factor  
 "σ": variance of the k\_factor  
 "TRL": technology readiness level

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## Technology Impact Forecasting

<b>"k" Factor RSE Generation</b>	Technical Metric "K" Factor Elements	Non-dimensional impact	
		Min (%)	Max (%)
	Wing area	0	18
	Vertical tail area	-40	0
	Horizontal tail area	-36	0
	Drag	-25	0
	Subsonic fuel flow	-17	1
	Wing weight	-33	4
	Fuselage weight	-27	0
	Electrical weight	0	10
	Engine weight	-50	0.5
	Hydraulics weight	-10	0
	AL wing structure manufacturing costs	-2.5	0
	O&S	-8	7
	RDT&E	-4	18
	Production costs	-6	22
	Utilization	-6	7

Constraint/Objective =  $f(k_1, k_2, \dots, k_n)$  as obtained from a Design of Experiments to obtain a second order equation of the form:

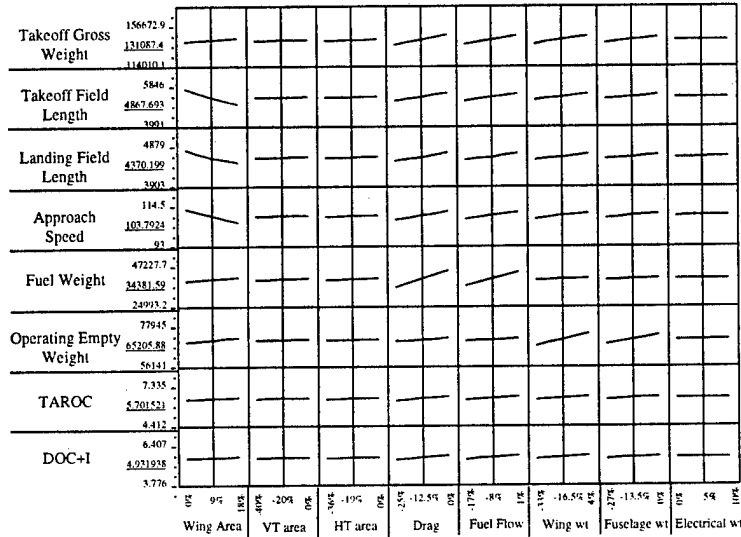
$$R = b_0 + \sum_{i=1}^k b_i k_i + \sum_{i=1}^k b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} k_i k_j$$

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## TIF Environment (1)

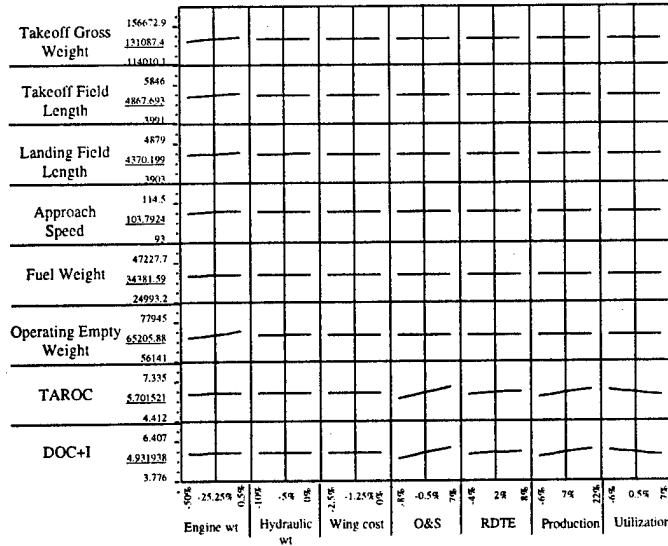


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## TIF Environment (2)

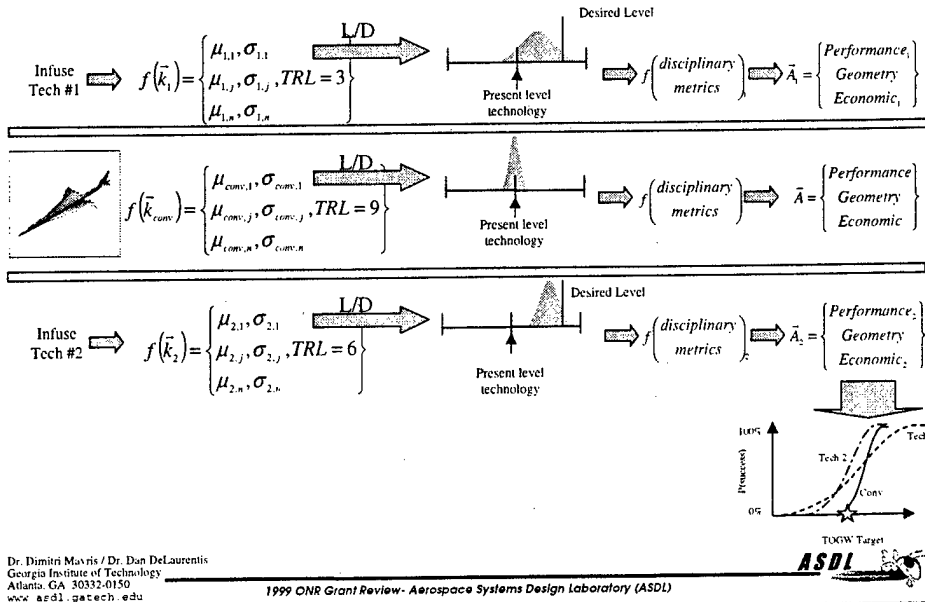


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## Technology Mapping



## Technology Evaluation

- The identification of the proper mix of technologies for a given system is dominated by the curse of dimensionality
- **Curse of Dimensionality**: the search for the proper mix of technologies which will “best” satisfy the system level metrics or attributes can be enormous
  - $2^n$  combinations, where “n” is the number of technologies
    - 9 technologies implies 512 combinations
    - 20 technologies implies 1,048,576 combinations
  - Computational expense of the analysis is the primary driver
    - *manageable*: full factorial investigation
    - *unmanageable*: genetic algorithm investigation

## Technology Evaluation: Full Factorial Investigation

Case	T1	T2	T3	.....	T9	Metric <sub>1</sub>	Metric <sub>2</sub>	.....	Metric <sub>n</sub>
1	-1	-1	-1	.....	-1	#	#	.....	#
2	-1	1	-1	.....	1	#	#	.....	#
3	-1	-1	-1	.....	1	#	#	.....	#
2*	1	1	1	.....	1	#	#	.....	#

evaluations of Metric RSEs if all technologies are compatible

"1" implies technology applied  
"-1" implies no technology

Metric value is determined from the RSEs

Consider an alternative with aircraft morphing (T3) and IHPDET engines (T9)

Recall:	Alternative with: T3	Alternative with: T9	Alternative with: T3+T9
$\bar{k}_i =$	$\bar{k}_3 =$	$\bar{k}_9 =$	$\bar{k}_{3+9} =$
$\begin{bmatrix} k_{.1} \\ k_{.2} \\ k_{.3} \\ k_{.4} \\ k_{.5} \\ k_{.6} \\ k_{.7} \\ k_{.8} \\ k_{.9} \\ k_{.10} \\ k_{.11} \\ k_{.12} \\ k_{.13} \\ k_{.14} \\ k_{.15} \end{bmatrix}$	$\begin{bmatrix} - \\ - \\ - \\ -3\% \\ -1.5\% \\ -3\% \\ -2\% \\ - \\ - \\ - \\ - \\ - \\ - \\ +2\% \\ -3\% \\ - \end{bmatrix}$	$\begin{bmatrix} - \\ - \\ - \\ - \\ -5\% \\ - \\ - \\ -20\% \\ - \\ - \\ -3\% \\ +3\% \\ - \\ +2\% \end{bmatrix}$	$\begin{bmatrix} - \\ - \\ - \\ -3\% \\ -6.5\% \\ -3\% \\ -2\% \\ - \\ - \\ -20\% \\ - \\ - \\ -3\% \\ - \\ +2\% \end{bmatrix}$

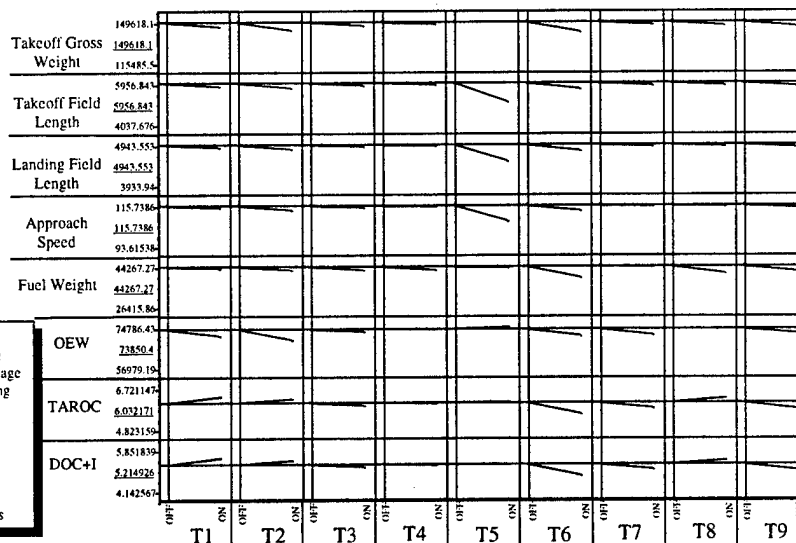
Metric RSE =  $f(\bar{k}_{3+9})$

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## Full Factorial Technology Evaluation



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## Technology Resource Allocation

- Based on the TIES method results, the most influential individual technologies can be compared to the baseline metrics in an efficient and rapid manner
- The most influential technologies can be identified so as to optimize program resource allocation for technology research and development to overcome constraints or meet objectives

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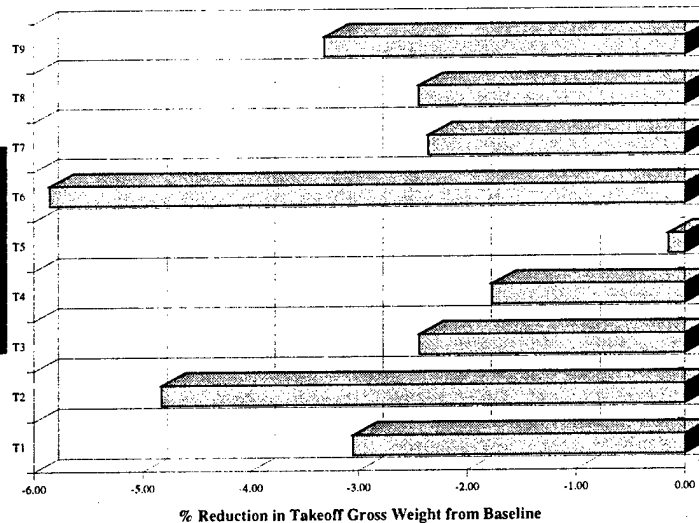
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## Technology Resource Allocation

**TOGW**

**Technologies:**  
T1: Composite Wing  
T2: Composite Fuselage  
T3: Aircraft Morphing  
T4: NLFC  
T5: Maneuver Load  
T6: AST Concept Engines  
T7: ISSA Structures  
T8: HLFC  
T9: IHPTET Engines



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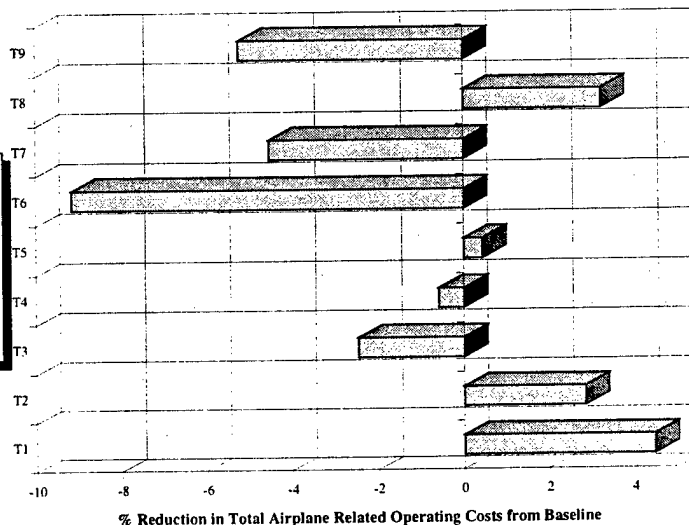
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# Technology Resource Allocation

## TAROC

- Technologies:**  
 T1: Composite Wing  
 T2: Composite Fuselage  
 T3: Aircraft Morphing  
 T4: NLFC  
 T5: Maneuver Load  
 T6: AST Concept Engines  
 T7: ISSA Structures  
 T8: HLFC  
 T9: IHPTET Engines



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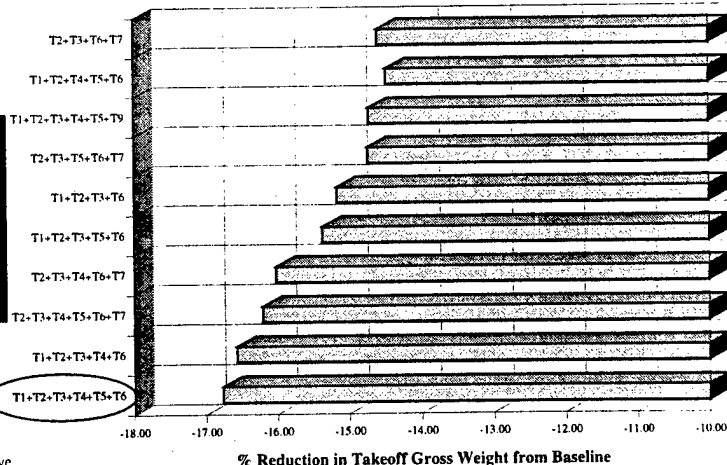
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# Top Alternatives

## Evaluation Based on Minimum TOGW

- Technologies:**  
 T1: Composite Wing  
 T2: Composite Fuselage  
 T3: Aircraft Morphing  
 T4: NLFC  
 T5: Maneuver Load  
 T6: AST Concept Engines  
 T7: ISSA Structures  
 T8: HLFC  
 T9: IHPTET Engines



"Best" Alternative for Minimum TOGW

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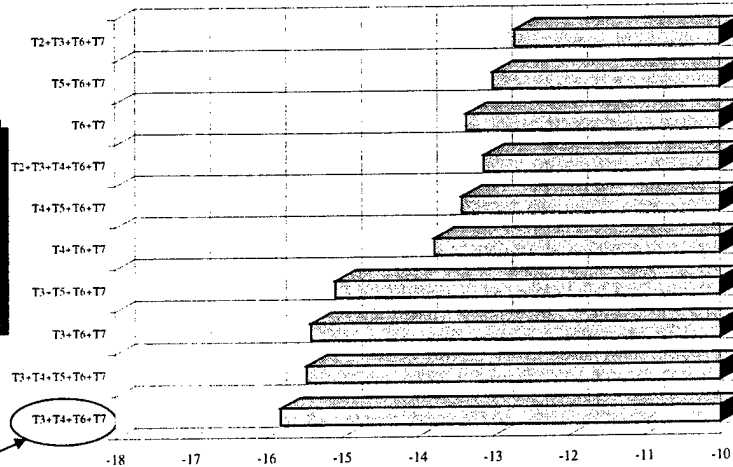
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# Top Alternatives

## Evaluation Based on Minimum TAROC

- Technologies:**  
 T1: Composite Wing  
 T2: Composite Fuselage  
 T3: Aircraft Morphing  
 T4: NLFC  
 T5: Maneuver Load  
 T6: AST Concept Engines  
 T7: ISSA Structures  
 T8: HLFC  
 T9: IHPTET Engines



