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MDAO Lessons-Learned & Best Practices

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Producing
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Analyzing

Outline

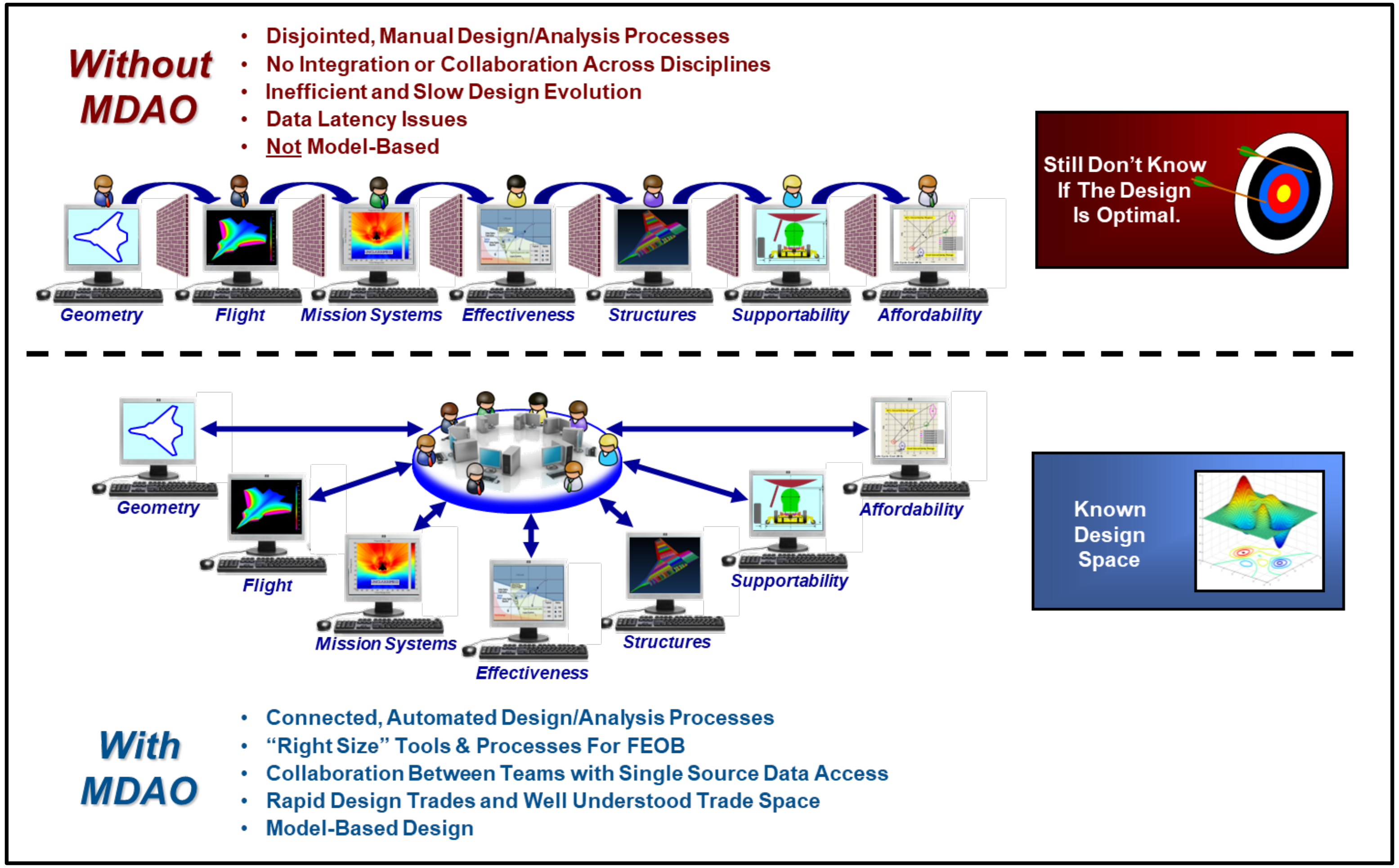
- What is MDAO?
- Why MDAO?
- Historical Perspective – Conceptual Design MDAO
- Fidelity of Analysis – Impacts & Factors to Consider
- Integrating MDAO & MBSE
- MDAO Design Process – Example of a Best Practice
- MDAO Lessons-Learned
- MDAO – Myths & Facts
- Summary

What is MDAO?

