Multifidelity Modeling and Multidisciplinary Optimization Techniques for Environmentally-Sensitive Aircraft Design

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Outline

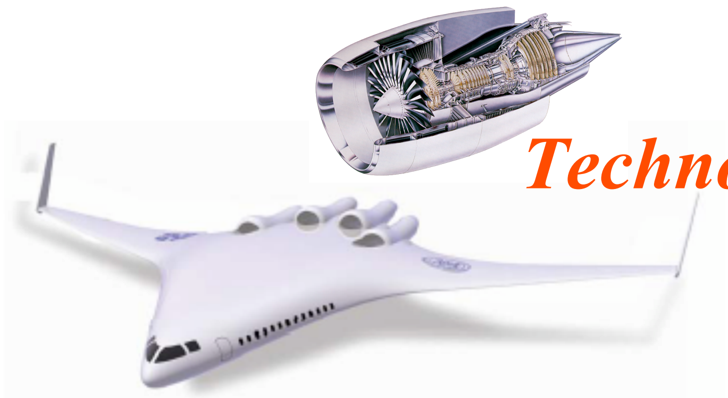
- Environmental tradeoffs and interdependencies
- Multidisciplinary design optimization and multifidelity modeling
- Examples:
  - Integrating design and operations
  - Advanced technologies for environmentally-sensitive aircraft design
  - Integrated decision-making: Aviation Environmental Portfolio Management Tool

Environmentally-Sensitive Aircraft Design

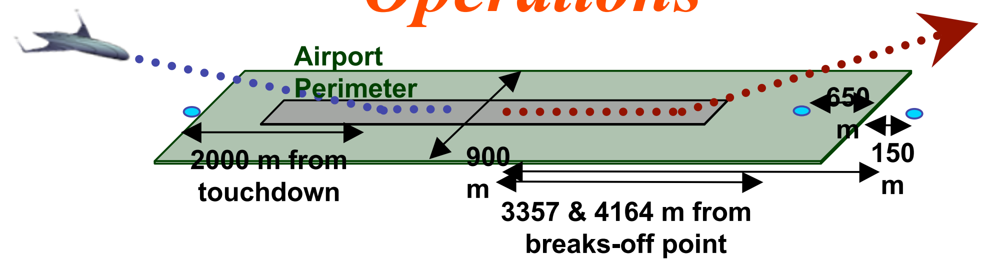
- Future aircraft must satisfy an increasingly diverse set of design requirements, many driven by stringent environmental constraints
- Requirements necessitate the use of advanced technologies, new operational strategies, and novel configurations
  - Traditional conceptual design models rely heavily on empiricism and past experience
- Research Objectives
  - Evaluate trade-offs between cost and environmental impacts during aircraft conceptual design using multidisciplinary optimization
  - Develop multifidelity optimization framework that can accommodate current and new designs
  - Investigate new design concepts

System Interdependencies are Key

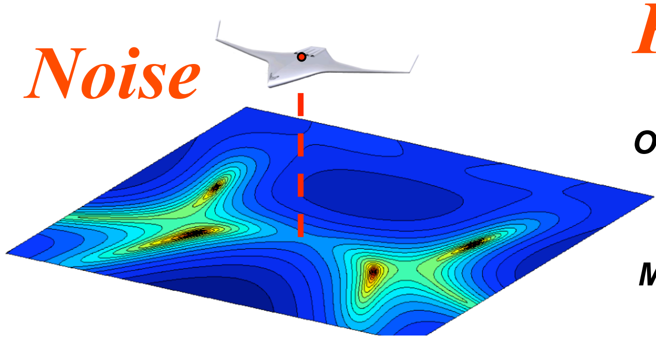
Technology



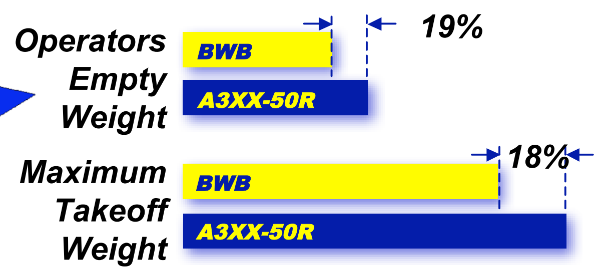
Operations



Noise

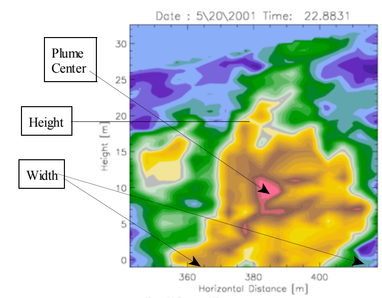


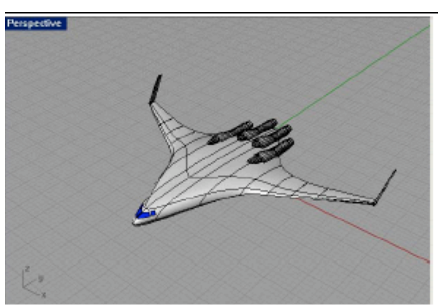
Performance



Cost

Emissions





Design

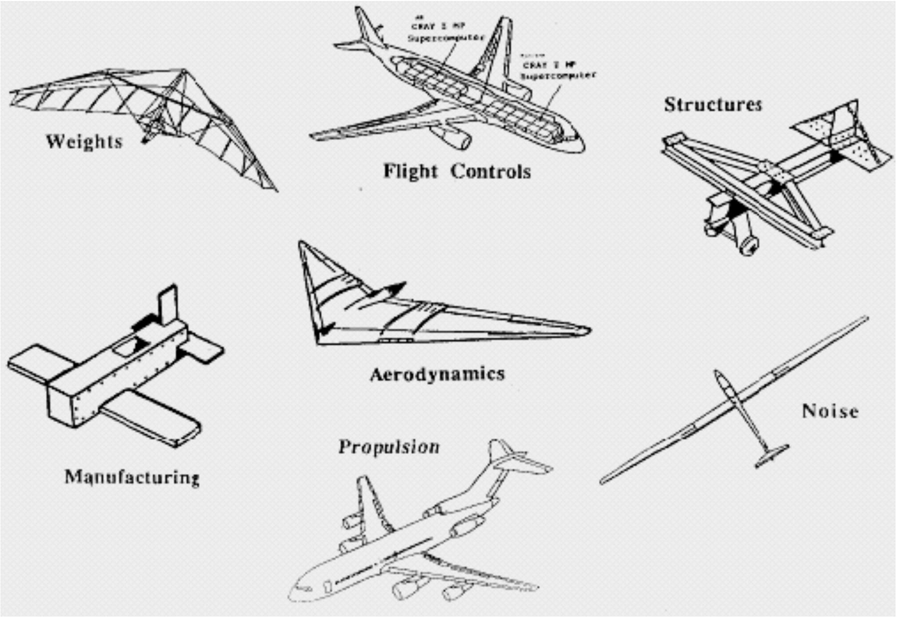
Regulation

EUROCONTROL

An integrated approach to design and decision-making is essential.