"Best" Alternative for Minimum TAROC

% Reduction in Total Airplane Related Operating Costs from Baseline

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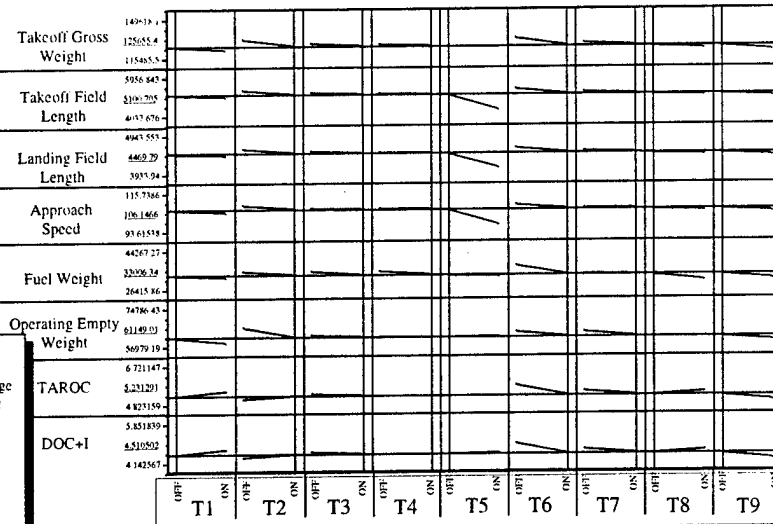
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# "Best" Alternative

## Evaluation Based on Minimum TAROC and TOGW

- Technologies:**  
 T1: Composite Wing  
 T2: Composite Fuselage  
 T3: Aircraft Morphing  
 T4: NLFC  
 T5: Maneuver Load  
 T6: AST Concept Engines  
 T7: ISSA Structures  
 T8: HLFC  
 T9: IHPTET Engines



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## Genetic Algorithm Investigation

- A simple deterministic proof of concept was performed with a genetic algorithm (GA) for the equal weighting OEC
- The identical mix of technologies from the TOPSIS technique was obtained
- Future work will focus on application of the GA method with probabilistic k\_factor vectors and multi-attribute and conflicting objectives

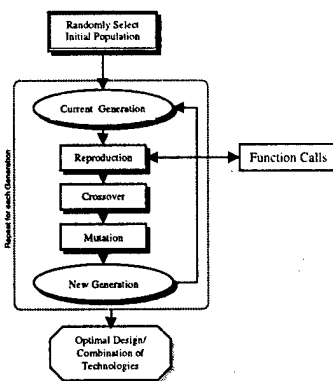
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## Genetic Algorithm Implementation

- Identify:
  - Number of Technologies
  - Number of Subsystems
  - Number of Metric Responses
- Specify/Provide:
  - Technology Impact Matrix (TIM)
  - Compatibility Matrix
  - Computation Metamodels for Metric Response
  - Multi-Attribute Decision Making Strategy
- GA yields:
  - best combination of technologies based on identified measures and provided information

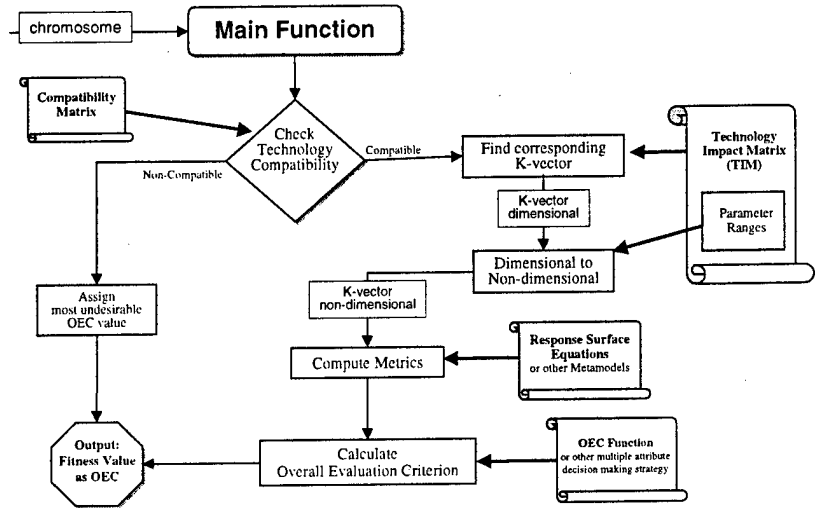


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# Genetic Algorithm Function Calls

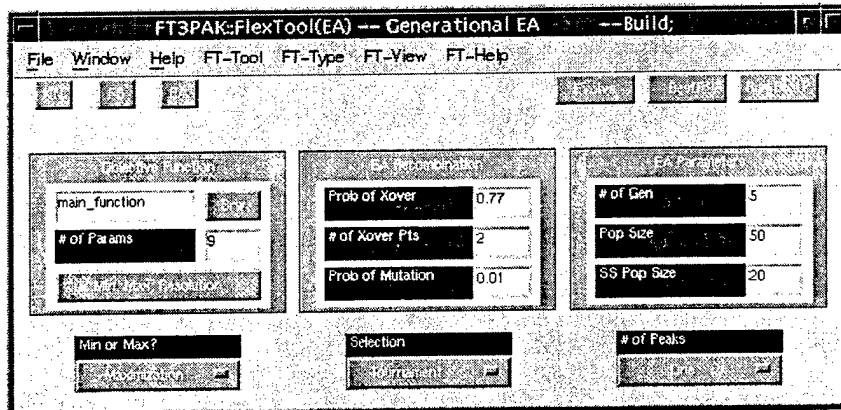


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# Specification of GA parameters



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## Conclusions

- A methodology for the systematic down-select of the proper mix of technologies which satisfies the imposed system level metrics was established
- Method could be interpreted for resource allocation of various technologies
- Future work will focus on:
  - probabilistic and stochastic evaluation
  - multi-attribute decision making with conflicting objectives
  - more technology combinations for GA implementation
  - other vehicle concepts

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## Multi Criteria Decision Making Technique for Systems Design: Joint Probabilistic Decision Making (JPDM)

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## Hypothesis: Multi Criteria Motivation

- Customer needs translate to system characteristics called attributes or constraints which become decision criteria for product selection.
- Complex systems have a multitude of attributes, such as life cycle cost, gross weight, excess power, safety, dependability, etc.
- Decisions based on one criterion/attribute may yield products with poor performance in other attributes.



A design method is needed that accounts for all criteria concurrently.

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## Hypothesis: Probabilistic Motivation

- Most assumptions made about the operational environment of the system are uncertain.
- Deterministic assumptions misrepresent the actual behavior/knowledge.
- Computer model fidelity introduces uncertainty in the output prediction.
- Use of new technologies adds uncertainty due to readiness/availability.



A probabilistic formulation of the design process is needed to capture and analyze uncertainties.

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## Typical Design Questions

- How to compare different design solutions with multiple objectives on an equal basis.
- How to compare different design solutions despite uncertainty about relevance and accuracy of design assumptions.
- How to trade one requirement for another.
- How to determine optimal solutions based on multiple objectives.

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## Shortcomings of Existing Decision Aids

Current multi criteria approaches determine either just the best solution of a small finite set based on many criteria, called Multi Attribute Decision Making (MADM), or the best solution of an infinite set based on just a few criteria, called Multi Objective Decision Making (MODM).

		Alternatives						
		Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	.....	Alt N
<b>Criteria</b>	<b>Crit 1</b>	Value	Value	Value	Value	Value		Value
	<b>Crit 2</b>	Value	Value	Value	Value	Value		Value
	<b>Crit 3</b>	Value	Value	Value	Value	Value		Value
	<b>Crit 4</b>	Value	Value	Value	Value	Value		<b>MODM</b>
	<b>Crit 5</b>	Value	Value	Value	Value	Value		Value
	<b>Crit M</b>	Value	Value	Value	<b>MADM</b>	Value		<b>JPDM</b>

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## Proposed Method

### Joint Probabilistic Decision Making (JPDM)

- Combines advantages of probabilistic treatment of uncertain information with multi criteria decision making.
- Determines the probability of satisfying all (specified) customer needs/criteria values as an objective function within TIES.
- Facilitates visual trade-offs for two requirements at a time.

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## Four Steps for Implementing JPDM

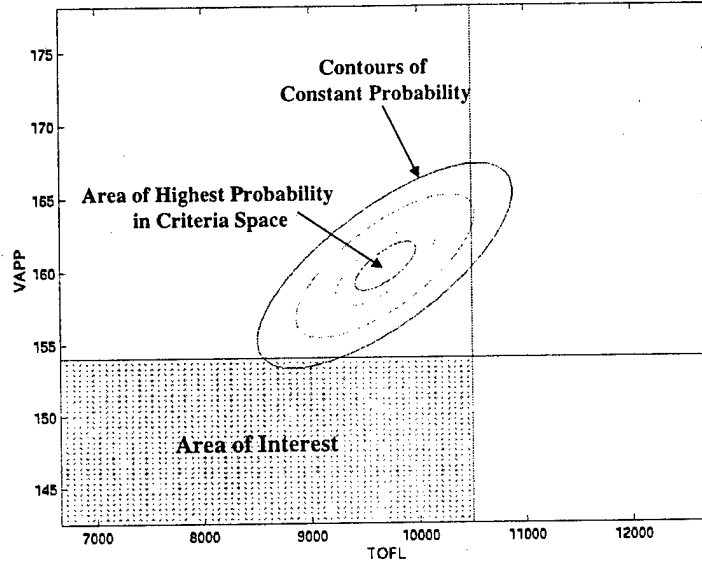
- Step 1:** Determine objectives/requirements of customer and designer.
- Step 2:** Assign probability distributions to design assumptions (fix design/control variables).
- Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.
- Step 4:** Determine solution with highest joint probability (two problems: MADM or MODM).

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## Joint Probability Density Function - 2D

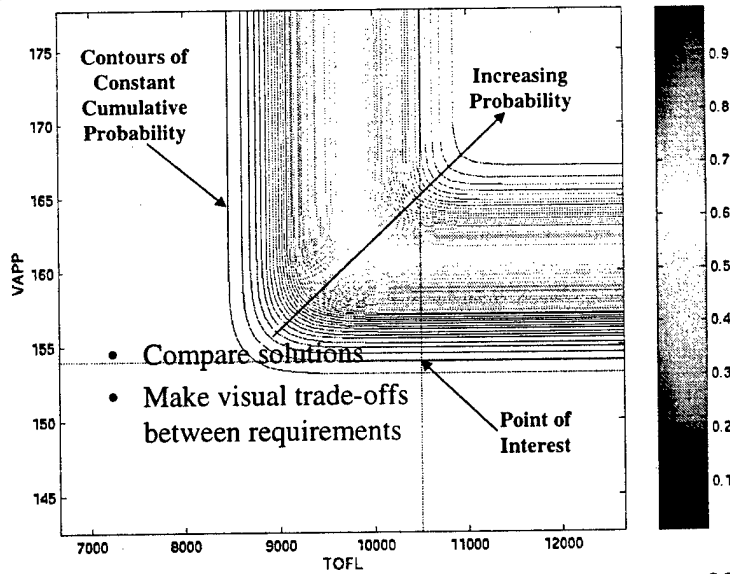


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## Joint Cumulative Distribution Function - 2D



- Compare solutions
- Make visual trade-offs between requirements

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## Implementation (cont'd)

- Step 1:** Determine objectives/requirements of customer and designer.
- Step 2:** Assign probability distributions to design assumptions (fix design/control variables).
- Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.
- Step 4:** Determine solution with highest joint probability (two problems: MADM or MODM).

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## Empirical Distribution Function (EDF)

- Estimates probability of occurrence of a specified event based on sample events.
- Counts how many times the event occurred in the sample.
- Denoted for one variable and sample  $x_i$ ,  $i=1$  to  $n$  by

$$\text{Density function: } f_X(a) = \frac{1}{n} \sum_{i=1}^n I(x_i = a) \quad I(x_i = a) = \begin{cases} 1 & \text{if true} \\ 0 & \text{if false} \end{cases}$$

$$\text{Cumulative function: } F_X(a) = \frac{1}{n} \sum_{i=1}^n I(x_i \leq a) \quad I(x_i \leq a) = \begin{cases} 1 & \text{if true} \\ 0 & \text{if false} \end{cases}$$

- Joint cumulative formulation, sample  $(x_i, y_i, z_i)$ ,  $i=1$  to  $n$ :

$$F_{XYZ}(a, b, c) = \frac{1}{n} \sum_{i=1}^n I(x_i \leq a, y_i \leq b, z_i \leq c)$$

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## EDF - Advantages/Disadvantages

- Advantages:
  - Most exact method
  - Does not need approximation with standard distributions
  - Estimates joint probability from data directly
- Disadvantages:
  - Needs large amount of data to be accurate
  - Requires modeling and simulation
  - Availability of data in conceptual and preliminary design may be limited or too expensive
  - Joint probability estimation itself is more time consuming

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## Joint Probability Model (JPM)

- Analytical model to estimate multivariate joint probability.
- Uses statistics of marginal distributions (mean  $\mu$  and standard deviation  $\sigma$ ).
- Uses correlation coefficients of criteria.
- Allows continued use of techniques that estimate marginal distributions.
- Example for bivariate normal model:

$$f_{XY}(a,b) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}} \exp\left\{-\frac{1}{2\rho^2-2}\left[\left(\frac{a-\mu_x}{\sigma_x}\right)^2 - 2\rho\left(\frac{a-\mu_x}{\sigma_x}\right)\left(\frac{b-\mu_y}{\sigma_y}\right) + \left(\frac{b-\mu_y}{\sigma_y}\right)^2\right]\right\}$$

- Formulation for n-variate normal model:

$$f(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma}) = \frac{1}{(2\pi)^{n/2} |\boldsymbol{\Sigma}|^{1/2}} e^{-Q_n(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma})/2}, \quad Q_n(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma}) = (\mathbf{x} - \boldsymbol{\mu})' \boldsymbol{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu}),$$

$\mathbf{x} \in \mathcal{R}^n \quad \boldsymbol{\Sigma} = \text{Correlation Coefficient Matrix}$

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## JPM - Advantages/Disadvantages

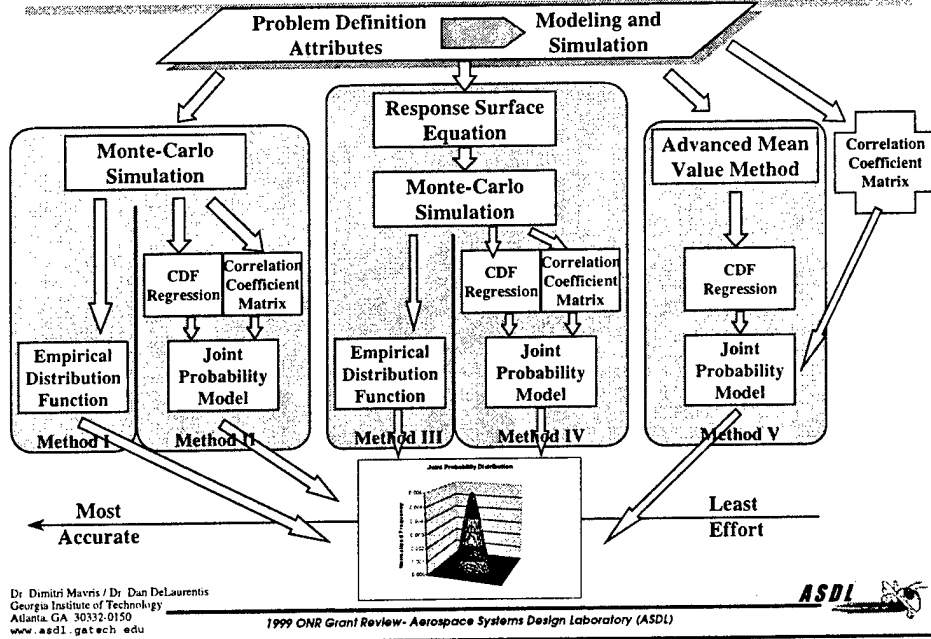
- Advantages:
  - Needs limited information for execution
  - Can employ expert guesses in case of lack of simulation
  - Fast evaluation of joint probability
  - Method can be used in conceptual or preliminary design
- Disadvantages:
  - Requires approximation of actual data by standard distribution
  - Requires correlation coefficient, which may not be available in early stages of design

