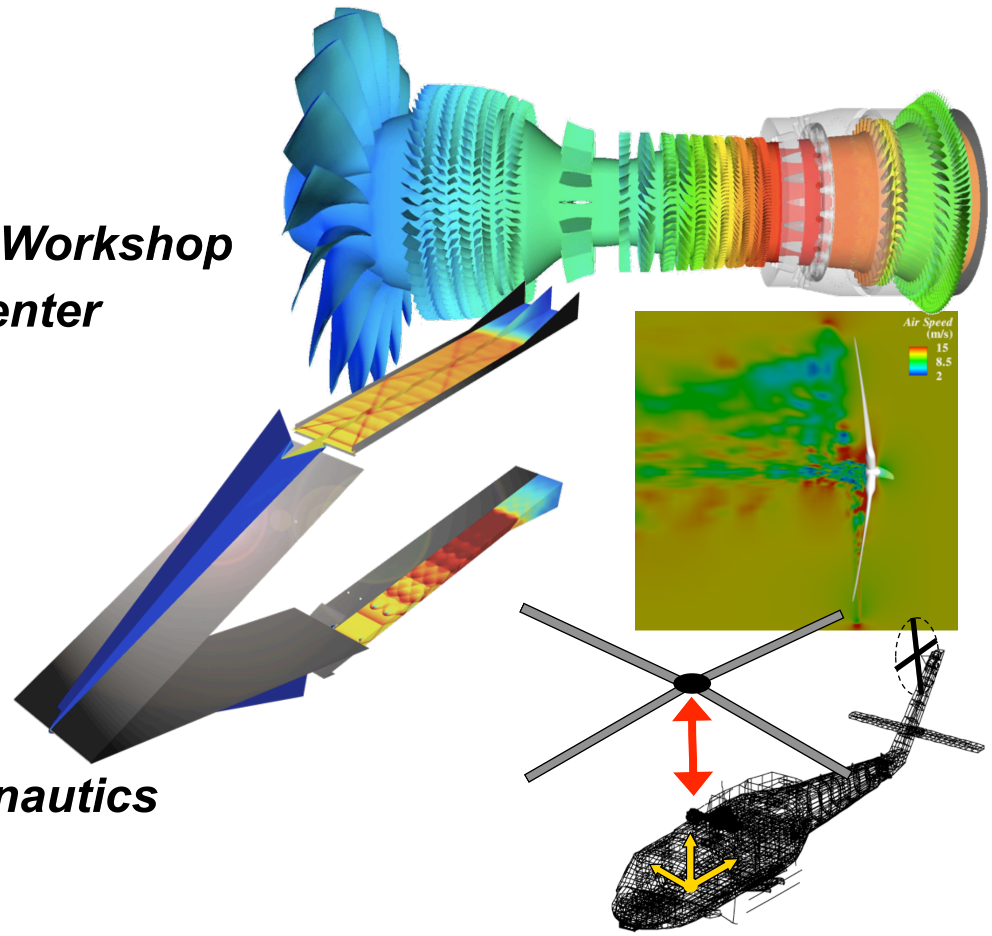
Some Thoughts on Applicability of Aerospace Analysis and Design Techniques to Wind Energy



Wind Energy Systems Engineering Workshop
NREL National Wind Technology Center
Louisville, CO
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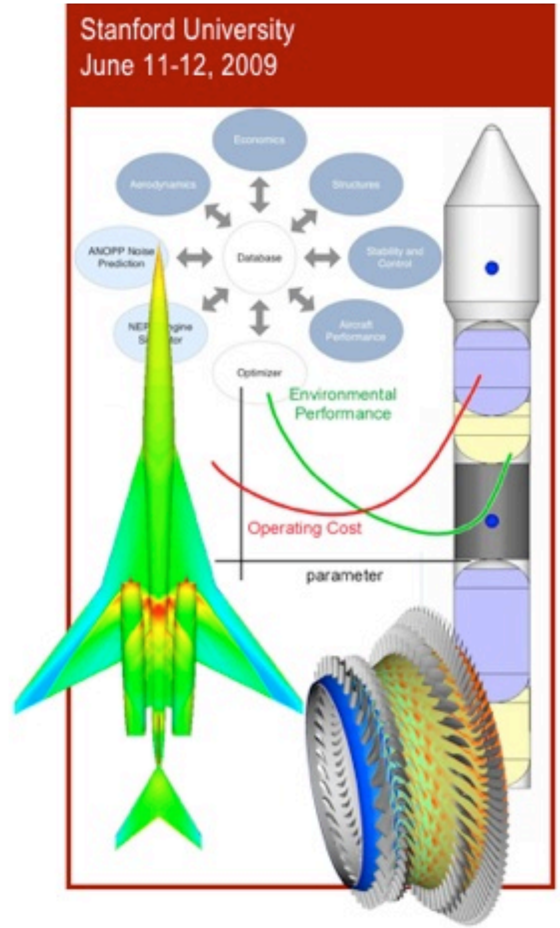
Brief Introduction to Our Work in Optimization

- Work in the department of Aero & Astro
- Main interests are in the application of high-fidelity simulation to the conceptual design of aerospace systems: aircraft, rockets, helicopters, engines (and by extension cars, trucks, UAVs, wind turbines, etc.)
- Significant difficulties/ challenges in many simulation and optimization topics