Multidisciplinary Design Optimization (MDO)

- Multidisciplinary approach to design
- Numerical optimization provides a systematic way to explore the design space
- Problem formulation is not obvious and requires engineering judgment



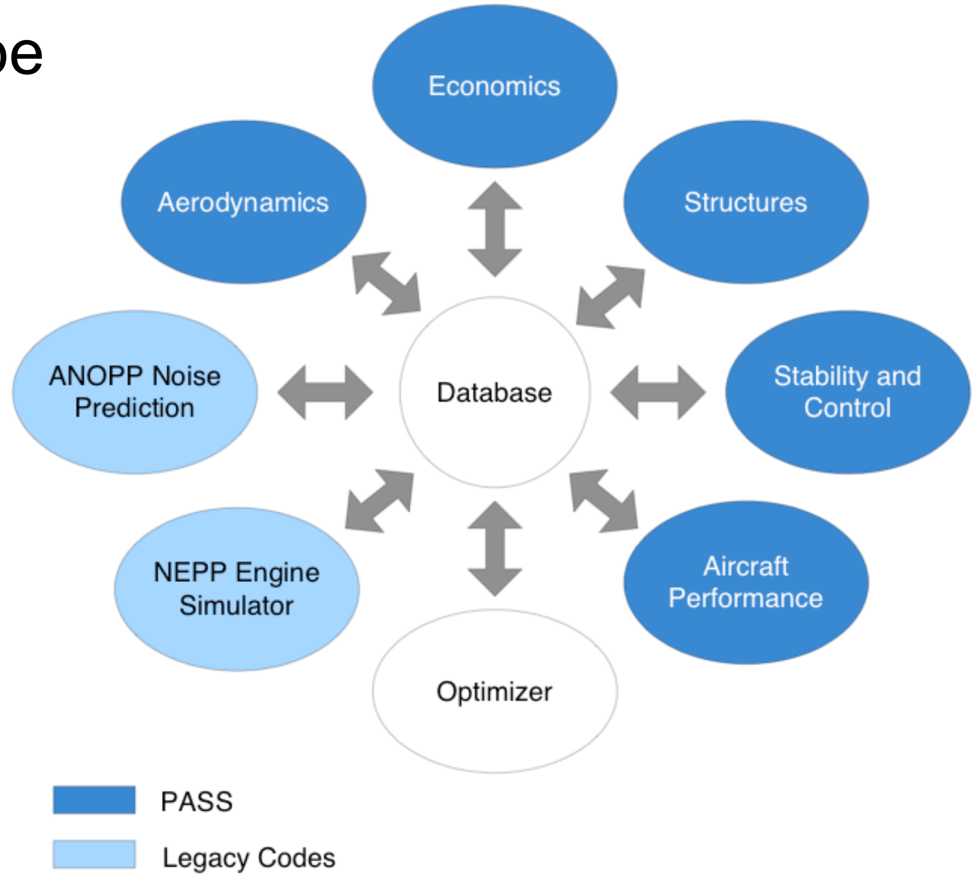
Source: Kroo (Stanford), http://adg.stanford.edu

- Challenges:
  - Incorporation of environmental, financial, operational effects
  - Incorporation of new technologies, unconventional aircraft concepts
  - Use of high-fidelity tools in early design at the system level
  - Accounting for uncertainty and variability

MDO: Aircraft Conceptual Design

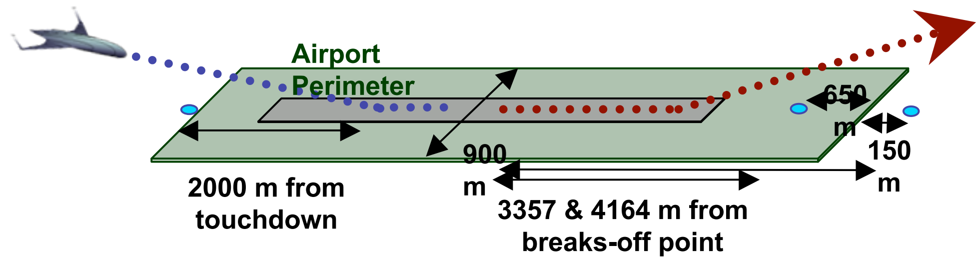
- Traditional multidisciplinary conceptual design tool must be supplemented with:
  - Environmental models
  - Operational design space
  - Models of new technologies
  - Higher-fidelity (physics-based) models

- Uncertainty must also be quantified and accounted for in the decision-making process.



Program for Aircraft Synthesis and Sizing (PASS), I. Kroo, N. Antoine, Stanford University.