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## Step 3 - Execution Accuracy Vs. Efficiency



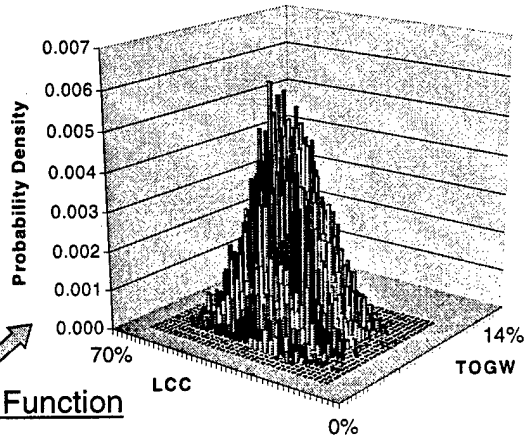
## Results - Method I

### Monte Carlo Simulation

10,000 samples

LCC	TOGW
10.5%	2.3%
5.3%	1.2%
43.8%	12.5%
•	•
•	•
•	•

### Joint Probability Distribution



### Empirical Distribution Function

$$f(LCC, TOGW) = \frac{1}{10,000} \sum_{i=1}^{10,000} I(LCC - \epsilon < lcc_i \leq LCC + \epsilon, TOGW - \epsilon < togw_i \leq TOGW + \epsilon)$$

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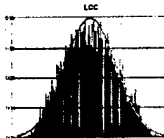
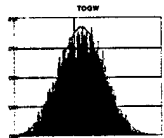
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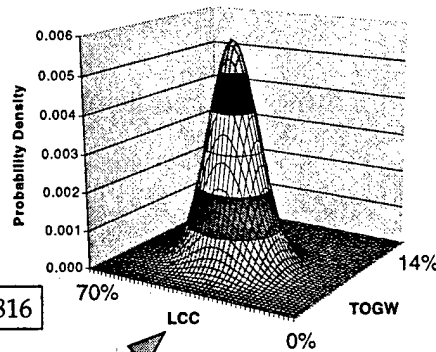
## Results - Method II

### Monte Carlo Simulation

10,000 samples

LCC	TOGW
10.5%	2.3%
5.3%	1.2%
43.8%	12.5%
	
$\mu=29.23\%$ $\sigma=7.69\%$	$\mu=6.70\%$ $\sigma=1.77\%$

### Joint Probability Distribution



$\rho = -0.1816$

$$f_{XY}(a, b) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}} \exp\left\{-\frac{1}{2\rho^2-2}\left[\left(\frac{a-\mu_x}{\sigma_x}\right)^2 - 2\rho\left(\frac{a-\mu_x}{\sigma_x}\right)\left(\frac{b-\mu_y}{\sigma_y}\right) + \left(\frac{b-\mu_y}{\sigma_y}\right)^2\right]\right\}$$

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## Results - Method III

### DOE (147 cases)

	LCC	TOGW
-1 -1 -1 -1 -1 -1 -1 -1 -1	10.5%	5.1%
-1 1 -1 -1 -1 1 -1 1 -1	25.7%	7.9%
1 -1 -1 1 1 -1 -1 1 1	4.8%	1.2%

Response Surface Equation

Monte Carlo Simulation

10,000 samples from RSE

Empirical Distribution Function

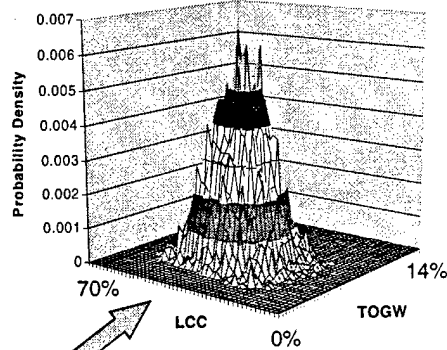
$$f(LCC, TOGW) = \frac{1}{10,000} \sum_{i=1}^{10,000} I(LCC - \varepsilon < lcc_i \leq LCC + \varepsilon, TOGW - \varepsilon < togw_i \leq TOGW + \varepsilon)$$

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Joint Probability Distribution



## Results - Method IV

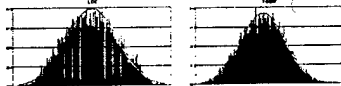
### DOE (147 cases)

	LCC	TOGW
-1 -1 -1 -1 -1 -1 -1 -1 -1	10.5%	5.1%
-1 1 -1 -1 -1 1 -1 1 -1	25.7%	7.9%
1 -1 -1 1 1 -1 -1 1 1	4.8%	1.2%

Response Surface Equation

Monte Carlo Simulation

10,000 samples from RSE



$\rho = -0.159$

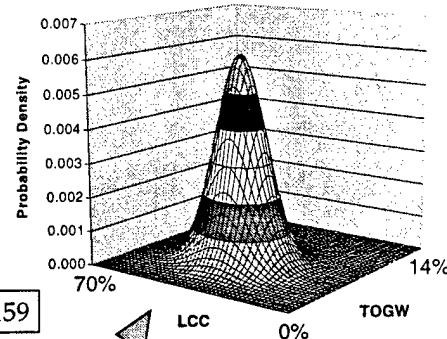
$$f_{xy}(a, b) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}} \exp\left\{-\frac{1}{2\rho^2-2}\left[\left(\frac{a-\mu_x}{\sigma_x}\right)^2 - 2\rho\left(\frac{a-\mu_x}{\sigma_x}\right)\left(\frac{b-\mu_y}{\sigma_y}\right) + \left(\frac{b-\mu_y}{\sigma_y}\right)^2\right]\right\}$$

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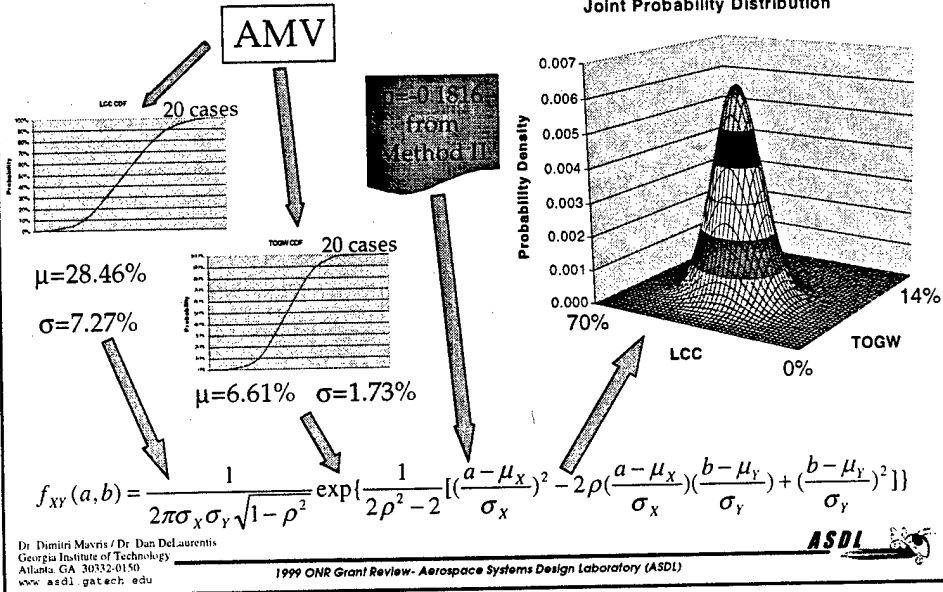
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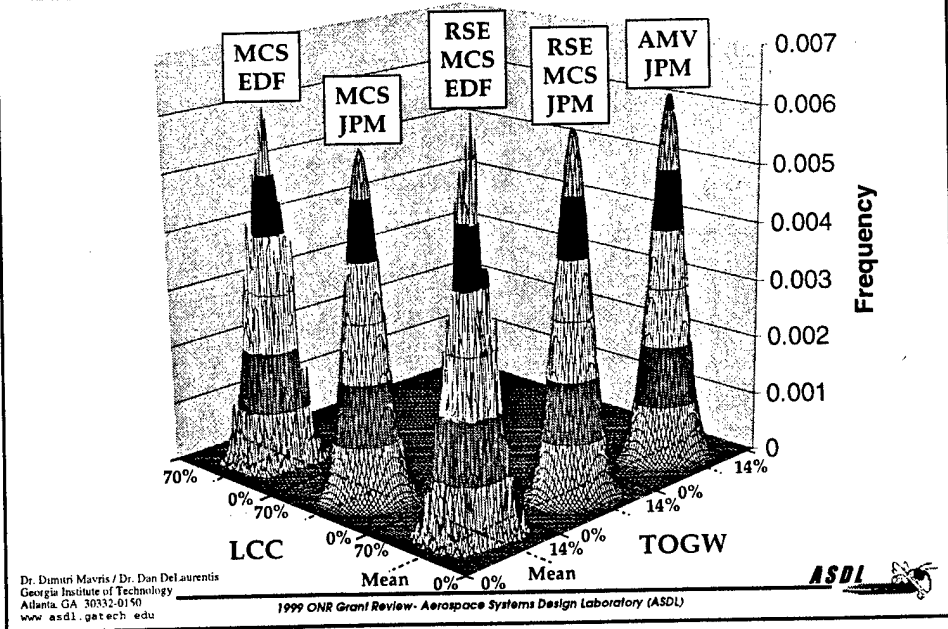
Joint Probability Distribution



# Results - Method V

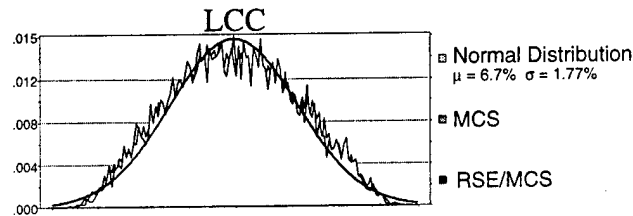


# Comparison of all JPFDs



## Comparison of Methods

- Good agreement of Response Surface Equation/Monte Carlo Simulation method and Monte Carlo Simulation directly on analysis code.
- Both distributions are approximated well by the normal distribution (due to nine input variables and the Central Limit Theorem).
- Normal approximation will be even better for non-uniform input distributions.



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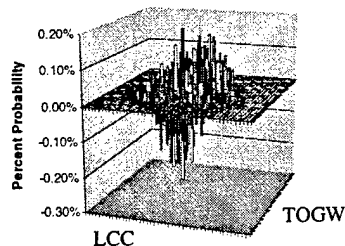


## Comparison of Methods (contd.)

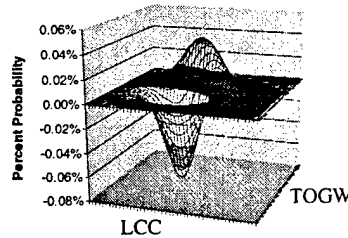
- Comparison of means and standard deviations shows similar prediction capability of methods.

	MCS/JPM	RSE/JPM	% Difference	AMV/JPM	% Difference
$\mu_{LCC}$	29.23%	28.71%	-0.40%	28.46%	-0.60%
$\mu_{TOGW}$	6.70%	6.66%	-0.04%	6.61%	-0.09%
$\sigma_{LCC}$	7.69%	7.32%	-4.73%	7.27%	-5.43%
$\sigma_{TOGW}$	1.77%	1.76%	-0.60%	1.73%	-2.53%
<b>Correlation</b>	-0.1816	-0.1590	-12.44%	(-0.1816)	-

MCS/EDF - AMV/JPM



MCS/JPM - AMV/JPM



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## Implementation (cont'd)

- Step 1:** Determine objectives/requirements of customer and designer.
- Step 2:** Assign probability distributions to design assumptions (fix design/control variables).
- Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.
- Step 4:** Determine solution with highest joint probability (two problems: MADM or MODM).

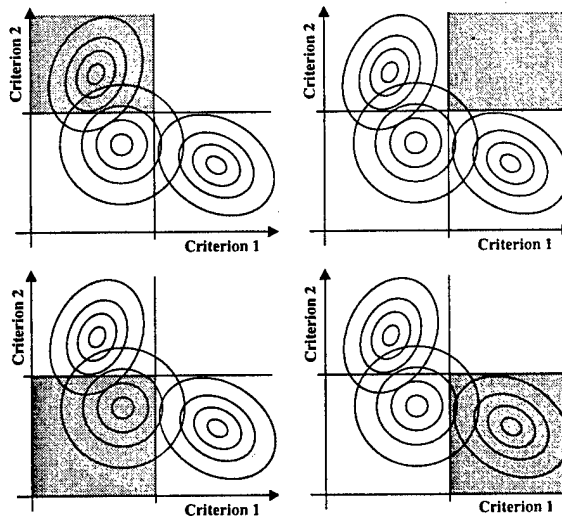
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## Step 4 - MADM

- Rank solutions based on joint probability.
- Select solution with highest probability.
- Conduct "What-If" studies for requirements/criteria.



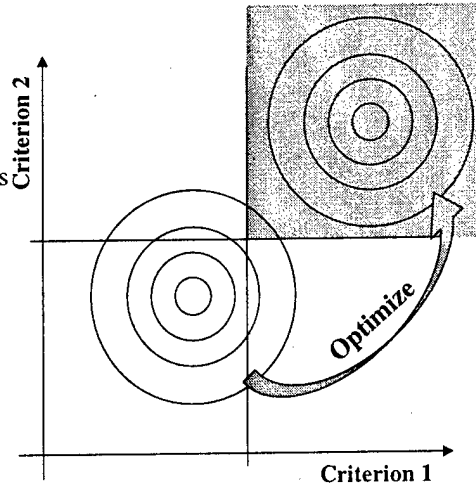
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## Step 4 - MODM

- Use joint probability as an objective function for generic optimizer.
- Use design/control variables as independent variables.
- Determine optimal solution with maximum probability of satisfying all requirements/criteria.



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## Conclusions

- A four step joint probabilistic decision making technique was introduced as part of the TIES method.
- Five JPDM methods (MCS/EDF, MCS/JPM, RSE/MCS/EDF, RSE/MCS/JPM, and AMV/JPM) were used to determine the joint probability example study with two criteria.
- JPDM technique is capable of treating uncertain information of early stages in design.
- JPDM technique introduces new objective function to multi criteria decision making: *probability of meeting all operational and design requirements concurrently.*
- JPM needs extension to capture other than normal distributions.

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## Section 4

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- 1. Introduction and Research Setting/Summary*
- 2. Overall Technical Approach for Affordable Systems Design*
- 3. Methods Implementation and Testbed Applications*
- 4. Key Advancements in Method Components*
- 5. Conclusions/Summary*

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## Section 4

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# Part A: Simultaneous Examination of Requirements and Technologies

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# Examining the Role of *Requirements*

## Synopsis

- Requirements drive initial design studies, procurement decisions, and ultimately *operational effectiveness and cost*
- However, it is often the case that design processes (and designers) overlook the impact of changes and/or ambiguity in requirements and fail to understand the relationships between requirements, technologies, and the design space
- ASDL has been tasked by ONR to investigate the role of requirements in affecting the design and S&T investment; and then to formulate a method for examining requirements simultaneously with design alternatives, technologies, affordability, etc.

## Tasks

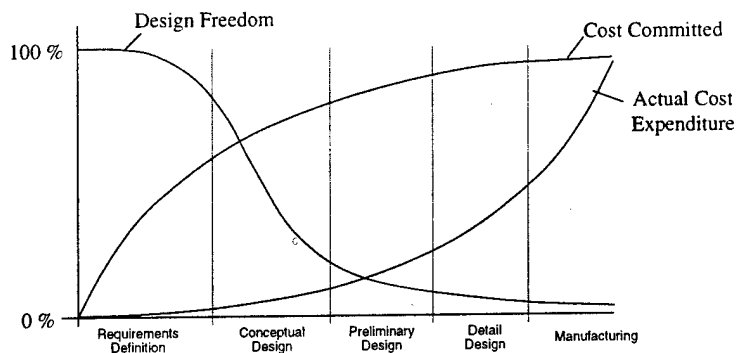
- Link the appropriate aircraft sizing/synthesis and economic tools plus probabilistic methods to create testbed environment; model the F/A-18C (using substantiation data for validation)
- With F/A-18E/F requirements (Ref. AIAA Paper 98-4701) as drivers, look at relation of technology metrics on requirements mathematically
- Provide ONR with the unique capability to examine the impact of requirements, desirements, and constraints on affordability decisions

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# The Importance of the Requirements Definition Stage



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## Expanding Missions: The F/A-18E/F

Maritime Air Superiority	Air Combat Fighter	Fighter Escort	Recce	Close Air Support	Air Defense Suppression	Day/ Night Attack	All Weather Attack
F-14D NATF			F/A-18 A/B/C/D			A-6F	
F/A-18 E/F							

Ref. Young, et al. AIAA-98-4701, 1998.

