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KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

AOE 4144: Applied CFD

A series of lectures by Prof. Raj (course co-instructor)

Reflections on the Effectiveness of Applied Computational Aerodynamics for Aircraft Design

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Advanced Development Programs

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Lecture 10

Topic 6: ACA Effectiveness – Status and Prospects (1 of 3)

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List of Topics

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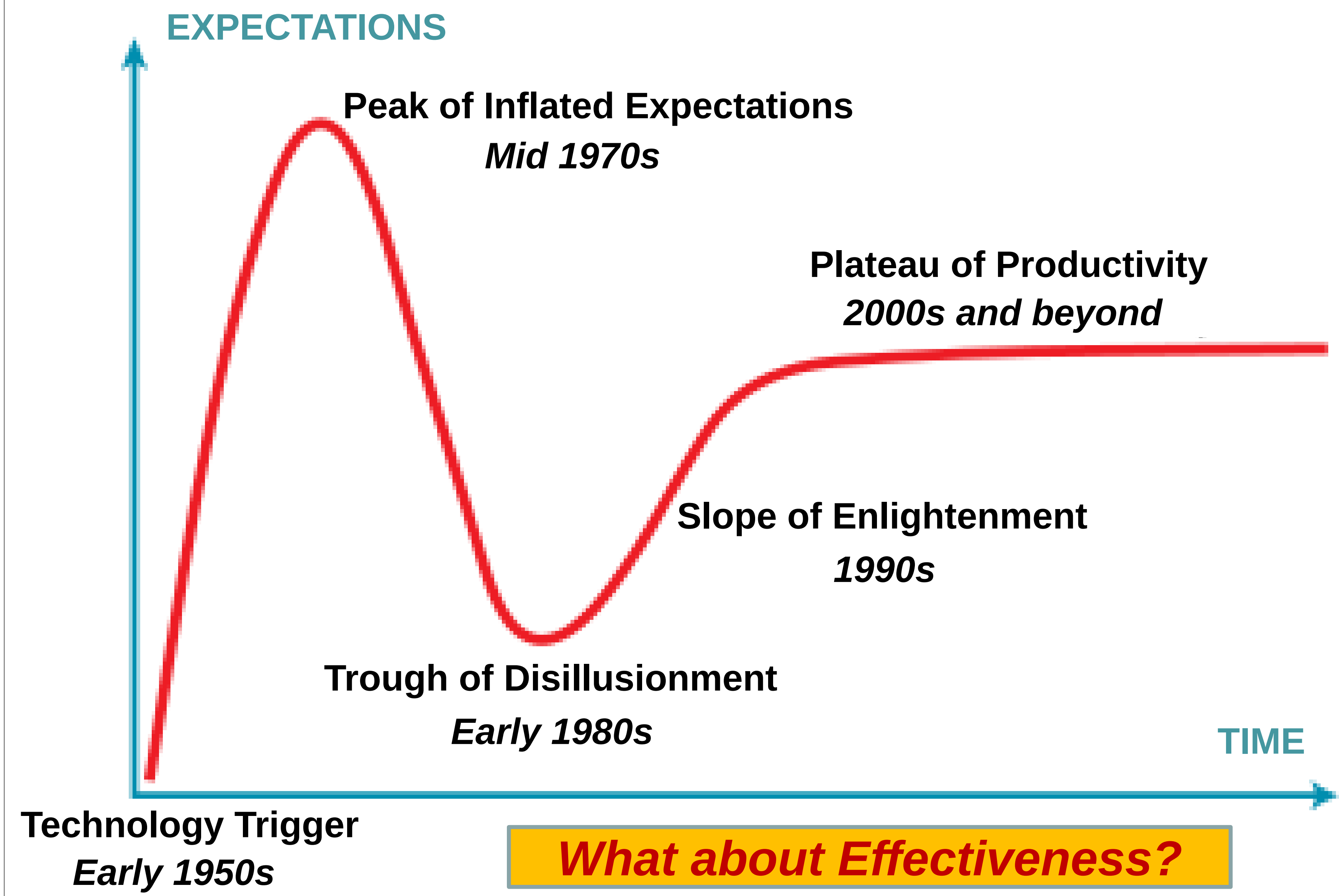
ACA Evolution Has Paralleled *Gartner Hype Cycle* of CFD Technology!



What about Effectiveness?

Source: https://en.wikipedia.org/wiki/Hype_cycle

A Closer Look at ACA Effectiveness

In this lecture, we shall examine

(a) outcomes of the efforts to assess the effectiveness of <u>RANS-based</u> ACA since the 2000

RANS CFD methods—the highest of the four levels of CFD methods—gained increasingly widespread use once their productivity reached an acceptable level around the year 2000

(b) obstacles to overcome for maximizing ACA effectiveness

Maximizing Effectiveness Has Been the "North Star" of Author's ACA Efforts Since the Inception of "Miranda's Law" in 1980

Assessment of ACA Effectiveness

Degree of ACA Effectiveness Depends on the Ability to Provide Credible Solutions (that Replicate Reality) While Meeting Cost & Schedule Constraints

- **Qualitative Approach**
  - This is the approach proposed by Miranda
  - Assessment is based on engineer's judgment about 'quality' and 'acceptance' factors
- **Quantitative Approach**
  - A simple *quasi*-quantitative approach is devised and proposed by the author
  - It uses an "effectiveness index" as a composite of a "quality index" and an "acceptance index" (See Appendix A)

Design Teams, in Collaboration with ACA Practitioners, Are Best Suited to Assess ACA Effectiveness, Not the Developers

Source: https://en.wikipedia.org/wiki/Hype_cycle

Author's Assessment of the Effectiveness of RANS-based ACA *(ca early 2000s)*

Less Than Satisfactory!

Although RANS simulations of full aircraft configurations are [acceptably?] quick and affordable, predictions of aerodynamic characteristics aren't always credible* *especially for complex flows dominated by separation and free vortices!*