Example: Integrating Technology and Operations

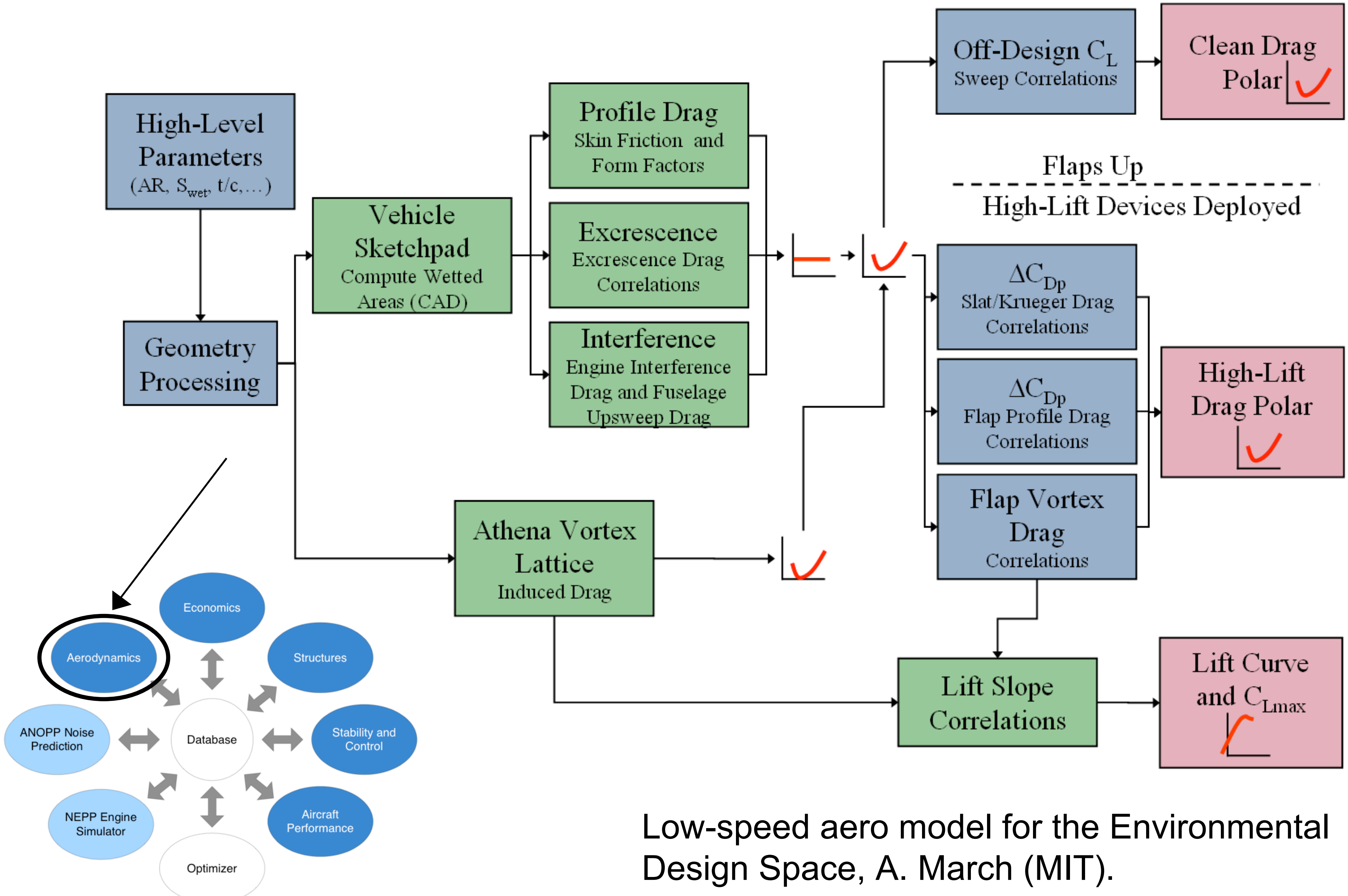


- Models that represent operations in existing design tools are not suitable for detailed assessment of environmental performance

- Existing detailed operational assessment models are not suitable for a vehicle design framework

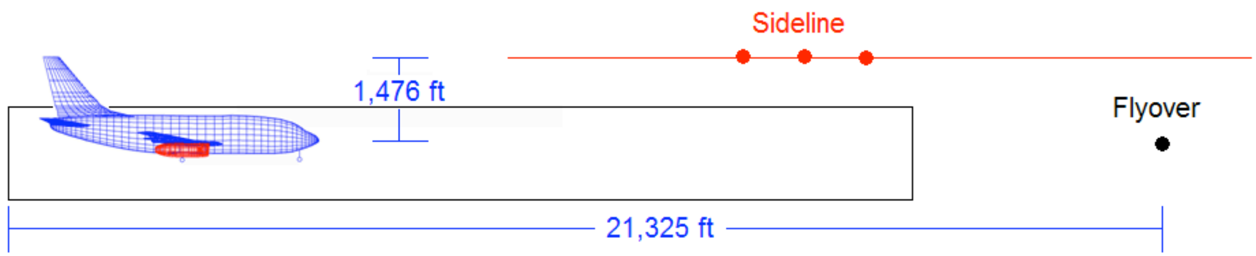
- Must account for uncertainty in operations

LTO Analysis Requires Detailed Low-Speed Aerodynamics Model



Low-speed aero model for the Environmental Design Space, A. March (MIT).

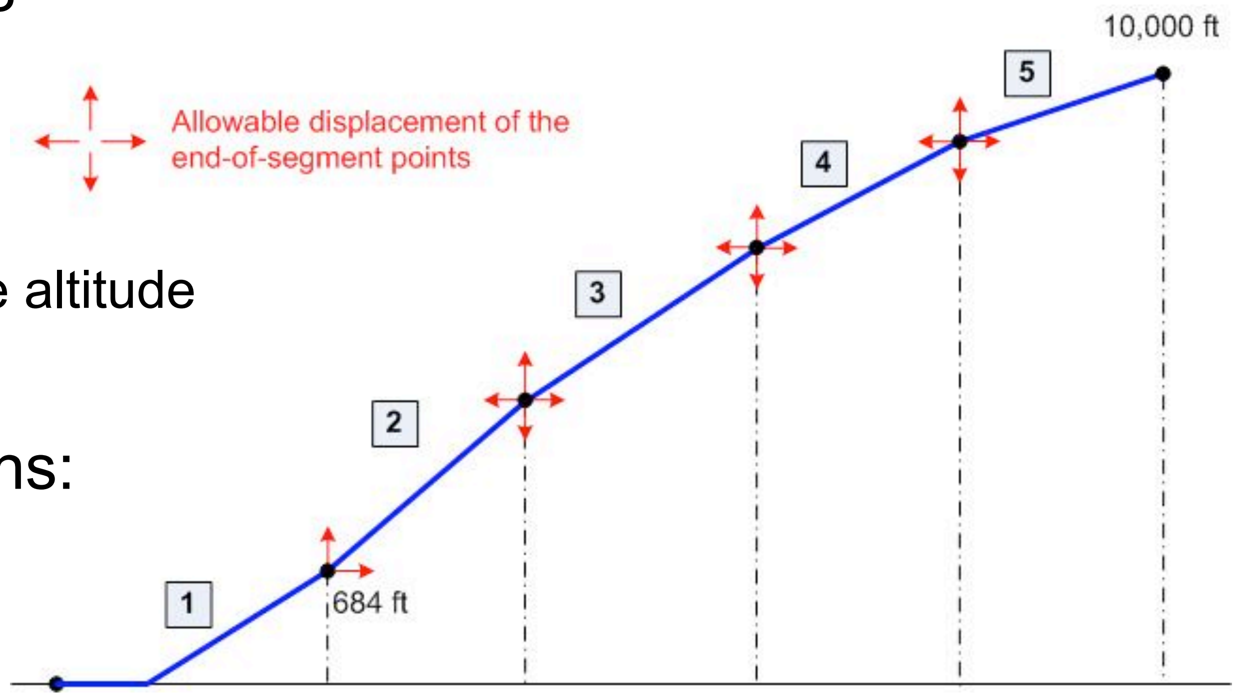
Environmental Assessment Requires Parameterization of Aircraft Operations



