Air Vehicle Design

AOE 4065 – 4066

II. Air Vehicle Design Fundamentals

Course Module A8

Trade Studies

Kevin T. Crofton Department of Aerospace and Ocean Engineering
Blacksburg, VA

AOE 4065-4066:
Capstone Air Vehicle Design (AVD) Course Modules (CMs)

Overview of AVD Courses

I. Foundational Elements

F1. Design: *An Engineering Discipline*

F2. Systems and Systems Thinking

F3. Basics of Systems Engineering

F4. Decision Making with Ethics and Integrity

II. Air Vehicle Design Fundamentals

A1. Purpose & Process

Conceptual Design

A2. Understand the Problem

A3. Solve the Problem

A4. Initial Sizing: *Takeoff Weight Estimation*

A5. Initial Sizing: *Wing Loading and Thrust Loading Estimation*

A6. Cost Considerations

A7. Concept to Configuration: *Key Considerations*

A7A. Configuration Layout: *Drawings & Loft*

Conceptual & Preliminary Design

A8. Trade Studies

A9. Use of Software Tools

A10. Preliminary Design: *Baseline Design Refinement & Validation*

III. Project Management Topics

P1. Basics of Project Management and Project Planning

P2. Project Organization

P3. Roles & Responsibilities of Team Members

P4. Project Execution: *Teamwork for Success*

P5. Project Risk Management

P6. Delivering Effective Oral Presentations

P7. Writing Effective Design Reports

Disclaimer

Prof. Pradeep Raj, Aerospace and Ocean Engineering, Virginia Tech, collected and compiled the material contained herein from publicly available sources solely for educational purposes.

Although a good-faith attempt is made to cite all sources of material, we regret any inadvertent omissions.

CRUCIALLY IMPORTANT

CMs only introduce key topics and highlight some important concepts and ideas…but without sufficient detail.

We must use lots of Reference Material* to add the necessary details!

(*see Appendix in the Overview CM)

Outline

A8. Trade Studies

A8.1 General Remarks

A8.2 Design (or Configuration) Trades

A8.3 Mission Trades

A8.4 Technology Trades

A8.5 Carpet Plot Technique

What is a Trade Study?

Definition: A Trade Study is a decision-making method used to identify the best solution among a group of proposed solutions.

- The Defense Acquisition Encyclopedia

- A trade study examines qualified solutions against criteria such as cost, schedule, performance, weight, system configuration, complexity, the use of Commercial Off-the-shelf (COTS), and many others.
- Trade Studies are performed throughout an acquisition program, from concept development through system design.
- Trade studies involve sequentially making small changes to the design parameters and comparing the results to the baseline values. For example, the ‘best’ pair of wing loading and thrust loading for the lightest weight aircraft is determined using a trade study that systematically varies a set of baseline values and determines the effect on aircraft weight (see Sect. A8.5)

Why conduct trade studies?

To meet the goal of the Aircraft Design Team which is to

"INTEGRATE all…geometrical and dimensional requirements, equipment, structural components…into a vehicle that is BALANCED with respect to flight in all phases of its flight envelope and ground operations…Satisfy the DESIRED requirements with the <u>lightest weight</u> (or least cost) vehicle."

-- Nathan Kirschbaum

Trade Studies are key to achieving the design goals

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Purpose of Trade Studies in Conceptual Design Phase

- **We have made initial estimates of** W_{TO}, W/S, T/W
- **We *assumed (or estimated)* values of several parameters,** AR, C_{D_0}, L/D, $C_{L_{max}}$, *sfc*, *V*, *cruise altitude*, **etc.**

- **Can we say that we have the *BEST (lightest weight) vehicle* that is *balanced* and *satisfies ALL customer requirements*?**

Trade Studies (aka Parametric Studies) are conducted to produce evidence to answer this question in the affirmative!

Bottom Line

- **Trade studies are pervasive in design**
- **The studies establish a basis for design decisions**

Caution: Use Trade Study results in conceptual design as "indicators" or "flags," not definitive answers—too early in the game!

"Only through the trade studies will the true optimum aircraft emerge." -- Raymer

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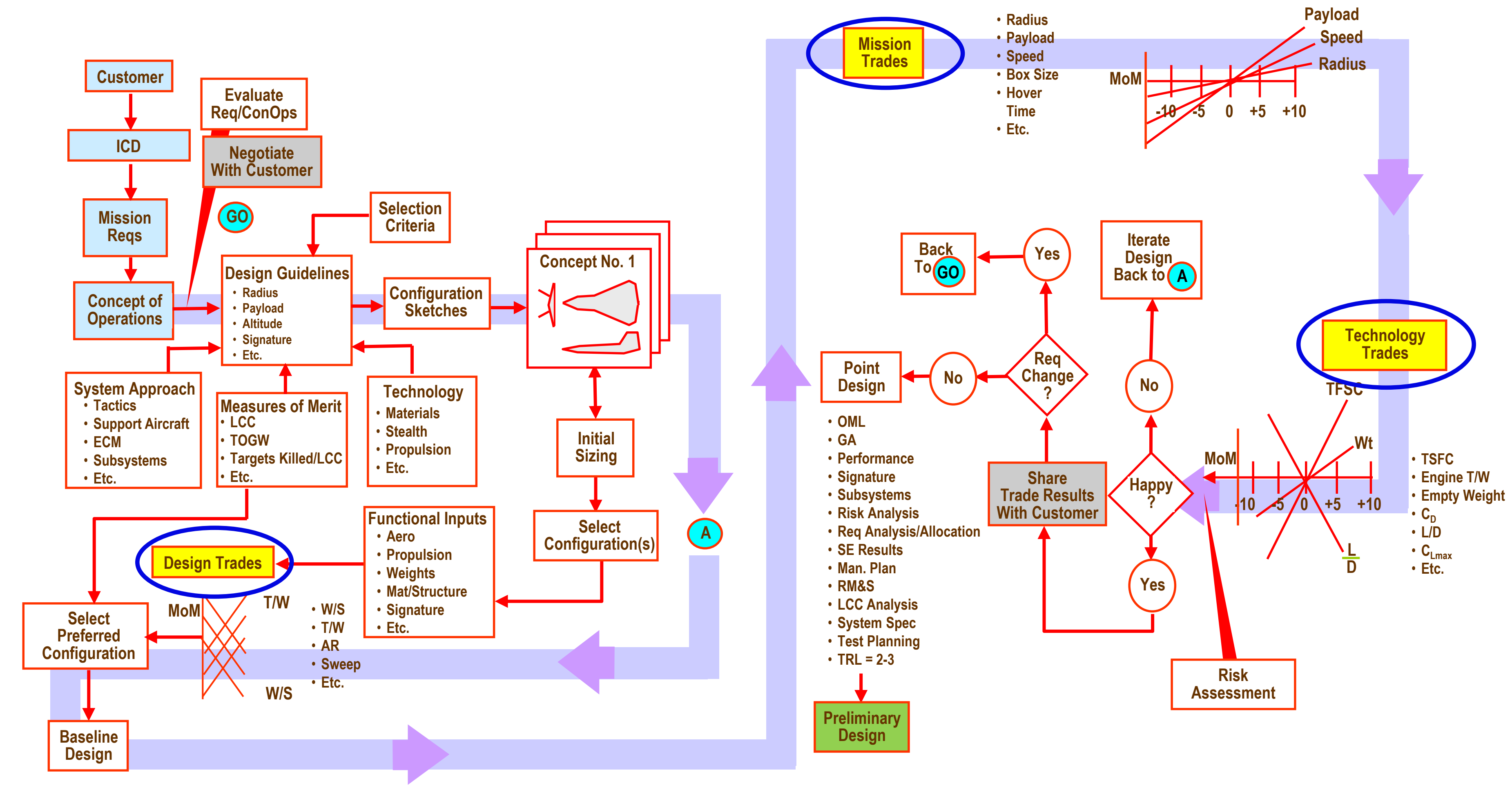
Types of Trade Studies in Aircraft Conceptual Design



Trade Studies help you select parameters for best design

Trade Studies Challenges

- ***Problem:*** **Of a large number of parameters that affect aircraft design,** ***what combination of parameters will give the BEST design (lightest–weight aircraft or another Measure of Merit such as cost or fuel consumption) while meeting all requirements?***
- ***"Brute-force" Approach:*** **Sort through all possible combinations of numerous parameters in a systematic manner to find the best set.**
  - Easier said than done! Impractical to do by hand
  - Motivator for computer-assisted Multidisciplinary Design Optimization (MDO)
- **Performing parametric analyses is a tall order.**
- **Collecting and compiling all results for comparative evaluation to select the best combination is even more daunting.**
- **Visual display of Results (multi-dimensional data) that easily "convinces" the customer that you indeed have the best combination is priceless!**

Example of Parametric Study for Cost* Optimization (VT Student Design Project)

	Preferred Concept	TS 6	TS 7	TS 8	TS 9	TS 10
Fuel Type	H2	H2	H2	H2	H2	H2
Loiter Velocity (kts)	150	200	200	200	150	175
Altitude (ft)	60000	65000	60000	65000	60000	65000
Endurance (days)	8	10	8	8	11	11
Payload (lbs)	2000	2000	3000	3000	2000	2000
TOGW (lbs)	13159	20186.21	20591.96	19206.49	14392.23	21005.86
Fuel Weight (lbs)	3878	8375.24	7677.5	6761.95	4658.48	8960.13
Aspect Ratio	40	40	40	40	40	30
Wing Span (ft)	260	260	260	260	260	260
Wing Area (square ft)	1690	1690	1690	1690	1690	2253.33
Wing Loading (psf)	7.79	11.94	12.18	11.36	8.52	9.32
Lift Coefficient (Loiter)	1.08	1.18	0.95	1.12	1.18	1.2
Loiter Power Required (hp)	115.46	245.04	226.66	236.86	129.62	279.14
Climb Power Required (hp)	314.85	550.89	538.66	527.87	347.69	597.41
Cruise Velocity (kts)	150	150	150	150	100	100
Aircraft per System	2	2	2	2	2	2
Cost (millions)	157.71	252.82	258.19	246.39	166.23	237.31

***Cost was the key Measure of Merit (MoM)**

Source: 2013-14 NASA HALE UAV Team (Lead: Schmit)

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Look at the number of significant figures for some parameters, e.g., TOGW, Wing Loading

See anything wrong?

***Cost was the key Measure of Merit (MoM)**

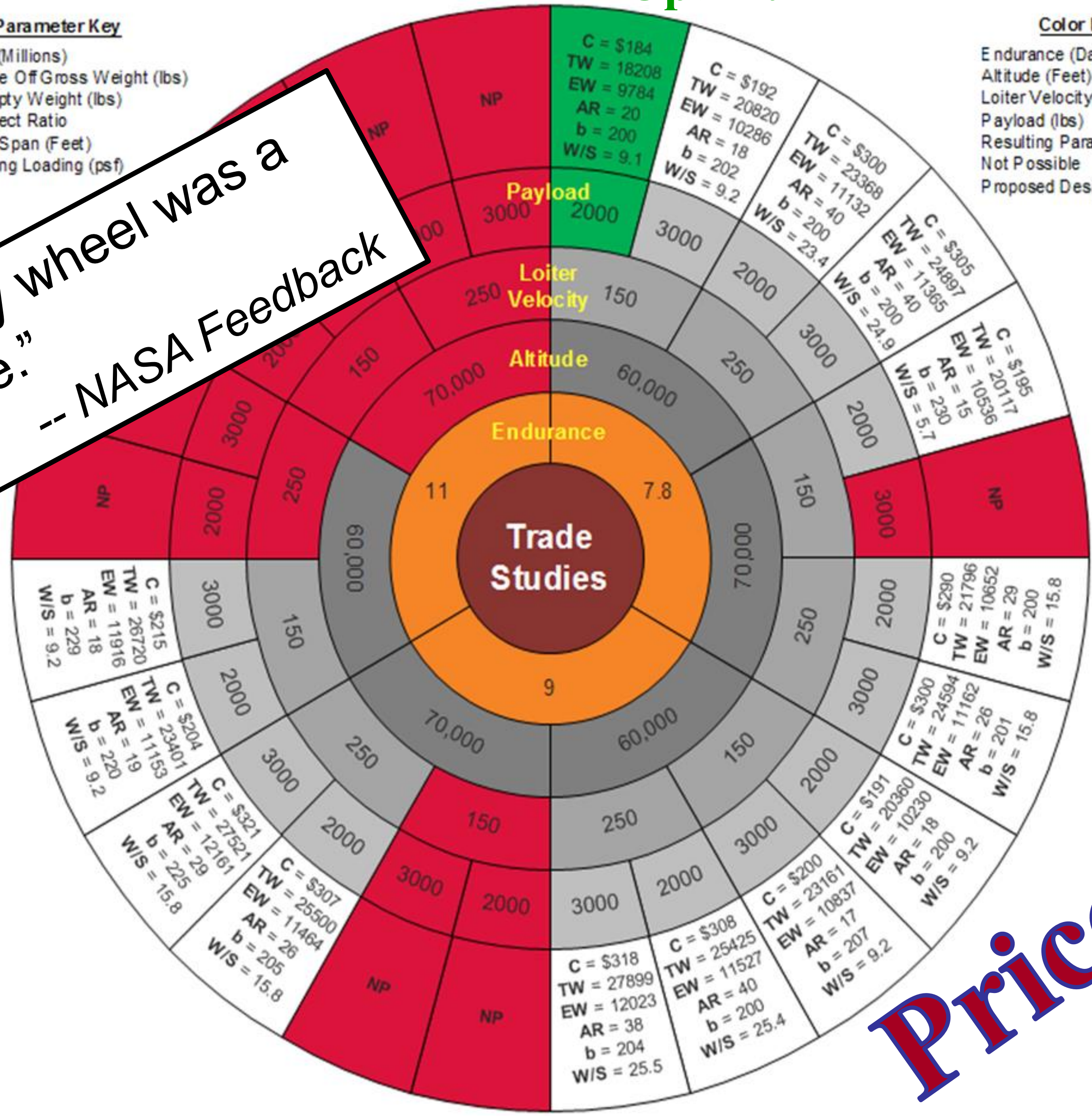
Source: 2013-14 NASA HALE UAV Team (Lead: Schmit)

Visual Display of Results

Parameter Key
- C - Cost (Millions)
- TW - Take Off Gross Weight (lbs)
- EW - Empty Weight (lbs)
- AR - Aspect Ratio
- b - Wing Span (Feet)
- W/S - Wing Loading (psf)

Color Key
- Endurance (Days)
- Altitude (Feet)
- Loiter Velocity (Knots)
- Payload (lbs)
- Resulting Parameters
- Not Possible
- Proposed Design

"Optimum"