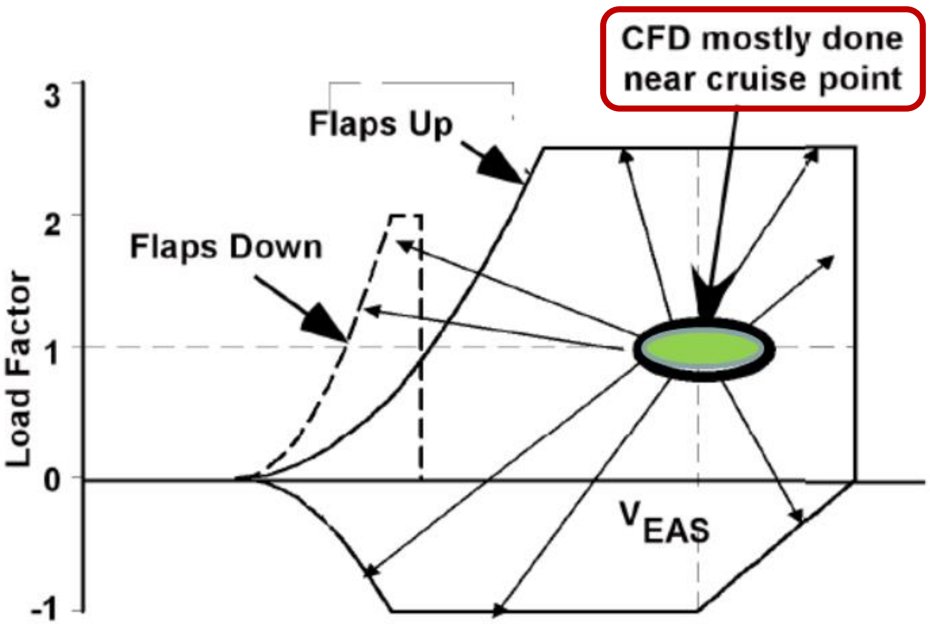
***credible:** *how faithfully do the predictions imitate reality*

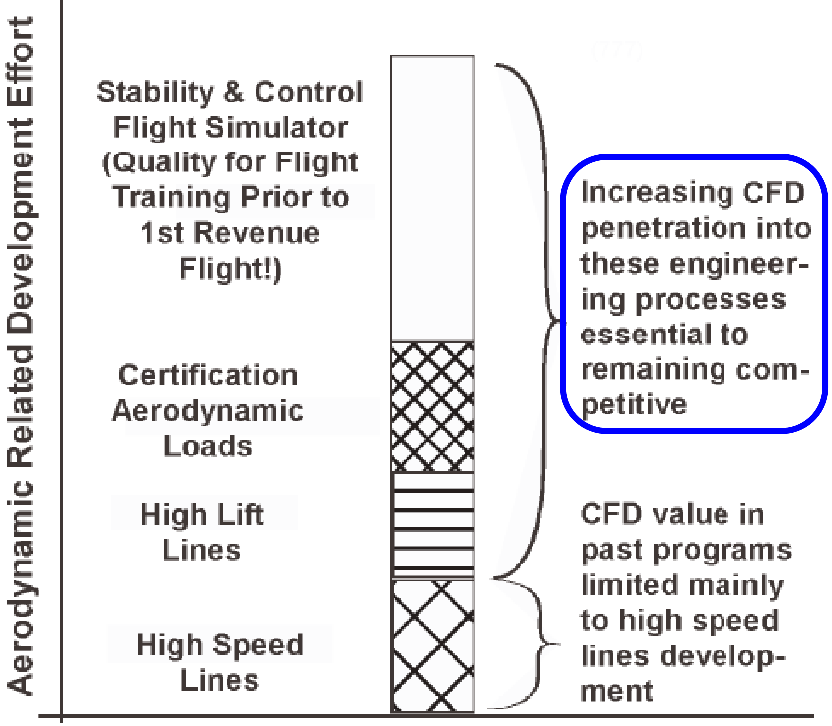
Dilemma when designing novel configurations in a *Simulation Based Design* (SBD) environment

- If RANS simulations predict flow separation or free vortices, are the data credible enough to invest additional time and effort for configuration redesign?
- If expensive and time-consuming wind-tunnel tests must be done for validating RANS predictions—doesn't it defeat the purpose of using RANS in the first place?

Boeing Assessment of RANS CFD for Aircraft Design Applications

Tinoco, E., Bogue, D., Kao, T., Yu, N., Li, P., and Ball, D., "Progress toward CFD for full flight envelope," *The Aeronautical Journal,* Royal Aeronautical Society, Vol. 109, Issue 1100, October 2005, pp 451-460.





"The major impact of CFD, delivered to date at Boeing, has mainly been related to its application to *high speed cruise*."

Severely Limited Scope of Applications

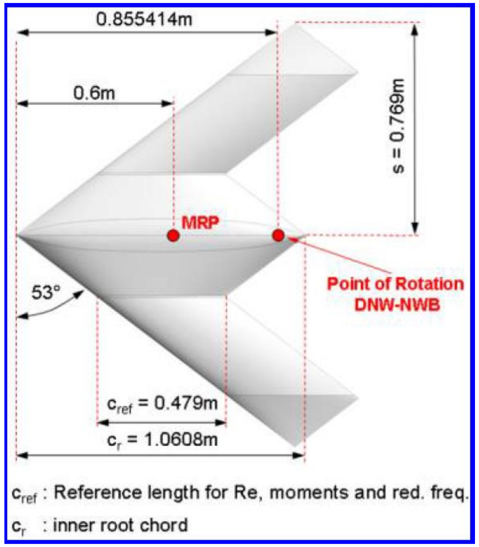
Source: Refs. 6.1.1

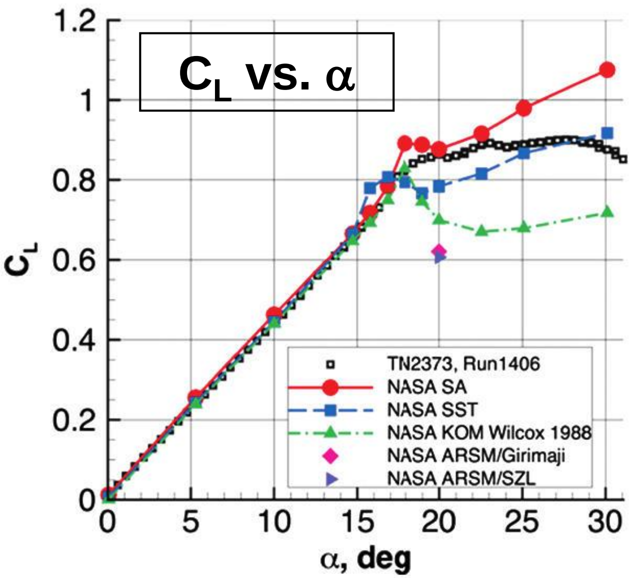
NATO RTO Assessment of RANS CFD

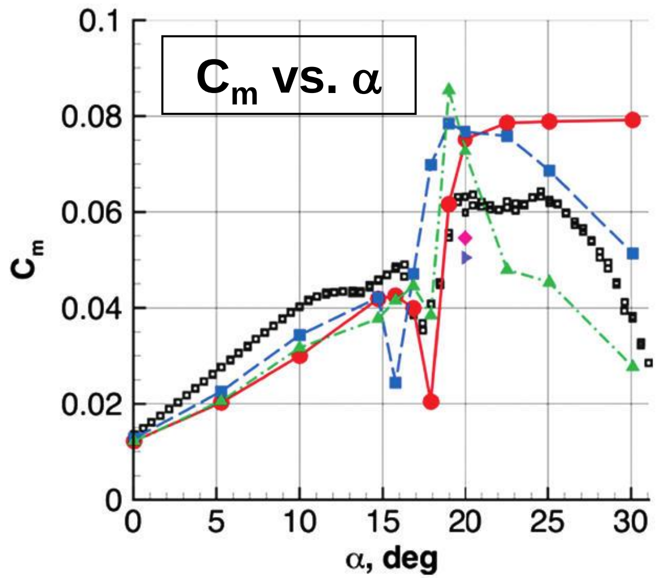
TetrUSS simulations by Frink et al, *AIAA Journal of Aircraft, 2012*

NATO RTO AVT-161: **S**tability **A**nd **C**ontrol **CON**figuration (SACCON)

M = 0.149; α = 0° to 30°; Re = 1.6×10^6







Wide variation in data among state-of-the-art turbulence models!