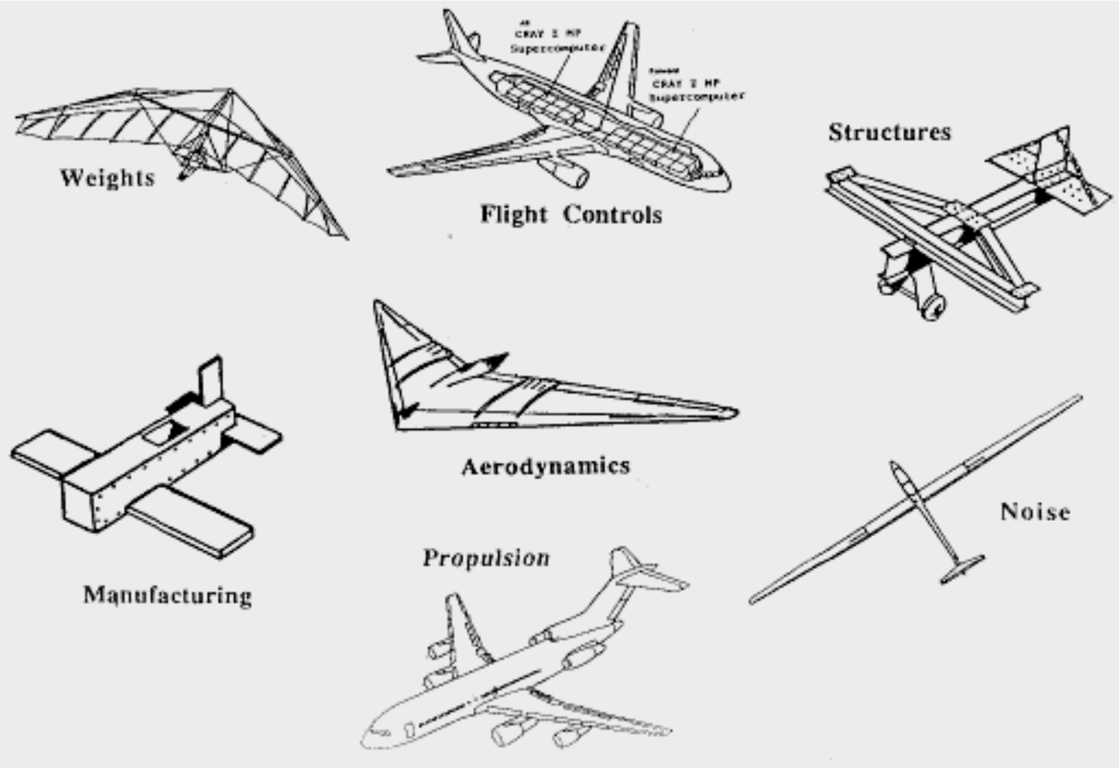
Annual Consortium meeting poster, 2009

Multidisciplinary Optimization (MDO)

- What is really MDO?
  - A field of engineering/mathematics that allows the modification of an existing design, including multi-discipline interactions, to arrive at a better one

- Problem formulation is not obvious and requires engineering judgment.

- "One can only make one thing best at a time."



MDO in Aerospace Engineering

- Arguably, aerospace engineering has been doing systems engineering and MDO for over 30 years. Are we done yet?

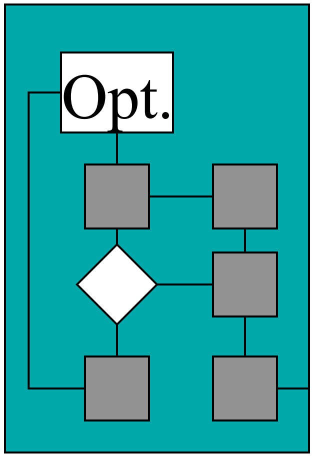
- We have gone through three generations of MDO tools in academia, but industry has only gotten (partially) to the second one.

- There have been many lessons learned and many useful techniques and tools developed. The key question is:

What can be learned from these experiences to help the development of Sys Eng techniques in wind power?

First Generation MDO

- Integrated multidisciplinary analysis and optimization
  - – Combine analysis/simulation with design method
  - – Exploit advances in computational power to evaluate virtual prototypes, search design space, improve design

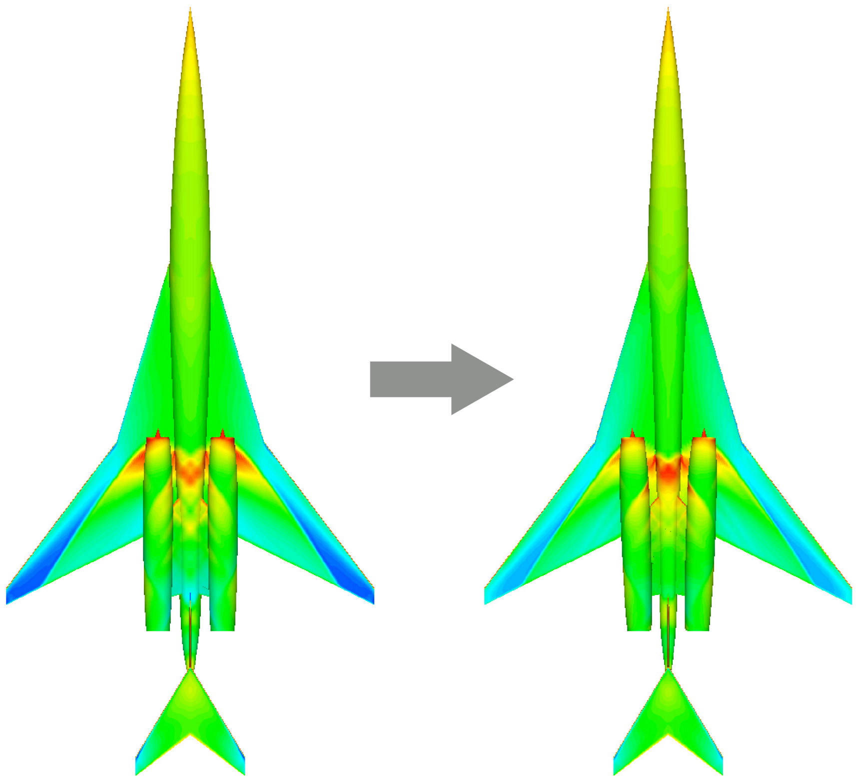


- Ideal for simple problems

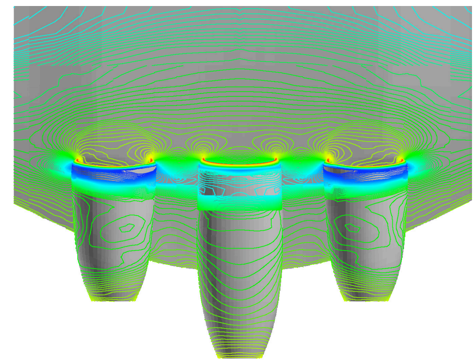
- Focus on optimization efficiency

First Generation MDO

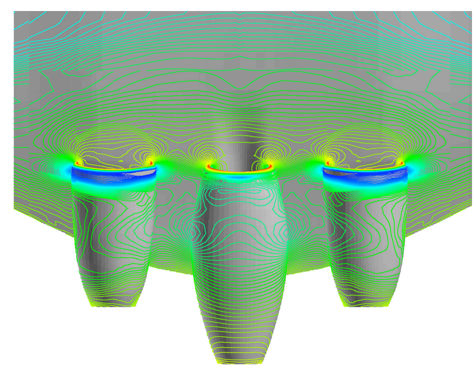
- SQP and related gradient-based methods have revolutionized aerospace design:



Baseline Optimized



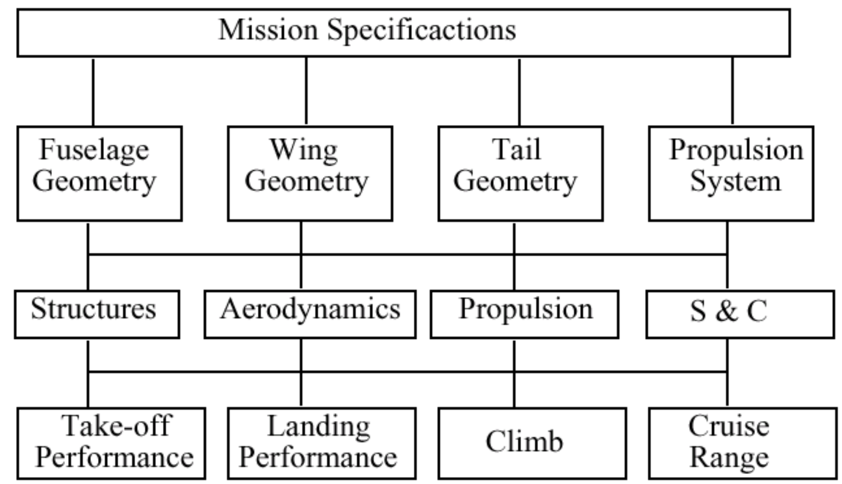
Baseline



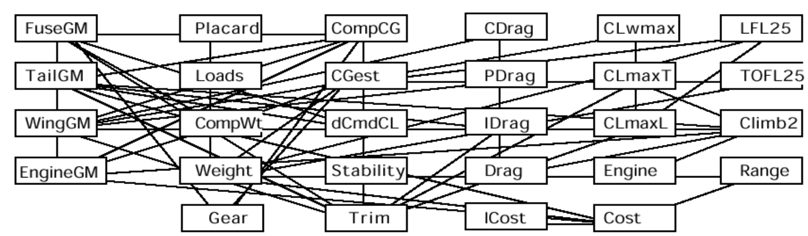
Optimized

First Generation MDO

- Integrated multidisciplinary analysis and optimization seems simple…

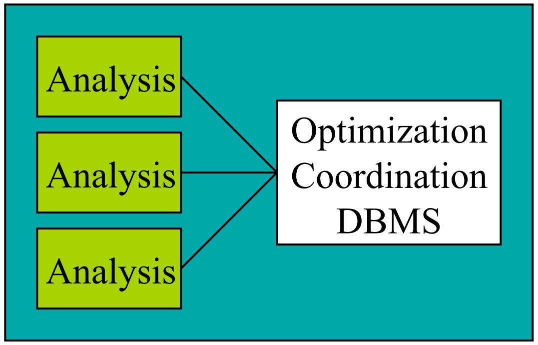


- … but difficulties with complexity, extensibility, maintenance in real world, large-scale applications.



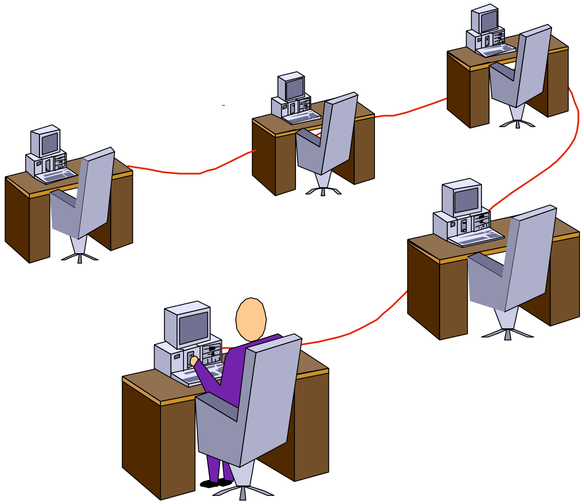
Second Generation MDO

- Analysis management, distributed analysis, and optimization



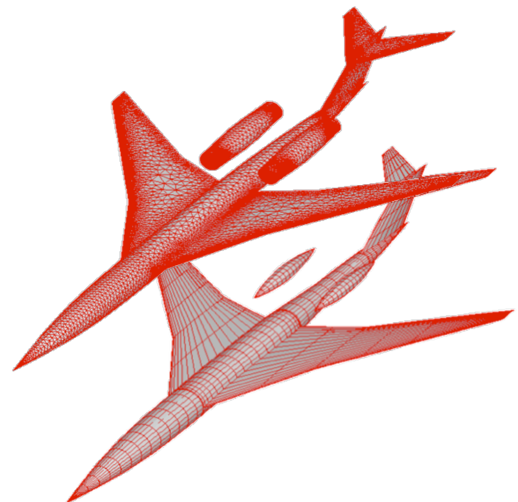
- Modular analysis

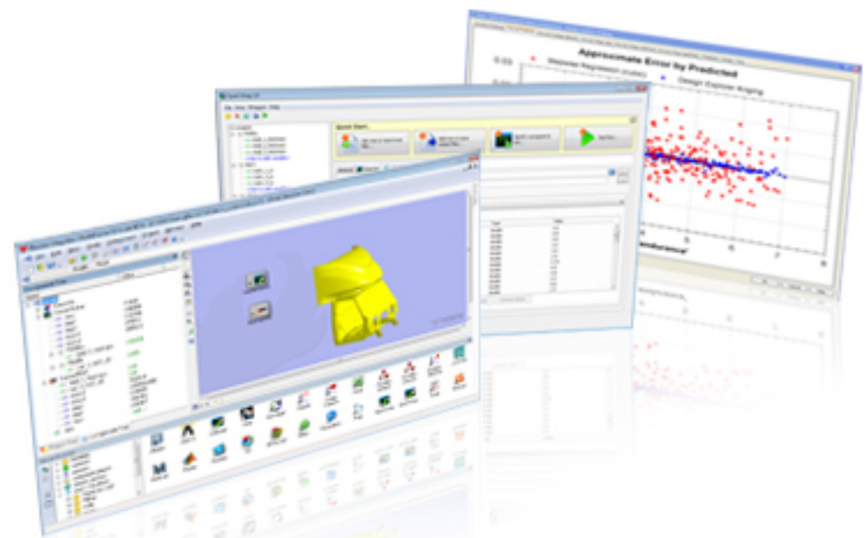
- Focus on interdisciplinary communication



Second Generation MDO

- Automation of analyses leads to process improvements
- Existing “recipes” prevent models of sufficient fidelity
- Infrastructure typically over-constraining