- Multidisciplinary Design Analysis and Optimization (MDAO) is a ***model-based simulation and optimization process*** that integrates analysis codes from multiple disciplines (e.g. aerodynamics, structures, propulsion, cost, and manufacturing) and associated design constraints to ***develop a more affordable and lower risk design meeting an overall objective.***

- MDAO frameworks have inherent capabilities to inform and interact with Model Based Systems Engineering (MBSE) environments.

- MDAO processes are used to *improve designs, satisfy conflicting requirements, verify "best" designs, assess feasibility of reaching design targets, speed up the design cycle, and make the right decisions early to reduce risk later in program*



MDAO Is Essentially Vehicle Design!

Why MDAO?

- **MDAO Enables:**
  - *Risk reduction* (technical, cost, & schedule) by preventing *late discovery of defects* & *expensive rework*
  - *First-Time Quality*
  - Dramatically *reduced recurring and non-recurring cost*
  - Optimization for both *performance & affordability, and mission effectiveness*
  - Assess the value of emerging technologies with appropriate physics-based analysis at the *system level*
  - Assessment of *trends and sensitivities* across the design space – $\partial(Effect)/\partial(Parameter)$

MDAO is a Disruptive Model-Based Methodology and Enabler of Robust Aerospace Vehicle Development

Conceptual Design MDAO – The Early Years

- Small team of engineers typically pulled together to answer a set of questions about a vehicle design, based on a set of requirements:
  - What does it look like? (Configuration Design)
  - How much does it weigh? (Mass Properties)
  - How fast / far does it go? (Propulsion, Aero, Aero-Performance)

Traditional "Flight" Disciplines

- Some aero-performance codes had very basic scaling rules (e.g. photographic) to "size" the as-drawn vehicle to meet mission requirements
- Empty weight was often used as a surrogate for cost
- Disciplines, such as Aero, Propulsion, & Mass Properties, had lower-fidelity analysis codes that were already in use in Conceptual Design, and were fast-running (i.e. seconds)
- Additional disciplines (e.g. structures, affordability, subsystems, reliability) were not typically present until after initial Conceptual Design, and often did not have lower-fidelity equivalents that could be run with the type of configuration / geometry information present in the very early design phases

- ***Initial MDAO Models Included These "Flight-Centric" Discipline Analysis Codes, Automating the Standard Conceptual Design Process – Early Example of Model-Based Design, & Stepping Stone for Later Developments***
- ***"Crawl, Walk, Run" approach to developing and gaining acceptance of MDAO***

Conceptual Design MDAO – Progression Through the Years

- The initial Flight-Centric MDAO models were a significant improvement over the manual process, and its acceptance on programs as a standard part of the design process continued to increase

- However, with success comes increased expectations, and gaps were sometimes identified in the Flight-centric process after the resulting configurations were analyzed by higher-fidelity codes and additional disciplines in Preliminary / Detailed Design
  - **Structures:** *Optimized wing is too thin – infeasible to build*
  - **Subsystems:** *Subsystems cannot handle thermal load demand*
  - **Affordability:** *Weight-based cost models do not reflect overall operating cost, cost of major systems, or manufacturing costs*
  - **Performance:** *Vehicle does not meet requirements after preliminary / detailed design – costly re-work required*
  - **Objective Functions:** *Is the lowest weight vehicle the best design, or is the best design the vehicle that has the highest probability of completing the mission (i.e. Mission Effectiveness)?*