Laminar-to-turbulent transition modeling: yet another challenge!

Predictions are NOT Credible for Flows with Separation and/or Free Vortices

Source: Ref. 6.1.2

RANS-based ACA:

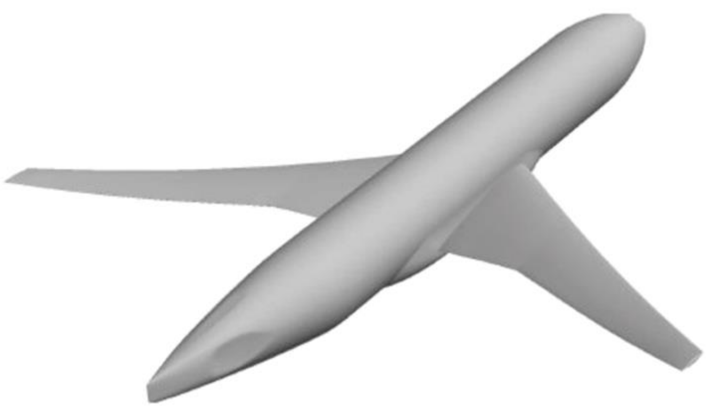
The Overarching Challenge

PRODUCING CREDIBLE SOLUTIONS

Assessing and Overcoming this Challenge Has Been a Constant Focus of the ACA Community Since the Early 2000s

Assessment of RANS Predictions:
Absolute (Total) Drag
AIAA CFD Drag Prediction Workshops (DPWs)

- **Formally initiated in 2000**; seven (7) workshops to date: 2001, 2003, 2006, 2009, 2012, 2016, and 2022; numerous publications
- **Primary Goal:** *Assess state-of-the-art CFD methods as practical aerodynamic tools for the prediction of forces and moments on industry-relevant geometries, with a focus on absolute drag.*
- **Test Cases:** *Variants of commercial transport wing-body configurations; transonic flows; many meshes and flow-solvers; multiple turbulence models*



Importance of Accurate Prediction Cannot Be Over Emphasized!

Source: Ref. 6.1.3

Importance of Accurate Drag Estimation

C-141 Cruise Drag (early 1960s)

- **Total Drag predicted based on wind-tunnel tests was within *One Count (0.0001) of flight data…***

  …but good agreement was due to Compensating Errors!
  - Minimum Profile Drag: *underpredicted*
  - Compressibility Drag: *overpredicted*

- **DoD Aeronautical Test Facilities Assessment Team (1997)**
  - *Question*: **Can we do better with improved wind-tunnel test techniques combined with CFD?**
  - *Answer*: **Cruise drag would be underpredicted by 3.5%**
    - *Considering only Reynolds Number Scaling*
      - *Minimum Profile Drag Underprediction—about eight (8) counts*
      - *Compressibility Drag Overprediction—eliminated*

Erroneous Predictions would Increase Fuel Cost by $688M (FY96 dollars) for Entire Fleet over Service Life

Source: Ref. 6.1.4

Importance of Accurate Drag Estimation

C-5 Cruise Drag (mid 1960s)

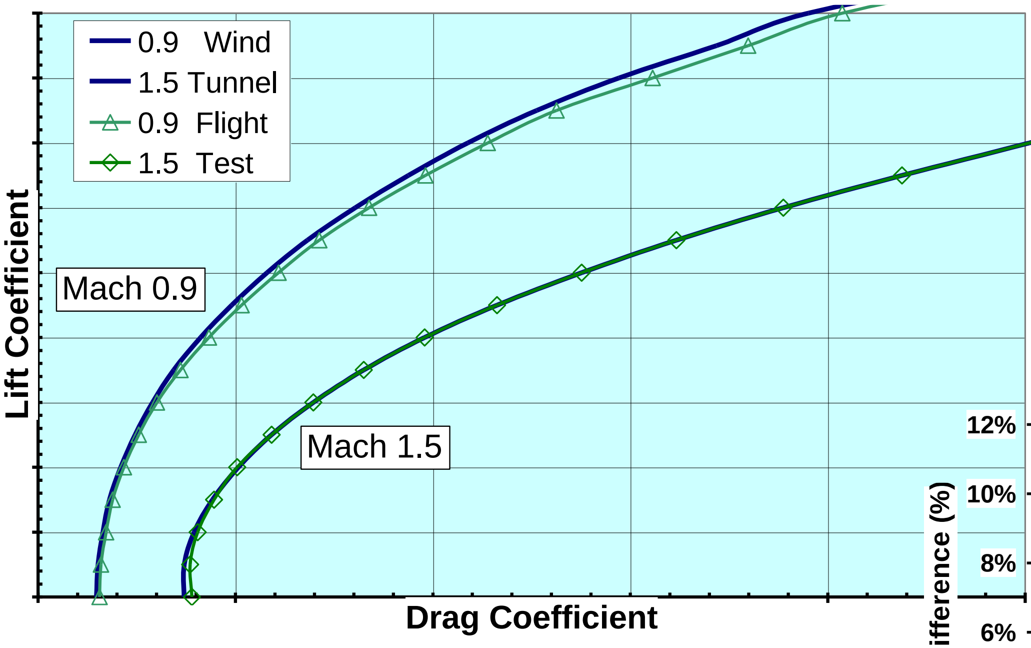
- **Total drag overpredicted by 2.5% based on wind-tunnel tests**
  - Minimum Profile Drag*: underpredicted by one scale-up method and correctly predicted by another*
  - Compressibility Drag*: overpredicted*

- **DoD Aeronautical Test Facilities Assessment Team (1997)**
  - *Question*: **Can we do better with improved wind-tunnel test techniques combined with CFD?**
  - *Answer:* **Cruise drag would be underpredicted by 1.5%**
    - *Considering only Reynolds Number Scaling*
      - Minimum Profile Drag Underprediction—*1% to 3%*
      - Compressibility Drag Overprediction—*eliminated*