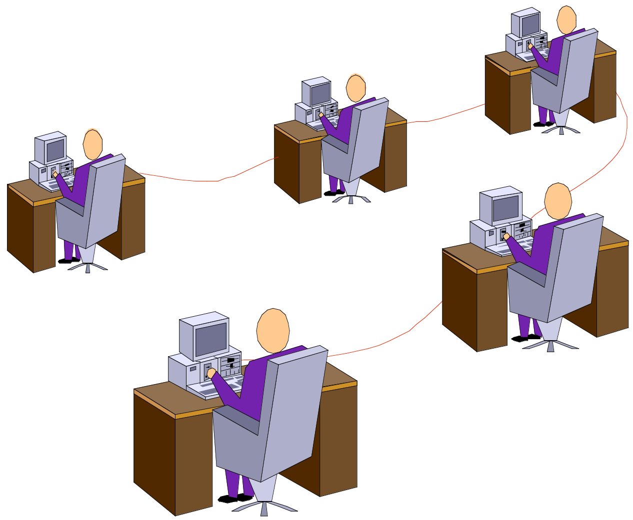


Model Center, Phoenix Integration

Next Generation MDO

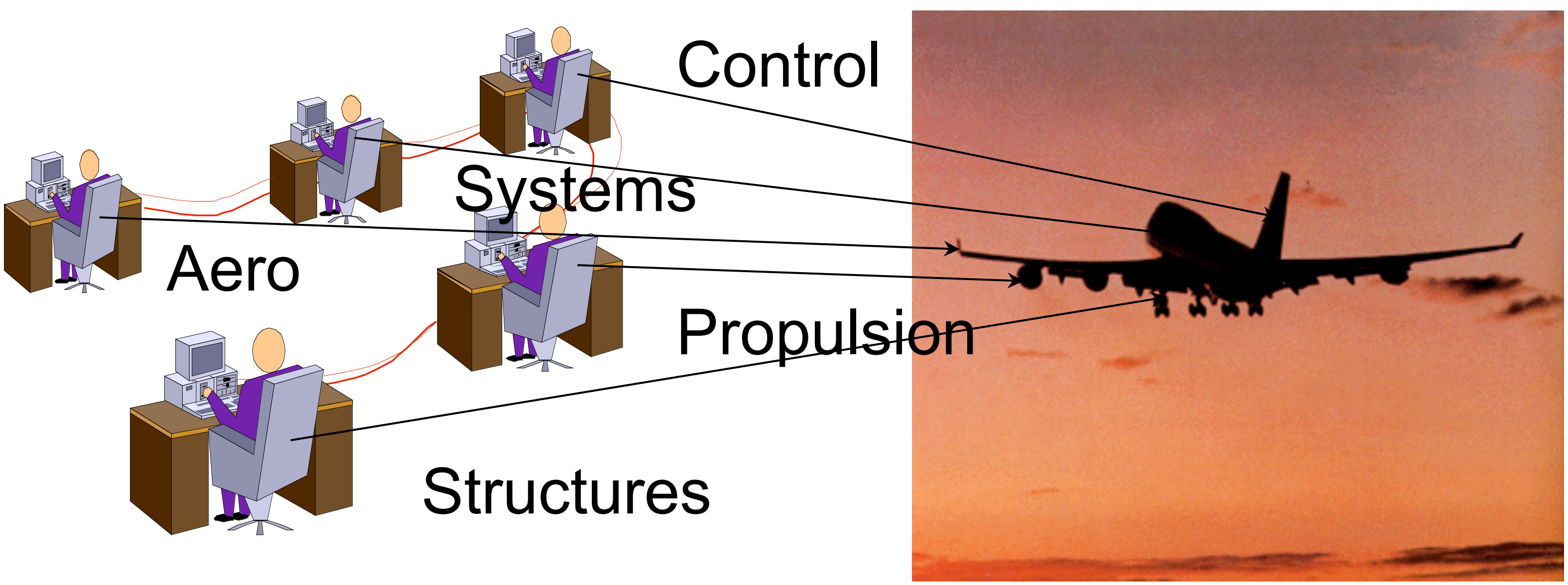
- The Goal: Distributed Design

- Why distributed design?
  - Improve efficiency
  - Manage complexity across scales
  - Permit use of discipline-based design tools
  - Provide autonomy and exploit experience of design teams
  - Consistent with current organizational structures



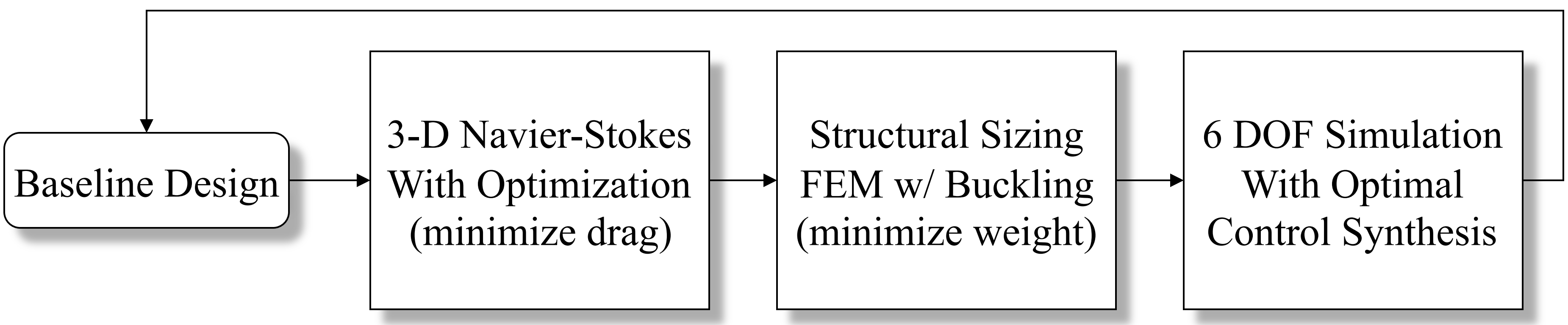
Next Generation MDO

- This is how engineering design is done now.
- But it is generally done with an ad-hoc architecture.



Next Generation MDO

- Informal approaches often lead to incorrect results
- Iterations continue until one runs out of time or money