"Trade study wheel was a great figure."
-- NASA Feedback

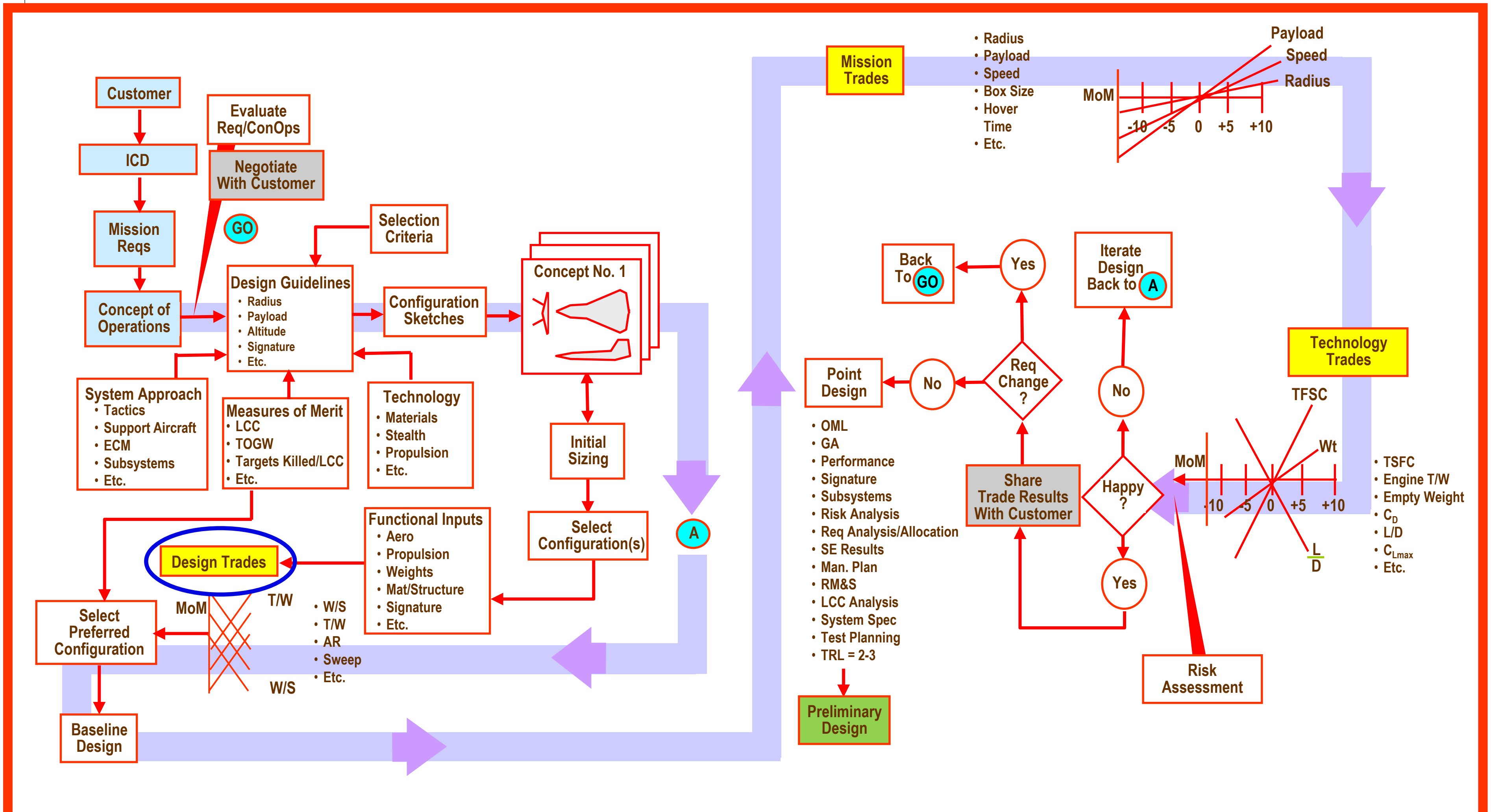
Priceless!

Source: 2013-14 NASA HALE UAS Team (Lead: Schmit)

Outline

A8. Trade Studies

Types of Trade Studies in Aircraft Conceptual Design



Trade Studies help you select parameters for best design

Design Trades
(aka Configuration Trades)

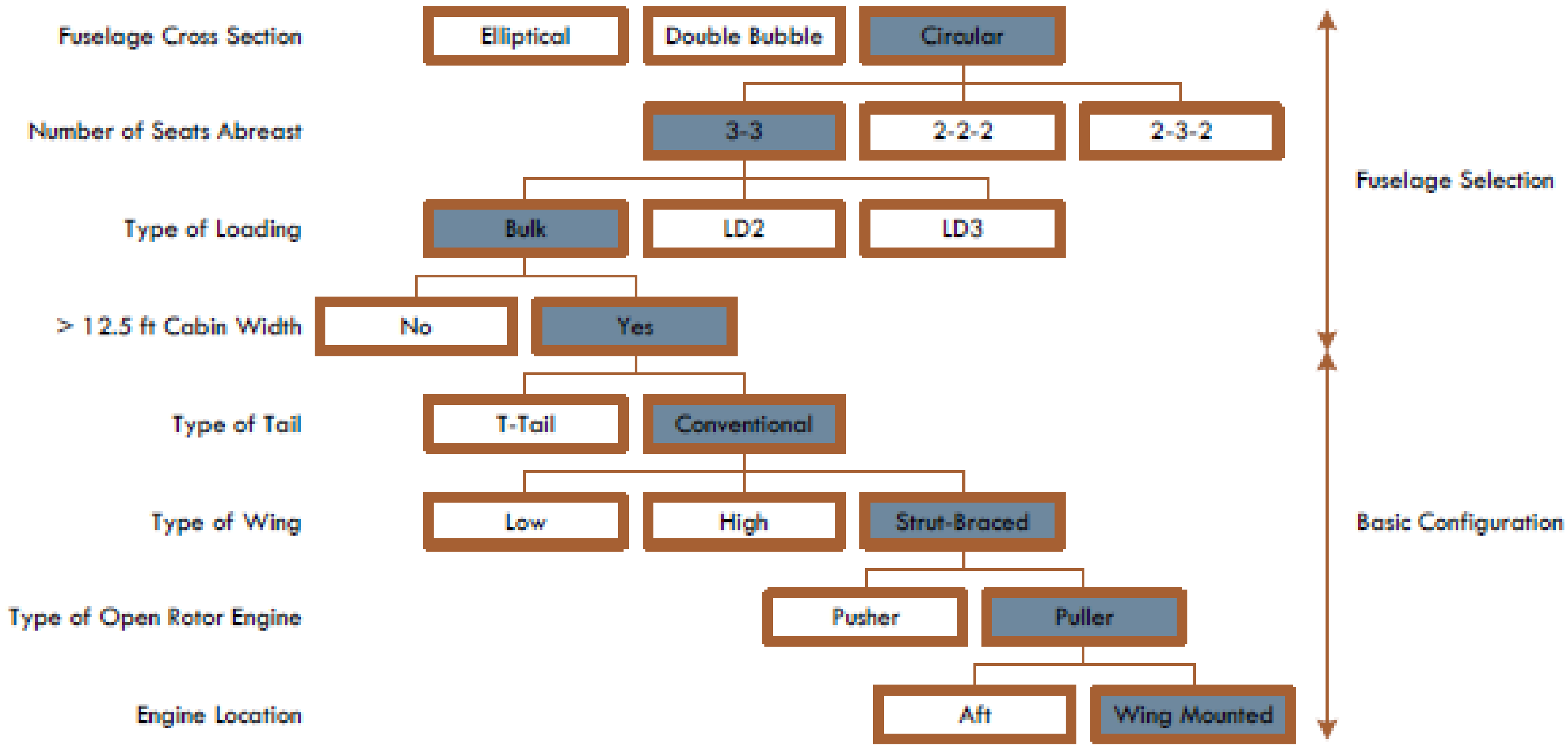
What would be the impact on MoM if design features were changed?

Examples of Design Features

- Wing size (affects wing loading)
- Wing shape (sweep, AR, taper ratio, etc.)
- High-lift devices (mechanical vs. powered)
- Fuselage size and shape (fineness ratio, cross-sectional area distribution, etc.)
- Tail configuration (aft tail, canard, tailless)
- Stability level (degree of static margin)
- Engine (turboprop, turbofan, turbojet, number of engines, bypass ratio, podded or buried, etc.)
- Inlet and nozzle (location, type)
- Materials (metals or composites)
- …

Design Trades facilitate selection of the right combination of design features for the most efficient vehicle to meet MoMs