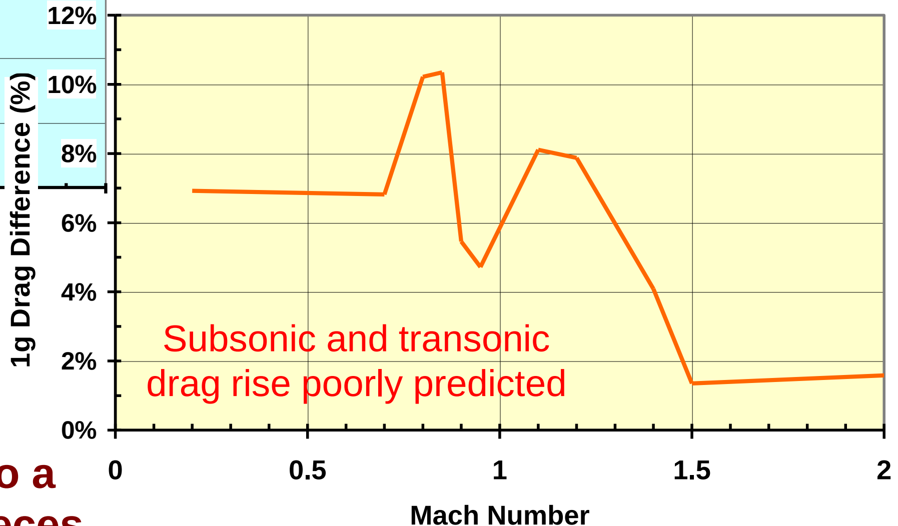
Inaccuracies in Drag Estimations Impacted Acceleration, Deceleration, Cruise and Loiter Performance

Source: Ref. 6.1.4

Importance of Accurate Drag Estimation
F-22 Cruise Drag Example (1990s)



Percent Drag Difference between Preliminary Flight Test Results and Wind Tunnel Predictions at 1G



- **Drag predicted using wind-tunnel tests matched well with flight test data for Mach 0.9 and 1.5**

- **Drag Differences may be due to a combination of interpolated pieces**
  - Thrust effects, auxiliary inlet and vents, control surface scheduling

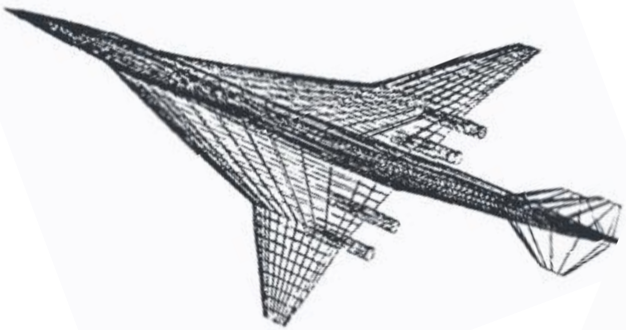
Inaccuracies in Drag Estimations Impacted Acceleration, Deceleration, Cruise and Loiter Performance

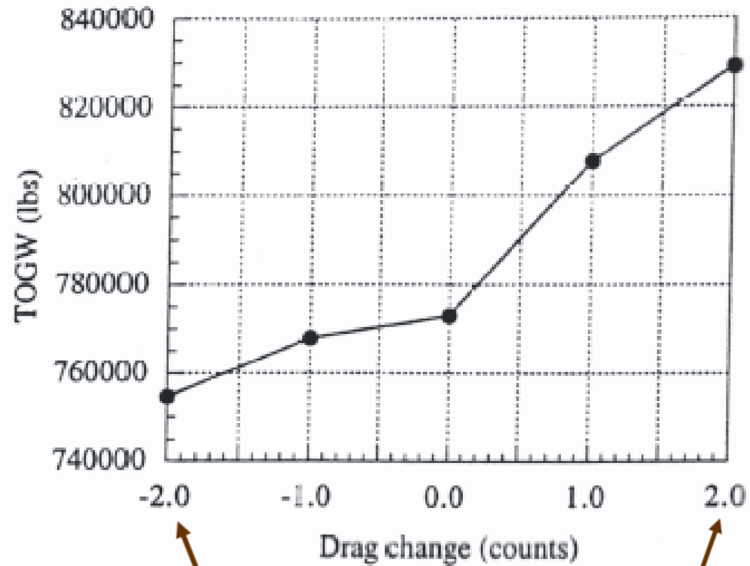
Source: Ref. 6.1.5

Importance of Accurate Drag Estimation

HSCT Conceptual Design MDO Study (mid 1990s)

- **High Speed Civil Transport**
  - *Cruise Mach Number: 2.4*
  - *Range: 5,500 nm*
  - *Payload: 250 passengers*





- TOGW = 772,907 lbs.
- Fuel Weight Fraction = 0.52
- Empty Weight Fraction = 0.39
- Aspect Ratio = 2
- L/D_{max} = 9.16

TOGW = 754,560 lbs.

TOGW = 829,100 lbs.

Just Two-count Cruise Drag Overestimation Increases Take-Off Gross Weight by More Than 7%!

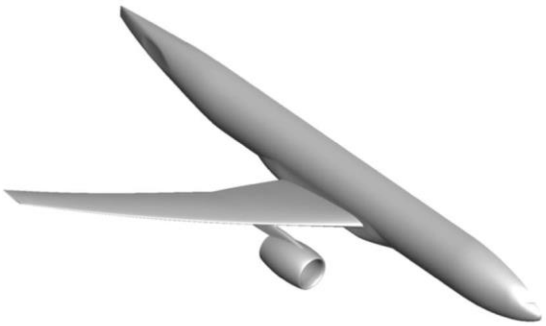
Source: Ref. 6.1.6

AIAA 6th CFD DPW (2016)

Some Interesting Findings: Tinoco et al, *Journal of Aircraft, 55 (4), 2018*

- **NASA Common Research Model (CRM) Wing-Body (WB)**
  - M = 0.85; Re = 40 million; C_L = 0.5
  - 54 datasets; multiple turbulence models
  - *Solutions exhibited "tighter" convergence of total drag with a spread of less than 10 counts [1 count = 0.0001]*

- **NASA CRM WB Static Aeroelastic Effect**
  - *Higher lift predicted at a given angle of attack, and more negative (nose down) pitching moment at a given lift coefficient than observed in test data.*
- **NASA CRM Wing-Body-Nacelle-Pylon**
  - *Drag increment predicted within the uncertainty of the test data… this is of significant importance to industry design processes*