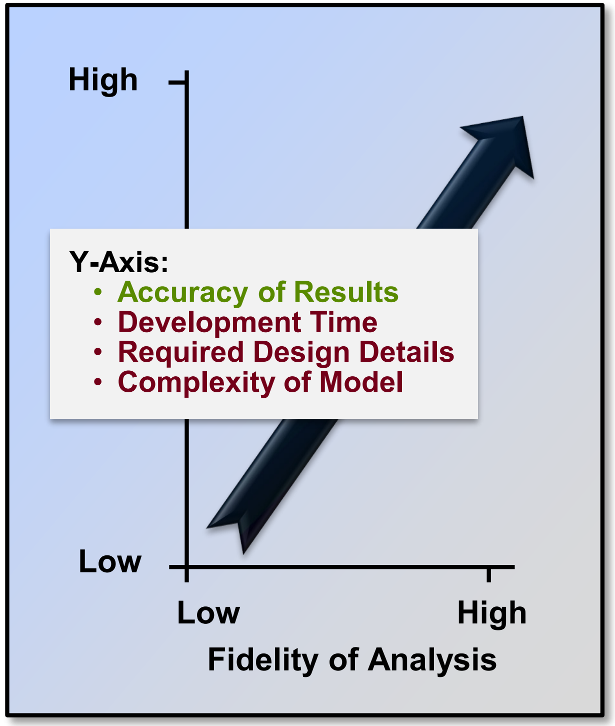
- Solution – Add disciplines, & *"bring fidelity forward"* … *But nothing comes for free!*
  - Programs want additional disciplines linked together, higher-fidelity analysis, and a more robust design – *Reduces probability of re-work in later design phases*
  - Programs also want to compress the upfront schedule and cycle time to achieve results – *Should a new program paradigm be considered?*
  - However, including additional disciplines, higher-fidelity analysis, and robust design increase the setup and cycle time (due to increased computational costs) – *Achieving the proper balance is important to support program schedule*

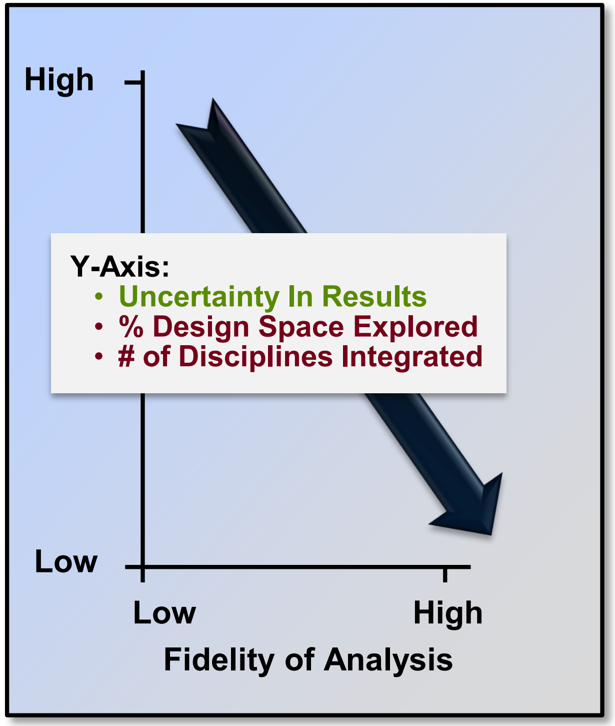
Where We Are Now & Headed in the Future – Integrating Physics-Based Analysis & Robust Design Earlier in the Program Design Cycle, While Also Preserving a Lower-Fidelity Capability for Rapid Turn-Around Needs of Certain Programs

Fidelity of Analysis – Impacts

- Development of models with *key coupled disciplines* at the *appropriate fidelity*
  - *What is important to couple, and what level of fidelity is required? Depends on question being asked, the platform, how fast the results are needed, and the design phase of program.*
  - *Tradeoff between fidelity level & analysis cycle time*