Example: Critical Design Choices for Configuration Down-selection

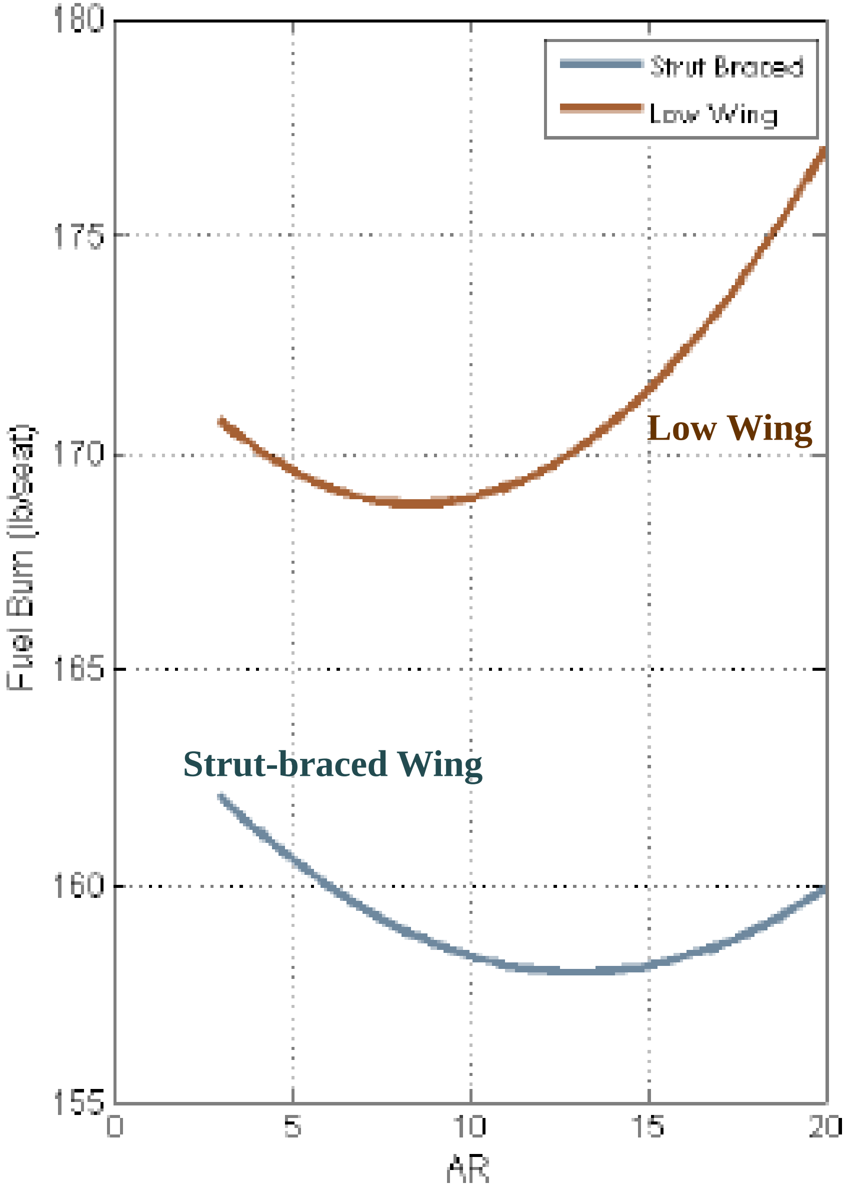


Source: 2009-10 AIAA UG Team Aircraft Design Winning Team, Cal Poly, SLO

Example: Best *AR* for Fuel Efficiency

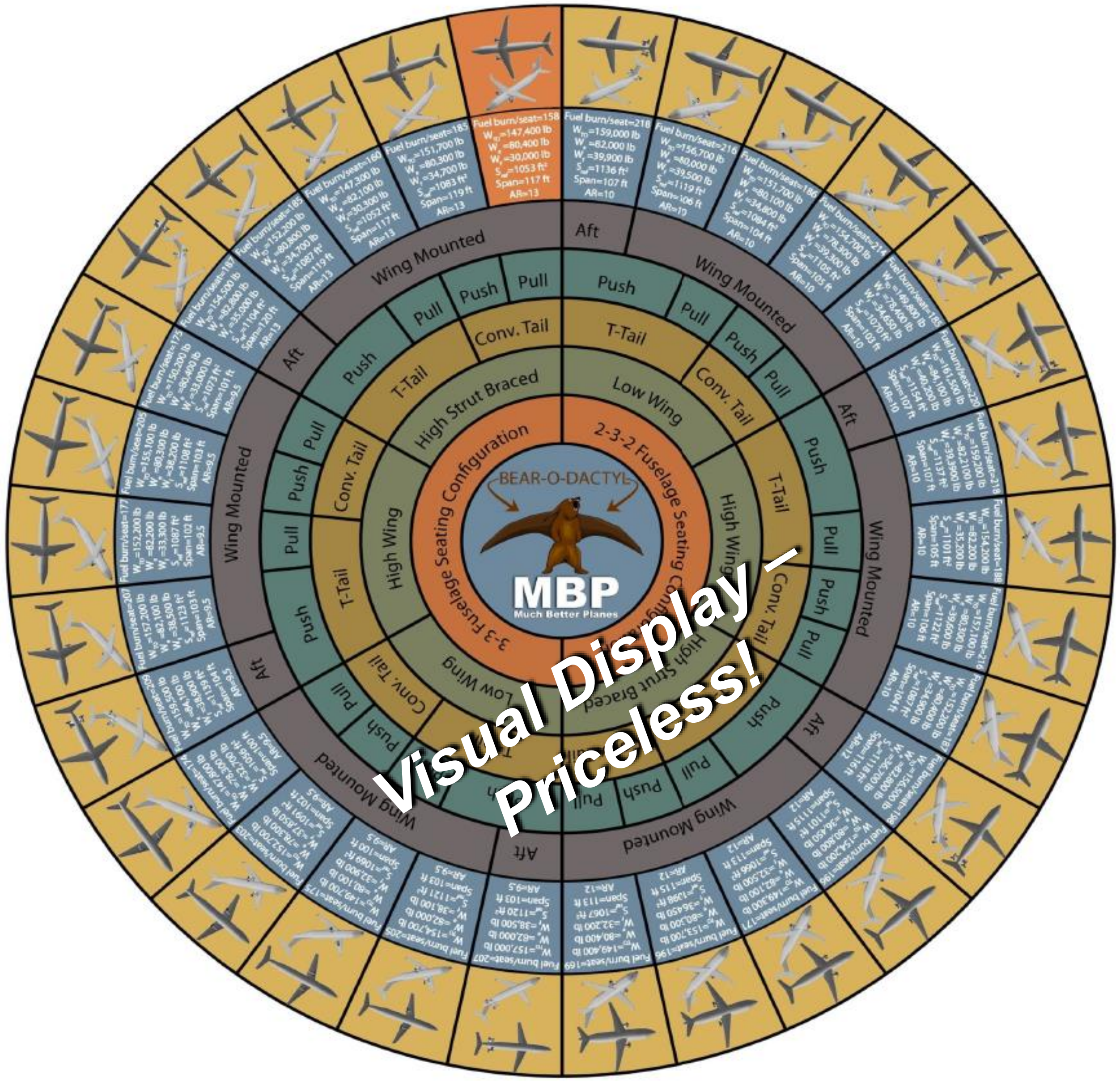
Design Objective

Minimize Fuel Burn for a Passenger Transport Aircraft



Source: 2009-10 AIAA UG Team Aircraft Design Winning Team, Cal Poly, SLO

Example of Configuration Trade Study



Source: 2009-10 AIAA UG Team Aircraft Design Winning Team, Cal Poly, SLO

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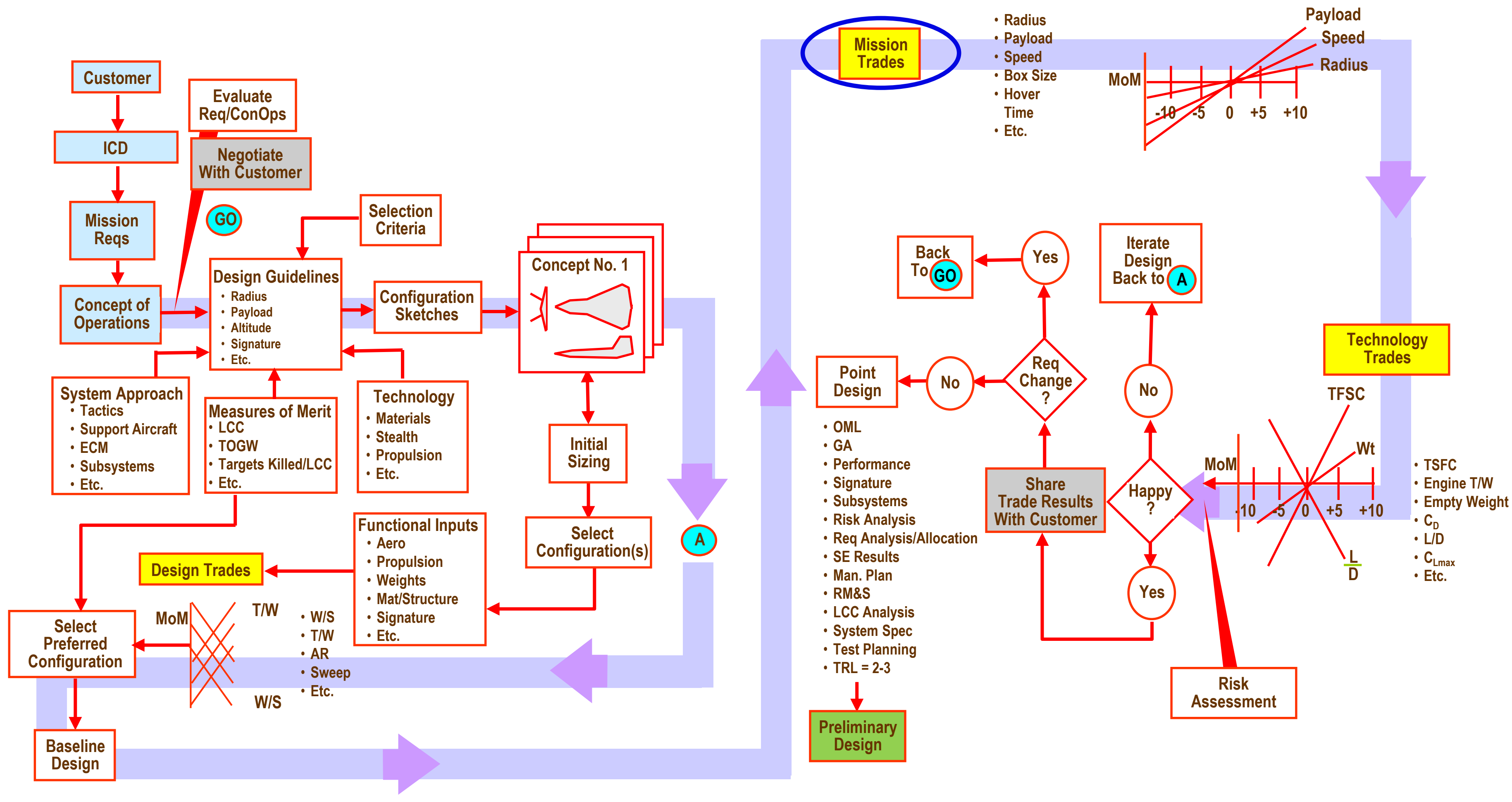
Types of Trade Studies in Aircraft Conceptual Design



Trade Studies help you select parameters for best design

13 August 2024

Courtesy of Lee Nicolai

Mission Trades

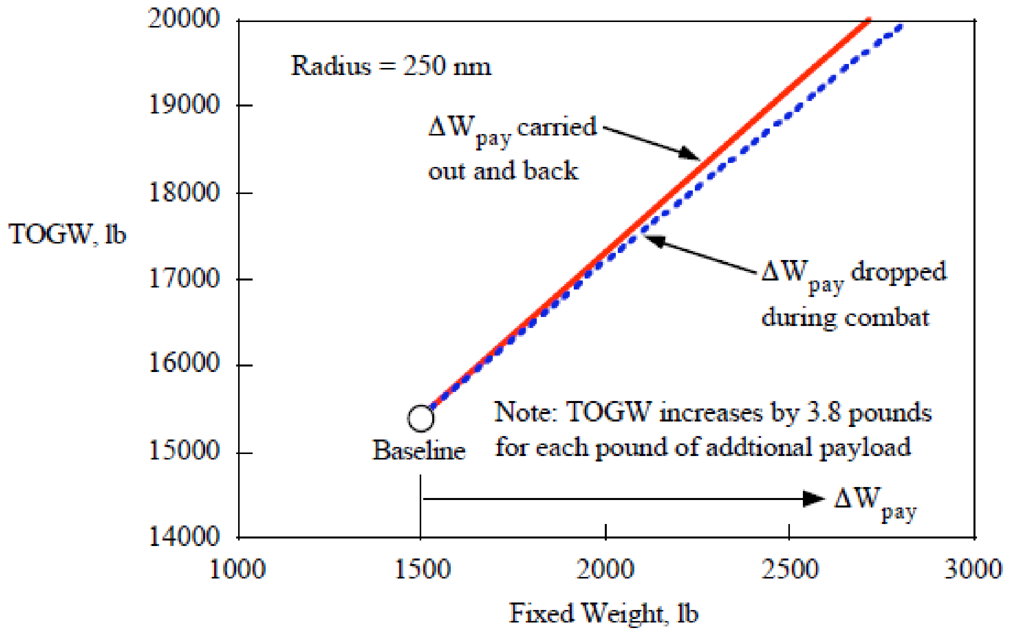
What **would be the impact on TOGW** ***if*** **we changed Payload (±25%), Range (±25%), Endurance (±25%), etc.?**

- Trade Study of TOGW for varying fixed weight gives weight sensitivity ratio, $\Delta W_{TO}/\Delta W_{payload}$, of 3.8!

- It is also called ***aircraft growth factor***.
  - Typically, larger the payload fraction, larger the growth factor.

Example:

W_{TO} Variation with Payload for Fixed Radius

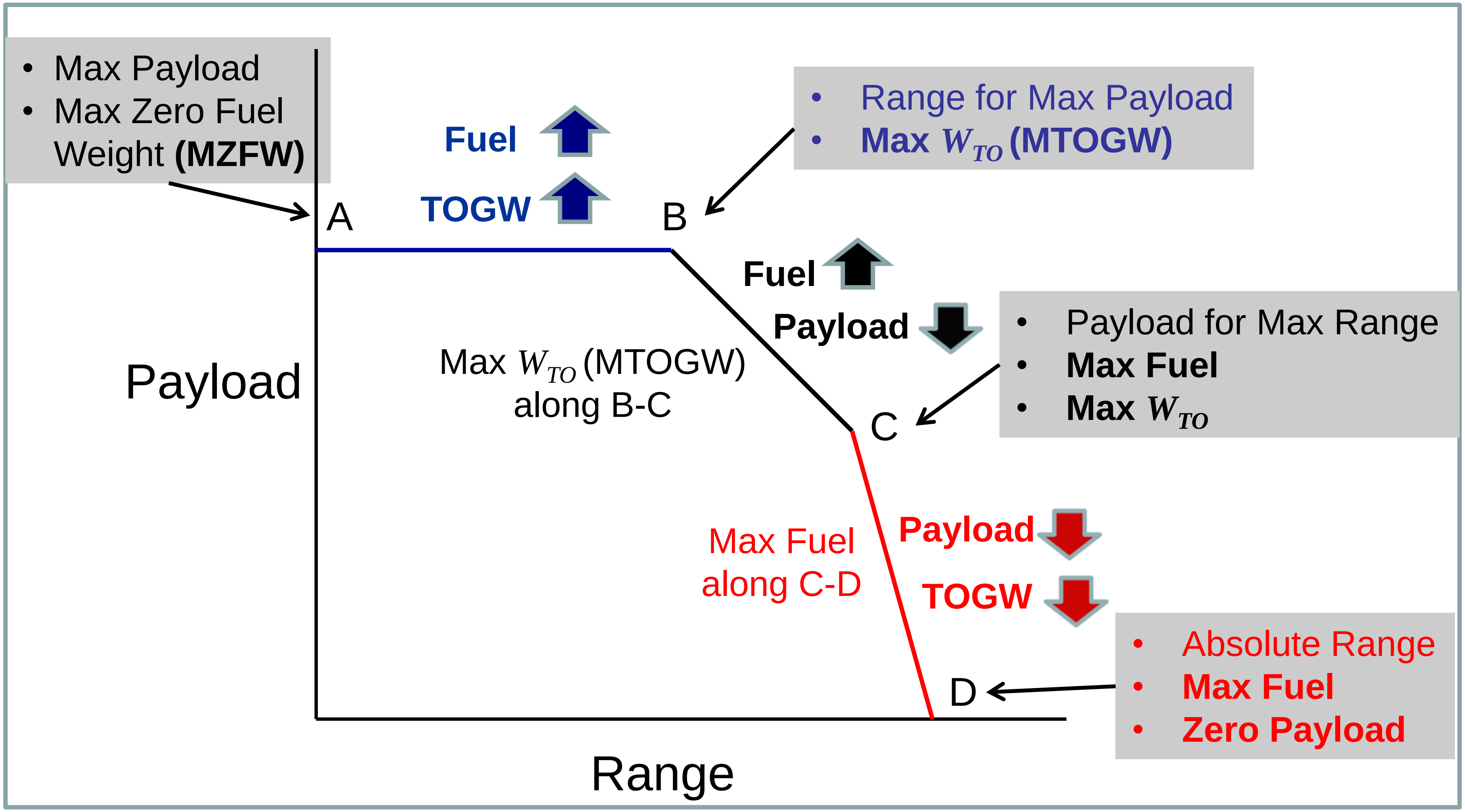


Source: Fig. 5.6, Ref. AVD 1 (Nicolai and Carichner)

- Use Mission Trade results to *identify requirements* that might be *dominant design drivers*—the ones to which TOGW is most sensitive.

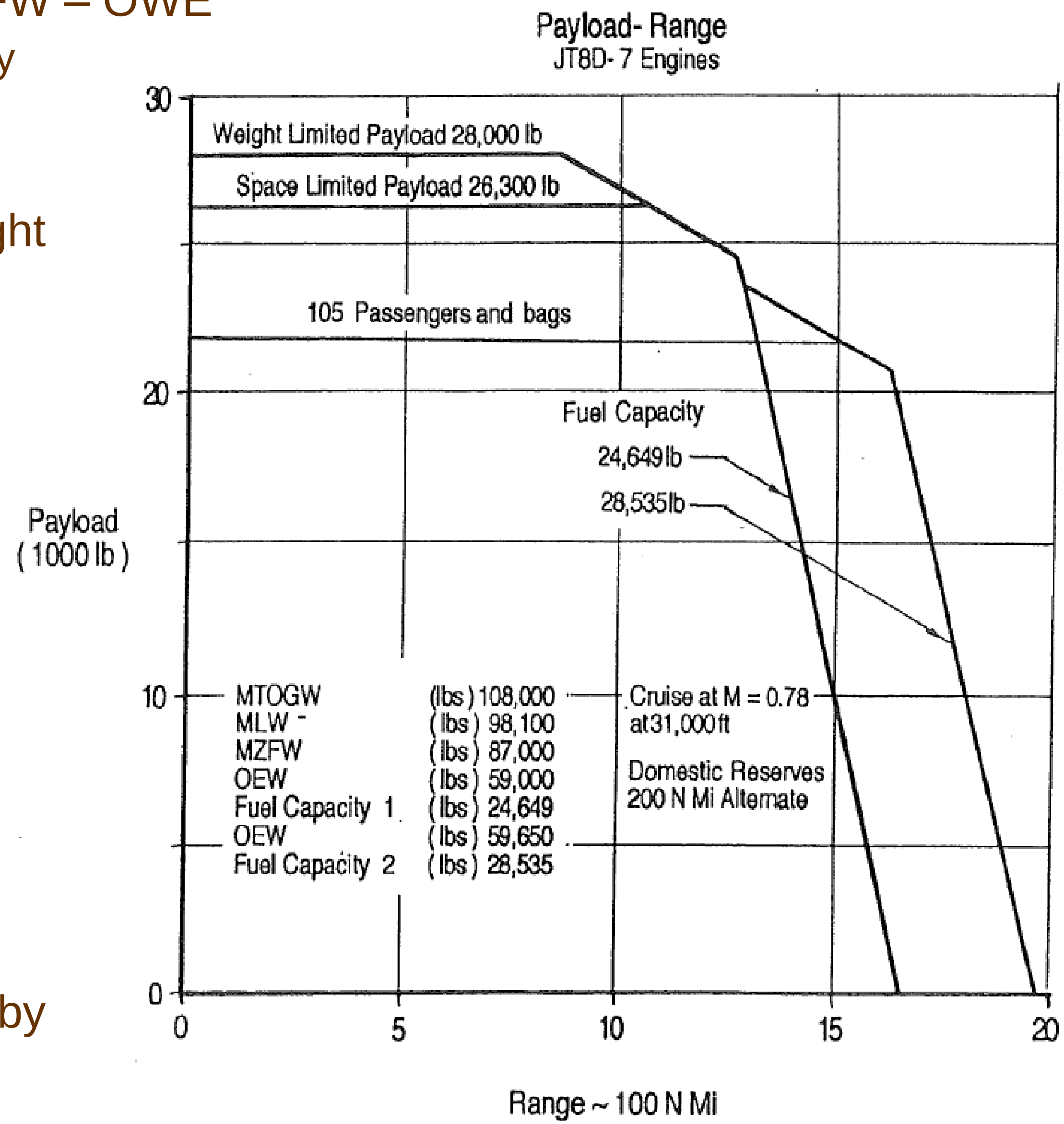
Payload-Range Trade

- Conducted for aircraft with range or payload as key drivers
- Payload-Range plots that are useful for interactions with customers; may be helpful in "refining" requirements



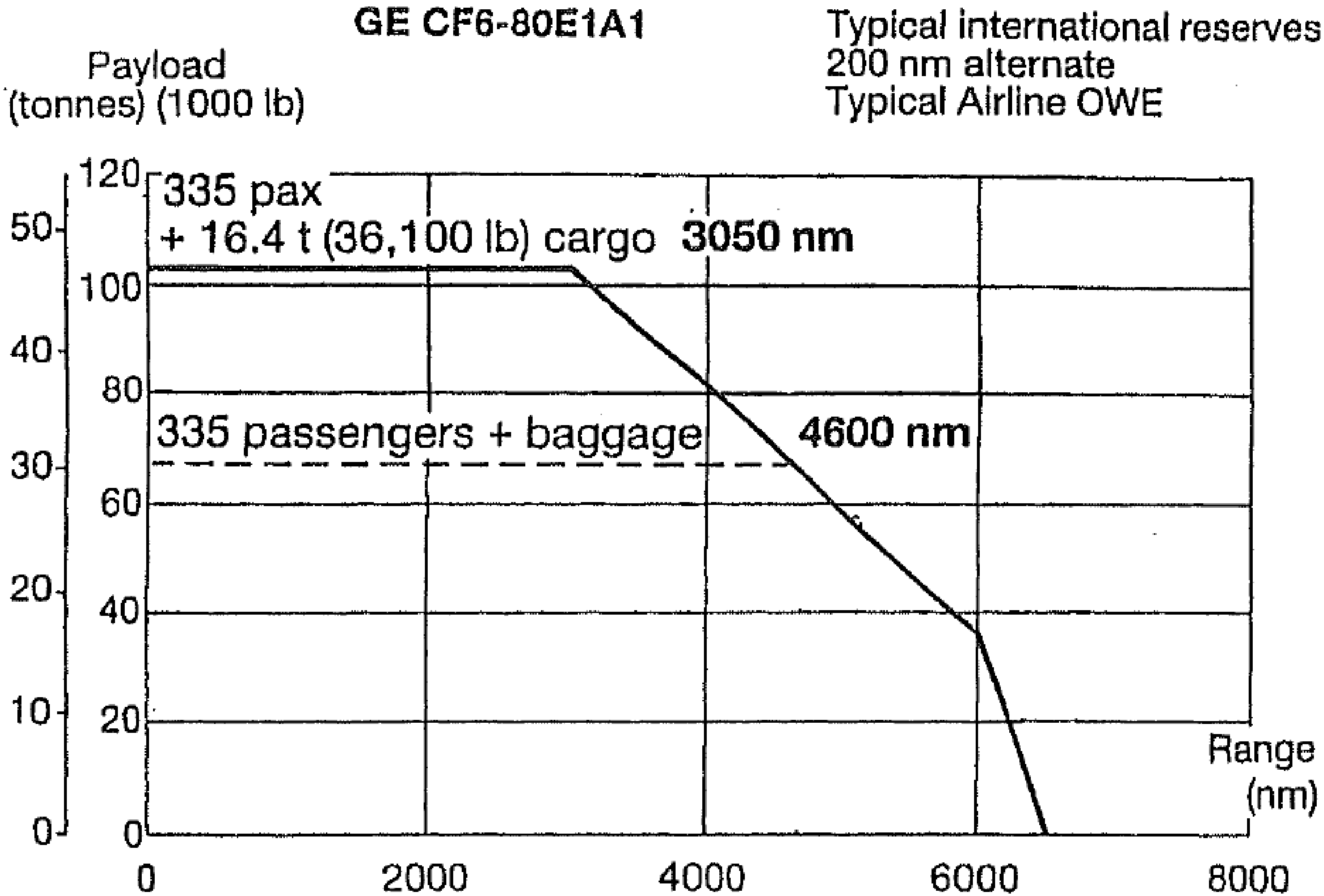
A Typical Payload-Range Curve

- Weight Limited Payload = MZFW – OWE
  - Space-limited payload is usually
  - slightly lower
- MZFW = MTOGW – Fuel Weight
- OWE = W_{empty} + $W_{nonexpendables}$
  - 2nd term covers Operational Items such as crew
  - No payload or cargo or fuel
- MTOGW sets the range based on (passengers + bags) payload
- Greater range for the same amount of (passenger + bags) payload can be achieved only by increasing fuel capacity