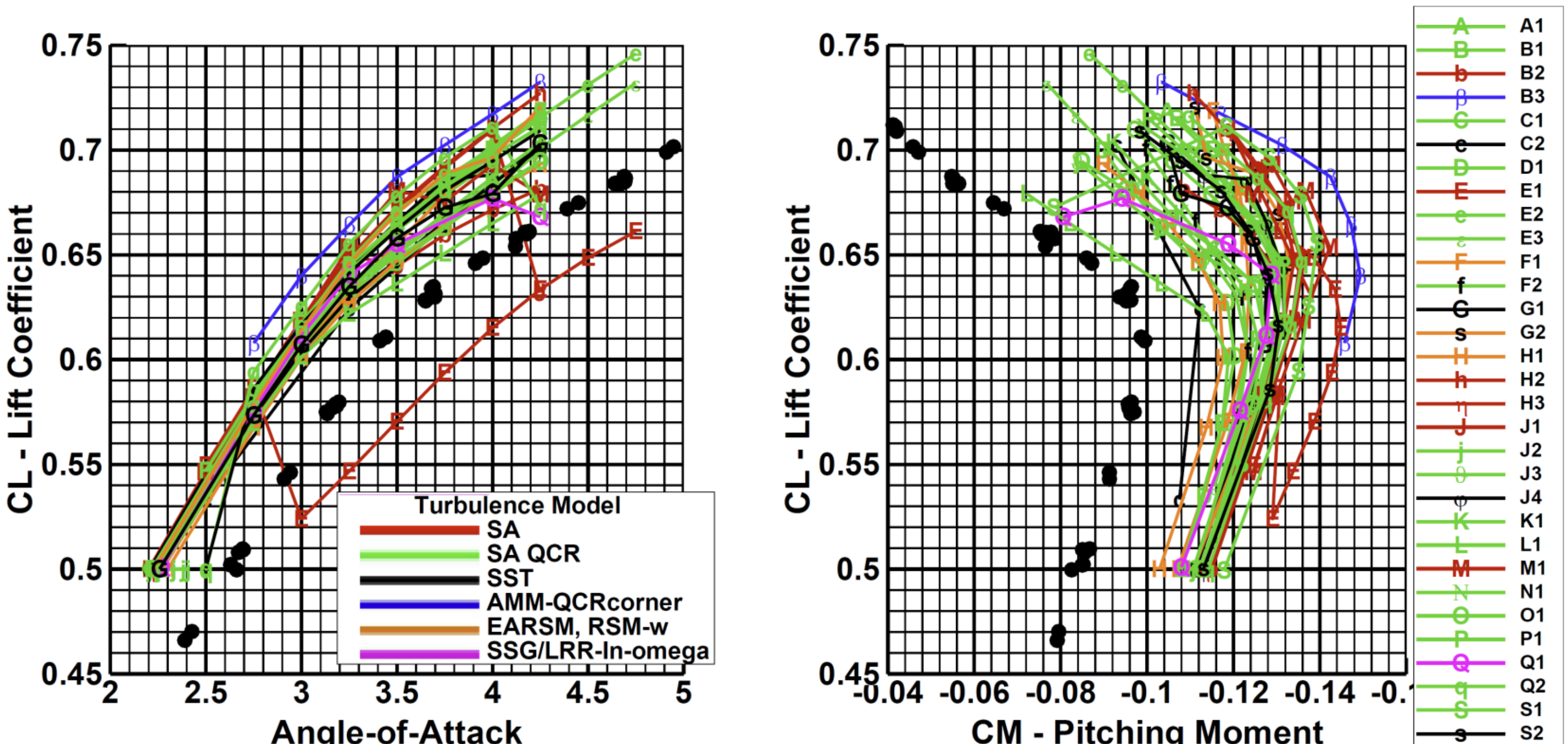
"One must ask if steady RANS is adequate for modeling this flow regime [with shocks and buffet]. Will URANS be adequate, or must one go to an eddy resolving method such as detached Eddy simulation to accurately simulate this flow regime?"

Source: Ref.6.1.7

AIAA 7th CFD DPW (2022): *Case 2a*

- **Wing-Body static aeroelastic/buffet study**
  - ***Investigate CFD predictions where significant flow separation is expected [around $\alpha = 4^o$]***
  - **M = 0.85; Re = 20 million; α sweep, 2.50° to 4.25° in 0.25° increments**
  - **29 datasets; six turbulence models**

NASA Common Research Model (CRM)



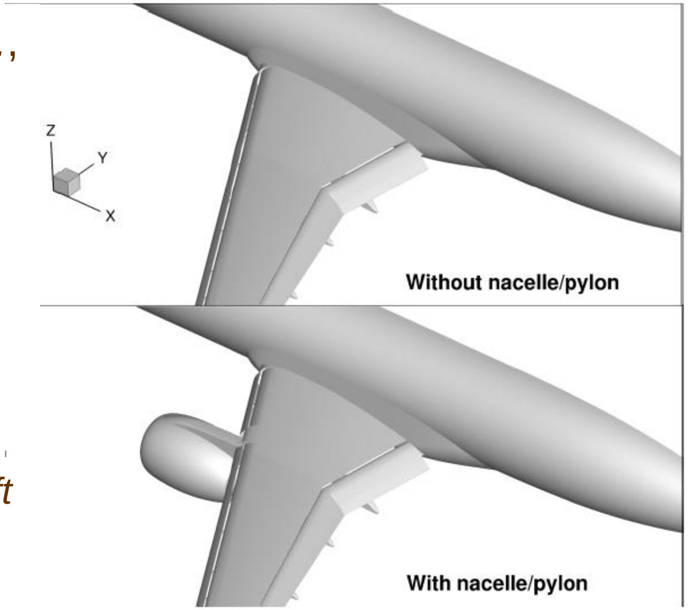
Source: Ref. 6.1.8

Assessment of RANS Predictions: *High-Lift Configurations*

AIAA High Lift Prediction Workshops (HiLiftPWs)

- **Formally initiated in 2009**; three (4) workshops to date: 2010, 2013, 2017, and 2022; numerous publications
- **Primary Goal:** *Assess the numerical prediction capability (mesh, numerics, turbulence modeling, high-performance computing requirements, etc.) of current-generation CFD technology for swept, medium/high-aspect ratio wings in landing/takeoff (high lift) configurations.*
- **Test Cases:** *Variants of commercial transport configurations; subsonic flows; variety of grid systems and flow solvers; multiple turbulence models*
- **Interesting Findings from 3rd HiLiftPW**: Rumsey *et al.*, *AIAA 2018-1258*

  JAXA Standard Model High-lift Configuration with and without Pylon/Nacelle
  - *Fairly tight clustering of results in the linear lift-curve range, and very large scatter in results near maximum lift*
  - *Differences between nacelle/pylon on and off were well predicted in general*
  - *Significant influence of grid for the solutions near maximum lift*
  - *Transition model results were inconsistent near maximum lift; reasonable results for the wrong reasons!*