Takeoff noise certification points

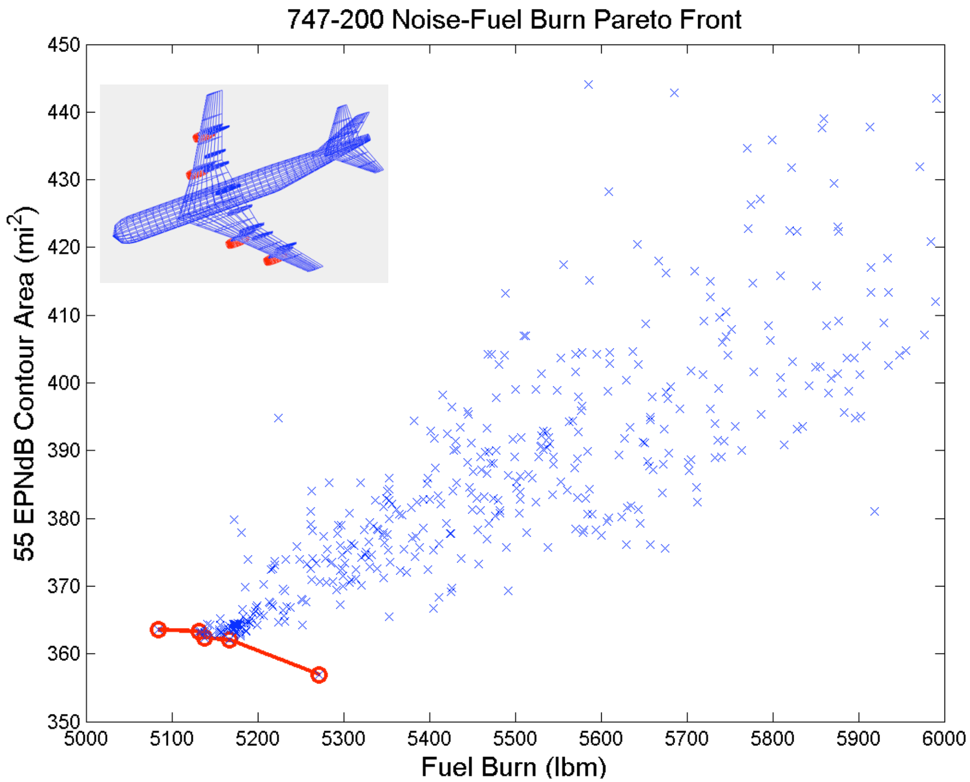
- Operational design variables:
  - flap setting
  - throttle setting
  - true airspeed
  - end-of-procedure altitude

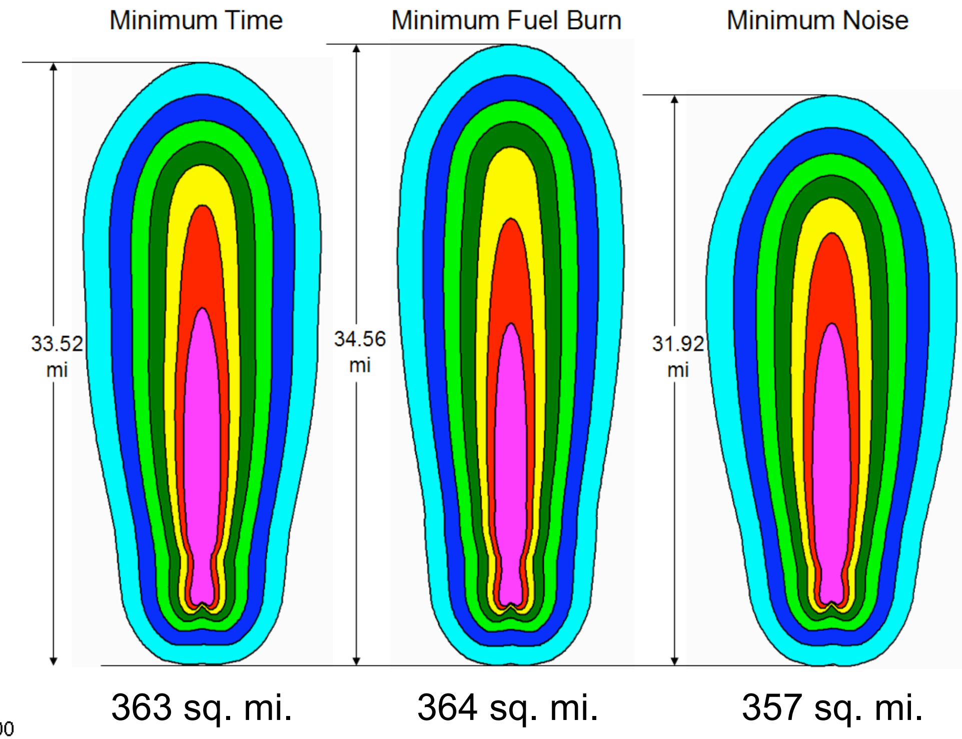
- Objective functions:
  - time to climb
  - fuel burn
  - noise

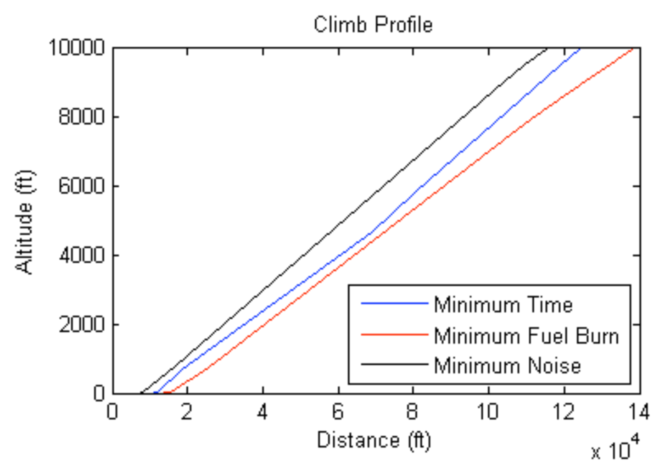


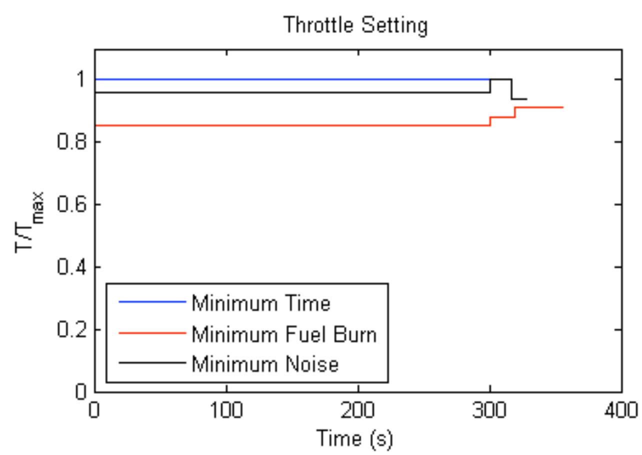
Parameterization of departure trajectory for optimization