Source: Fig. 15-4, Ref. AVD 13 (Schaufele)

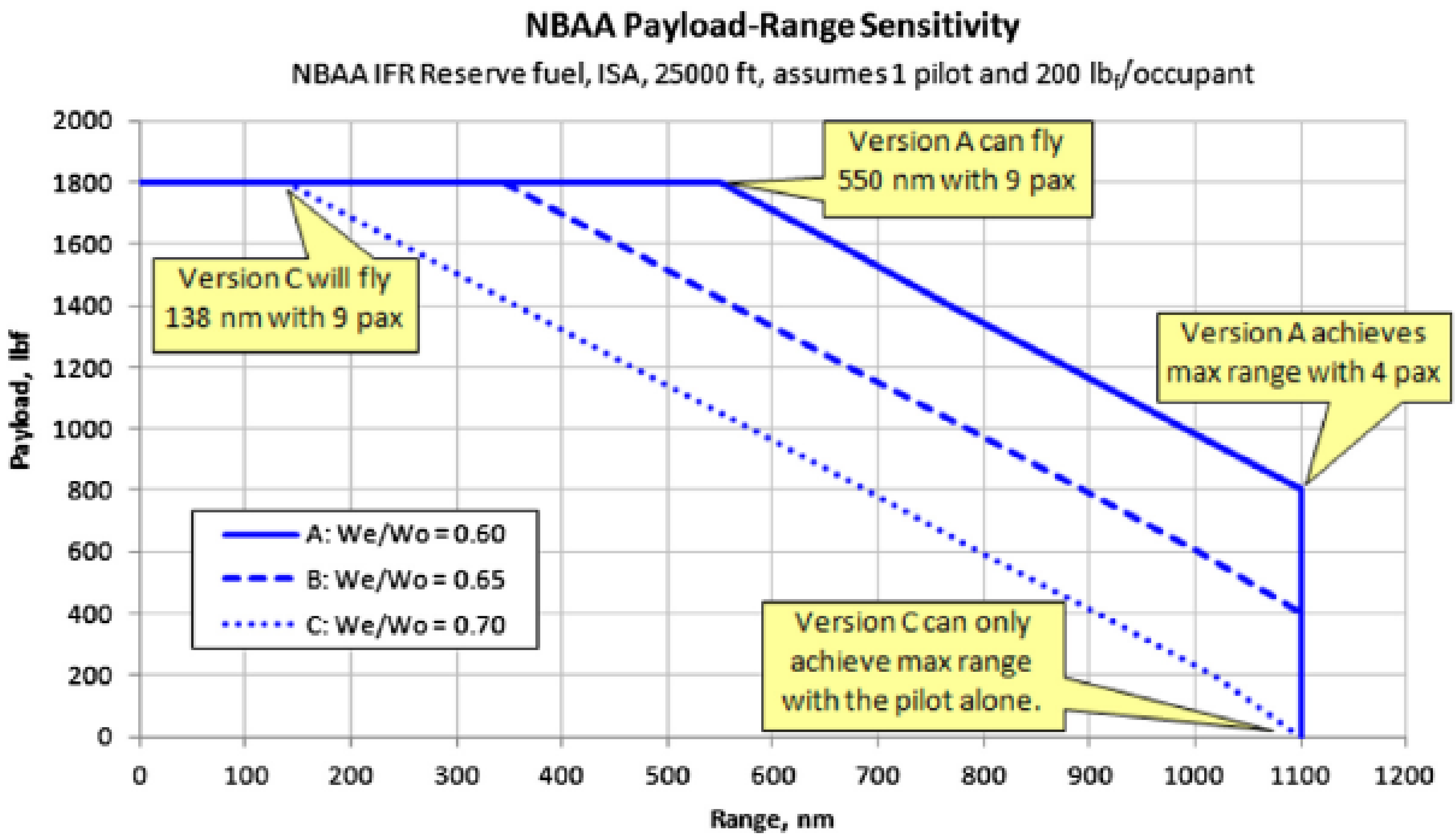
A330-300 Payload-Range Capability



Source: Fig. 15-1, Ref. AVD 13 (Schaufele)

Payload-Range Parametric Study

- Nine-passengers, each 200 lb_f
- Maximum TOGW of 7,500 lb_f & max fuel weight of 2,000 lb_f



Empty Weight would be a dominant design driver!

Source: Fig. 20-17, Ref. AVD 4 (Gudmundsson)

Outline

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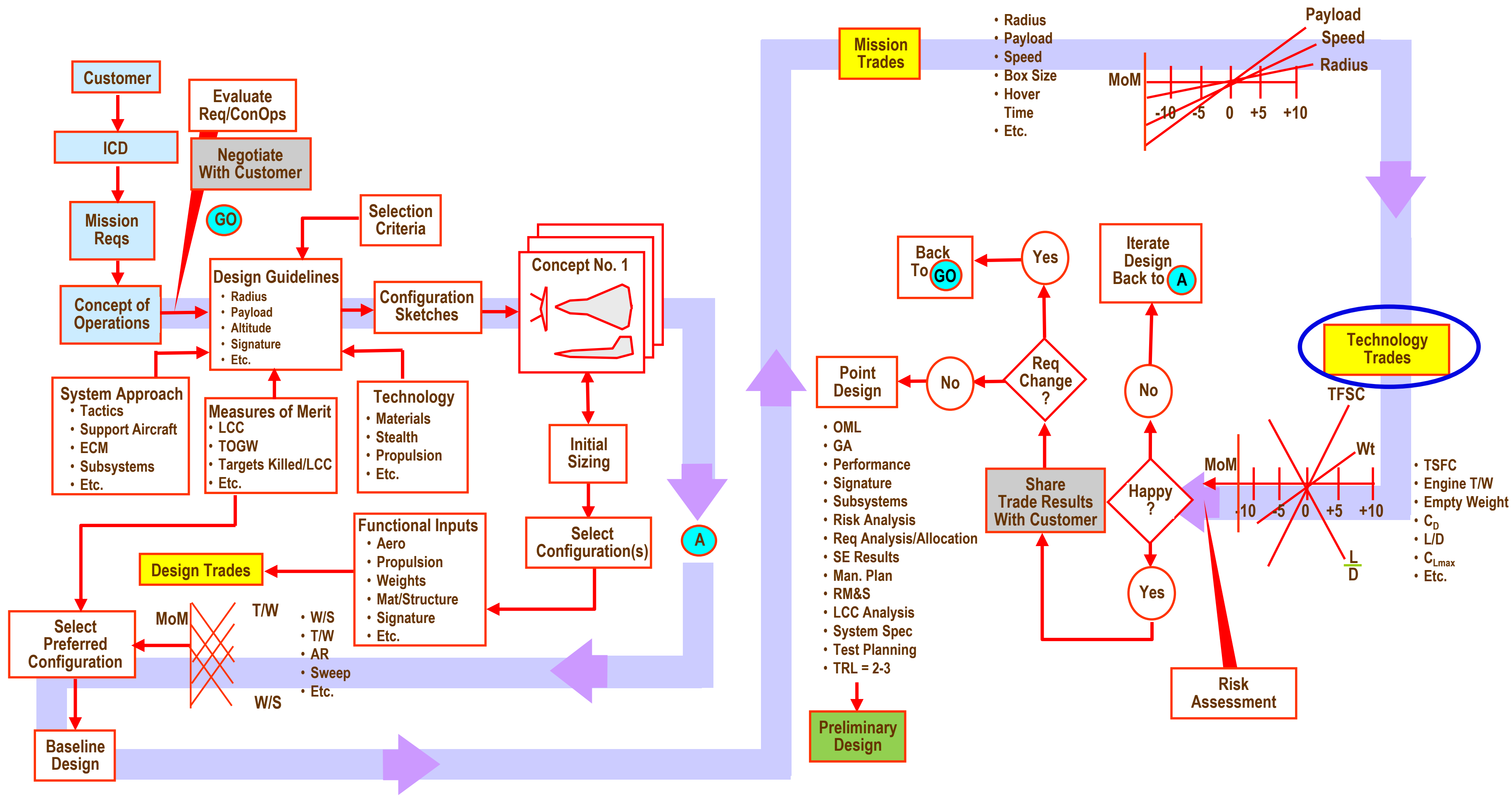
Types of Trade Studies in Aircraft Conceptual Design

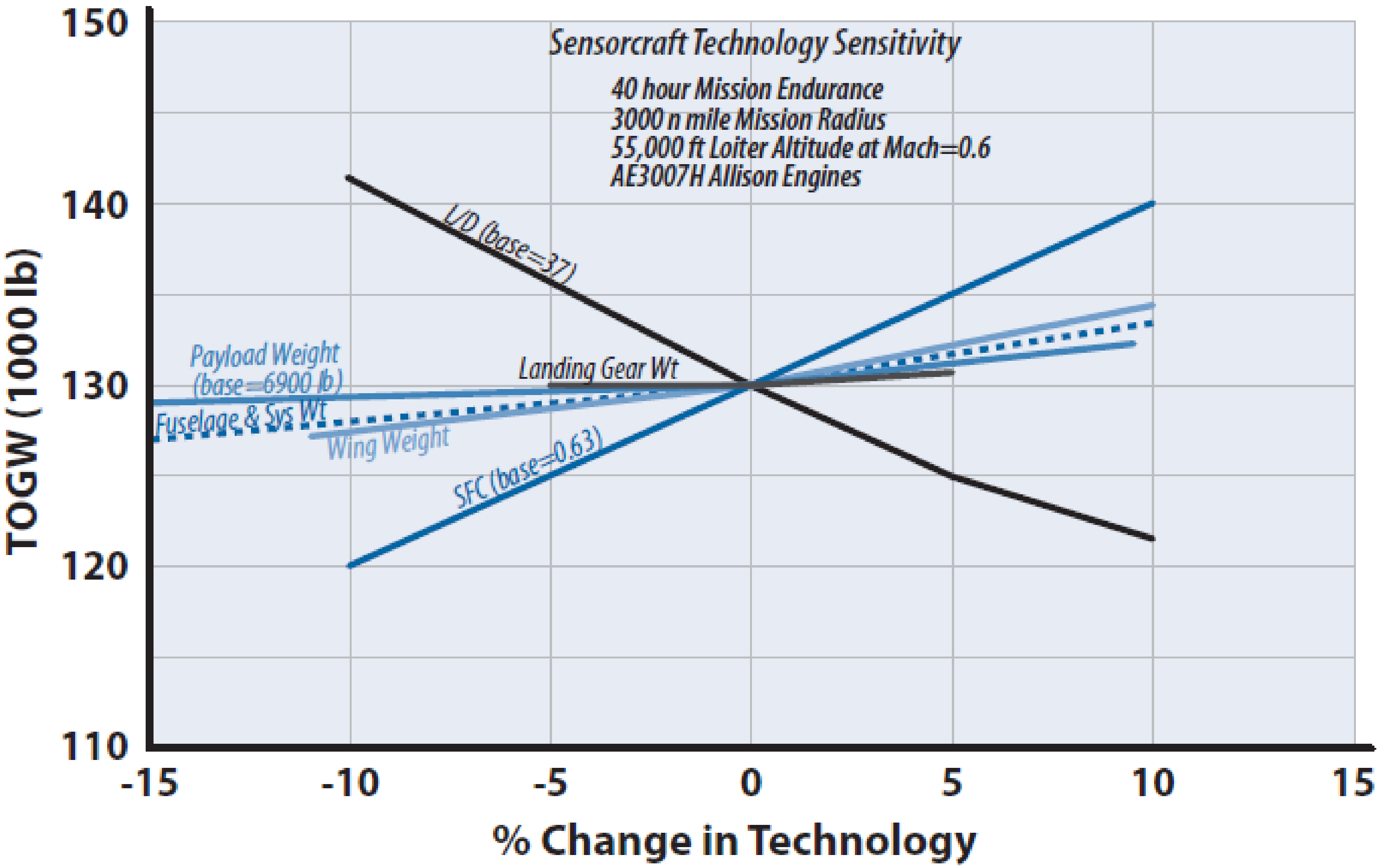


Trade Studies help you select parameters for best design

Courtesy of Lee Nicolai

Technology Trades

What would be the impact on TOGW (or some other MoM) if we <u>could</u> change L/D (±10%), sfc (±10%), Wing Weight (±10%), etc., etc.?