Level	Analysis / Verification	Design Phase
0	Parametric, Empirical, Equation	**Exploratory**
1	Major Components Modeled, Point Mass, Linearized Analysis	**Conceptual**
2	All Geometry Components Modelled & Packaged, 3-DOF, Euler CFD, Linear S&C	**Preliminary**
3	6-DOF, Navier-Stokes CFD, Non-Linear S&C, 3D Finite Element Analysis	**Preliminary**
4	Full Physics Based Analysis, LES/DNS CFD, Non-Linear Dynamic Responses, Physical Test	**Detailed**





Moving More Towards Physics-Based Analysis Earlier in the Program Design Cycle to Reduce Design Iterations/Rework and Improve Integrated System Performance and Affordability – Merging of Conceptual & Preliminary Design

Fidelity of Analysis – Factors to Consider

- Does the data feeding higher-fidelity analysis (e.g. geometry) have high enough quality?
- Is the necessary detail for the higher-fidelity analysis present?
- How do you efficiently handle the significant increase in the number of Design Variables?
- Are there robustness issues applying the higher-fidelity analysis code over the wide design space typically surveyed in Conceptual Design?
- Are High Performance Computing (HPC) and distributed computing resources available where the model will be run?
- Will the extended setup and cycle time be acceptable to support program schedule milestones?
- What are potential the options for incorporating higher-fidelity analysis in a conceptual design MDAO model?
  1) Direct running of analysis – *High computational cost, most accurate*
  2) Surrogate / Response Surface Models (RSMs) – *Potentially long initial setup time, optimization bounded by design variable ranges used to create RSM, loss of accuracy in RSM, fast running*

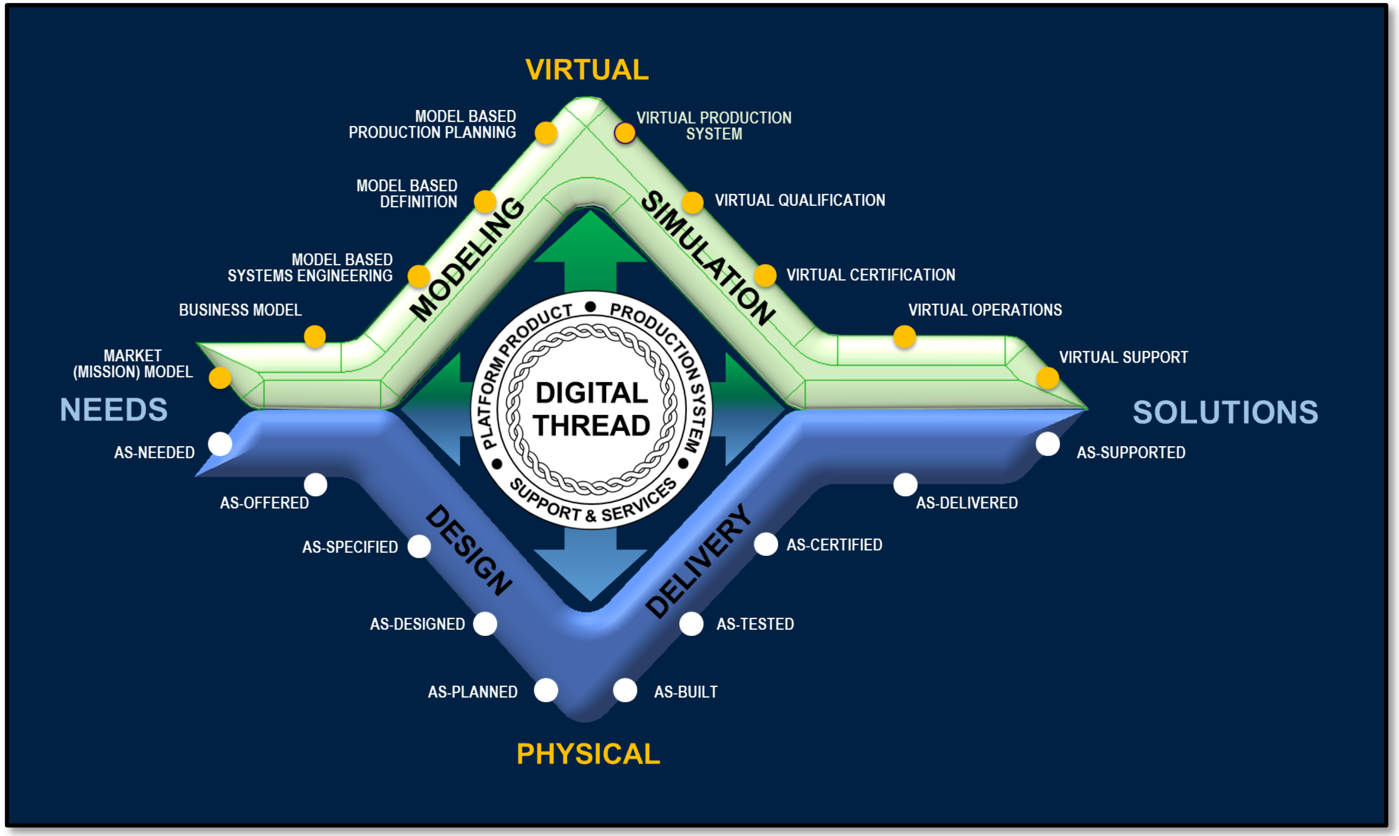
Physics-Based Codes Also Enable the Analysis of Non-Standard Configurations that Could Not Previously Be Assessed Through Traditional Lower-Fidelity Empirical Methods