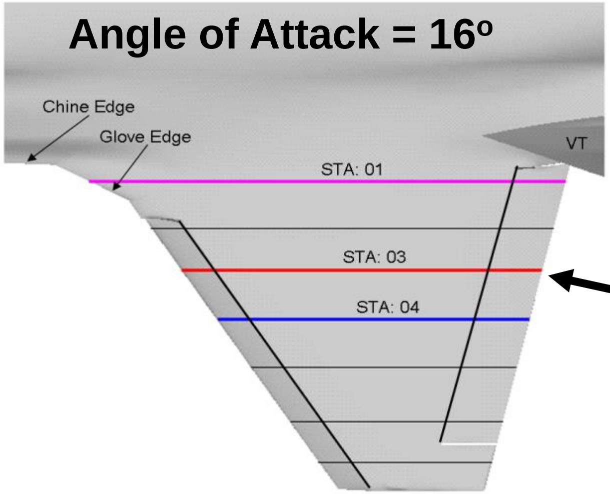


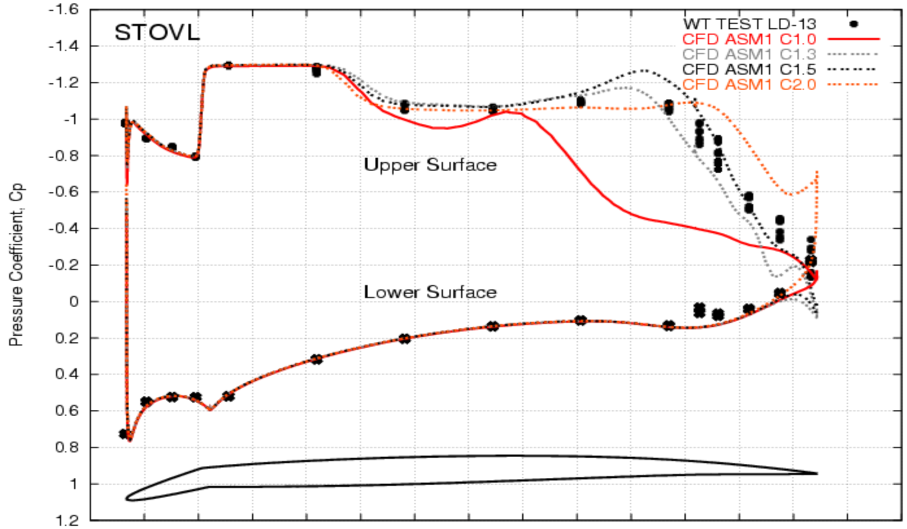
Source: Ref. 6.1.9

Two Key Factors Hamper Credibility of RANS Predictions

1. Numerical Models

Example: *Solution sensitivity to compression factor in limiter function in MUSCL* algorithm of Falcon V3.4 code*

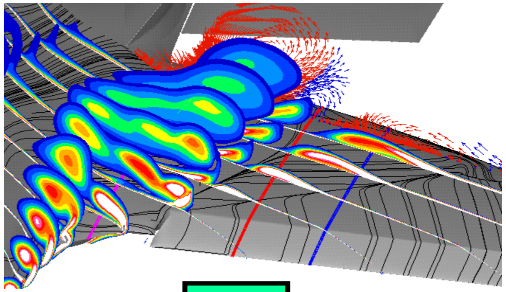




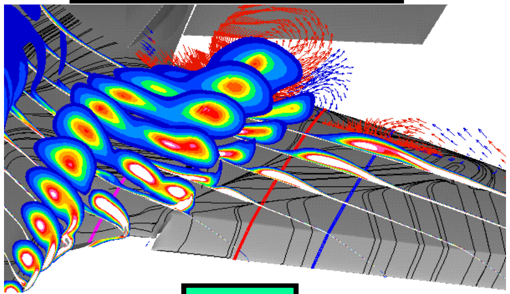
2. Turbulence Models

Example: Solution Sensitivity to Turbulence Modeling

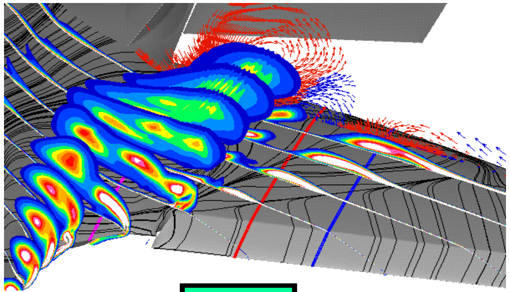
VORTICITY MAGNITUDE



K-KL



ASM1



ASM2

ASM - Algebraic Stress Model

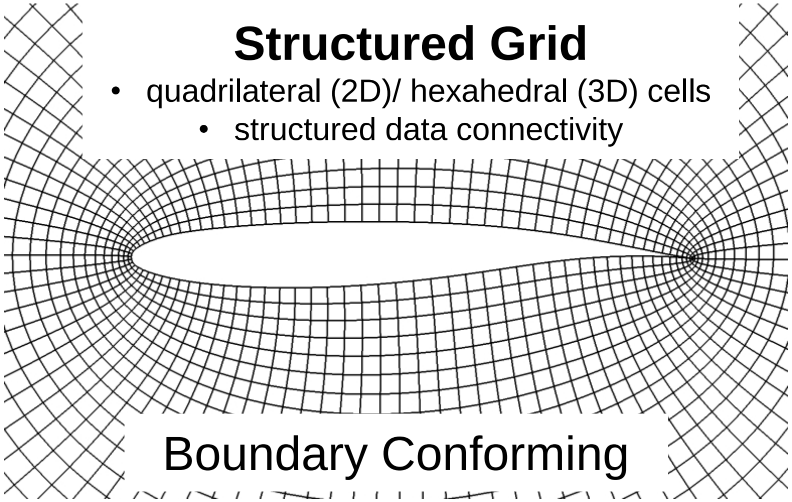
"All Models are Wrong, But Some Models are Useful" -- George Box, 1997