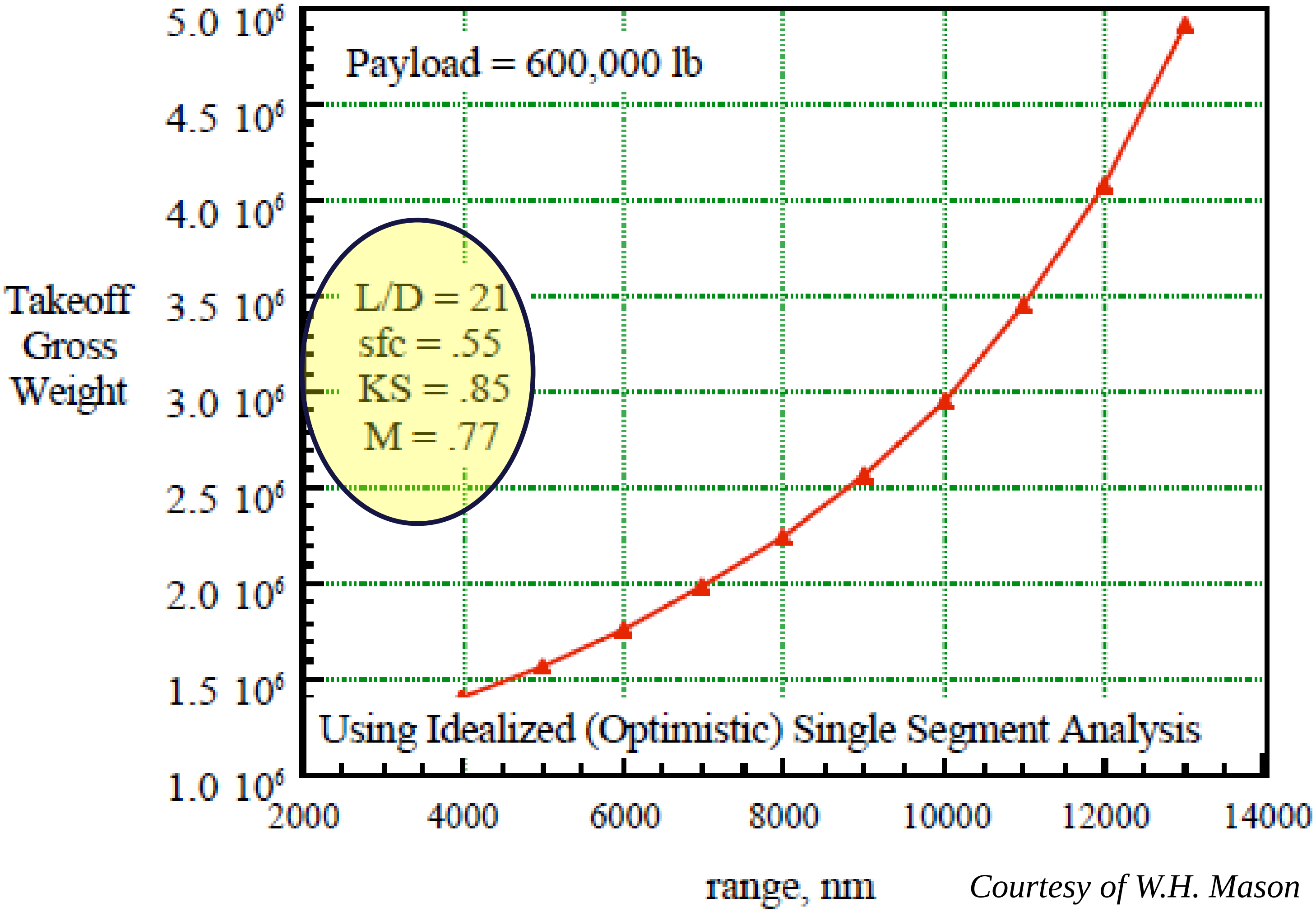
Source: Fig. 25.7, Ref. AVD 1 (Nicolai and Carichner)

Benefits of Technology Trades

- **Technology Trades provide a basis for Risk Analysis**
  - Consequence (or impact) of technology failing to perform
  - Probability of technology failing to perform

- **Results useful for Technology Investment Planning**
  - Payoffs of accelerated technology maturation

W_{TO} Variation with Range for Fixed Payload



Courtesy of W.H. Mason

For a specified technology level, "exponential" growth in TOGW could limit maximum Range

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A8.5 Carpet Plot Technique

To facilitate learning about parametric studies for multiple independent variables…

…we will talk about Carpet Plots

- *"The graphed values of a function of more than one variable, read from an ordinate at points located by the intersection of curves of constant values of each of the variables."* –Collins Dictionary
- A powerful techniques widely used to depict the response of a system of two or more independent variables and one or more dependent variables

Consider an example with three parameters (*start small*!)

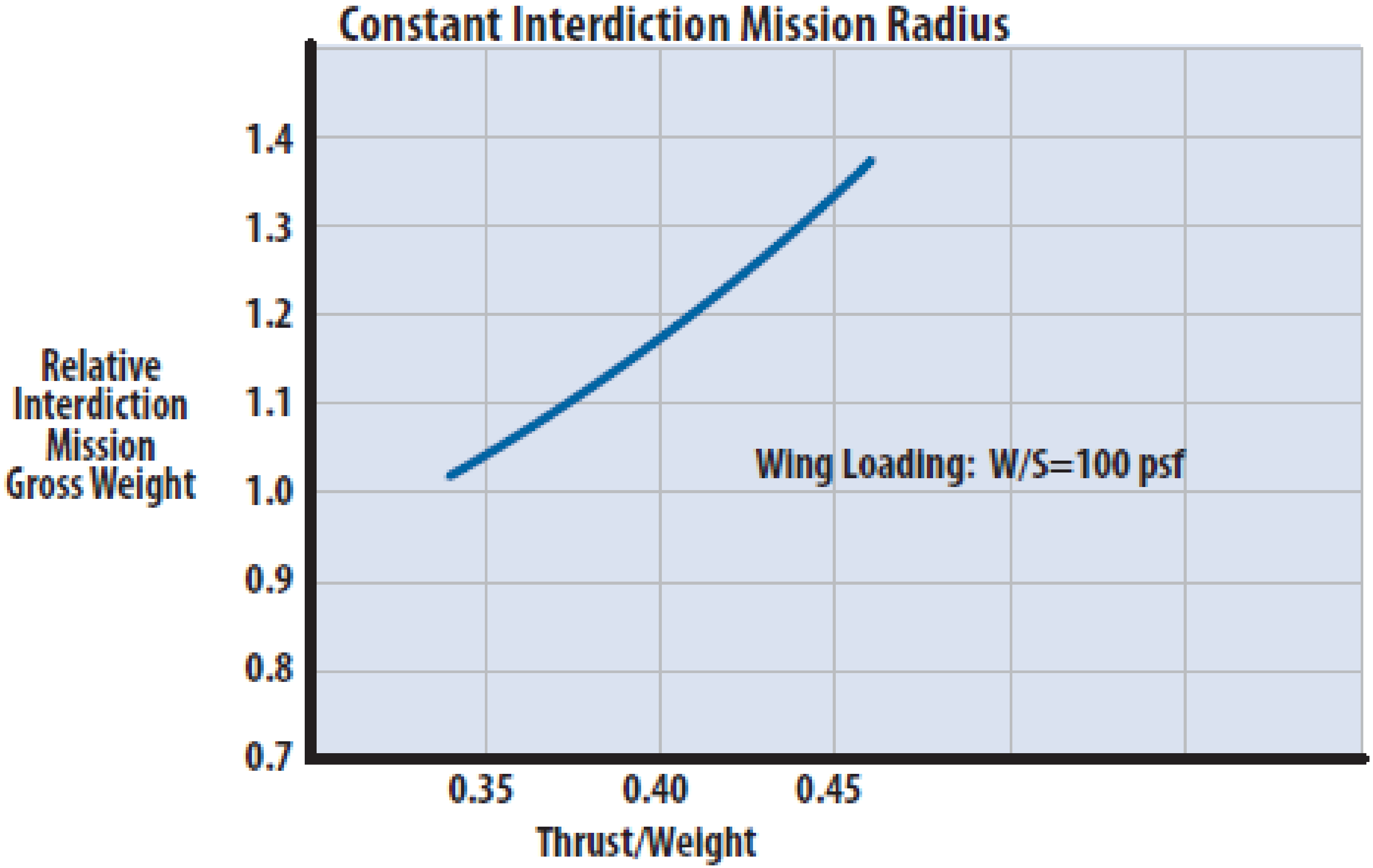
- Take-off Gross Weight, W_{TO} *(Dependent Variable)*
- Wing Loading, W/S *(Independent Variable)*
- Thrust Loading, T/W *(Independent Variable)*

Questions to answer for this example

1. How does W_{TO} change with different combinations of W/S and T/W?
2. What combination best meets customer needs?

Carpet Plots: Step A (Starting Point)

Step A. Basic **Two-variable Plot**

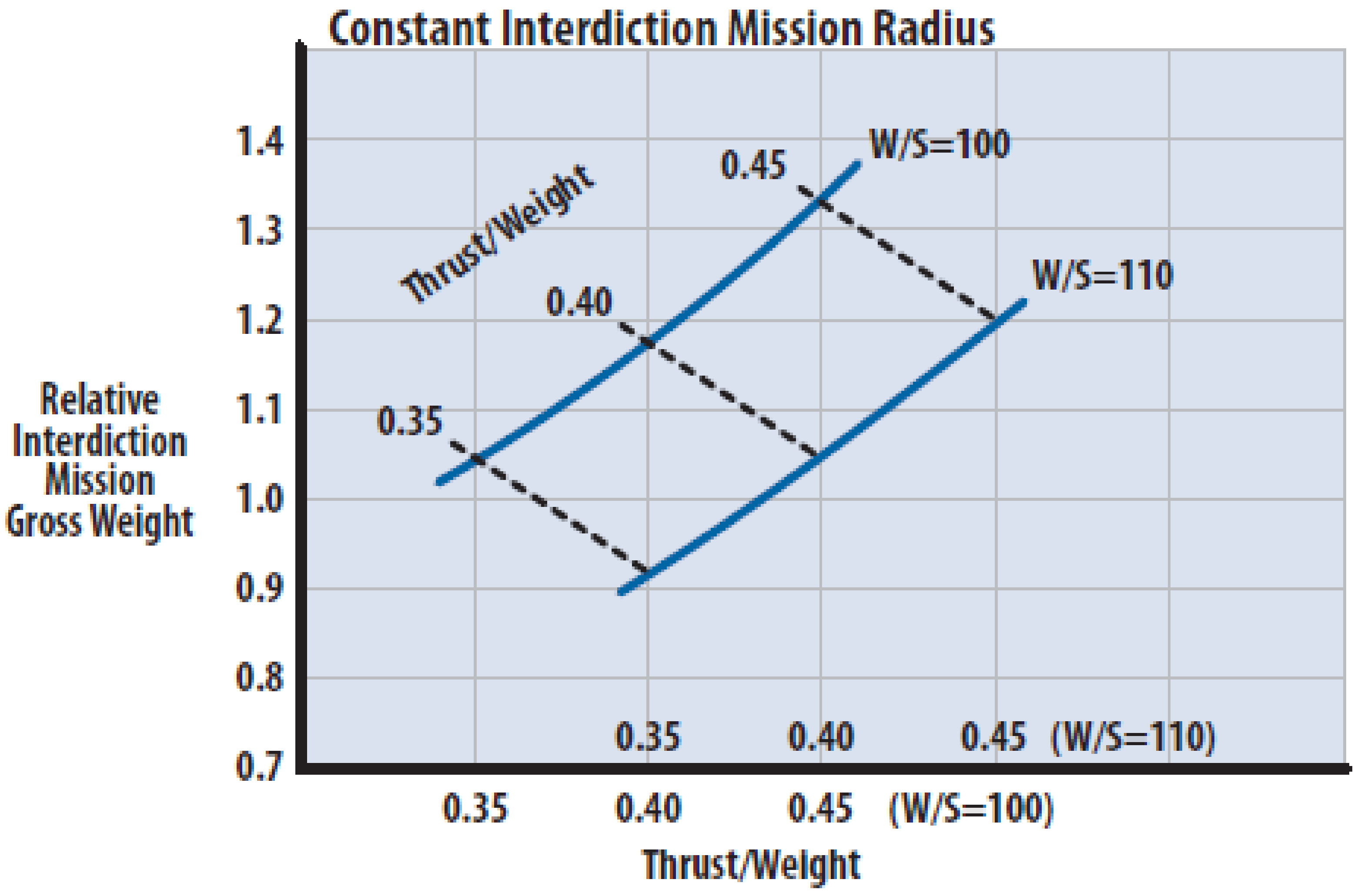


Make Individual Plots for <u>Several</u> Wing-loading Values

Source: Figure 25.3, Ref. AVD 1 (Nicolai and Carichner)

Carpet Plots: Step B

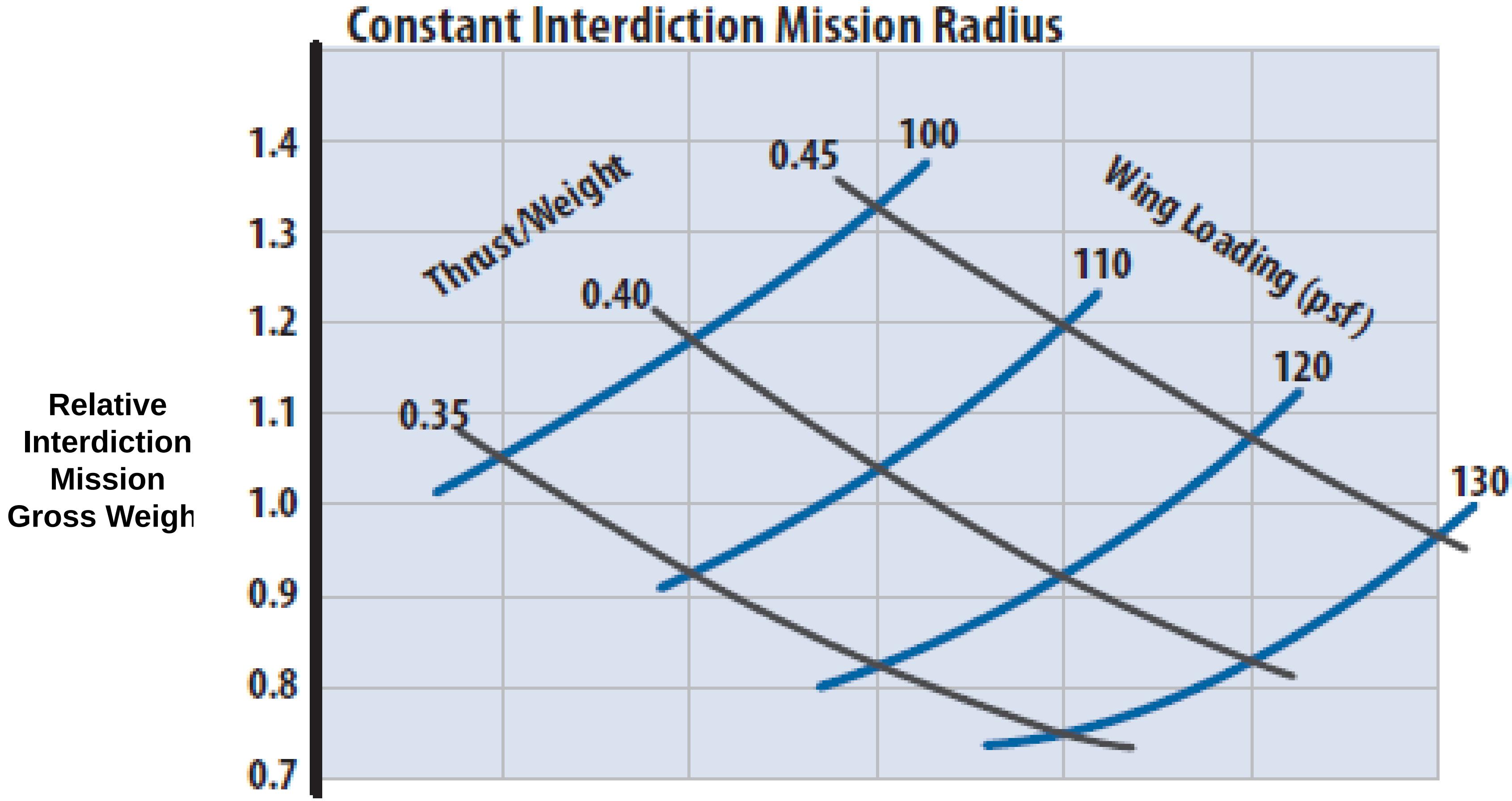
Step B. Three variables with ***abscissa scale shift***



Source: Figure 25.3, Ref. AVD 1 (Nicolai and Carichner)