How can such multi-role vehicles be examined as potential solutions for the war-fighter with respect to technologies, requirements, and design constraints ?

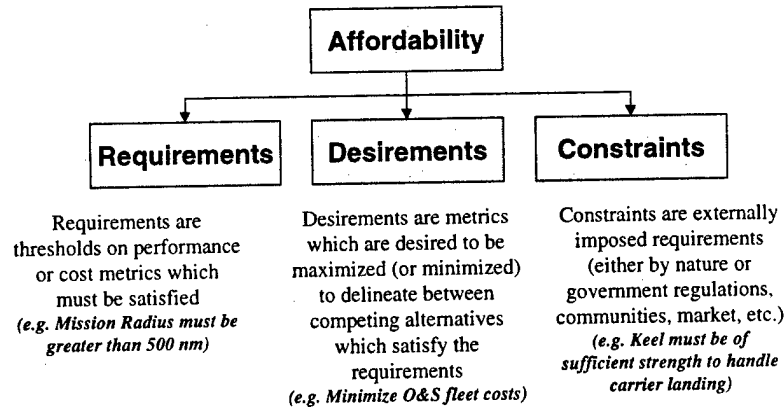
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## Affordability: Components and Definitions

A design or S&T investment problem has the following top level structure:



This structure provides the starting point for the TIES F/A-18C process....

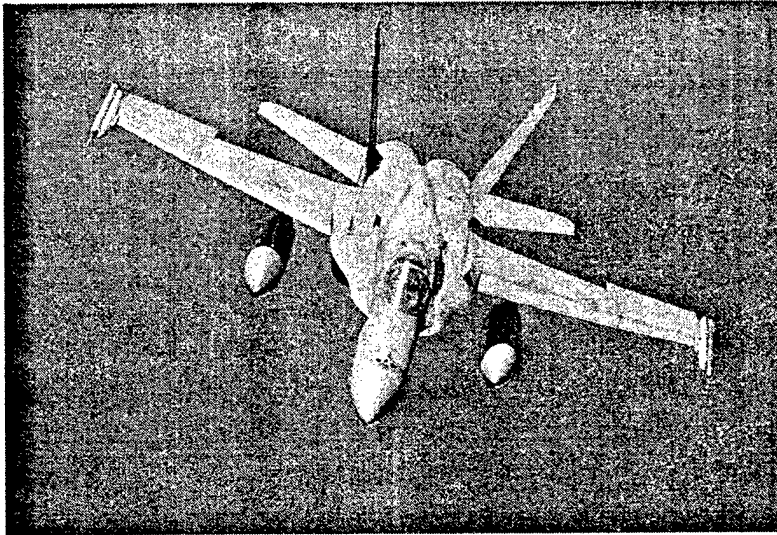
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# F/A-18C Modeling

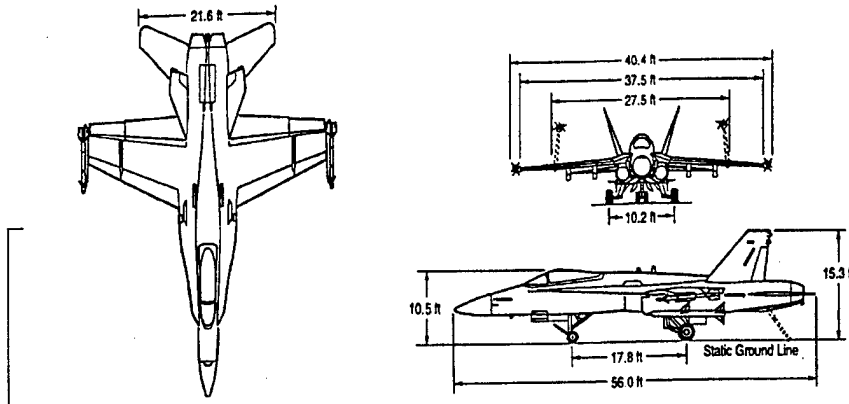


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# Basic Geometry

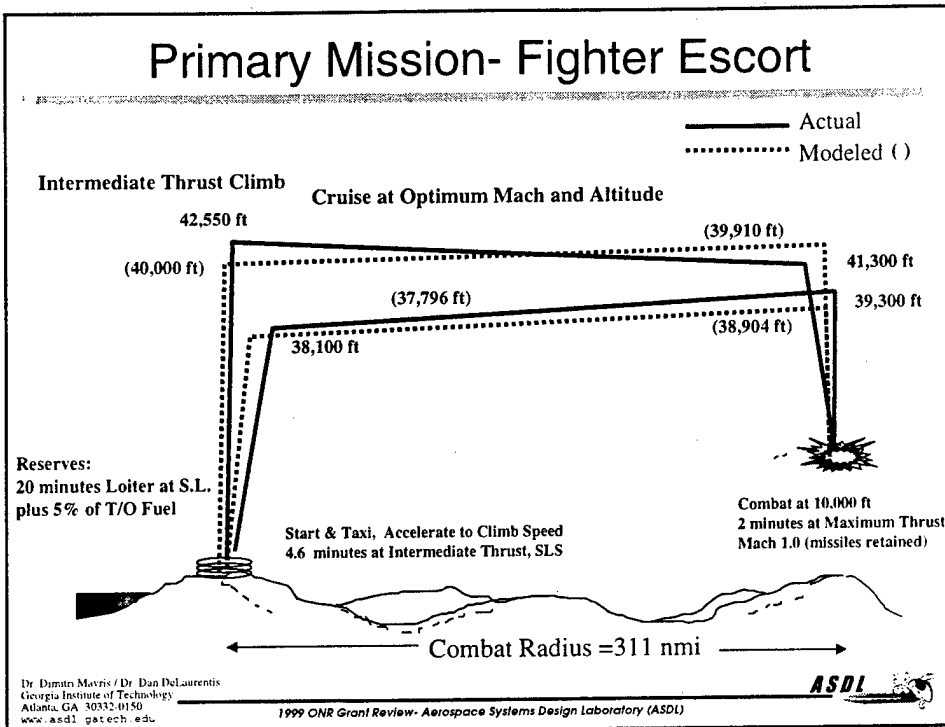


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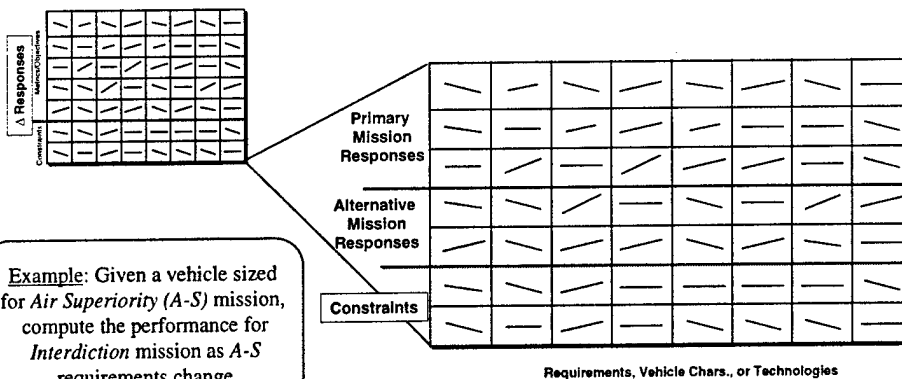


# Primary Mission- Fighter Escort



# Alternate Missions- Addressing Multi-role Capability

- Requirements can include performance against a wide variety of missions
- Vehicle sizing proceeds based on a primary mission and then fallout performance of the sized vehicle on alternate missions is computed and tracked



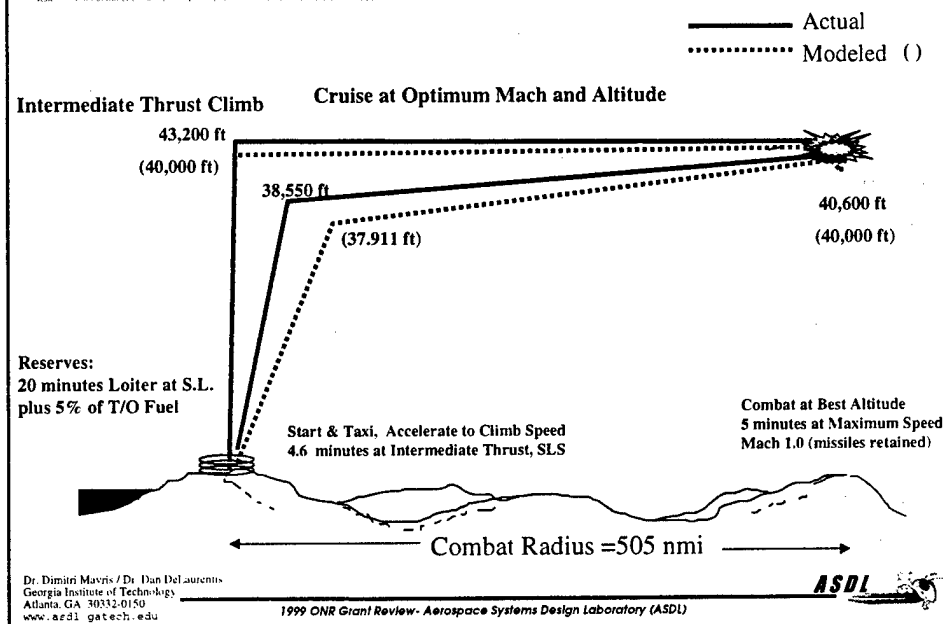
**Example:** Given a vehicle sized for Air Superiority (A-S) mission, compute the performance for Interdiction mission as A-S requirements change

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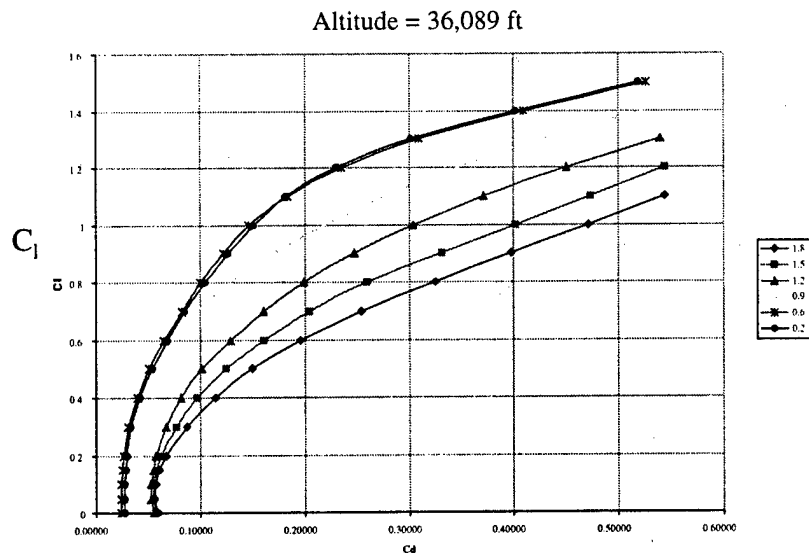
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# Alternate Mission: Hi Hi Hi



# Drag Polars for Varying Mach Numbers



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# Propulsion Modeling

## F404-GE-402 Augmented Turbofan Engine

- The F404-GE-402 is an increased performance derivative of the F404 and is used in the F/A-18C
- Features a dual-spool mixed flow turbofan architecture, 3X7X1X1 turbomachinery configuration
- F404 Engine performance deck based on installed engine data for the F/A-18C
- Engine performance data source: "F/A-18C Substantiating Performance Data with F404-GE-402 Engines" Report MDC91B0290

### General Specifications:

- Thrust: 17,700 lb
- SFC (max A/B): 1.74 lbm/lbf-hr
- SFC (IRP): 0.81 lbm/lbf-hr
- Airflow (SLS): 146 pps
- Weight: 2,282 lb
- Length: 159 in
- Diameter: 35 in



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# Weight Breakdown- Validation

- Sizing/Synthesis Code Used: FLIGHT OPTimization System (FLOPS)
- F/A-18C Baseline Modeled in FLOPS calibrated against actual substantiation data from manufacturer
- Highly accurate model (errors in weights less than 1%)

F/A18C Weight Breakdown Comparison		
Group	F/A18C	Baseline Model
Wing	3,919	3,918
Tail Group	1,005	1,006
Body	5,009	5,009
Alighting Gear	2,229	2,228
Propulsion Group		
Engines	4,420	4,417
Engine Section		
Gear Box	921	922
Controls		
Starting System		
Fuel System	1,078	1,078
Flight Controls	1,061	1,062
Auxiliary Power Plant	206	206
Instruments	84	84
Hydraulics	351	352
Electrical	592	592
Avionics	1,864	1,864
Armament, Gun, Launchers, Ejectors	948	948
Furnishings, Load/Handling, Contingency	631	631
Air Conditioning	641	642
Crew	180	180
Unusable Fuel	207	207
Engine Fluids	114	115
Chaff, Ammunition	252	252
Miscellaneous	58	58
<b>Operating Weight Empty</b>	<b>25,770</b>	<b>25,771</b>
Missiles		1,410
(2) AIM-7F	1,020	
(2) AIM-9L	390	
Mission Fuel	10,860	10,857
<b>Takeoff Gross Weight</b>	<b>38,040</b>	<b>38,038</b>

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## Economic Assumptions

- MALCCA (Military Aircraft Life Cycle Cost Analysis) in-house code used to determine notional aircraft economics
- Baseline File created starting with defaults based on the military aircraft assumptions (primarily sourced from F-15 and F-16 data)

Inflation Factor	3.3%
Dollar Year	1994
Year of Program Initiation	2000
Final Year of Production	2023
# Operational Vehicles	2530 units
System Economic Life	20 years

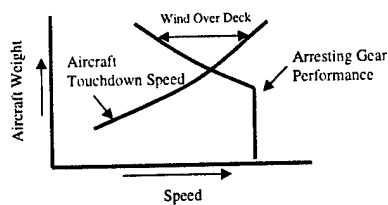
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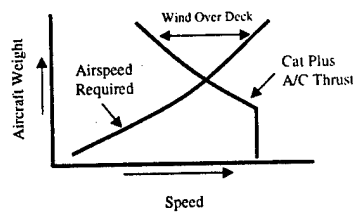


## Wind Over Deck

Recovery Wind Over Deck



Launch Wind Over Deck



- Aircraft Touchdown Speed =  $1.05 * V_{app}$
- Airspeed Required = Calculated Liftoff Speed
- Arresting Gear Performance Calculated at Limit Capacity

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## Breakdown of Responses to Describe a Vehicle

Top-Level requirements related to the mission

Design Variables, Economic Variable and Vehicle Attributes

$$\text{Response (i.e. GW)} = \text{function (Requirements, Vehicle Characteristics, } k_{TP}, k_{TM})$$

- To cope with this large problem, evaluate it in "snapshots", where most inputs are held constant while a subset of the inputs varies
- This approach allows the consideration of mission requirements and applied technologies along with the geometry of the vehicle
- Snapshots 1,2,3 provide "deltas" in responses wrt baseline

Technology k-factors (related to performance and to manufacturing)

Use Response Surface Method once again !