Integrating MDAO & MBSE

- **MBSE:** Linked *Architectural / Descriptive Models* Replace Documents, Authoritative Source of Truth

- **MDAO:** Coupled *Engineering Analysis Models* Replace Isolated Analysis, Automation of Standard Design Process (Modeling & Simulation)

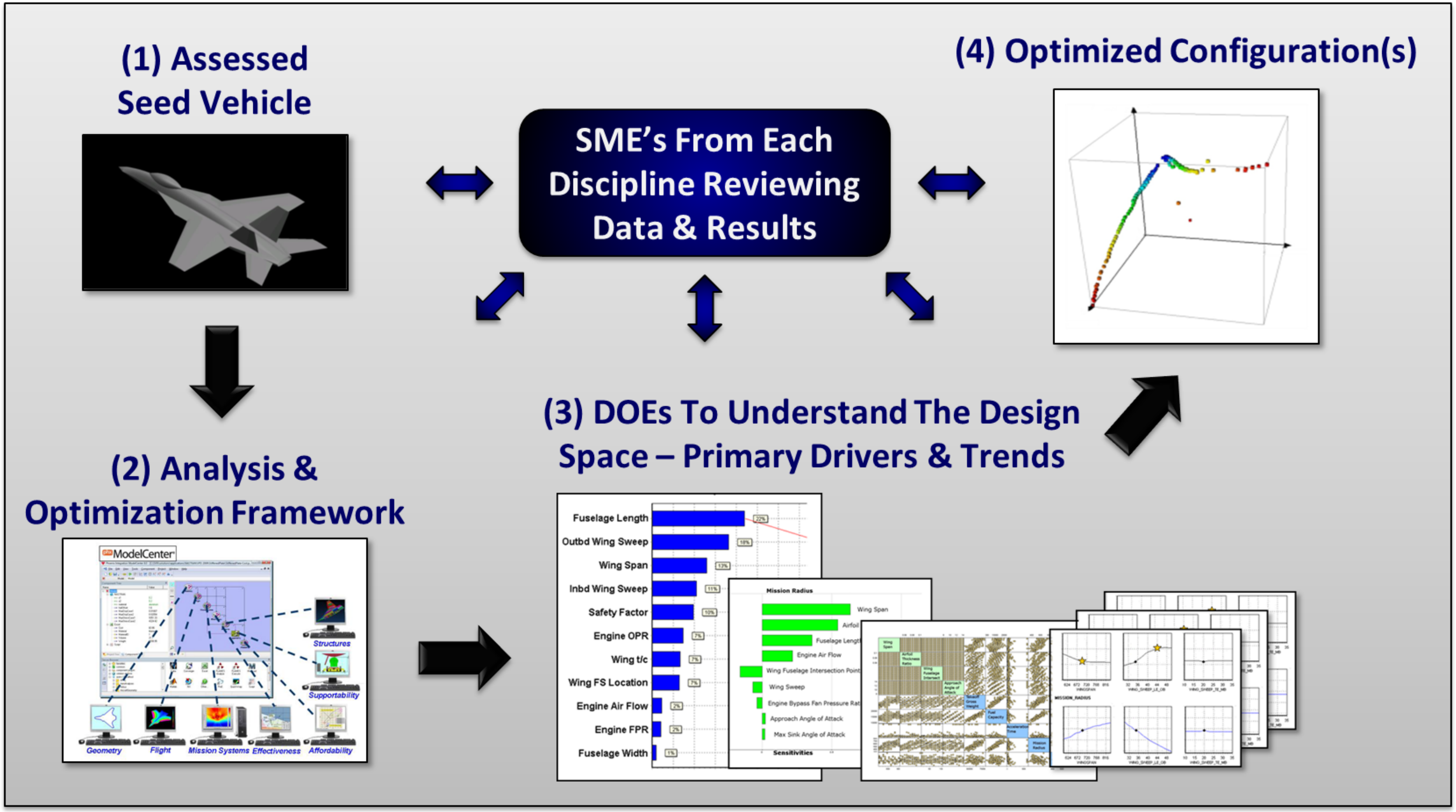
- **The Connection:** *MBSE Drives the Engineering Design / Analysis / Optimization and Captures Results*