Carpet Plots: Step C

Step C. Completed Carpet Plot

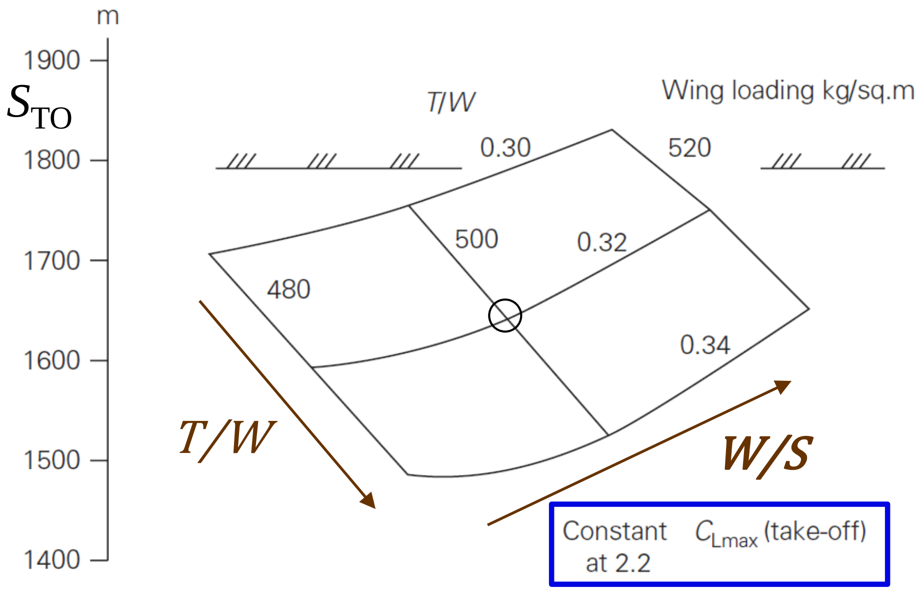


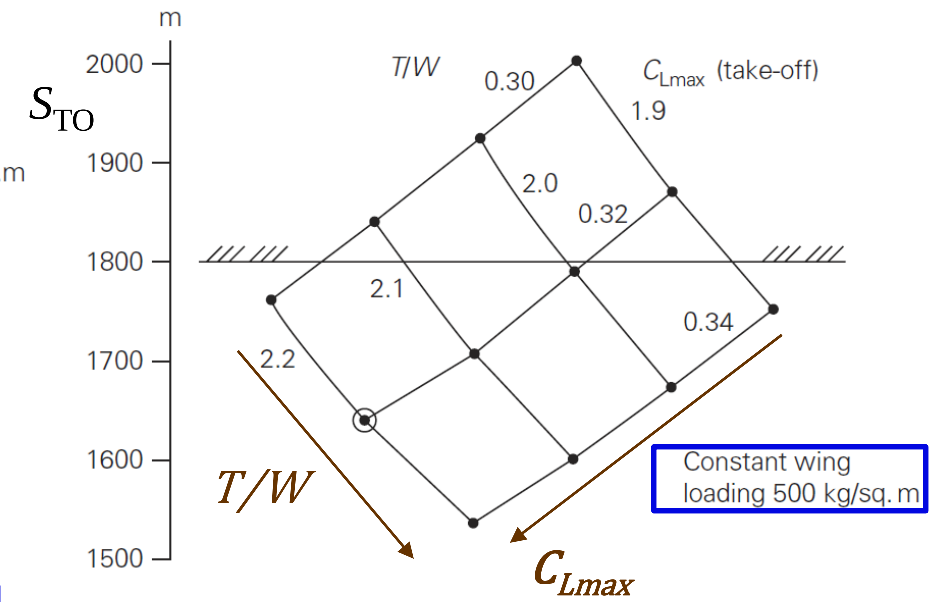
Note: ***abscissa scale deleted***

Source: Figure 25.3, Ref. AVD 1 (Nicolai and Carichner)

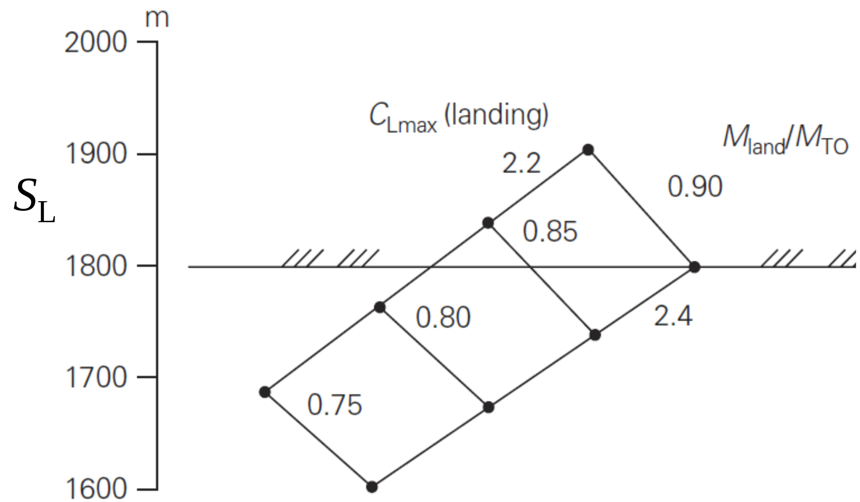
Trade Studies Example

- **Take-off Parameters**





- **Landing Parameters**



Source: Chapter 4, Ref. AVD 21 (Jenkinson)

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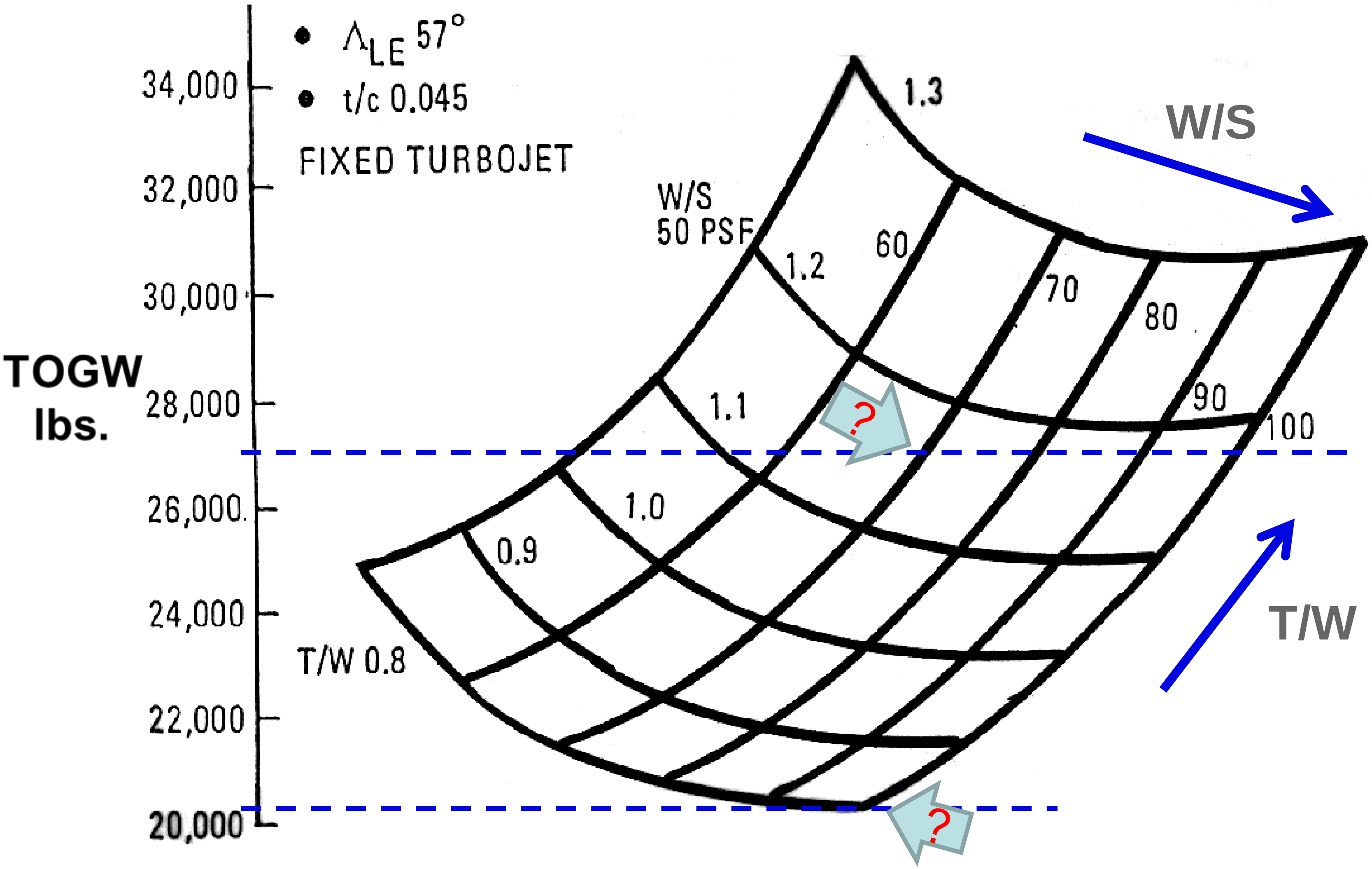
Value of Carpet Plots:
A Supersonic Fighter Example

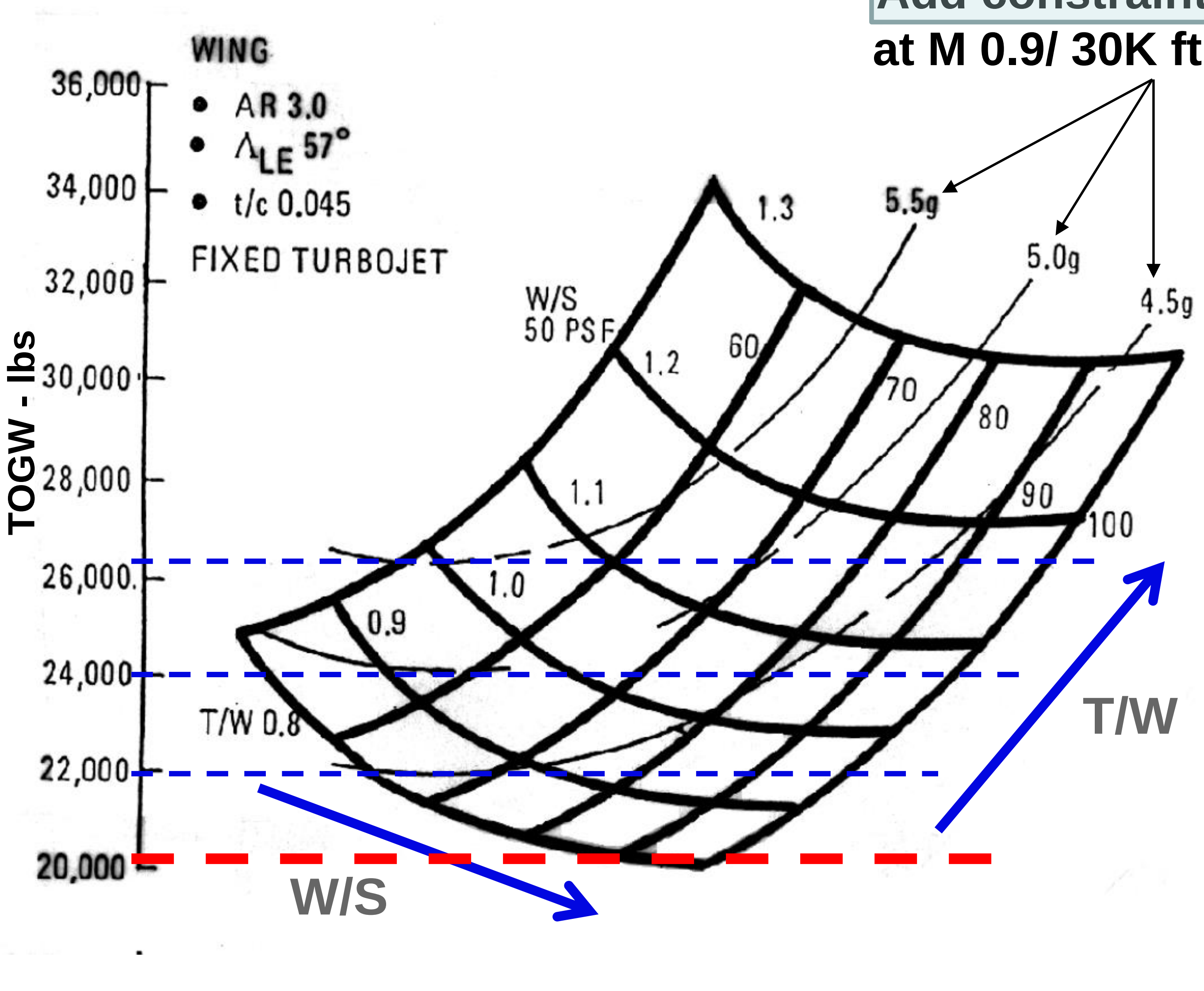


What is the "best" combination to meet ALL requirements?