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## Snapshot 1 Responses and Top Level Requirements

Δ Responses/Desiresments Metrics/Objectives Constraints	R <sub>1</sub>	↘	↘	↘	↘	↘	↘	↘	↘
	R <sub>2</sub>	↘	↘	↘	↘	↘	↘	↘	↘
	R <sub>3</sub>	↘	↘	↘	↘	↘	↘	↘	↘
	R <sub>4</sub>	↘	↘	↘	↘	↘	↘	↘	↘
	R <sub>5</sub>	↘	↘	↘	↘	↘	↘	↘	↘
	R <sub>6</sub>	↘	↘	↘	↘	↘	↘	↘	↘
	R <sub>7</sub>	↘	↘	↘	↘	↘	↘	↘	↘
		Req.1	Req.2	Req.3	Req.4	Req.5	Req.6	Req.7	Req.8
		Range	Payload	P <sub>s</sub>	t <sub>loiter</sub>	turn rate	Δf <sub>w</sub>	Δwt <sub>w</sub>	Mach

Example Responses:

Gross Weight  
Probability of Survival  
Lethality  
O+S  
Acquisition Cost

Approach Speed (constraint)  
TOFL (constraint)

T/W and W/S may belong in either the requirements or the responses section - depending on how the programs are set up

### Top Level Requirements

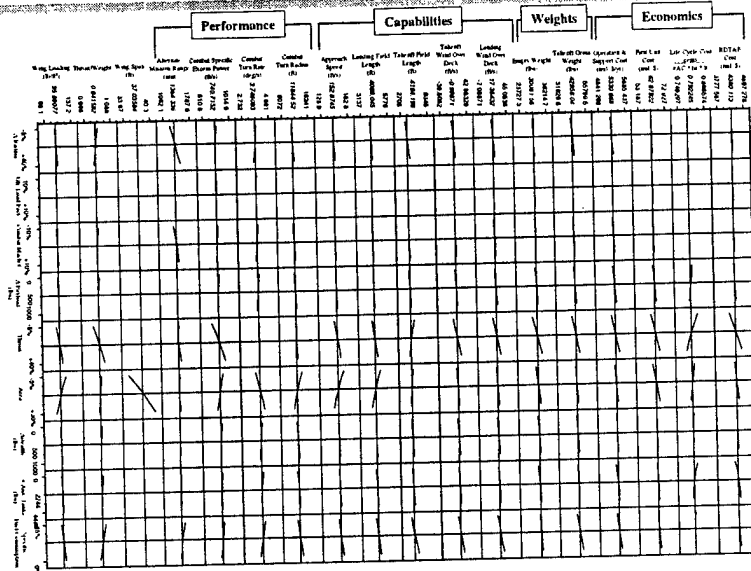
This approach de-emphasizes the geometry of an aircraft, and instead focuses on the mission requirements. However, it does require a baseline aircraft configuration. **Geometry and Technologies are fixed**, while Requirements vary. Each vector of top level requirements maps to a specific mission.

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# Requirement RSEs for Notional F/A-18C

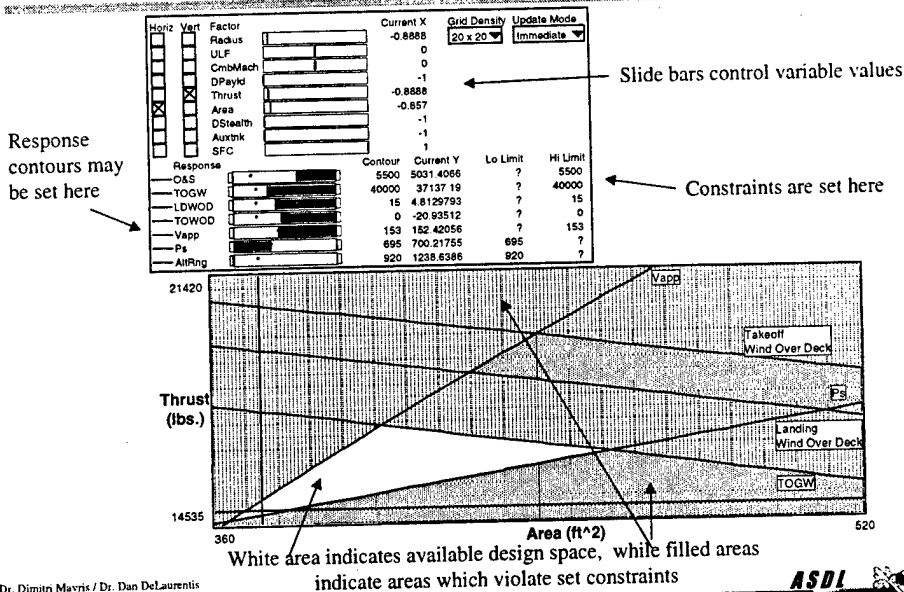


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## Requirements Exploration: F/A-18C Design Contours

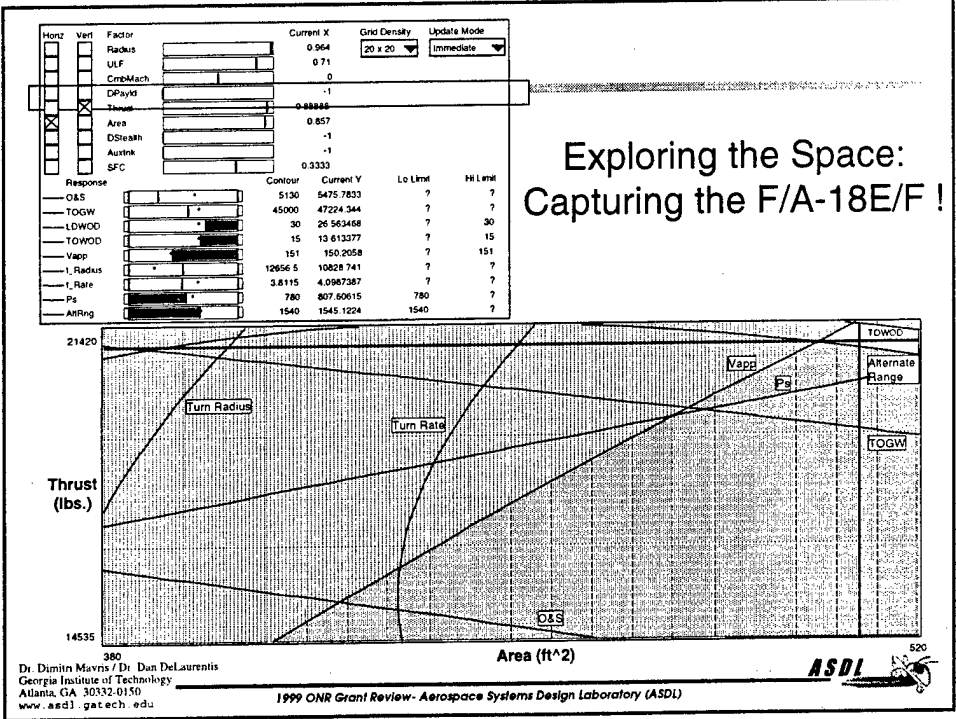
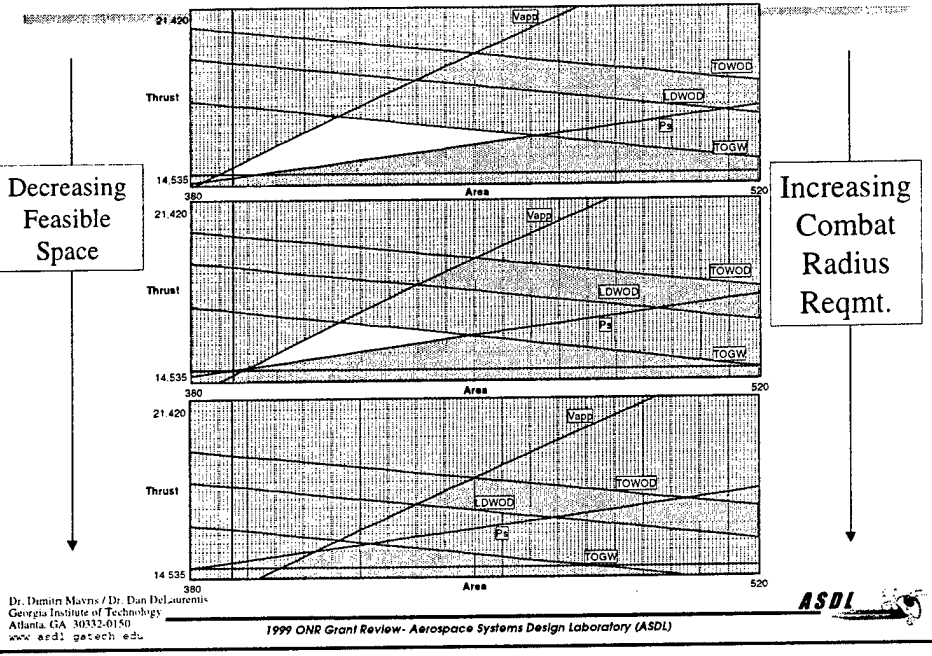


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# Effects of Increase in Combat Radius Req.



# Responses vs. Vehicle Characteristics

Snapshot 2

Δ Responses/Desirements Constraints Metrics/Objectives	R <sub>1</sub>	—	—	—	—	—	—	—	—
	R <sub>2</sub>	—	—	—	—	—	—	—	—
	R <sub>3</sub>	—	—	—	—	—	—	—	—
	R <sub>4</sub>	—	—	—	—	—	—	—	—
	R <sub>5</sub>	—	—	—	—	—	—	—	—
	R <sub>6</sub>	—	—	—	—	—	—	—	—
	R <sub>7</sub>	—	—	—	—	—	—	—	—
		DV1	DV2	...	EcV1	EcV2	...	T/W	W/S
		Design Variables			Economic Variables			Attributes	

Geometry/Attribute relationship:

Turbine Inlet Temperature (TIT)

Specific Fuel Consumption (SPC)

Engine Cycle Variables

↑  
Level of Abstraction

## Vehicle Characteristics

Here, the Requirements and Technologies are fixed, but the vehicle characteristics are allowed to vary. Each vector of Design Variables, Economic Variables and Attributes maps to a specific geometry of a configuration.

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# Responses vs. Technology k-factors

Snapshot 3

Δ Responses/Desirements Constraints Metrics/Objectives	R <sub>1</sub>	—	—	—	—	—	—	—	—
	R <sub>2</sub>	—	—	—	—	—	—	—	—
	R <sub>3</sub>	—	—	—	—	—	—	—	—
	R <sub>4</sub>	—	—	—	—	—	—	—	—
	R <sub>5</sub>	—	—	—	—	—	—	—	—
	R <sub>6</sub>	—	—	—	—	—	—	—	—
	R <sub>7</sub>	—	—	—	—	—	—	—	—
		k <sub>TP</sub> 1	k <sub>TP</sub> 2	k <sub>TP</sub> 3	...	k <sub>TM</sub> 1	k <sub>TM</sub> 2	k <sub>TM</sub> 3	...
		Related to Performance				Related to Manufacturing			

Technology k-factors are expressed in Δ%, compared to a baseline set of technologies

This is also known as the TIF (Technology Impact Forecasting) environment

## Technology k-factors

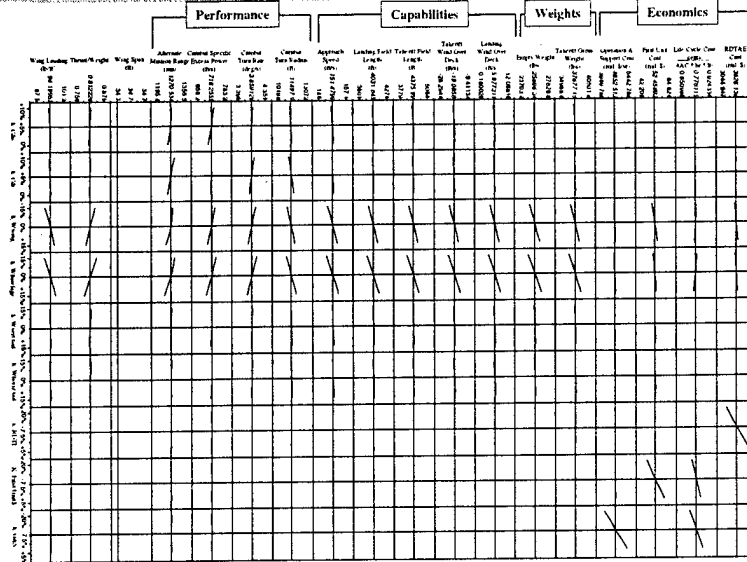
Here, the Requirements and the Vehicle are fixed, but the technologies are allowed to vary. Each vector of technology k-factors maps to a specific combination of applied technologies.

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# Technology RSEs for Notional F/A-18C

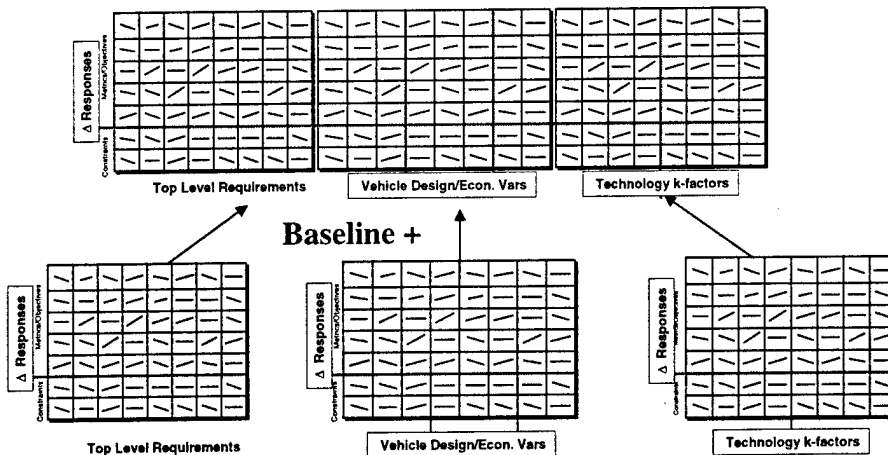


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# Additive Creation of the Overall Environment



Assumption: Interactions among the input variables exist only within each group  
 (Or regroup the inputs to eliminate interaction across subspaces)

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## Additive Creation of the Overall Equation

Fix all other groups  
(vehicle and technologies)  
and let only one group  
(requirements) vary

$$\Delta GW = (b_0)_k + \sum(\text{req.1, req.2, req.3...})$$

Fix all other groups  
(requirements and vehicle)  
and let only one group  
(technologies) vary

$$\Delta GW = (b_0)_{TPA} + \sum(k_{TP1}, k_{TP2}, \dots, k_{TM1}, k_{TM2}, \dots)$$

**Response (i.e.  $\Delta GW$ ) = function (Requirements, Vehicle Characteristics,  $k_{TP}$ ,  $k_{TM}$ )**

Fix all other groups  
(requirements and technologies)  
and let only one group  
(vehicle characteristics) vary

$$\Delta GW = (b_0)_{VA} + \sum(DV1, DV2, \dots, EV1, EV2, \dots, Attr1, Attr2, \dots)$$

**Then:**

$$GW = (b_0)_{\text{overall}} + \sum(\text{req.1, req.2, req.3...}) + \sum(DV1, DV2, \dots, EV1, EV2, \dots, Attr1, Attr2, \dots) + \sum(k_{TP1}, k_{TP2}, \dots, k_{TM1}, k_{TM2}, \dots)$$

This equation can now be re-solved for any parameter that might be of interest

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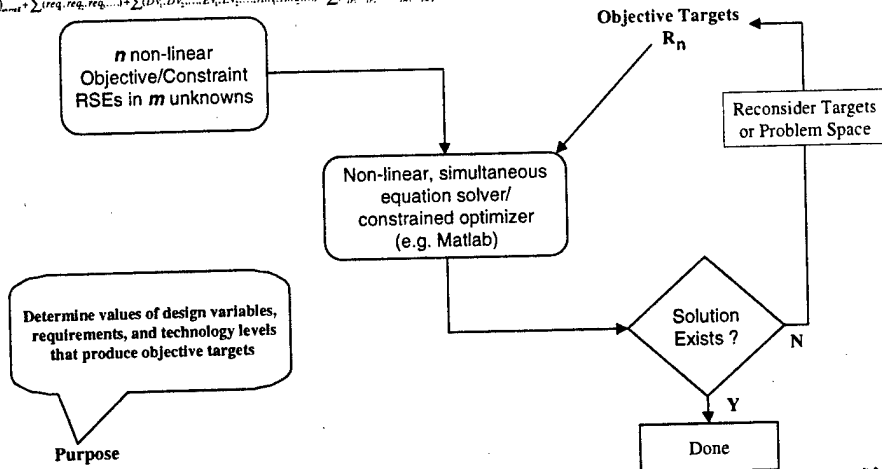
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## Is there a Solution??