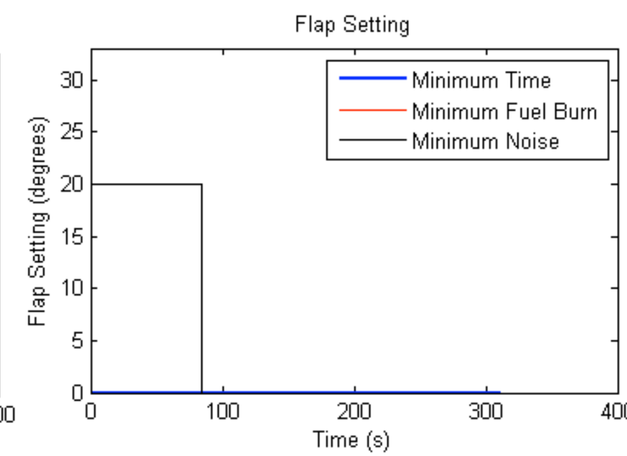
Optimization Results: Tradeoffs Among Environmental Performance Metrics





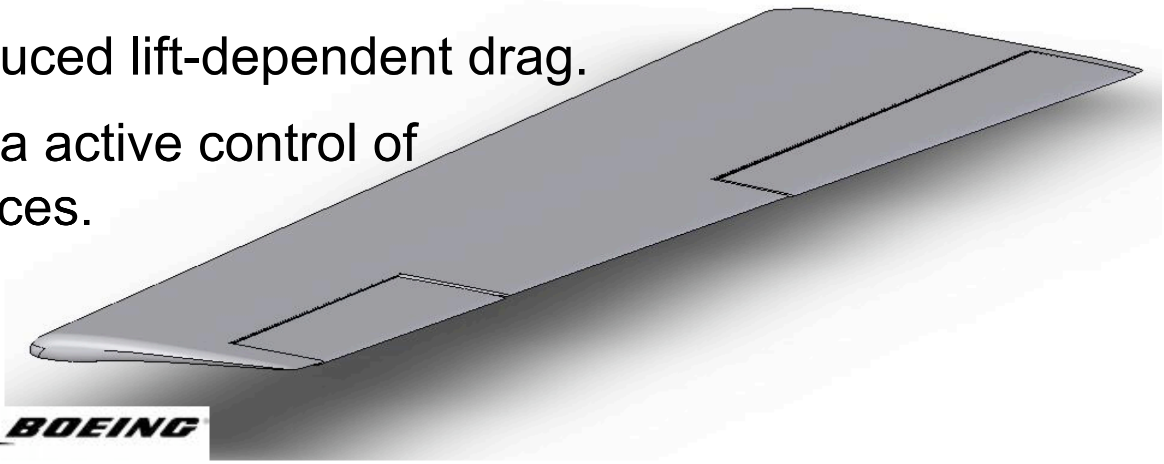






Example: Advanced Technologies for Environmentally-Sensitive Aircraft Design

- Tighter coupling between aerodynamics, structures, and control early in the design process can yield a concept with dramatically improved fuel efficiency and thus dramatic reductions in CO_2 emissions.
- Expected design characteristics:
  - Very high bypass ratio engines
  - Low wing sweep for extended laminar flow. Restricts section thickness which places more critical demands on wing structure.
  - Slatless wing for reduced noise and simpler compatibility with laminar flow. Leads to reduced wing loading and higher gust loads.
  - High wing span for reduced lift-dependent drag.
  - Gust load alleviation via active control of wing trailing-edge devices.



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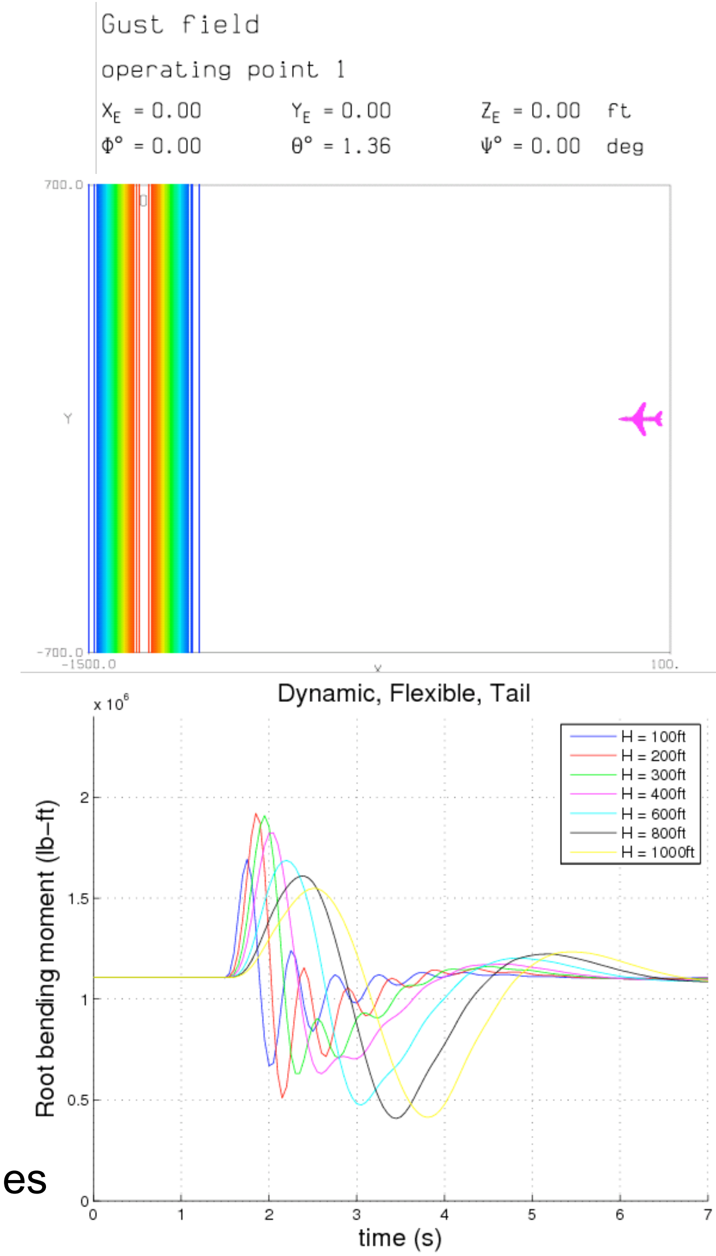
Conceptual Design of Environmentally-Sensitive Aircraft Requires New MDO Approaches