Courtesy of W.H. Mason

Using a Carpet Plot:
A Supersonic Fighter Example

Add constraints for *g's* at M 0.9/ 30K ft. altitude

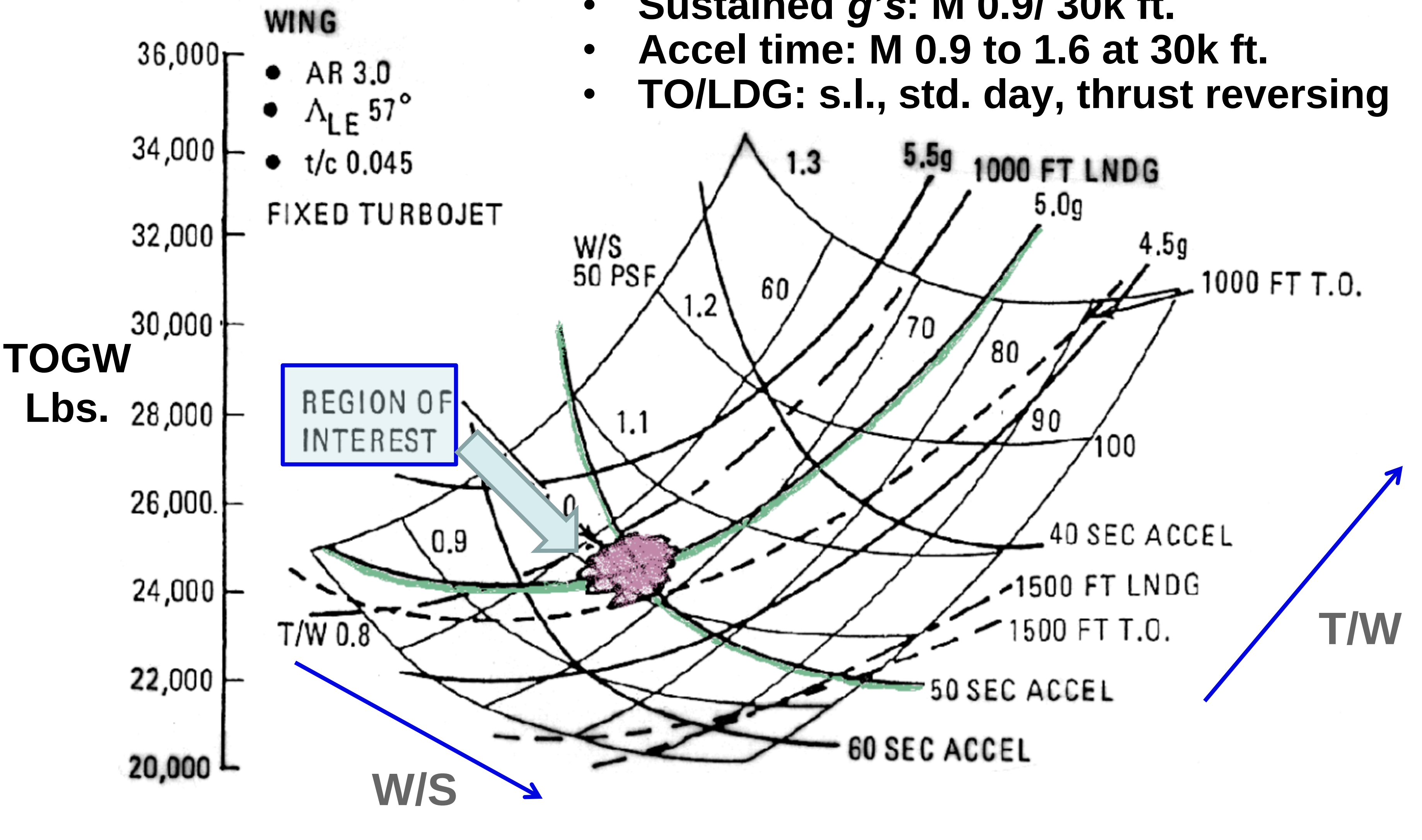


Courtesy of W.H. Mason

Using a Carpet Plot:
A Supersonic Fighter Example

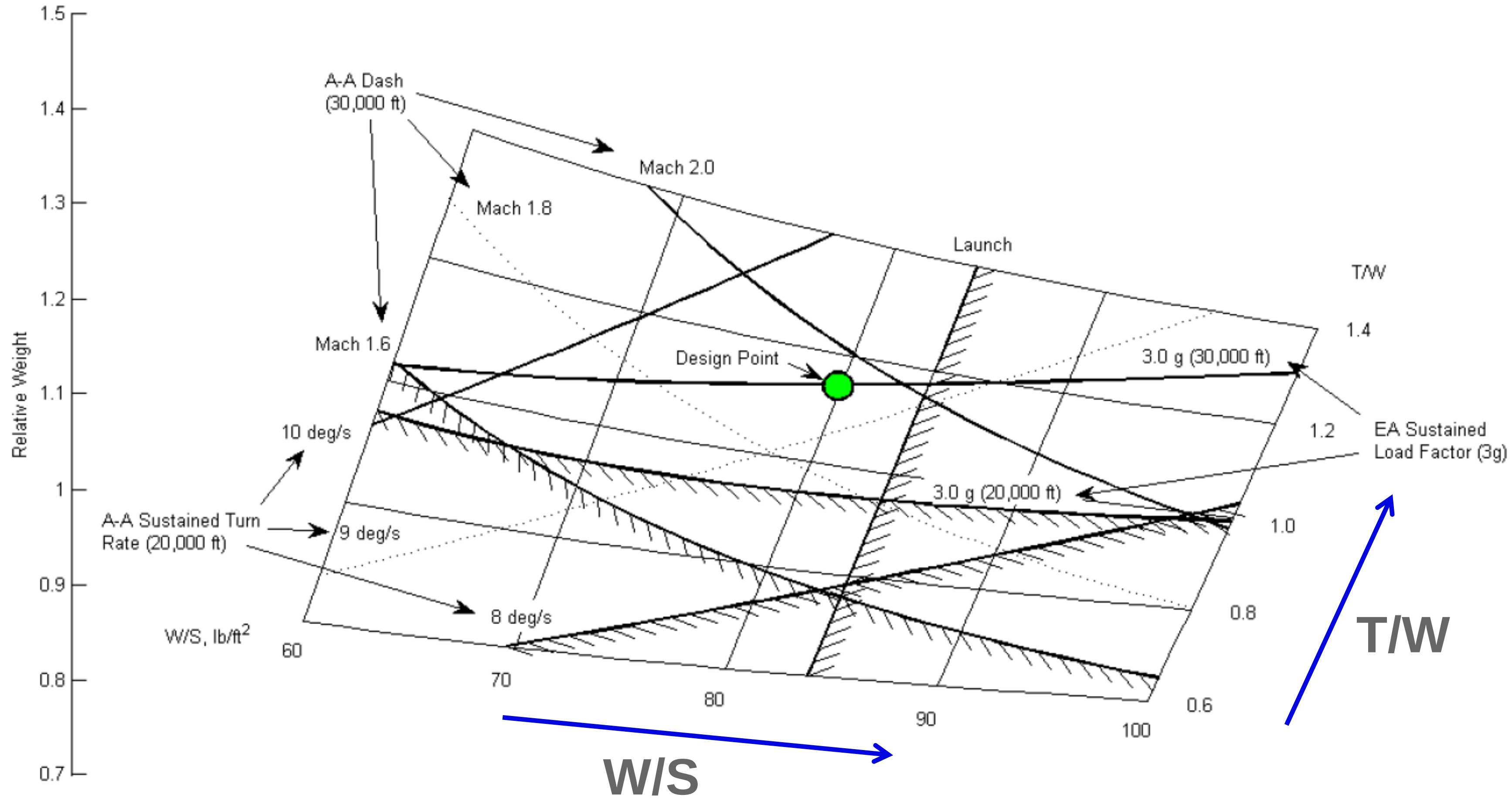
More Constraints

- **Sustained *g's*: M 0.9/ 30k ft.**
- **Accel time: M 0.9 to 1.6 at 30k ft.**
- **TO/LDG: s.l., std. day, thrust reversing**



Courtesy of W.H. Mason

F/A-36 Carpet Plot with Constraints

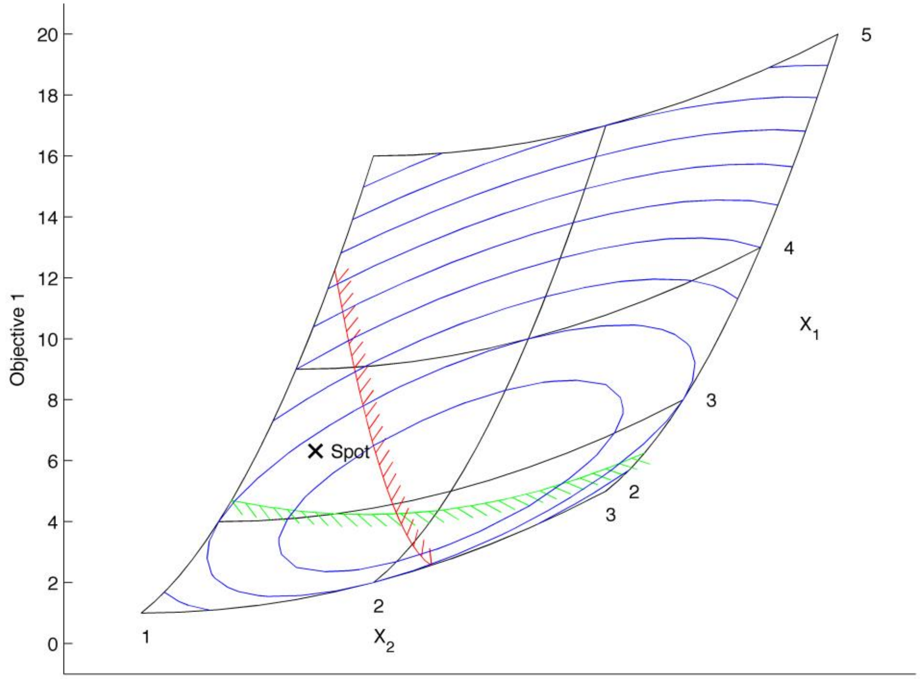


Source: 2013-14 NAVAIR Carrier-based Tactical Fighter Team, VT (Lead: Williams)

Suggested Software for Carpet Plots

***1. Carpet Plot Toolkit*, Version 1.0, by Rob McDonald, in MathWorks**

https://www.mathworks.com/matlabcentral/fileexchange/40831-carpet-plot-toolkit



***2. Generation of Carpet Plots*, Sydney Powers**

http://www.dept.aoe.vt.edu/~mason/Mason_f/SD1CarpetsbySAP.pdf

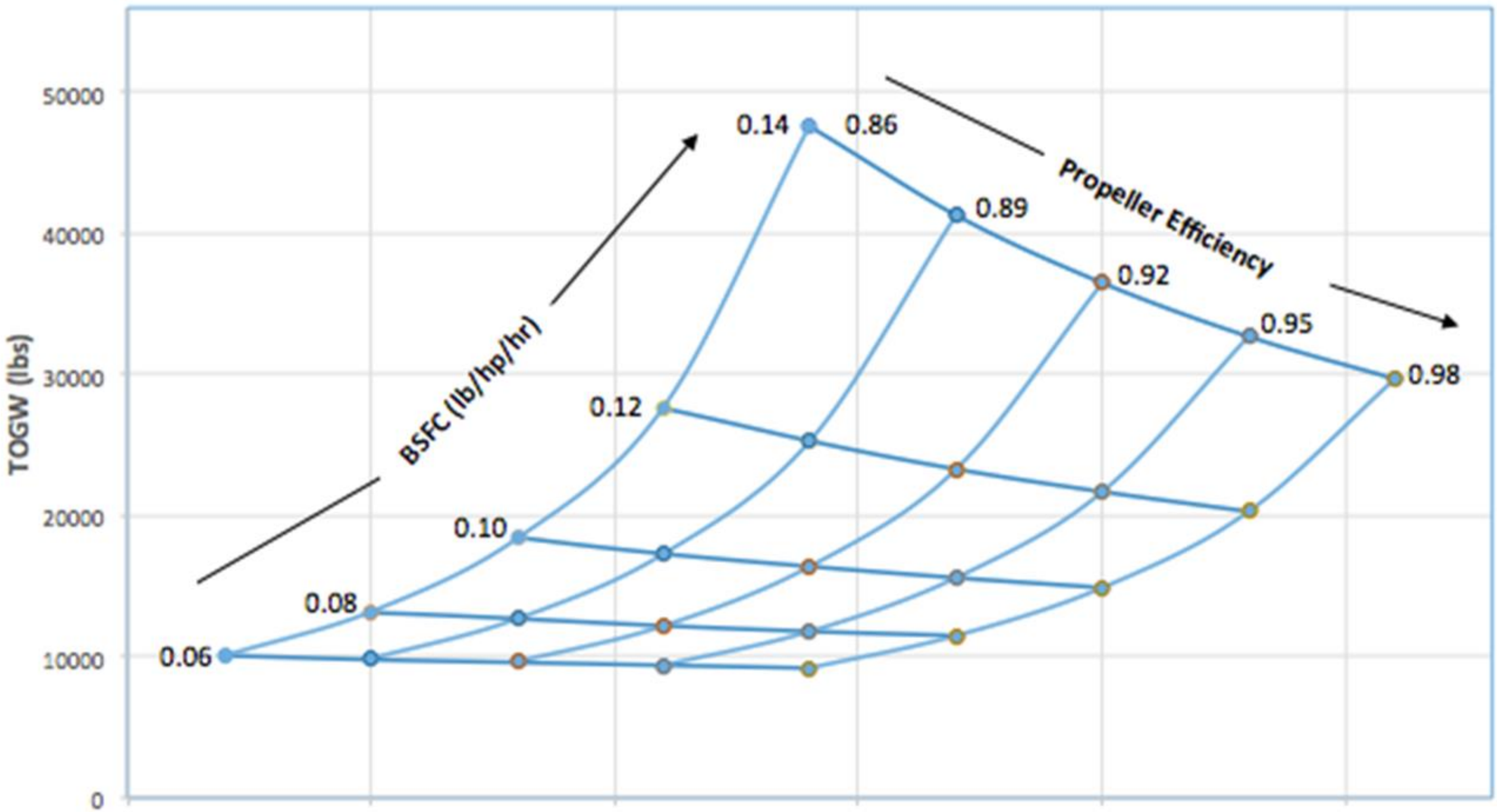
Note:

Carpet Plot is a general technique, not limited to just determining the best combination of W/S and T/W for minimum W_{TO} (takeoff gross weight).

A Three-parameter Carpet Plot

Effect of BSFC and Propeller Efficiency on TOGW
Notice different parameters (not W/S and T/W)

HALE UAS Example

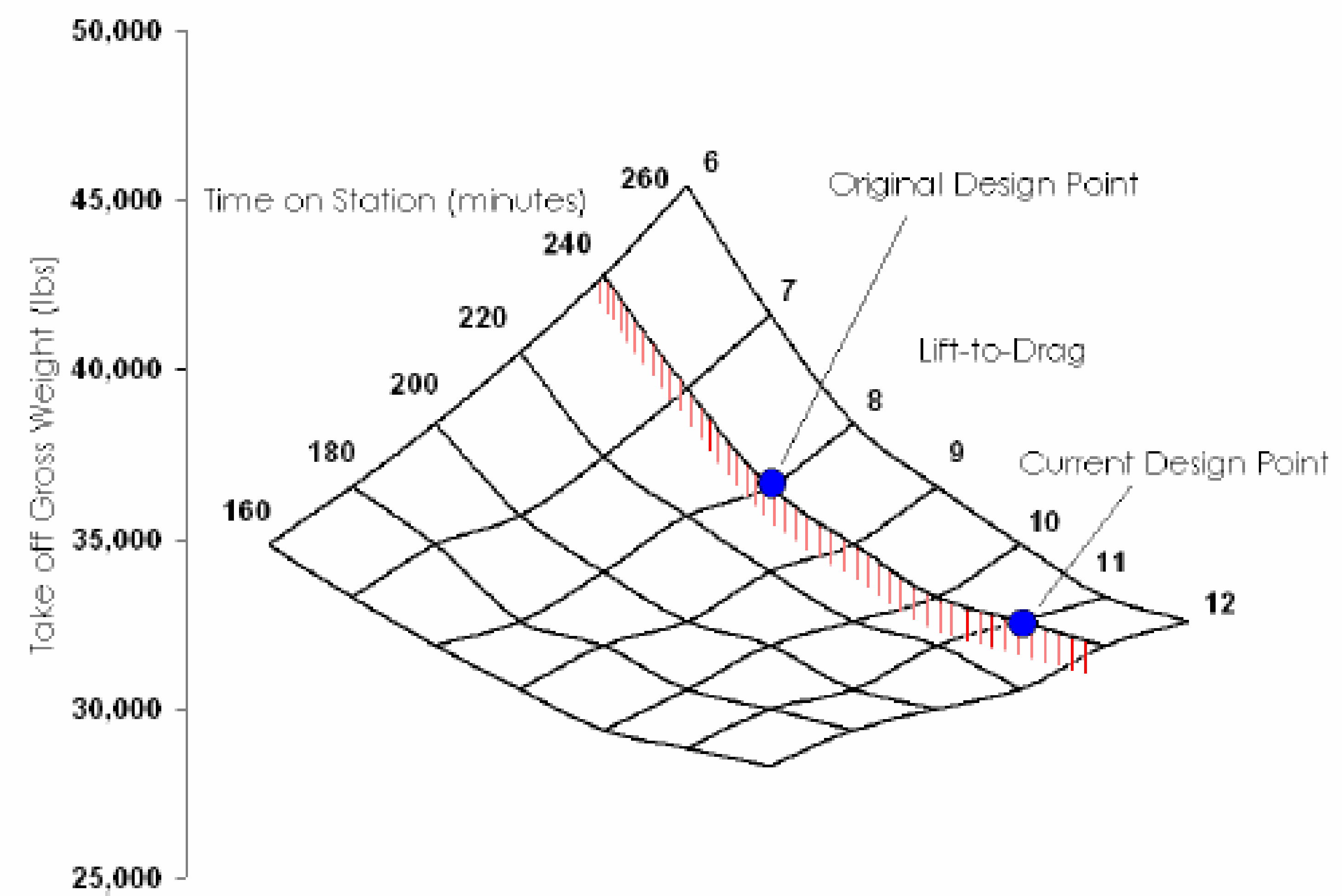


Higher Sensitivity of TOGW to BSFC than Propeller Efficiency

Source: 2013-14 NASA HALE UAS, VT (Lead: Brown)