The set of coupled, non-linear RSEs can be used to determine if a solution exists for given metric targets

$$R = (b_0)_{\text{overall}} + \sum(\text{req.1, req.2, req.3...}) + \sum(DV1, DV2, \dots, EV1, EV2, \dots, Attr1, Attr2, \dots) + \sum(k_{TP1}, k_{TP2}, \dots, k_{TM1}, k_{TM2}, \dots)$$



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## One Example Application on the Notional F/A-18C

### Objective:

Minimize the Gross Weight of a multirole fighter (Notional F/A-18C baseline)

### Equality Constraint:

Required Primary Mission radius = 357 nm (+15% from baseline)  
Required Delta Weight for Stealth = 500 lbs.

### Inequality Constraints (deltas with respect baseline):

$\Delta \text{AltRng} \geq 4\%$ ,  $\Delta \text{OEWS} \leq -4\%$ ,  $\Delta \text{\$O\&S} \leq -3\%$ ,  $\Delta P_s \geq 2\%$ ,  
 $\Delta \text{TurnRt} \geq 3\%$ ,  $\Delta \text{TurnRad} \leq -3\%$ ,  $\Delta \text{WOD} \leq -3$  knots

### Free Variables:

Requirements: *Ult. Load Factor, Combat Mach, Payload, Thrust, Wing Area, Aux. Tanks*  
Technology K-Factors: *Minimum Drag, Induced Drag, Wing Weight, Fuselage Weight, Vertical Tail Wt., Horizontal Tail Wt., SRDTE, \$1st Unit Prod., \\$O&S*

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## Screenshots and Example Results

### Results:

#### Objective:

$\Delta \text{GW} = -8.8\%$

#### Inequalities:

$\Delta \text{AltRng} = 6.9\%$

$\Delta \text{OEWS} = -10.1\%$

$\Delta \text{\$O\&S} = -3\%$

$\Delta P_s = 3.6\%$

$\Delta \text{TurnRt} = 4.8\%$

$\Delta \text{TurnRad} = 6.7\%$

$\Delta \text{WOD} = 6$  knots

Analysis routines  
created in MATLAB®

```

function [C, Ceq] = nonlincon_1(X0)
% This function defines the objective function and constraints for the
% optimization problem. The input X0 is the initial design point.
% The output C is the objective function value, and Ceq is the vector of
% equality constraint values.

% Parameters
ALTR=2; OEWS=-1; Pa=2; TRM=2; TRC=2; WOC=2;
BB=1;
DLF=20(1);
CR=20(3);
DP=20(4);
TR=20(5);
SW=20(6); DB=20(7); AZ=20(8); WF=20(9);

% Constraints
C=[...];
Ceq=[...];

% Objective function
calc_constrains(X0);
Cobj = 9.07584616+RD*1.0015678+DLF*0.8359634+CR*0.19465237+...
DP*1.50702985+TR*1.02412009+SW*1.15773627+DB*0.50707013+AZ*2.70448042+...
WF*1.18808948+TRC*0.209546+DLF*0.071121+DLF*ULF*0.0024562+...
CR*DB*0.0006376+CR*DLF*0.00468542+CR*CR*0.01326324+DP*RD*0.00918137+...
DLF*DLF*0.01270773+DP*CR*0.0014725+DP*DP*0.0009591+TR*RD*0.02226037+...
TR*ULF*0.01477992+TR*CR*0.00744621+TR*DP*0.0018764+TR*TR*0.0020094+...
SW*RD*0.01210335+SW*DLF*0.02588615+SW*CR*0.00191815+SW*DP*0.0039232+...
SW*TR*0.00123335+SW*TR*0.0021462+SW*RD*0.00911704+DB*DLF*0.01405278+...
    
```

The constraints/objectives/targets can be quickly changed and the optimization re-executed

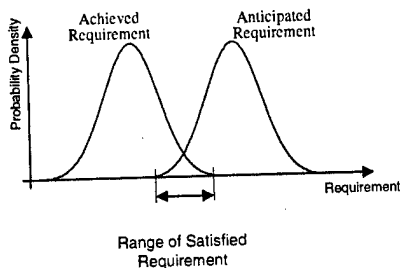
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# Future.....Incorporating Probabilistics: Achieved vs. Anticipated Requirements

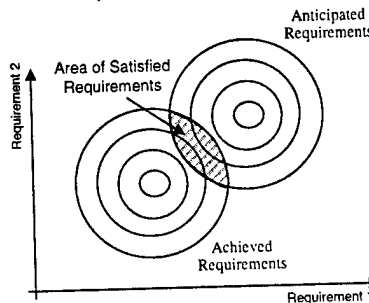
## One Requirement - 1-Dimensional Plot



$$\begin{aligned}
 P(\text{Satisfying Requirement}) &= P(\text{Req}_{\text{Anticipated}} - \text{Req}_{\text{Achieved}} > 0) \\
 &= P(RD > 0)
 \end{aligned}$$

$$\begin{aligned}
 P(\text{Satisfying Requirements}) &= P(\overline{\text{Req}}_{\text{Achieved}} - \overline{\text{Req}}_{\text{Anticipated}} > \overline{0}) \\
 &= P(\overline{RD} > \overline{0})
 \end{aligned}$$

## Two Requirements - 2-Dimensional Plot



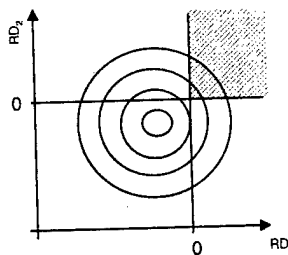
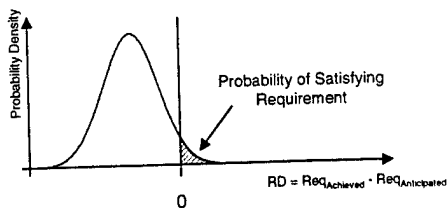
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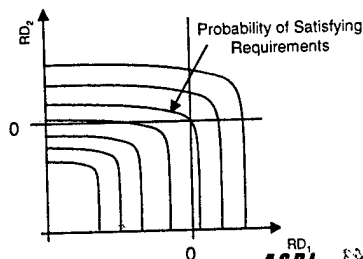
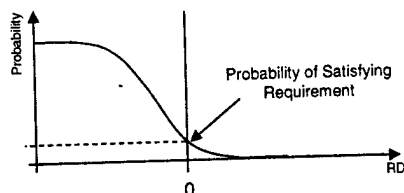


# Probability of Satisfying Requirements

## Probability Density Functions



## Cumulative Probability Functions



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## Section 4

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- 1. Introduction and Research Setting/Summary*
- 2. Overall Technical Approach for Affordable Systems Design*
- 3. Methods Implementation and Testbed Applications*
- 4. Key Advancements in Method Components*
- 5. Conclusions/Summary*

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## Section 4

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### Part B: Investigation of Advances in Soft Computing and Mathematical Sciences for Affordability Measurement and Prediction

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## Tasks

- Main Tasks:
  - ... development of a comprehensive database of key characteristics, relevant bibliographies, and clear identification attributes and limitations as to these techniques.
  - ... for each examined technique, definitions, maturity status, data on leading scientists and organizations advantages and problems, software implementation, practical applications and 'pointers' to the problems to be addressed within the affordability science.
- Main Assumptions:
  - ... customer's concept of affordability
  - ... no more than 10 -15 areas and a certain period of time due to diversity and dynamism
- Results:
  - Comprehensive database of important modern mathematical techniques and their characteristics as applicable to affordability science.
  - Recommendations on use, limitations and desirable development of mathematical techniques with respect to affordability

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## Research Motivation?

- Find elements that can serve as a formal foundation for affordability science
- Selected the areas of investigation so as to have a broad range of application domain to address a wide variety of problems.
- Organize this broad range into categories and identify their primary area of concern on a higher level.
- Map critical areas in affordability science which would benefit from additional methods to the categories of solution techniques.

This will yield

- ⇒ The areas/categories which are the most critical to the affordability science on a higher level
- ⇒ A better understanding and greater insight as to where each of these techniques stands and
- ⇒ How they can be used to have the greatest positive impact on affordability science, and science and society in general.

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## Overview/Summary of Investigated Areas

<u>Method</u>	<u>Description</u>	<u>Applications</u>
Rough Sets	Uncertainty Management Upper and Lower Approximations	Uncertainty representation, knowledge analysis and analysis of conflicts, identification of data dependencies, Information-preserving data reduction
Artificial Neural Networks	Pattern Recognition and Function Approximation, Non-linear Regression	Approximate Reasoning, Pattern Recognition, Function Approximation, Time-Series Prediction
Genetic Algorithms	Genetics and Chromosome representation, Evolutionary Algorithms	Global Optimization, Applicable to discrete variables and parameters, Genetic Representation
Fuzzy Logic	Fuzzy vs. Crisp Uncertainty Representation Approximate Reasoning	Representation of incomplete, uncertain or partially true knowledge, Knowledge Management, Approximate Reasoning
Chaos Theory and Theory of Fractals	Dynamical Systems Fractal Structures	Dynamical Systems, Chaotic Behavior, Image Coding, Wavelets
Granulation and Aggregation	Granular Computation	Clustering, Approximate Classification, Optimization, Approximate Reasoning
Game Theory	Decisions players make in a well-defined game	Analysis of strategic concepts, Partial Prediction on partial knowledge, Decision Support
Ordinal Optimization	Ranking and Optimization Method	Optimization, Ranking, Selection of the 'best'
Semiotics	Signs similar to those used in natural languages	Analysis of language, Linguistic Concepts, Logic of Signs
Knowledge-Based Systems	Expert Systems, Knowledge- or Rulebase, Inference, Reasoning	Reasoning: Diagnostics, Certification, Design



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## Level of Application of a Method

- Ranks the techniques relative to each other between the two extremes
  - A may be more specifically tailored to an application or
  - A method encompasses fundamental and basic principles
- Compare only those on the same or a similar level of application
- Techniques on different or the same levels of application may build on each others principles or be integrated as hybrids
- Basic techniques with a low level of application are fundamental notions, they
  - generally require more work to be applied than those with high-level applications already specified and
  - can usually be applied to a much wider range of problems than high-level specific applications
- Techniques which evolve from a fundamental, basic stage to one or more high-level applications may all be known under the same name
- The Level of Application marks the first dimension in the classification scheme

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How broad is the range from theory to application?  
A sample of techniques

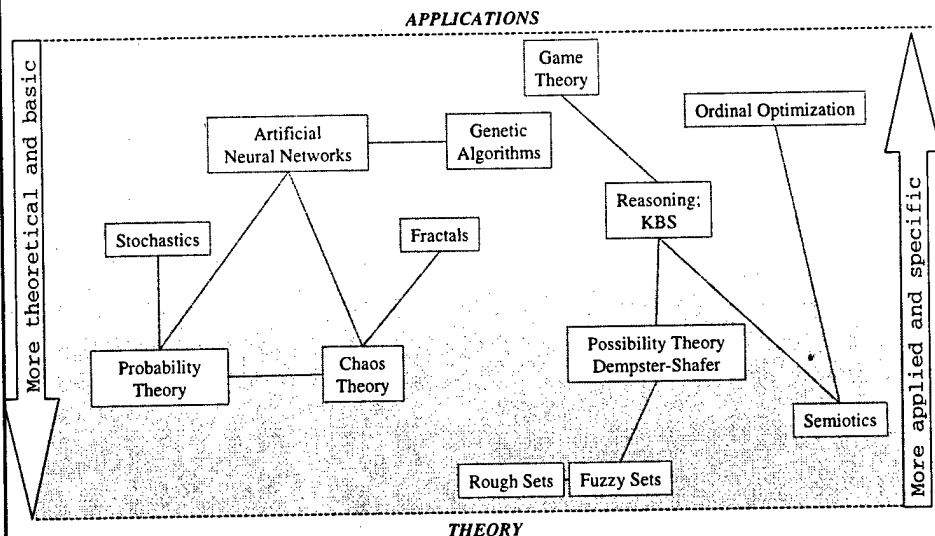
Method	Description	Application Level
• Artificial NN	Computational methods	procedure
• Chaos	Dynamical Systems	specific basic
• Fractals	Mathematical representation	specific basic
• Fuzzy Logic	Mathematical notion	basic
• Game Theory	Modeling Strategy Situations	application
• Genetic Algorithms	Discrete Optimization	application
• Aggregation/Granulation	Clustering and Optimization	basic, application
• Expert Systems	Reasoning	procedure
• Ordinal Optimization	Ranking Optimization	application
• Rough Sets	Mathematical notion	basic
• Semiotics	Signs and Language notion	basic

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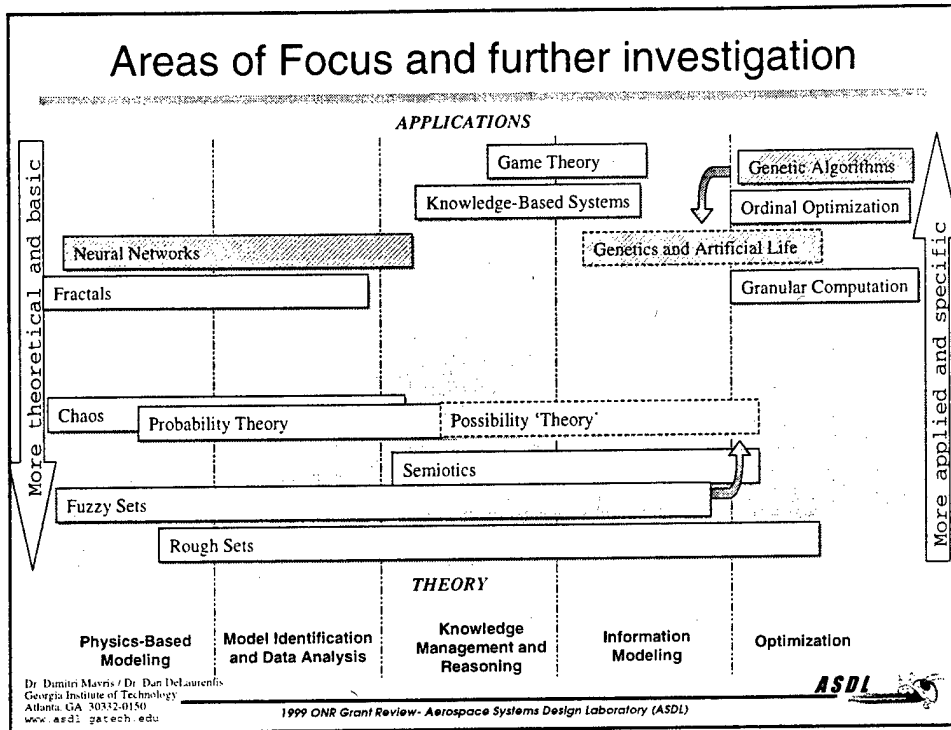
Where do these methods fit in?