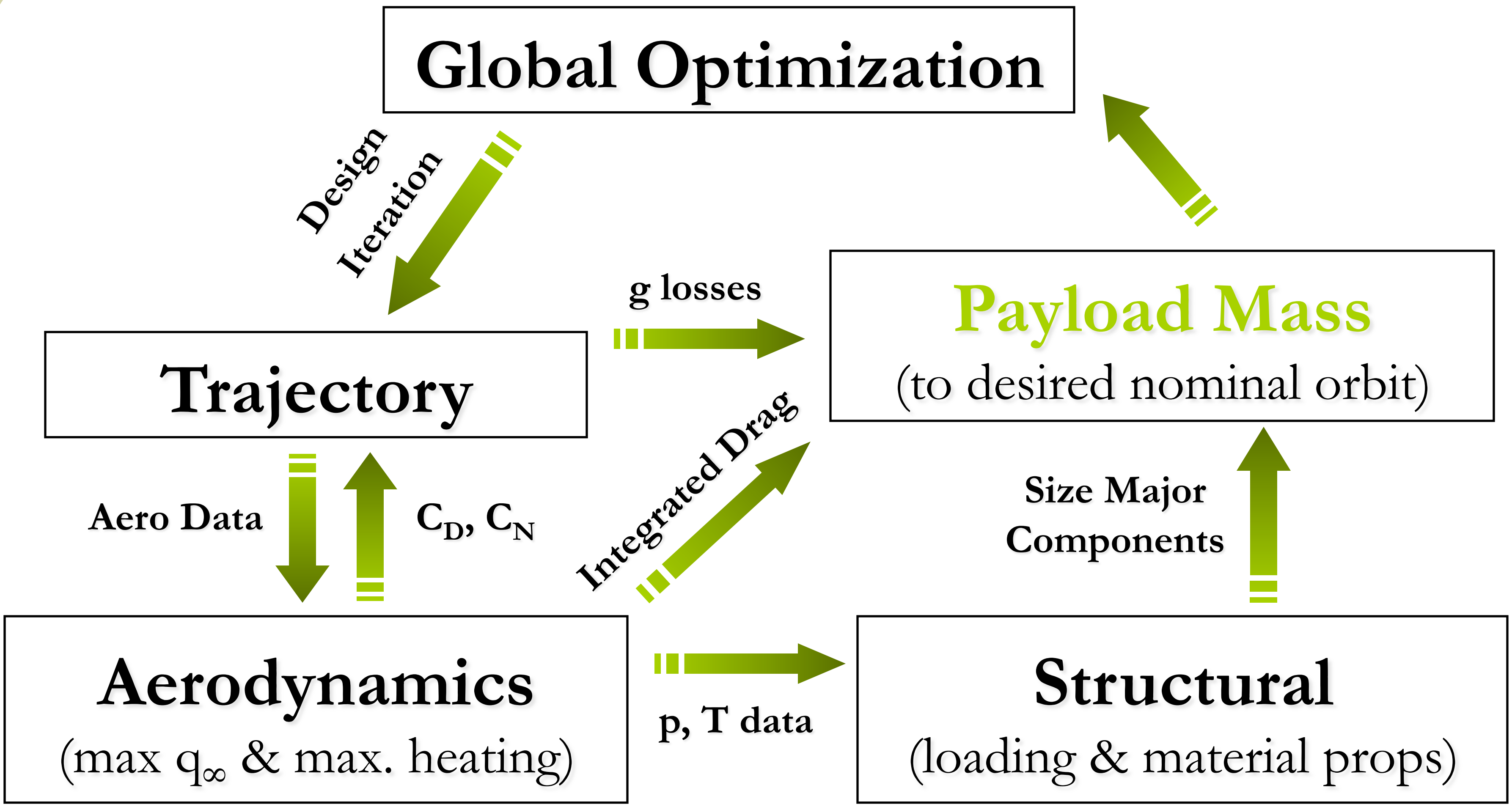


Actual Project Structure

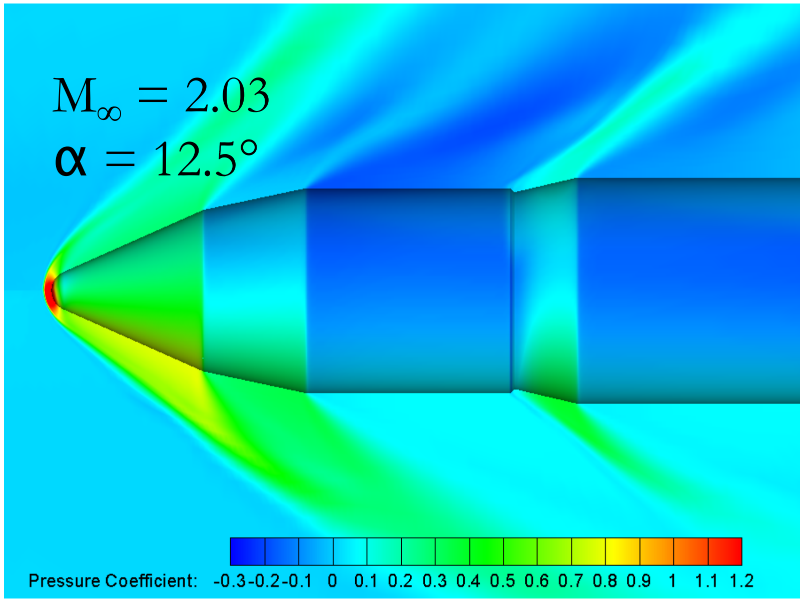
Lessons Learned

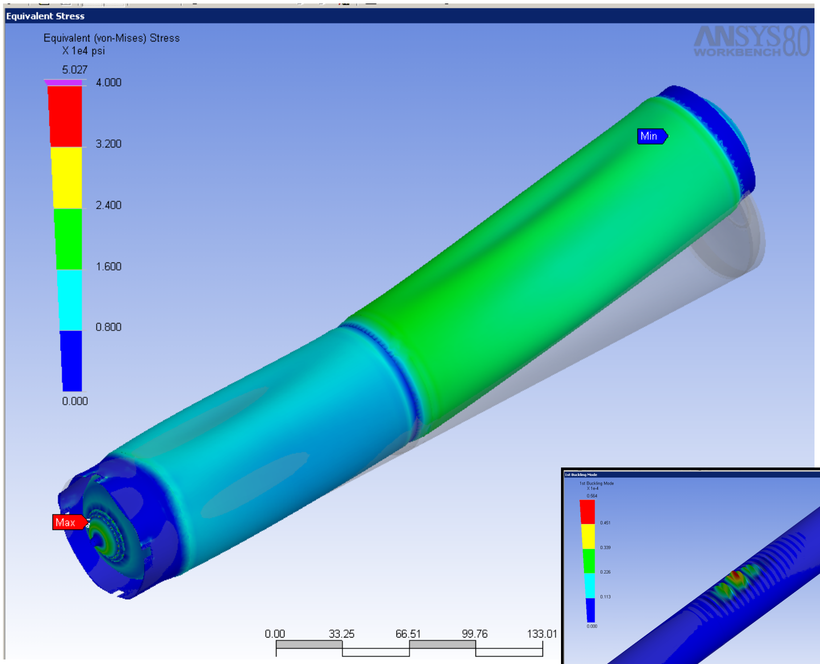
- Optimization techniques:
  - Which problems are best suited to which approaches?
  - What are the expected costs? Analysis? Sensitivities?
  - Single- vs multi-objective
- Approximation theory / surrogate modeling / trust region management
  - How can we reduce the cost of optimization?
  - What kinds of approximations are better suited to what problems?
  - How do we guide the analysis/optimization sequence to obtain accurate results robustly?
- MDO / Analysis / Design architectures
  - What are the best ways to partition a problem that is too hard to handle with 1st gen MDO?
  - How can we accelerate the analysis / optimization?
  - Have these methods been truly effective?

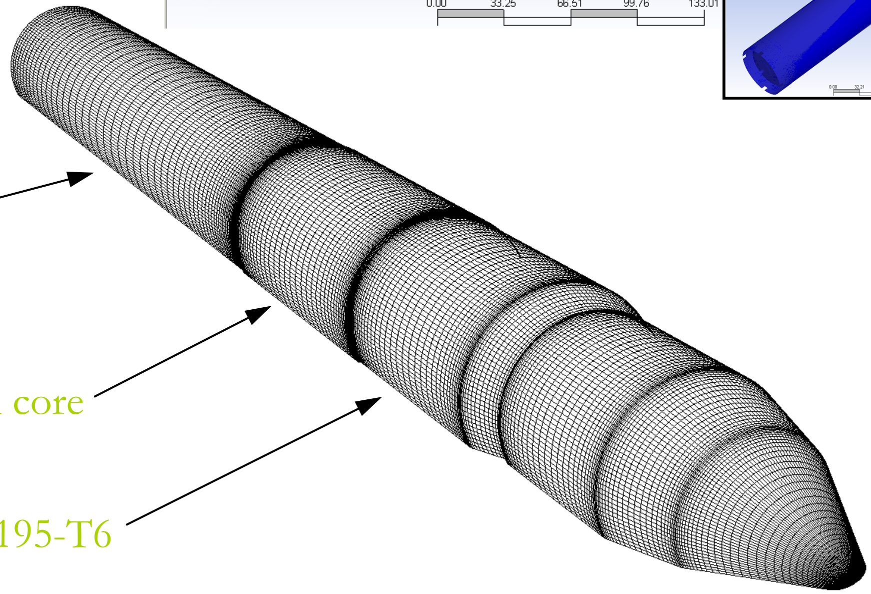
Multi-Disciplinary Design of Launch Vehicles