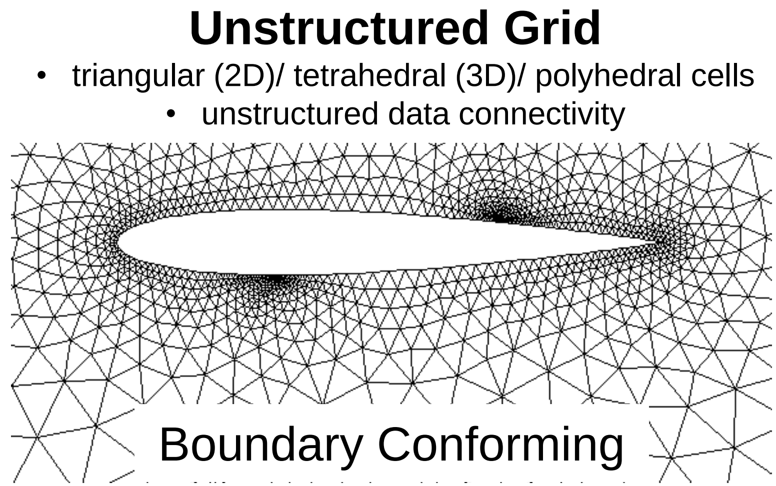
Monotonic **U**pstream-centered **S**cheme for **C**onservation **L**aws

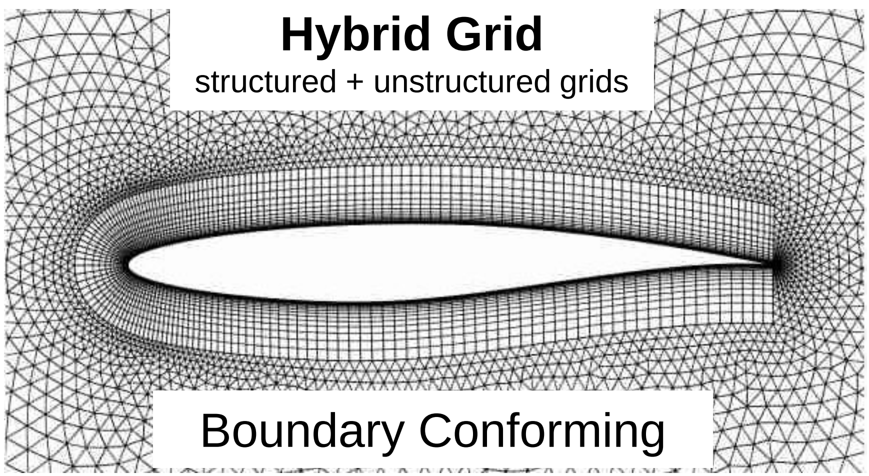
Source: Ref. 5.2.49

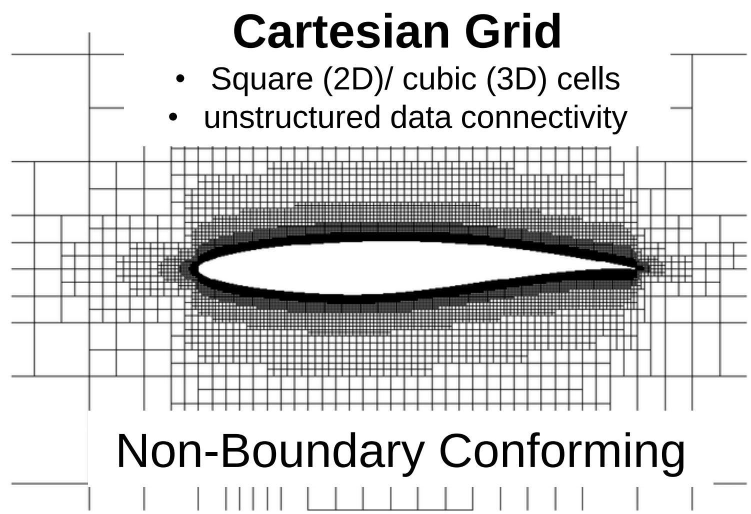
No Shortage of Grid Types

To Discretize the Spatial Domain for Numerical Modeling of Euler/RANS PDEs









***Discretization errors** contribute to differences between computed and exact solutions*

Difficult to Assess Errors: Exact Solution Not Known a Priori

Image Source: Internet; also Ref. 6.1.10

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No Shortage of Numerical Algorithms for *Solving Euler & RANS PDEs on Various Types of Grids!*

Year	Developer(s)	Scheme
1969	MacCormack	Two stage scheme for hyperbolic equations
1973	Boris & Book	Flux Corrected Transport (FCT) oscillation control via slope limiters
1974	Van Leer	Higher-order Godunov scheme - MUSCL
1981	Steger & Warming	Flux splitting
1981	Jameson, Schmidt, Turkel	Shock capturing via controlled diffusion – full convergence to steady state
1981	Ni	Multigrid Euler solver
1983	Roe	Approximate Riemann solver
1983	Harten	Theory of Total Variation Diminishing (TVD) schemes
1983	Jameson	Agglomeration multigrid full approximation storage (FAS) scheme for Euler equations
1985-86	Jameson, Baker, Weatherill	Airplane Code: 3D Euler equations on unstructured mesh – edge based data structure
1986-88	Yoon-Jameson	Lower-Upper Symmetric Gauss Seidel (LU-SGS) scheme
1987	Harten, Engquist, Osher, Chakravarthy	Essentially Non-Oscillatory (ENO) scheme
1990	Cockburn & Shu	Local Discontinuous Galerkin (LDG) method
1991	Jameson	Multigrid dual time stepping scheme for unsteady flow
1993	Liou	Advection Upstream Splitting Method (AUSM) scheme
1994	Jameson	Theory of Local Extremum Diminishing (LED) scheme
1994-96	Liu, Osher, Chan, Shu	Weighted ENO (WENO) scheme
2001	Jameson-Caughey	Nonlinear Symmetric Gauss-Seidel (SGS) multigrid scheme

Minimize Truncation, Dispersive, and Dissipation Errors

Source: Ref. 6.1.11

Lecture 10: Key Takeaways

- **ACA evolution has paralleled *Gartner Hype Cycle* of CFD Technology**
- **Degree of ACA effectiveness depends on the ability to provide credible solutions while meeting cost & schedule constraints**
- **Reliable use of RANS limited to cruise part of flight envelope—hence less than satisfactory effectiveness (Boeing Assessment, 2005)**
- **RANS predictions not always credible, especially for complex flows dominated by separation and free-vortices (NATO RTO Assessment, 2012)**
- **Overarching challenge for RANS-based ACA: PRODUCING CREDIBLE SOLUTIONS**
- **Community initiatives to systematically assess RANS CFD capabilities and shortcomings**
  - AIAA CFD Drag Prediction Workshops—the first one in 2001
    - *Accurate prediction of drag is of critical importance to design teams*
  - AIAA High Lift Prediction Workshops—the first one in 2009
- **Two factors hamper credibility of solutions: (1) Numerical Models; and (2) Turbulence Models**
- **Numerical Models – No shortage of options for grids to discretize spatial domain, and for numerical algorithms to solve Euler/RANS PDEs on the various types of grids**
  - *Solution of discretized equations is not necessarily a solution of the differential equation!*