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### Screenshot of the Summary Web Pages:

http://www.asdl.gatech.edu/affordability/newmethods/

**Affordability Measurement and Prediction Research and Development Program**

Office of Neural Research

**Advances in Soft Computing and Mathematical Sciences**

This page provides a summary of the results which were found in the field of soft computing and mathematical sciences in view of their applicability. The methods which were investigated include:

- Fuzzy Logic
- Artificial Neural Networks
- Genetic Algorithms
- Theory of Fuzzy Sets
- Knowledge-Based Systems
- Chaos Theory
- Theory of Fractals
- Game Theory
- Ordinal Optimization
- Semiotics

The pages contain a description and introductory summary of the background of each of the methods, some examples and applications, and links to other useful websites. These methods were found to be useful in the areas of:

- Neural Networks
- Fuzzy Logic
- Genetic Algorithms
- Ordinal Optimization
- Semiotics

**Theory of Rough Sets**

The notion of rough set has been investigated since the 70's and has been found useful in the regimes of knowledge acquisition and data mining. The theory was originated by Zdzislaw Pawlak in 1970's as a result of a long term program of fundamental research on logical properties of information systems, carried out by him and a group of logicians from Polish Academy of Sciences and the University of Warsaw, Poland. The methodology is concerned with the classificatory analysis of imprecise, uncertain or incomplete information or knowledge expressed in terms of data acquired from experience. The primary notions of the theory of rough sets are the approximation space and lower and upper approximations of a set. The approximation space is a classification of the domain of interest into disjoint categories. The classification formally represents our knowledge about the domain, i.e. the knowledge is understood here as an ability to characterize all classes of the classification, for example, in terms of features of objects belonging to the domain. Objects belonging to the same category are not

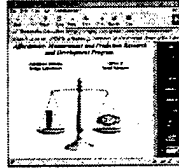
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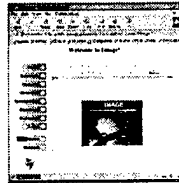
## Other Web Sites of Interest



Aerospace Systems Design Laboratory  
[www.asdl.gatech.edu](http://www.asdl.gatech.edu)



ASDL Affordability Research  
[www.asdl.gatech.edu/affordability](http://www.asdl.gatech.edu/affordability)



ASDL Architecture Research  
[www.asdl.gatech.edu/image](http://www.asdl.gatech.edu/image)

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## Summary

- Database of methods and key characteristics
  - In electronic form, available on the web
  - Summary write-ups for each technique, addressing function, type of implementations and other summary information and characteristics
  - Reference Bibliography for each technique
- Method for classification of techniques according to 'dimensions', such as
  - Level of Application
  - Problem Domain in terms of decision making
  - Select Techniques to apply and give further consideration
- Application examples of:
  - Genetic Algorithms for Technology Impact Forecasting (high application level, optimization)
  - Artificial Neural Network for Metamodel-building (medium application level, function approximation)
  - Fuzzy Logic to Possibilistics for uncertainty management (basic, low application level with broad range)

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## Section 4

# Part C: Stochastic Methods Research

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## Stochastic Methods Task Summary

Main Objective: To define the requirements and identify the specific tools for the transition from a probabilistic decision-making mechanism for Affordability to a stochastic environment.

Specific Tasks:

- Establish the need of a time-varying model (current shortcomings)
- Identify the needed elements of a proper stochastic approach including mathematical tools, decision-making models, etc,
- Recommend ways that the environment assists (not hinders) the making of rational decisions (resource allocations)

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## Why Stochastics ?

- ◆ Technology readiness changes in time
- ◆ Fidelity Uncertainty changes in time
- ◆ Customer requirements change in time
- ◆ Fitness landscapes (i.e. objective function surfaces) change in time
- ◆ Operational environment changes in time
- ◆ Budget allocations change in time

..... **Bottom line:** Both deterministic and probabilistic variables involved in identifying and designing affordable systems evolve in time. Stochastic methods are needed.

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## Analogies: Common Applications of Time Series Prediction

- Weather forecasting
- Sales forecasting
- Economic forecasting (i.e., price)
- Stock market forecasting
- Manufacturing forecasting
- Prognostic of incoming failures
- etc.

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## Issue: Prediction of Stochastic Systems

What is time series prediction ?

- **Time series prediction** --> find the future values  $\{x_{N+1}, x_{N+2}, \dots\}$  Given  $\{x_1, x_2, \dots, x_N\}$ , where  $x_t$  is the series value sampled at time  $t$ .
- (Takens, 1981) If the series is deterministic, there exists  $d, \tau$  and  $f(\cdot)$  such that for every  $t > (d \cdot \tau)$

$$x_t = f(x_{t-\tau}, x_{t-2\tau}, x_{t-d\tau})$$

Unfortunately, there is no exact method to find  $d, \tau$  and  $f(\cdot)$  when the series is too small (less than  $10^d$  samples for  $d$  and  $\tau$ )

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## Shortcomings: Current Prediction Methods

- There are major weaknesses with current time-series methods need to be overcome:
  - Generally only valid for very short term prediction (i.e. can only predict next steps  $x_{N+1}, x_{N+2}$ )
  - Lack ability to incorporate *causality*, especially through reasoning/learning
- Studies under this grant focused on advanced time-series prediction methods. In particular, a neural-network model is under development for the prediction of airline load factor and fuel price based on historical data and cause/effect relationships

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## The Classical Approach

Many time series can be modeled by two simple models

- Autoregressive (AR)

$$Z_t = \phi_0 + \phi_1 Z_{t-1} + \phi_2 Z_{t-2} + \dots + a_t$$

- Moving average (MA)

$$Z_t = \phi_0 + \theta_1 a_{t-1} + \theta_2 a_{t-2} + \dots + a_t$$

- Combination of two models (ARMA)

$$Z_t = \phi_0 + \phi_1 Z_{t-1} + \phi_2 Z_{t-2} + \dots + \theta_1 a_{t-1} + \theta_2 a_{t-2} + \dots + a_t$$

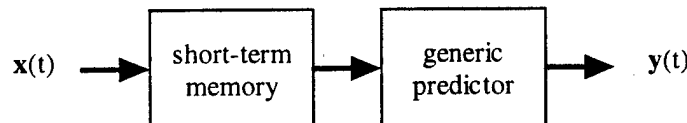
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## Neural Network Approach

- (Hornik 1989) showed that neural networks can be used as universal function approximators.
- For time series prediction problems, let's assume we know  $d$ ,  $\tau$  and want to find  $f(\cdot)$  using neural networks.
- For *nonstationary* time series prediction, the network must have *memory* that holds the past events and an associator that used the memory to predict

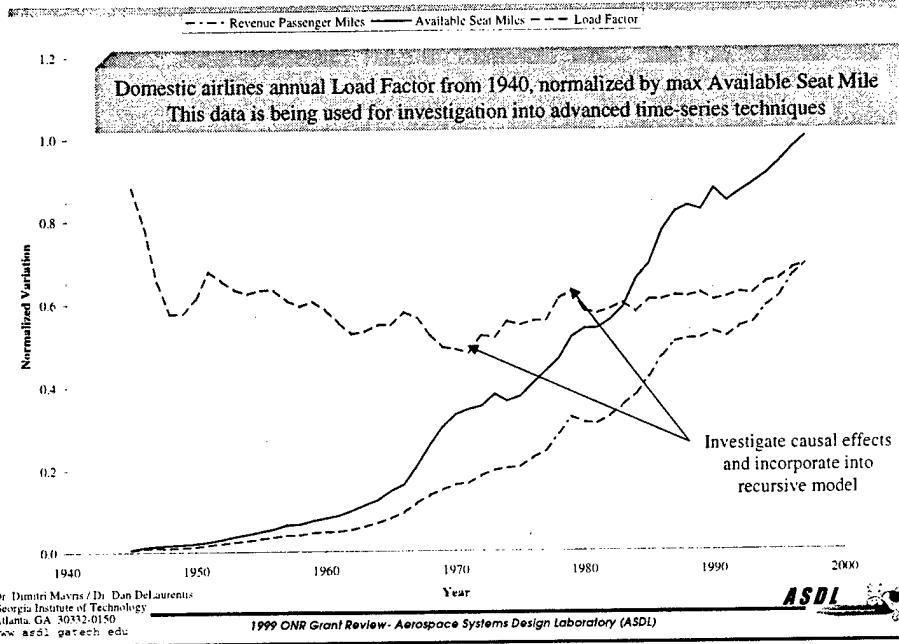


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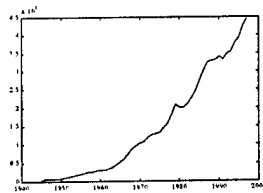


# Data Example



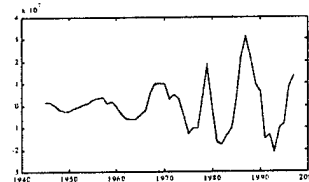
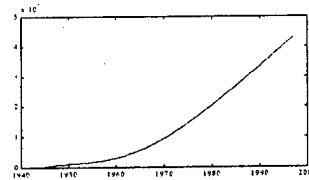
# Prediction of Revenue Passenger Miles

Feed-forward neural network results:



Historical data

Trend



Oscillating detail

**Observation: Trend is exponential, but oscillation is increasing in amplitude, perhaps a sign of the rapid pace of change in the emerging globalization of markets/societies**

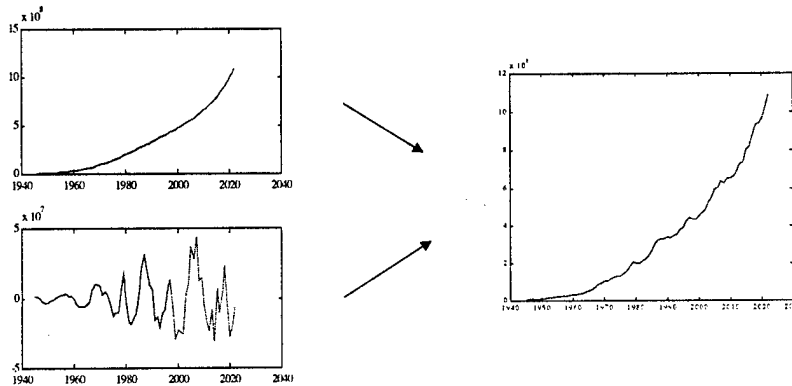
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## RPM Prediction (cont.)

Feed-forward neural network results:  
Trend can be captured, but without causal factors, oscillation  
for short term prediction is impossible



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## Representation of Stochastic Processes

### Motivation

- Information must be readily available at all times during decision-making processes
- Information is stochastic and highly dynamic
- Information must be easily transformed into knowledge
- Information is distributed and very large amounts exist

### Research

- Study methods for representing stochastic processes in the context of decision-making

### Findings

- Evolutionary modeling techniques exist
- Difficulty in identifying axis of change; area for future research
- Results from ONR base research plays a key role in the structure of the information model

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## Definitions in the Context of this Research

- **Information**  
*A collection of data describing products and processes.*
- **Knowledge**  
*Information in context.*
- **Transaction**  
*A valid action that has occurred.*
- **Event**  
*A transaction that happens at a specified time.*

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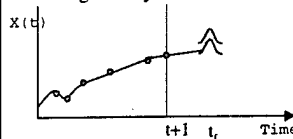
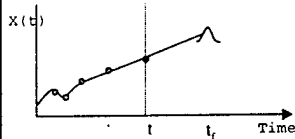
## Evolutionary Data Structures

- **Current database technologies using linked-lists can be used to store forecasting information.**

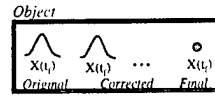
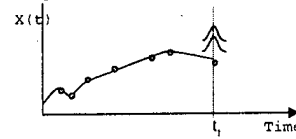
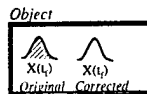
Distributions can be stored in objects and keyed to time

Linked list structures can be used to store information as it evolves over time. This is needed so that decision-making history can be stored.

Object must be able to store both stochastic history and discrete event as well as return appropriate result when queried.



Object  
 ~~$X(t_f)$~~   
Do not delete old data



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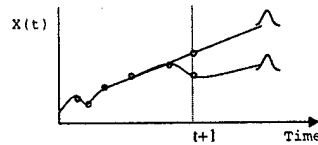


## Additional Forecasting Scenarios

- The following scenarios are expected in forecasting. They are more difficult to map and manage as data structures and require further investigation.

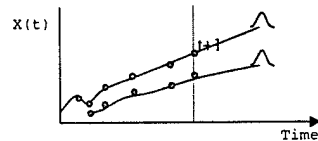
### Branching - (Subject of Current Research)

Decision path separation because of budget constraints, shift in requirements, and technological impacts



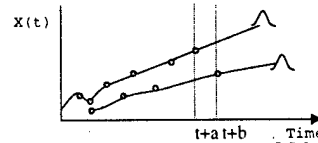
### Parallelism

Multiple decision paths can occur during technology trades, bidding, and multi-purpose designs



### (A)Synchronization

Decision paths may not be synchronized as tasks are delegated to different groups and technologies are evaluated as they matures  
Decision paths may be done independently



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## Formulation of a Stochastic Object Framework

- Preliminary Findings**
  - Advantages
    - Permit storage of both stochastic and deterministic information
    - Sound temporal framework exists for managing information
  - Disadvantages
    - Assumes time is the axis of change
    - Complex decision making paths difficult to implement and manage
- Characteristics of a Stochastic Object Framework**
  - Transaction-Based
    - Allows for non-temporal considerations to affect events; Situation Calculus is necessary for modeling transactions and their relationship to time
    - Multiple axes of change can be modeled
  - Evolutionary
    - Permit storage of deterministic and stochastic information in same structure
    - Permits growth from a data set with few sparse points to a fully populated legacy data history

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## More on the Axis of Change

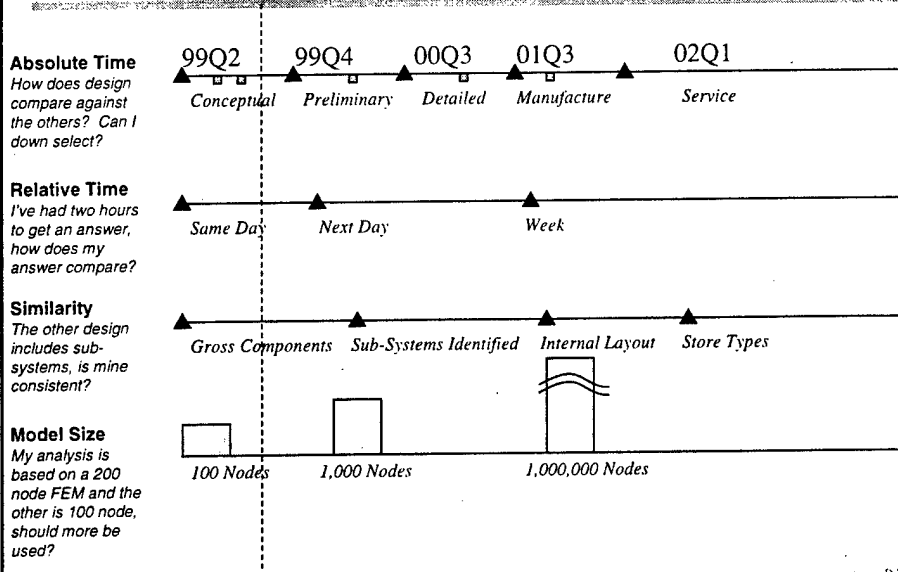
- During the course of the preliminary research, the time axis presented difficulty when time was used as a key for tracking decision making actions. Time is important for forecasting but may not be relevant for:
  - Predictions
  - Comparisons
  - Forecasting across multiple domains
  - Other decision-making processes
  
- More research needs to be done on quantifying other axes of change.

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## Some "Axes of Change" within an Enterprise



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## Summary of Issues

- Tied to Stochastic Modeling
  - Can temporal methods be extrapolated to other axes? How are decisions impacted?
  - Which axis of change is needed for a particular decision type or class?
  - How can decisions be mapped against the axes? How can the axes be mapped against each other?
- Other Issues
  - Investigation into information quantity and quality. How much data is needed? When is extrapolation acceptable?
  - Identify situations where real-time and near real-time information storage are applicable.

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## Section 4

# Part D: Decision Tree Networks Research

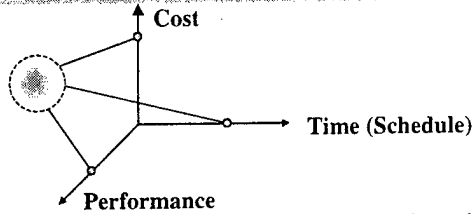
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## Stochastic Decision Trees: Motivation

Uncertain system state (fuzzy, stochastic, non-linear, ...)