- More detailed controls models than usual in conceptual design
- Close integration of aerodynamics, structural dynamics, and controls
- For some disciplines, physics-based models of the desired fidelity are too expensive to be used within the optimization process
- Proposed approach: multifidelity optimization with a hierarchy of models



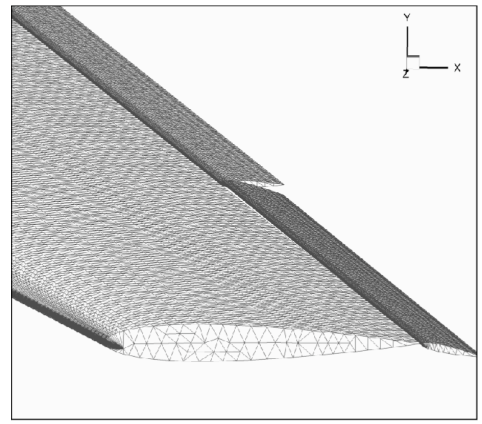
Gust encounter studies
K. Fidkowski (MIT)

Conceptual Design: Multifidelity Models

$$\begin{array}{ll} \text{minimize} & f(\mathbf{u}) \\ \text{subject to} & \mathbf{c}(\mathbf{u}) \le 0 \end{array}$$

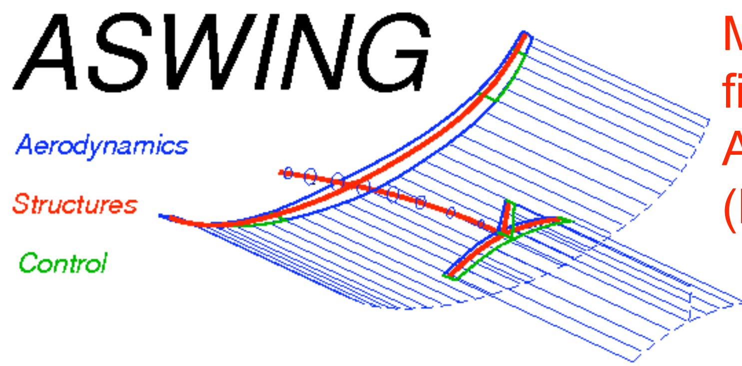
$$\begin{array}{ll} \text{minimize} & \hat{f}(\hat{\mathbf{u}}) \\ \text{subject to} & \hat{\mathbf{c}}(\hat{\mathbf{u}}) \le 0 \end{array}$$

- Reduced complexity of f(¢) and **c**(¢)
  - Simplified physics
  - Model reduction
  - Other surrogate models (data fit, multigrid, etc.)



High-fidelity: Cart3d (Euler CFD)

- Reduced complexity of **u**
  - Different design descriptions
  - Decreased resolution of design representation

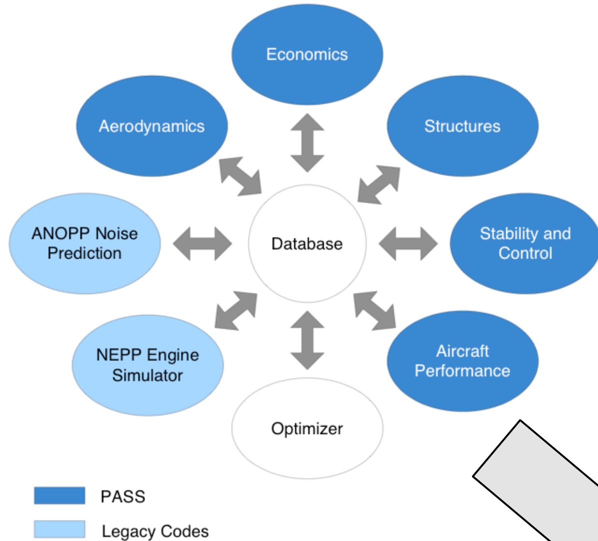


Medium-fidelity: ASWING (lifting line)

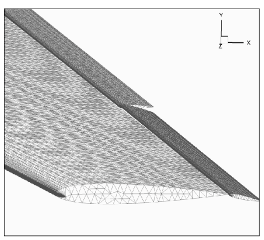
$$L = \pi \rho U c \left(w_G(0)\phi(s) + \int_0^s \frac{dw_G(\sigma)}{d\sigma} \psi(s-\sigma)\, d\sigma \right)$$

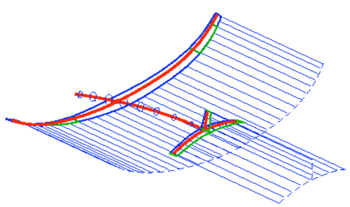
Low-fidelity: analytical (Wagner/Küssner)

Conceptual Design: Multidisciplinary Design Optimization with Multifidelity Models