MDAO / MBSE Focus => Establish How MDAO Processes Will Integrate Seamlessly Within the Digital Thread

Successful Integration of MDAO Creates a Path for Integrating all Analyses into Model-Based Engineering

MDAO Design Process – Example of Best Practice



MDAO Lessons-Learned

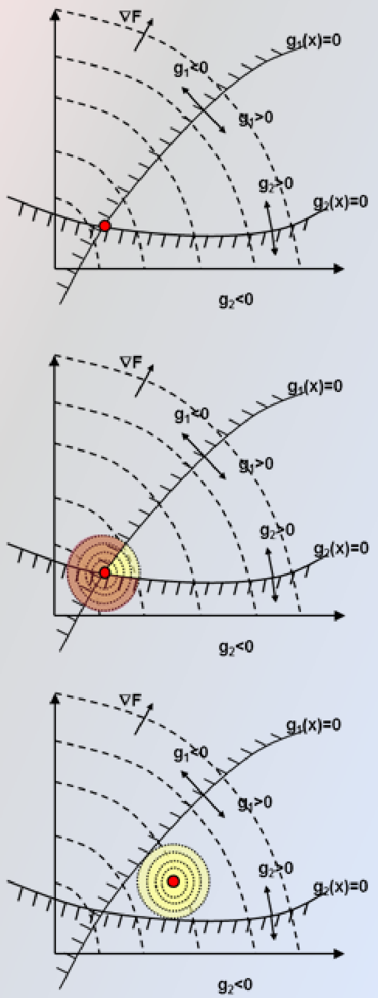
- Program "Pull" vs. "Push" for acceptance of MDAO – Success Builds Upon Success
- ***Diversity of Aerospace Product Line*** – Platform specific analysis codes can limit replication opportunities
- Basic MDAO models need to be ready-to-go – ***Capability Ready at Program Start***
- Spiral development of capabilities, infrastructure and applications is needed to achieve the full potential of MDAO
- Build MDAO into the program schedule from the start – Ensure program schedule will support the setup and cycle time for the required fidelity of analysis
- Integrate the analysis codes that the SMEs use in their stand-alone analysis – ***Builds trust and confidence in results***
- Inclusion of discipline SMEs in all steps of the MDAO process – ***Builds trust and confidence in results***
- Model-Based Engineering initiatives are accelerating the acceptance and inclusion of MDAO in the standard design process – ***MDAO is Model-Based Engineering!***

** Representative of the platform / configuration type, and not launched or production programs*

MDAO Lessons-Learned (cont.)