The dynamics of the future "project (venture) - external environment" system is complex and uncertain. In affordability studies, three classes of metrics are to be taken into account simultaneously: time, cost, and performance.

The following types of relationships are characteristic to the system:  $T_i = f(T_j, C_k, P_l)$ ,  $C_i = f(T_j, C_k, P_l)$ , and  $P_i = f(T_j, C_k, P_l)$ , where  $T_i$  is time,  $C_k$  is cost, and  $P_l$  is performance of activities (processes) and events (milestones), which constitute the system structure.

This Tri-Variate (Time - Cost - Performance, or T/C/P) Affordability Problem needs the metrics on all three axes to be quantified intelligently. The objective of the decision maker is to search for potentially optimal and critical alternatives and paths in the system dynamics.



Adequate analytical methods are required to derive and examine these relationships in affordability studies

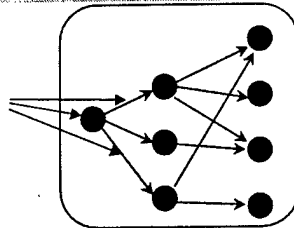
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## Task Connectivity

TIES Method Output



Fuzzy-Stochastic Decision Tree-Network

### TIES Analysis

- \* Technology Impact Forecast Equations
- \* Technology Confidence Estimates (TRLs)
- \* Feasibility/Viability Estimates



The TIES method generates input information for the tree network in form of specifications of activities (processes) and events (milestones)

### VERT-3F Fuzzy Stochastic Modeling Method

- \* Information mapping and integration
- \* Simulation of system's life cycle logic, constraints and objectives (failure and success conditions) using time, cost and performance metrics and their relationships



Fuzzy-stochastic tree-network models simulate the "project-environment" life cycle dynamics under uncertainty

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## Project Details (Case Study)

### Project's life cycle phases (network models)

**P1 (N1):** new technologies RDT&E phase  
**P2 (N2):** vehicle design phase  
**P3 (N3):** test article production, T&E, and certification phase  
**P4 (N4):** vehicle production, operation & retirement phase

### New technologies (T1, ..., T4)

**T1:** High-temperature composite wing - to reduce weight and improve temperature tolerance  
**T2:** Circulation control - to improve the vehicle's takeoff and landing performance  
**T3:** Hybrid laminar flow control - to reduce high-speed flight drag  
**T4:** Advanced engine concept - to reduce engine's s.f.c., and noise and emissions levels

### New technologies performance metrics

**1. T1 - High-temperature composite wing:**  
**Y11:** Wing weight reduction, %  
**Y12:** Surface work temperature increase, °K  
**2. T2 - Circulation control:**  
**Y21:** Lift-over-drag force increment, %  
**Y22:** Thrust losses, %  
**3. T3 - Hybrid laminar flow control:**  
**Y31:** Supersonic drag coefficient reduction, %  
**Y32:** Subsonic drag coefficient reduction, %  
**4. T4 - Advanced engine concept:**  
**Y41:** Specific fuel consumption reduction, %  
**Y42:** Fly-over noise reduction, EPNdB  
**Y43:** Side-line noise reduction, EPNdB

### System alternatives (V0, ..., V14)

**V0 (baseline)** = none of technologies is used  
**V1** = T1  
**V2** = T2  
**V3** = T3  
**V4** = T4  
**V5** = T1 + T2  
**V6** = T1 + T3  
**V7** = T1 + T4  
**V8** = T2 + T3  
**V9** = T2 + T4  
**V10** = T3 + T4  
**V11** = T1 + T2 + T3  
**V12** = T1 + T2 + T4  
**V13** = T2 + T3 + T4  
**V14** = T1 + T2 + T3 + T4

### System level metrics

#### 1. Flight performance metrics group (M1, ..., M4):

<b>M1:</b> Landing Approach Speed	$V_{LA}$	≤ 155	fts
<b>M2:</b> Landing Field Length	LFL	≤ 11,000	ft
<b>M3:</b> Takeoff Field Length	TOFL	≤ 11,000	ft
<b>M4:</b> Takeoff Gross Weight	TOGW	≤ 1,000,000	lbs

#### 2. Environmental performance metrics group (M5, M6):

<b>M5:</b> Fly-Over Noise (Stage III)	FON	≤ 106	EPNdB
<b>M6:</b> Side-Line Noise (Stage III)	SLN	≤ 103	EPNdB

#### 3. Economic performance metrics group (M7, ..., M10):

<b>M7:</b> Aircraft Acquisition Price	Acq\$	Minimize	FY98SM
<b>M8:</b> Required Yield per RPM	\$/RPM	≤ \$0.13 (*)	FY98SM
<b>M9:</b> Direct Operating Cost Per Trip	DOC/T	Minimize	FY98SM
<b>M10:</b> R&D, T&E Costs	RDTEC	Minimize	FY98SM

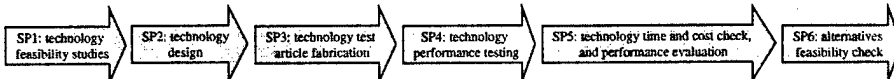
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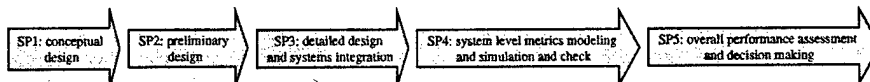
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## Vehicle's Life-Cycle Tree-Network Models

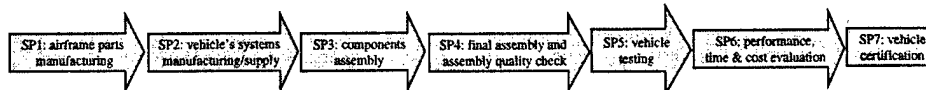
### N1: New Technologies Research Development, Testing & Evaluation (RDT&E) Phase



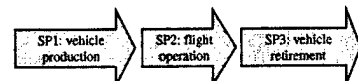
### N2: Vehicle Design Phase



### N3: Test Article Production, Testing, Evaluation and Certification (PTE&C) Phase



### N4: Vehicle Production, Operation & Retirement Phase



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## VERT-3 Modeling and Simulation Process

### Step 1. Decision situation formalization

Define the problem, define success and failure conditions and decision criteria, establish the alternatives to solve the problem

### Step 2. Flow network specification

Formulate the model, specify main activities and events of the "venture - external environment" system dynamics

### Step 3. Input data collection

Collect the data on main activities and events, represent the data in the form of probability distributions, histograms, and/or mathematical relationships

### Step 4. Tree-network programming

Translate the tree-network model into VERT input system, program and debug the model

### Step 5. Network verification and validation

Verify and validate the model, conduct sensitivity ("what-if") analysis

### Step 6. Network simulation and results analysis

Design the simulation experiments, conduct the experiments, process, and analyze results

### Step 7. Alternatives selection

Compare alternatives, identify the worst and the best outcomes (critical/optimum paths)

### Step 8. Results generalization and communication

Present the final study to the decision maker in a concise format, make recommendations regarding those activities and milestones and their parameters, which are time, cost and performance drivers on both critical and winning paths; estimate project's overall risk and success under key uncertainty hypotheses (scenarios)

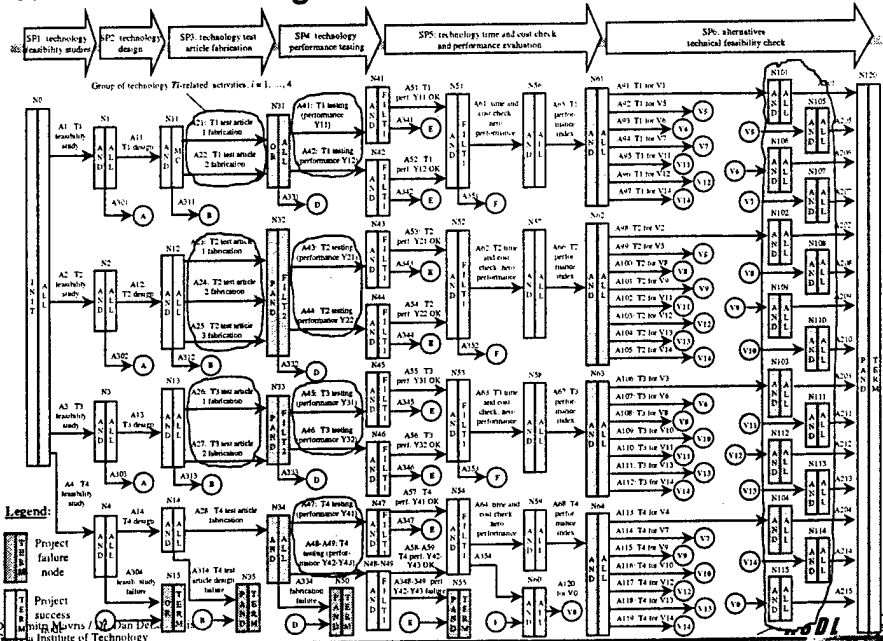
Iterations are possible

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## N1: New Technologies RDT&E Phase Network (Version 2)



## Section 5

- 1. Introduction and Research Setting/Summary**
- 2. Overall Technical Approach for Affordable Systems Design**
- 3. Methods Implementation and Testbed Applications**
- 4. Key Advancements in Method Components**
- 5. Conclusions/Summary**

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## Summary of Year 2 Results

1. Significant enhancements to the TIES affordability environment est. in Year 1
  - ◆ *Pilot Studies: Environment prototype for Navy's F-18C, NASA's HSCT, a notional 150 pax transport, and a short-haul civil tiltrotor*
  - ◆ *JPDM incorporation and validation; n-variate math model constructed*
  - ◆ *Genetic Algorithm for technology combinatorial selection problems*
  - ◆ *Fuzzy Decision tree constructed to treat stochastic affordable technology selection problem, an evolution of TIES to include schedule/cost as well as performance*
2. Completion of the investigative research into mathematical and soft computing techniques and stochastics, resulting in:
  - ◆ *Web-based database of advanced math and soft computing techniques relevant to affordability measurement and prediction, including current investigators, computer codes, and transition status*
  - ◆ *Several implementations of methods (Fuzzy sets, GA's, Neural Networks)*
  - ◆ *Roadmap towards stochastic methods established, research goals prioritized*
3. A powerful mathematical tool to examine the simultaneous impact of vehicle requirements & technologies has been created and initially tested on a F/A-18C case, including carrier suitability constraints.
4. Methods have been integrated in Graduate level curriculum

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## Key Research Innovations

- Recognizing the need for a physics-based, quantitative link between affordability metrics, uncertainty, and technology infusion, the use of disciplinary metric k-factors was a breakthrough in facilitating affordability decision-making
- Recognizing the need for a rapid, accurate assessment of system feasibility and viability, the "5-Step Feasibility/Viability" process, including TIES, was an important breakthrough
- A mathematical environment collecting requirements, design variables, and technologies for simultaneous examination during concept formulation
- Recognizing the need for a probabilistic measure that did not have the shortcomings of traditional arithmetic composite objectives, the JPDM was an important breakthrough
- Finally, the TIES environment was a "integration breakthrough" which incorporates many of the other breakthroughs

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## ASDL Gov't/Industry Technology Transfer ('97-'01)

**ONR Code 36**  
**Basic Research in Affordability Science**

(Ongoing and planned)

### Gov't/Industry

NAVAIR-Pax River  
NAVSEA-China Lake  
NUWC  
STTR  
STTR  
Lockheed Martin (Ft Worth)

Boeing (St. Louis)/DARPA  
Boeing (Long Beach)  
NASA Langley SAB

Air Force Research Laboratory  
ONR/Boeing/Lockheed  
Rolls-Royce Allison  
General Electric Aircraft Engines

### Collaboration/Technology Transfer

- Mngt. Briefed; Validation study with F-18 or JPATS
- Strong interest in ASDL methods for hypersonic missile
- ASDL methods for torpedo validation and design app.
- Affordability for Surface Combatants
- Simulation-Based Acquisition, Affordability Science
- UCAV Technology Impact Forecast (TIF)
- Manufacturing (JSF)
- Application to Study of Synthetic Jet Tech.
- *MUST* Cost Initiative for C-17
- HSCT TIF, Subsonic Transport TIF
- Goal-Based Outcome Study
- UCAV TIF
- Composite Affordability Initiative
- T-406/V-22 TIF
- Robust Design Simulation Applications

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## Grant Publications Update (June 98 through Oct. '99)

### Journal Articles submitted and accepted:

1. Mavris, D.N., DeLaurentis, D.A., Bandte, O., Hale, M.A., "The Role of AI in a New Virtual Aircraft Design Environment," accepted and to be published in special issue of *Engineering Applications of Artificial Intelligence (EAAI)*, estimated publication in early 2000.

### Conference Papers presented and in process of submittal to Journals in '99:

1. Mavris, D.N., DeLaurentis, D.A., "A Stochastic Design Approach for Aircraft Affordability," 21st Congress of the International Council on the Aeronautical Sciences (ICAS), Melbourne, Australia, September 1998. ICAS-98-6.1.3. (intended for *AIAA Journal of Aircraft*)

2. Bandte, O., Mavris, D.N., DeLaurentis, D.A., "Determination of System Feasibility and Viability Employing a Joint Probabilistic Formulation", 37th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 11-14, 1999. AIAA 99-0183. (intended for *AIAA Journal of Aircraft*)

3. Mavris, D.N., Kirby, M., Qiu, S., "Technology Impact Forecast for a High Speed civil Transport," AIAA/SAE World Aviation Congress and Exposition, Anaheim, CA, September 28-30, 1998. AIAA-98-5547. (intended for ... TBD)

4. Daberkow, D.D., Mavris, D.N., "New Approaches to Conceptual and Preliminary Aircraft Design: A Comparative Assessment of a Neural Network Formulation and a Response Surface Methodology", World Aviation Congress and Exposition, Anaheim, CA, September 28-30, 1998. SAE-985509. (intended for ... TBD)

5. Mavris, D.N., Kirby, M., "Technology identification, Evaluation, and Selection for Commercial transport Aircraft," for presentation at 58th annual conference of Society of Allied Weight Engineers, May 1999.

### To be presented:

1. Mavris, D.N., Daberkow, D.D., "Knowledge Representation, Utilization and Reasoning in the Conceptual Aircraft Design Process." Abstract submitted to the World Aviation Congress, San Francisco, CA, Oct. 19-21, 1999.

2. Mavris, D.N., Kirby, M.R., Daberkow, D.D., "Technology Evaluation and Selection via a Genetic Algorithm Formulation for Aerospace Systems." Abstract submitted to the World Aviation Congress, San Francisco, CA, Oct. 19-21, 1999.

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## ONR Grant: ASDL Ph.D. Student/Staff Support

Number of Ph.D. Students Supported: 8

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Ms. Danielle Soban (ASDL)	Mr. Andy Baker (ASDL)
Ms. Elena Garcia (ASDL)	Ms. Linda Wang (ASDL)
Ms. Shobana Murali (Math)	Mr. Noppadon Khiripet (EE)

Number of Masters Students Supported: 8

Multidisciplinary Professional Team: 8

Dr. Dimitri Mavris (AE)	Dr. Daniel DeLaurentis (AE)
Dr. Dan Schrage (AE)	Dr. Mark Hale (AE)
Dr. Leonid Bunimovich (Math)	Dr. George Vachtsevanos (EE)
Dr. Jimmy Tai (AE)	Dr. Ivan Burdun (AE)

+ Over 40 students exposed to methods in graduate design curriculum

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## Some Future Plans

### Stochastic Affordability Prediction; Decision Making

Continued Development of TIES

Validation Studies (Collaboration with Navy Centers)

Application of methods to new systems for Navy

### Evolutionary technology, system fitness, resource allocation

Mathematical Modeling/Solution for Military A/C Requirements

Technology Landscapes

### Genetics, Complexity and Artificial Intelligence

Develop methods for revolutionary technological change

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