Multi-Disciplinary Design of Launch Vehicles

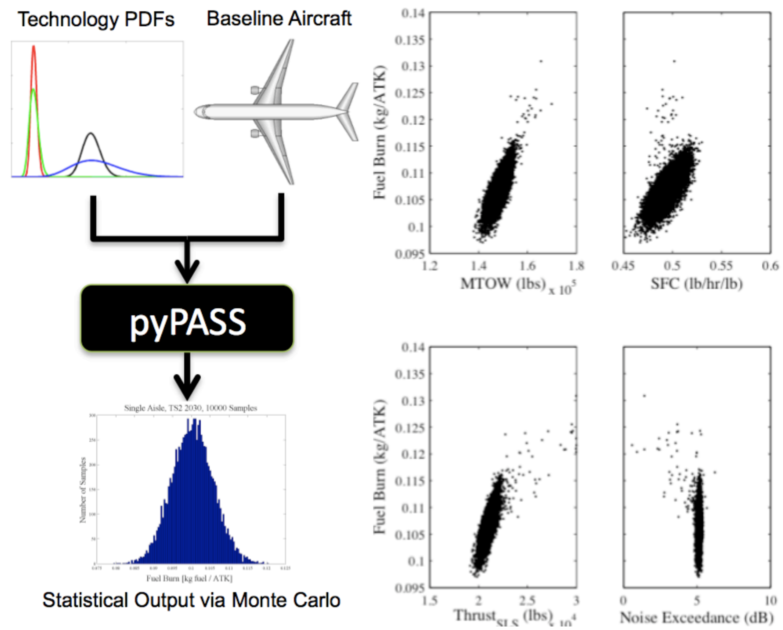


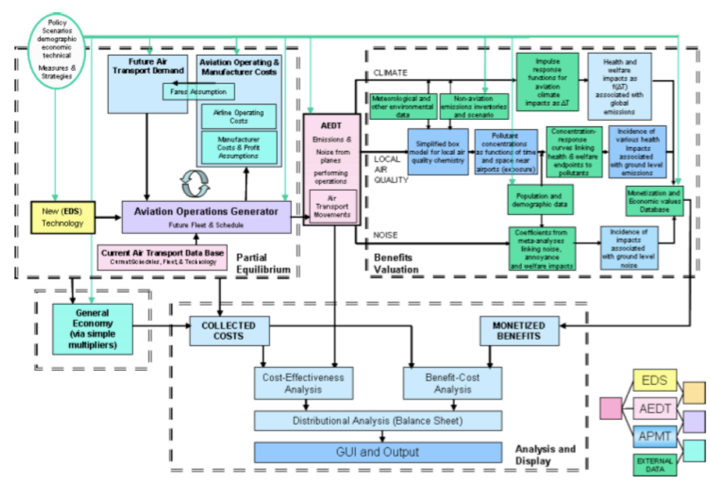




Design for Environmental Impact of the Entire NAS

- Problem of similar complexity to wind power system analysis and design
- Probabilistic models for future aircraft fleet…
- flying the routes/schedules of multiple airlines…
- performance and economic models accounted for…
- interactions with current and future (NextGen) ATM procedures being investigated…
- FAA has pursued these tools/ environment for approximately 6-8 years, based on a previous legacy system (but with all components redeveloped). Sounds familiar?





FAA EDS/AEDT/APMT Schematic

Do These Apply to Wind Energy?

- At the level of the isolated wind turbine, it is hard to argue against a fairly direct translation between aerospace (aircraft, launch vehicle, etc) and wind energy:
  - Similar complexity in the systems (including transient phenomena)
  - Similar disciplines involved (fluids, structures, reliability, loads, fatigue…)
  - Similarities in the design spaces to be explored.
- At a wind farm level, some techniques could be leveraged effectively:
  - Surrogate modeling
  - Multi-fidelity analysis and optimization techniques
- At the highest system level (equivalent to the complete National Air Transportation System), there are examples of how these problems could be tackled, but all answers are not available.

What Are The Current Gaps?

- Because of the complexity of the analysis of even isolated wind turbines, wind-farm- and system-level simulations are likely to exceed the computational capabilities of the largest supercomputers.

- How can we manage the fidelity / accuracy / uncertainty vs. computational cost dilemma?

- What portions of the system-level models are fraught with epistemic uncertainties and how do we produce timely results to make decisions in a probabilistic environment?

- Our community is attempting to answer many of these questions at the moment.

Current Research Elements

- Novel Optimization / Decomposition Methods
- Multi-fidelity System Modeling for Design
- Design Under Uncertainty

New Approaches for Distributed Design

- Decomposition and distributed design
- Collectives and complex system design
- Efficient handling of highly-coupled MDO problems
- **Efficient handling of high-fidelity tools in MDO problems**

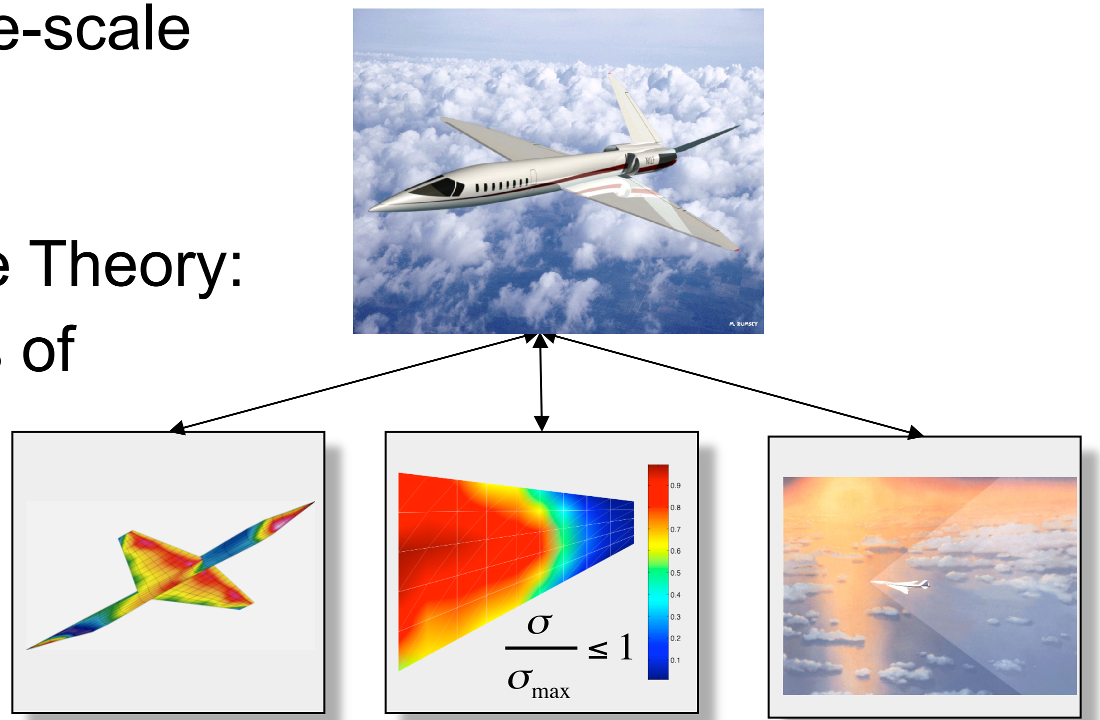
Decomposition and Distributed Design

- Collaborative Optimization:

A mathematical and software framework for large-scale design

- Collectives/Game Theory:

Design of Systems of Interacting Agents



Aerodynamics

Structures and Manufacturing

Environmental Compatibility

Research Elements: Multi-Fidelity Modeling

Multi-Fidelity System Modeling for Design

- High-Fidelity design at the system level is prohibitively expensive

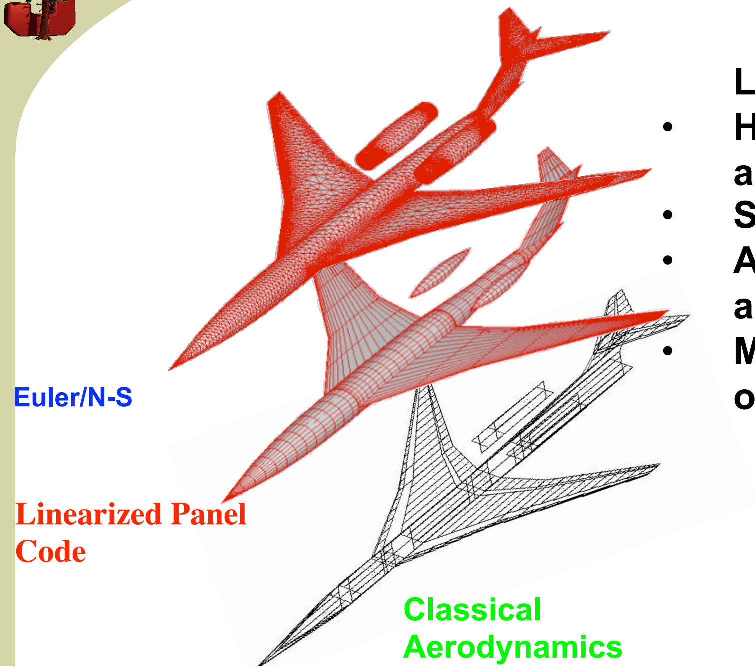
- Disconnect between high-fidelity analysis tools and lower-fidelity system tools

- Multi-Fidelity design frameworks provide the bridge
  - –New methods using reduced order and surrogate modeling
  - –Variable complexity design methods

Research Elements: Multi-Fidelity Modeling

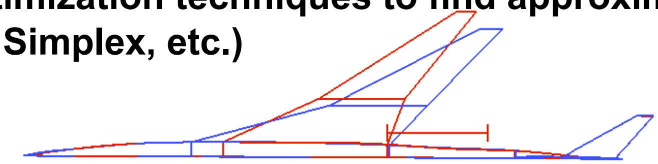
- Hierarchy of analysis methods
  - Constructed with analyst experience/intuition
  - Derived with formal reduced-order-modeling techniques
- Variable complexity model descriptions
  - Parameterization of design with different levels of fidelity
  - Parameterization of design environment (e.g. mission) evolving as design proceeds
- Formal management
  - Demonstrated techniques that dictate when it is appropriate to use one model vs. another
  - Guarantee of convergence to the true, highest accuracy optimum

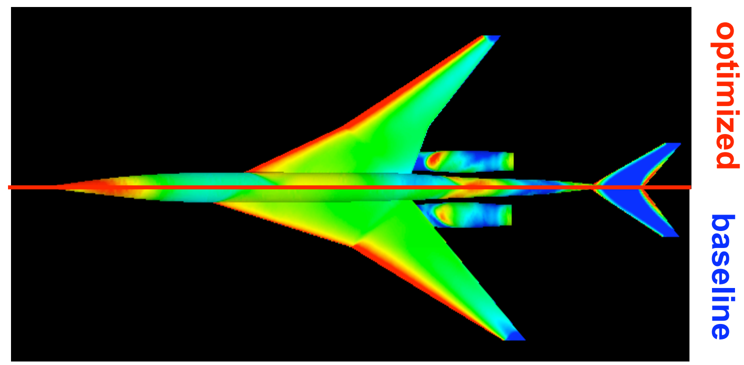
Research Elements: Multi-Fidelity Modeling

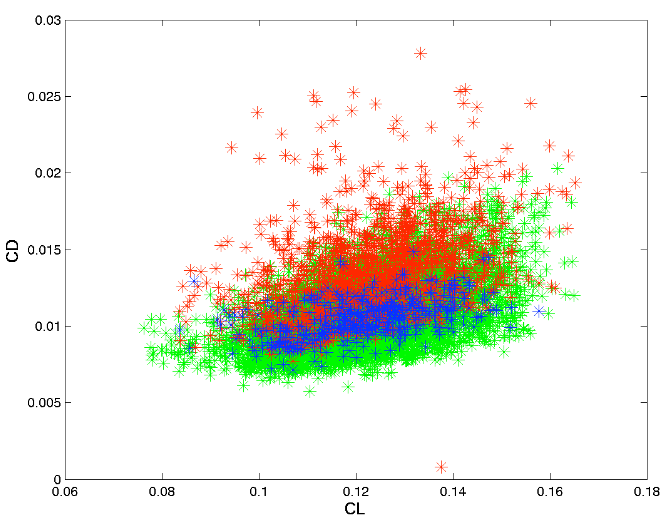


Level 1

- **Hierarchically enrich solution database and obtain high-fidelity approximations at low cost**
- **Surrogates used in realistic design (multi-objective, constraints)**
- **Advanced, adaptive techniques (Kriging, RBF) to guide selection of all analyses in design space**
- **Multi-modal optimization techniques to find approximate global optimum (GAs, Simplex, etc.)**







Level 2

Use adjoint-based, complete configuration, aerodynamic shape optimization techniques to recover performance that may have been lost by inaccuracy of the surrogate models in some regions of the design space