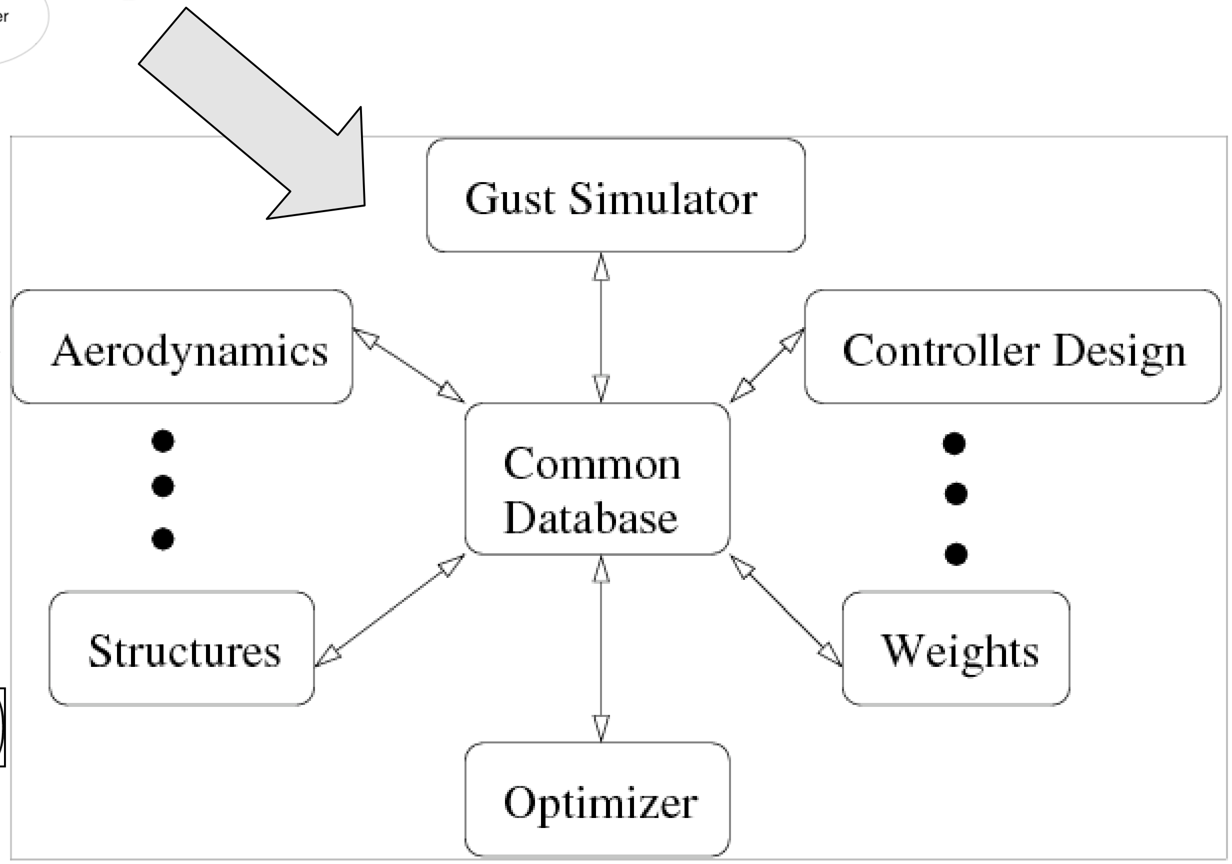


Collaborative work with K. Fidkowski (MIT), I. Kroo (Stanford), E. Cramer (Boeing), F. Engelsen (Boeing)





$$L = \pi \rho U c \left(w_G(0)\phi(s) + \int_0^s \frac{dw_G(\sigma)}{d\sigma} \psi(s-\sigma) d\sigma \right)$$



Integrated Decision-Making: Aviation Environmental Portfolio Management Tool

(reports available at www.partner.aero)

PARTNER

An FAA/NASA/TC-sponsored Center of Excellence

inputs

Policy scenarios
- Certification stringency
- Market-based measures
- Land-use controls
- Sound insulation

Market scenarios
- Demand
- Fuel prices
- Fleet

Environmental scenarios
- CO_2 growth

Technology and operational advances
- CNS/ATM, NGATS
- Long term technology forecasts

APMT

outputs

Cost-effectiveness
- $/kg NOx reduced
- $/# people removed from 65dB DNL
- $/kg PM reduced
- $/kg CO_2 reduced

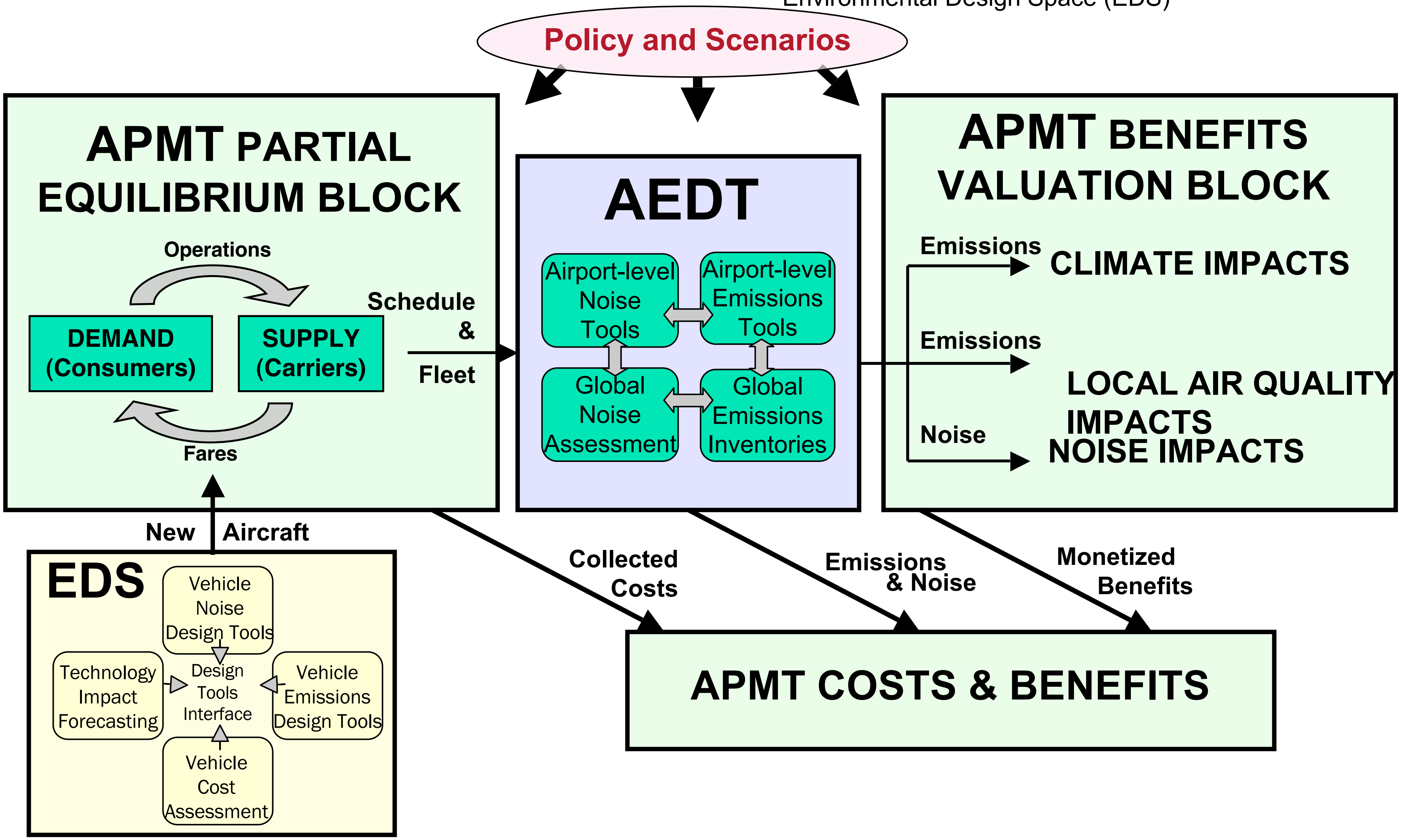
Benefit-cost
- Health and welfare impacts
- Change in societal welfare ($)