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Topic 6

6 ACA Effectiveness: Status and Prospects *(2000 and Beyond)*

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6 ACA Effectiveness: Status and Prospects *(2000 and Beyond)*

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Appendix A

Quasi-quantitative Approach for Assessing ACA Effectiveness

The proposed quasi-quantitative approach defines an *effectiveness index (E)* as a composite of *quality index (Q)* and *acceptance index (A)*

$$E = Q \times A$$

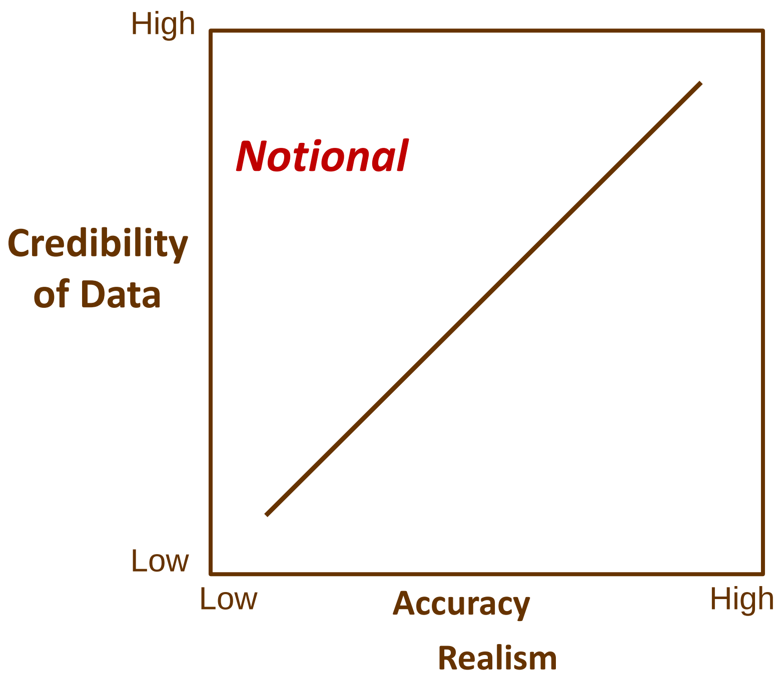
- ***Effectiveness index (E)*** **is the outcome/result of effectiveness assessment**
- ***Quality index (Q)*** **represents the level of 'credibility' of data generated by the computational simulations *for a target application***
  - 'Credibility' of data is a function of two factors: *Accuracy* and *Realism*
    - *Accuracy*—the degree to which the results of numerical simulations match the *correct* or *exact* values (*verification*)
    - *Realism*—the degree to which computational results represent *reality* *(validation)*
- ***Acceptance index (A) represents the level of*** **'acceptability' of a simulation by users and customers for a target application**
  - 'Acceptability' is a function of four factors: *applicability*, *usability*, *affordability*, and *responsiveness*
    - *Applicability*—the degree to which a procedure is applicable to the problem at hand
    - *Usability*—how easy the procedure is for ['non-expert'] users to use
    - *Affordability*—lower the cost [labor + computer], higher the affordability of simulations
    - *Responsiveness*—lower the turnaround time [elapsed time from go-ahead to data delivery], higher the responsiveness to customer needs

Source: Ref. 5.2.1

Quality Index (Q) Estimation

Quality index (Q) **represents the level of 'credibility' of a computational simulation** ***for a target application*** **which is a function of** ***Accuracy*** **and** ***Realism***

- *Accuracy*—the degree to which numerical results match the correct value
- *Realism*—the degree to which computational results represent reality



Higher the credibility, higher the Q

Quality Index, $Q = \sum_{i=1}^{2} W_i S_i$

Factors	Weights (W_i)	Score (S_i)
1. Accuracy		
2. Realism		

Weight Scheme (W_i)

$$0 \le W_i \le 1$$

$$\sum_{i=1}^{N} W_i = 1$$

Scoring Scheme (S_i)

Low	0 – 0.4
Medium	0.4 – 0.7
High	0.7 – 1.0

Users selects relative weights and assigns scores for the two factors

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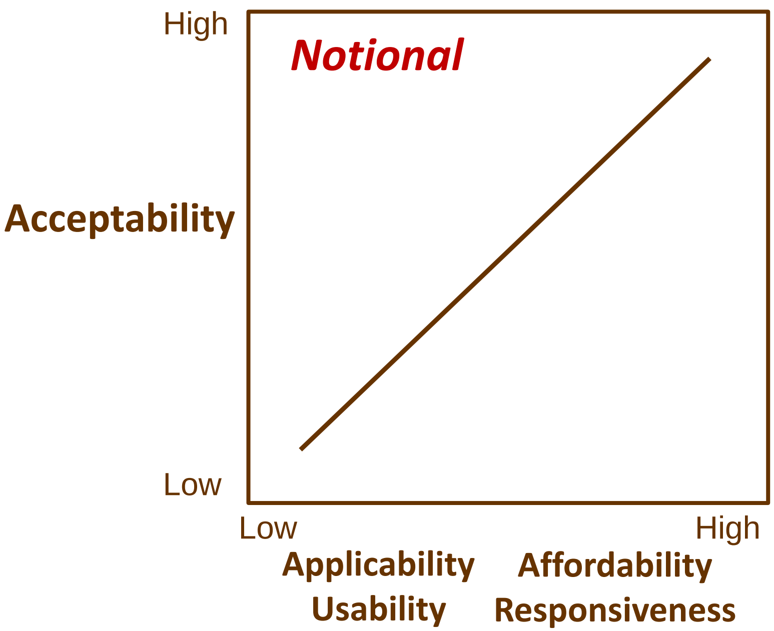
Acceptance Index (A) Estimation

Acceptance index (A) represents the level of* 'acceptability' of computational simulation by users and customers for a target application, and is a function of *applicability*, *usability*, *affordability*, and *responsiveness

- *Applicability*—the degree to which a method is suitable for the problem at hand
- *Usability*—how easy a computational procedure is for ['non-expert'] users to use
- *Affordability*—lower the cost (labor + computer), higher the affordability
- *Responsiveness*—lower the turnaround time (elapsed time from go-ahead to data delivery), higher the responsiveness



Users selects relative weights and assigns scores for the four factors

Acceptance Index, $A = \sum_{i=1}^{4} W_i S_i$

Factors	Weight (W_i)	Score (S_i)
1. Applicability		
2. Usability		
3. Affordability		
4. Responsiveness		

Weight Scheme (W_i)

$$0 \le W_i \le 1$$

$$\sum_{i=1}^{N} W_i = 1$$

Scoring Scheme (S_i)

Low	0 – 0.4
Medium	0.4 – 0.7
High	0.7 – 1.0

Higher the acceptability, higher the A

Effectiveness Index (*E*)

$$E = Q \times A$$