Go to Level 1

Research Elements: Design Under Uncertainty

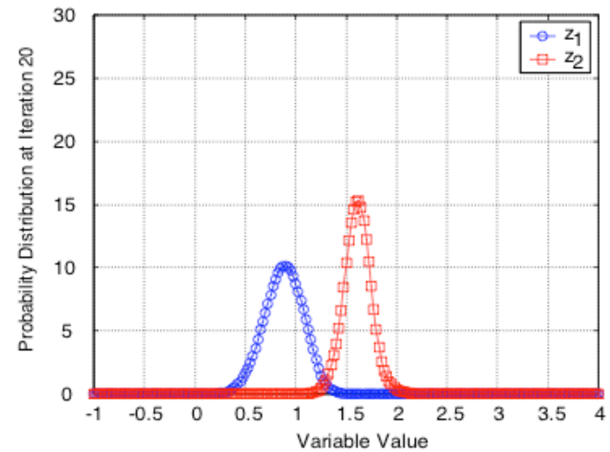
Design Under Uncertainty

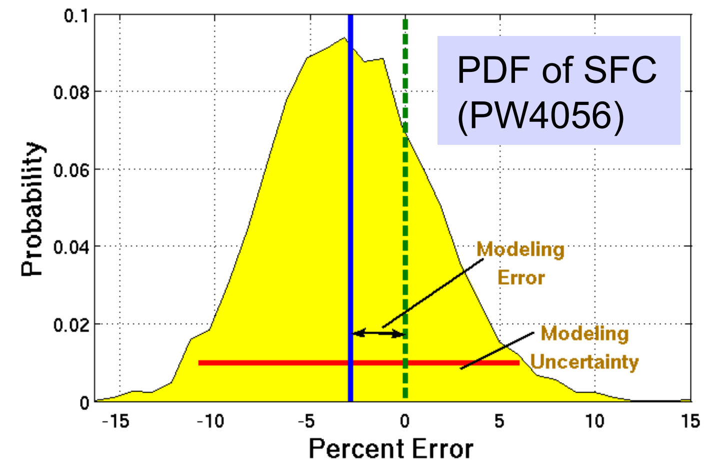
- Uncertainty in model, operation, parameters, requirements (failure/risk)
- Essential element in design of complex systems
- Multidisciplinary optimization traditionally with a narrow focus
  - Continuous problems/models
  - Deterministic

Research Elements: Design Under Uncertainty

Design Under Uncertainty

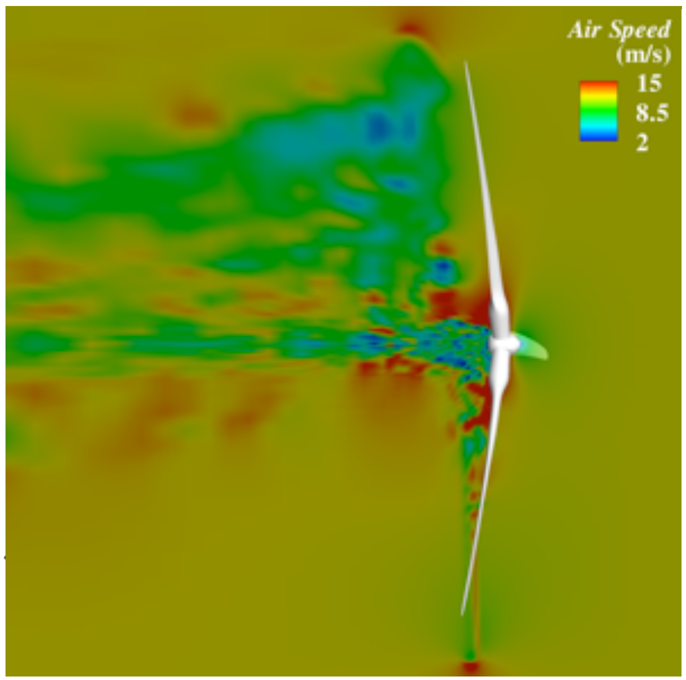
- Surrogate-based methods
- Monte Carlo simulation (importance based?)
- Reduced-order modeling
- Probability-based search methods





Some Overarching Comments

- Large-scale multi-physics simulations are coming of age. They are beginning to be used in aerospace industrial practice and in wind power. However….



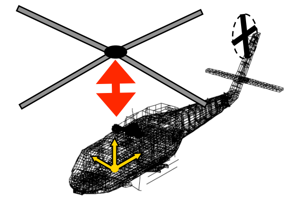
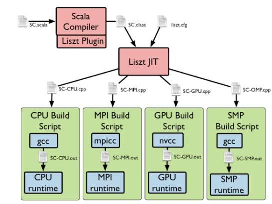
How do we take this?

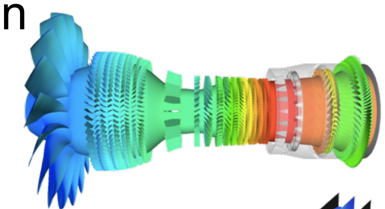
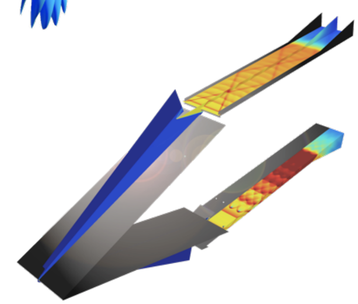
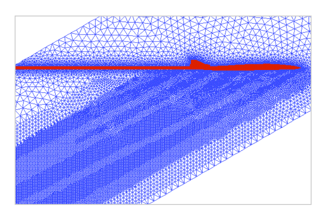
And turn it into this?

Some Overarching Comments (II)

- Industrial design practice is *repetitive* by nature: *we must be able to repeatedly simulate with high fidelity*
- The real world is multi-physics and multi-disciplinary: *we must be able to quickly and accurately integrate multiple physical scientific computing models*
- The world is uncertain…input parameters are uncertain, models are uncertain: *we must account for all sources of uncertainties in our simulations*
- At the end of the day, engineering is about making a good system better: *we must couple to optimization procedures*

Easier Said Than Done…

- Repeated simulations with high fidelity:
  - Fast and accurate solution procedures
  - Reduced order models
  - Leveraging high-performance computing architectures
- Integrating multi-physics models:
  - The science of integration: accuracy, stability, automation
  - The plumbing of integration: code coupling, parallelism, environments
- Uncertainty quantification:
  - Intrusive and non-intrusive techniques
  - Aleatory (non-reducible) and epistemic (reducible)
  - Curse of dimensionality
- Optimization:
  - Design with high fidelity: surrogates (multi-fidelity), adjoints
  - Design in “difficult” spaces: discontinuous and noisy
  - Design under uncertainty: robust design

Some Closing Comments

- In the pursuit of a true, open, and flexible systems-engineering capability of wind energy systems, some key ingredients will be needed:
  - A flexible framework, based on open standards, to enable easy interfacing of multiple modules and testing of different ideas to properly architect the system
  - A hierarchy of component modules (analyses) with different fidelity/cost ratios that are specifically designed for multi-disciplinary analysis and optimization
  - Single- and multi-fidelity surrogate modeling techniques (possibly reduced order models)
  - An uncertainty quantification framework to enable decision making (robustness, reliability, etc)
  - A variety of optimization techniques that are able to handle the variety of analyses and problem setups within the context of the framework.

Some Closing Comments (II)

- Many frameworks exist (both commercial and open source): some experience with these and a representative sample of existing tools would be beneficial
- Clear articulation of intended goals / requirements for the framework will guide specifics of components and implementation
- Some logical progression of test cases (from single turbine to large systems) needed to validate approach and keep all developers honest
- “A journey of a thousand steps…”