Distributional analyses
- Who benefits, who pays
- Consumers
- Airports
- Airlines
- Manufacturers
- People impacted by noise and pollution
- Special groups
- Geographical regions

Global, Regional, Airport-local

APMT: Approach

Aviation Environmental Portfolio Management Tool (APMT)
Aviation Environmental Design Tool (AEDT)
Environmental Design Space (EDS)



Vital Link Policy Analysis

Georgia Tech

HARVARD SCHOOL OF PUBLIC HEALTH

MITRE

mvaconsultancy

BB&C

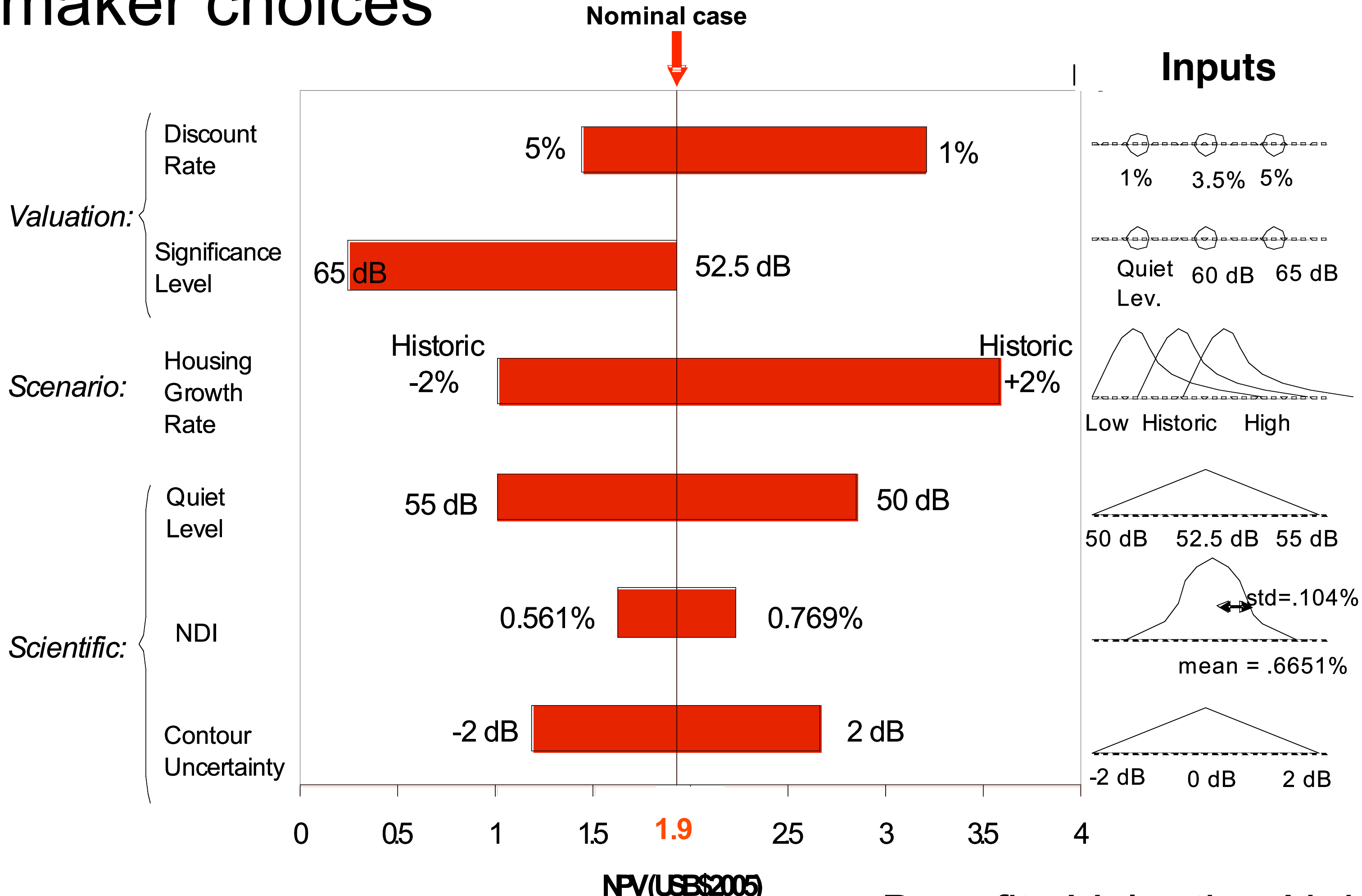
UNC CAROLINA ENVIRONMENTAL PROGRAM

the VOLPE center

wyle laboratories

APMT: Representation of Uncertainty and Preferences

Use of "Tornado" charts to communicate uncertainty sources and importance of policy maker choices



Preliminary Results Only--Do not cite

Benefits Valuation Noise Module

APMT: Expected Outcomes and Practical Applications

- Expected outcomes
  - Deliver APMT component of an integrated policy-analysis framework to support ICAO/CAEP and JPDO decision-making
    - Aviation Environmental Portfolio Management Tool (APMT)
    - Aviation Environmental Design Tool (AEDT)
    - Environmental Design Space (EDS)

- Practical applications
  - Support ICAO/CAEP decision-making (goal = CAEP/8, 2010)
  - Support JPDO/NGATS decision-making
  - Identify high leverage uncertainties and research needs

Summary

- Integrated approach to decision-making is key:
  we cannot focus on just a single environmental metric

- Significant opportunities exist for reducing environmental impact of future aircraft
  - Requires a highly-integrated, multidisciplinary approach to design

- Uncertainty must be quantified and accounted for
  in the decision-making process