- Uncertainty Quantification (UQ) and Design Under Uncertainty (DUU) – Builds robustness in optimized design solutions
- Rapid & robust parametric geometry is key to feed downstream physics-based analysis
- “MDAO hardening” of analysis tools is critical – Port legacy codes to modern programming languages to remove excessive I/O, enable parallelization
- It is important to build in feasibility checks for analyses and geometry to avoid designs that are numerically feasible, but not able to be built or fly
- COTS tools can carry risks – License cost/availability, update compatibility, memory usage, parallel processing, etc.
- Programming skills are essential for developing models, but care has to be taken in model design to enable easier transition to program personnel
- As fidelity is brought forward, need to leverage computing resources (e.g. clusters, cloud computing, distributed processing) – Will these be available on the targeted program?
- MDAO integration frameworks reduce the learning curve and enable broader application of MDAO
- Design of Experiments (DOEs) useful for model checkout, design space trends, and sensitivities before optimizing
- Optimizers will exploit weaknesses in your MDAO model
- Feedback from users that are not the developers is critical to transitioning capability on program

Why Uncertainty Quantification Is Important



MDAO – Myths & Facts

Myth: MDAO is a tool

Fact: MDAO Is a *Process* or an *Approach*

Myth: MDAO is "Push-The-Button-Get-An-Answer"

Fact: SME's from each discipline should be engaged at all stages of the process reviewing data

Myth: MDAO will reduce upfront schedule/time investment

Fact: Typically longer upfront time investment compared to single stand-alone analysis – *Patience is required! The big payoff is downstream!*

Myth: Once you build an MDAO model, no further updates are necessary

Fact: Even existing models often need to be tailored to the study at hand, and continuous improvement is required (e.g. analysis fidelity, disciplines)

Myth: If an analysis code works stand-alone, it is ready for MDAO

Fact: Analysis codes typically have to be "MDAO Hardened"

Myth: Parametric geometry is easy

Fact: Rapid and robust parametric geometry is still very difficult, especially if you intend to capture the configurator's intent

Myth: The optimized configuration is the main goal of MDAO

Fact: Optimization is just one aspect – the sensitivities across the design space are also very valuable

Summary

- Key aspects of MDAO:
  - Enables balancing performance & affordability, and optimization based on mission effectiveness
  - Provides design space sensitivities – *Cost of requirements / constraints*
  - Reduces the probability of late defects and expensive re-work – *Risk reduction*
- Successful MDAO implementation requires a strong supporting foundation in people, organization, processes, and culture
- Balancing up-front setup time and analysis cycle time with required accuracy and program schedule is key – *Multi-fidelity & right-sized fidelity approaches*
- Robust design is critical
- MDAO continues to demonstrate value to programs, and continues to expand in implementation – *Becoming a normal part of the standard vehicle / configuration design process*

MDAO is a Model-Based Engineering Process for Conceptual Design – The Digital Thread Starts Here!

Backup Slides

Abstract

MDAO models for Conceptual Design have evolved over the years from being first focused on Flight centric lower-order analysis codes (e.g. Geometry, Mass Properties, Aerodynamics, Propulsion, Aero-Performance), to the coupling of additional disciplines (e.g. affordability, structures, subsystems, mission effectiveness) at varying levels of fidelity. This expansion in capability has followed the successful adoption of MDAO as an accepted and now expected part of the normal vehicle design process, and recognition of MDAO as a critical enabler for reducing program technical risk, delivering first-time quality, and Model-Based Engineering.

This presentation will focus on best practices and lessons-learned from both the development of MDAO models and the application of MDAO on programs within Boeing.

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