A Three-parameter Carpet Plot

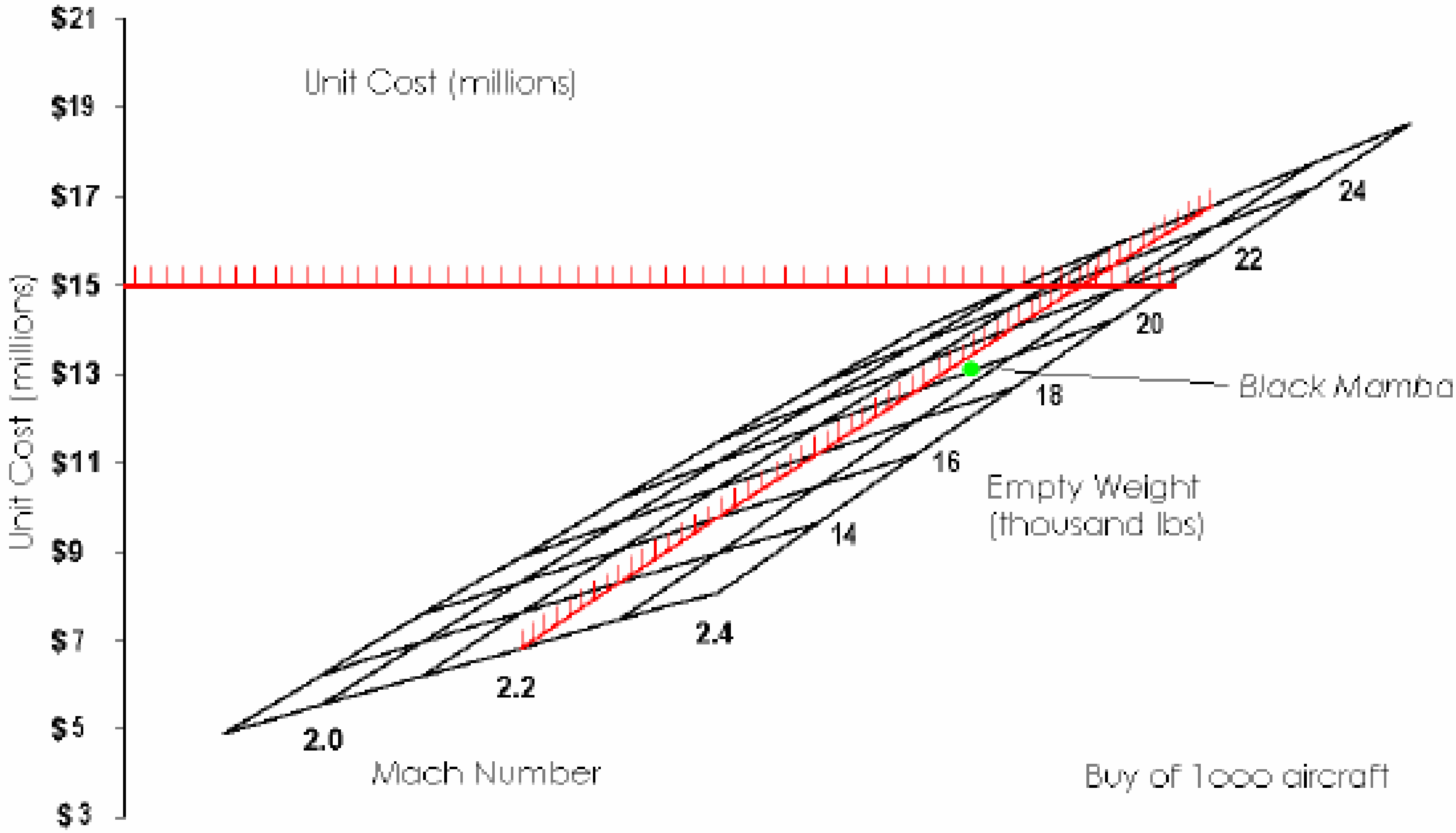
Effect of L/D on TOGW



Source: 2005-06 AIAA Team Design, The Black Mamba, Cal Poly, SLO

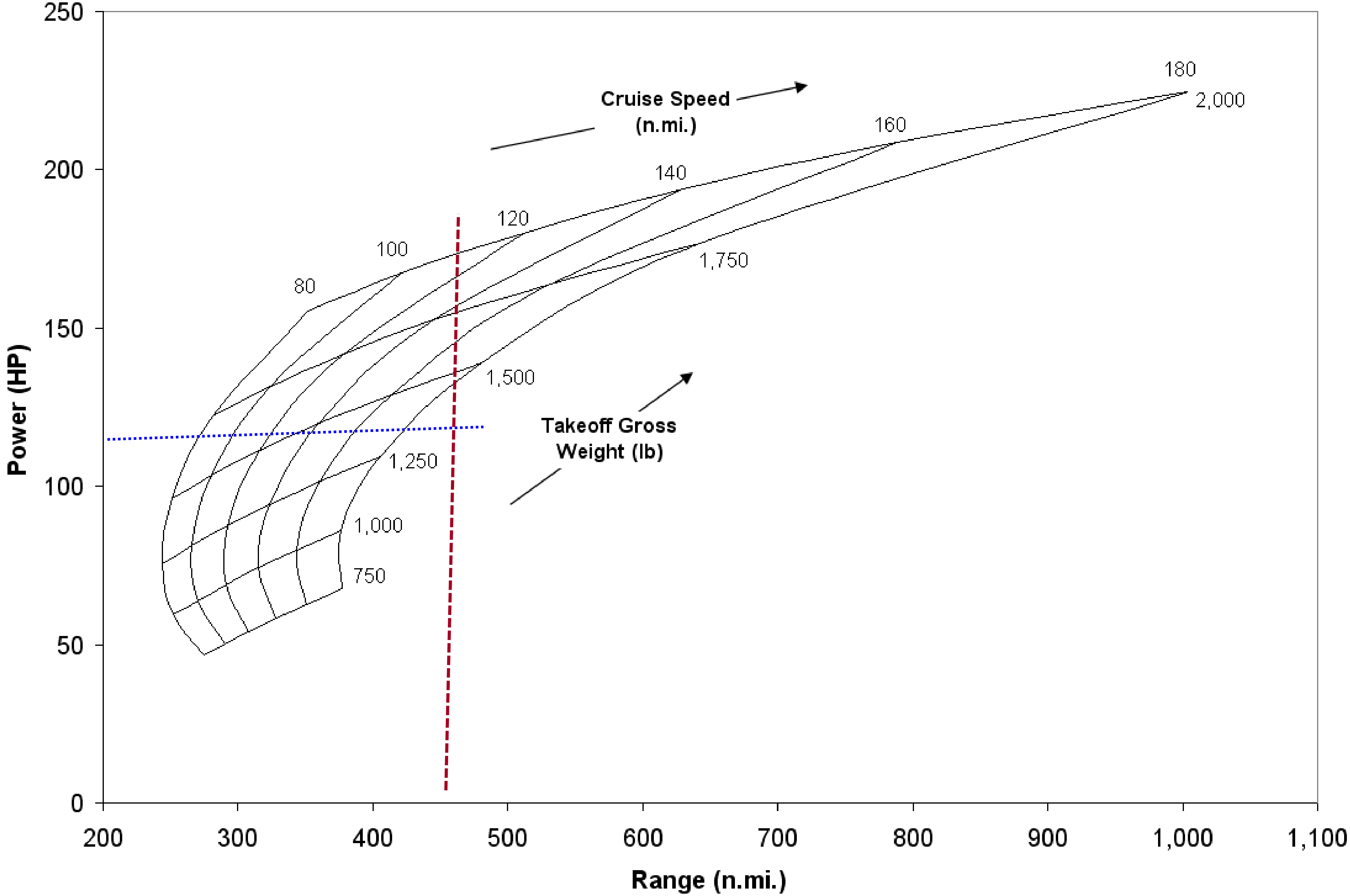
Three-parameter Carpet Plot

Effect of Empty Weight and Mach Number on Cost



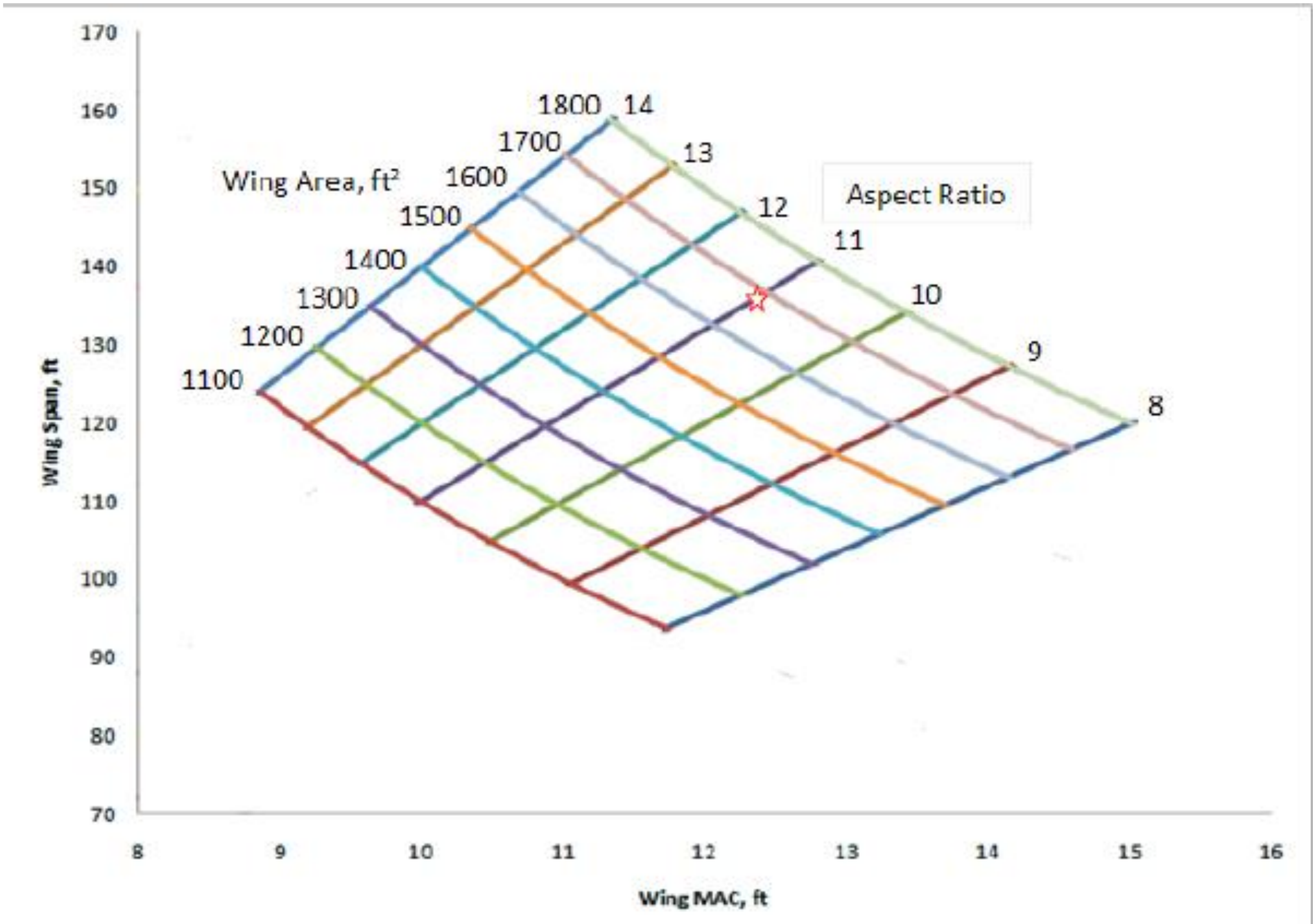
Source: 2005-06 AIAA Team Design, The Black Mamba, Cal Poly, SLO

A Four-parameter Carpet Plot



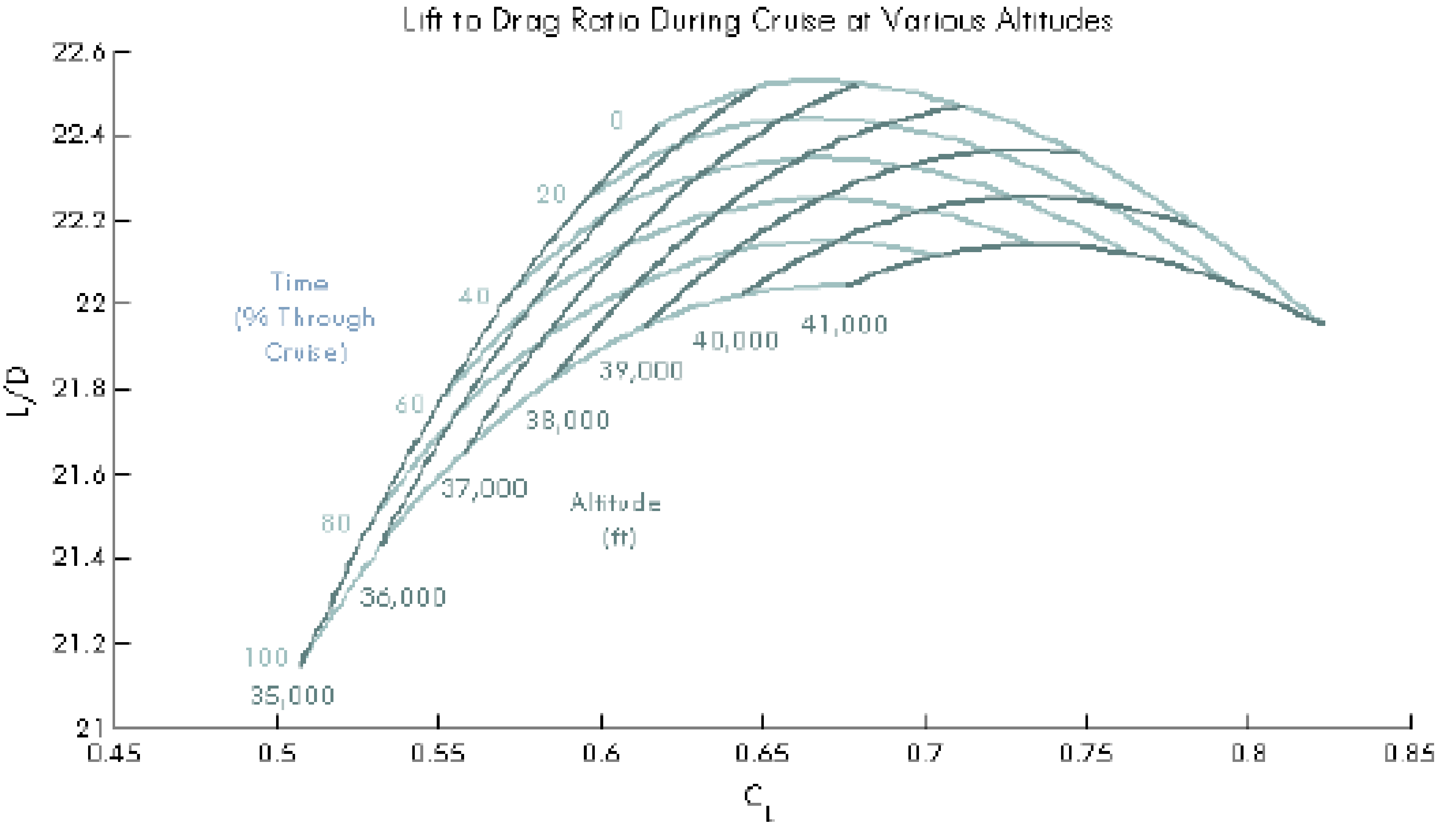
Courtesy of D.W. Hall, Personal Communication

A Four-parameter Carpet Plot



Source: 2008-09 AIAA Team Design, VT (Lead: Blizard)

A Four-parameter Carpet Plot



Source: 2009-10 AIAA UG Team Aircraft Design Winning Team, Cal Poly, SLO

Recommended Readings

Ref. No.	Chapter	Author(s)	Title
AVD 1	**Chapter 25**	Nicolai, L.M. and Carichner, G.E.	***Fundamentals of Aircraft and Airship Design*** **,** ***Volume I—Aircraft Design*** **,** AIAA Education Series, AIAA, Reston, VA, 2010.
AVD 2	**Chapter 19**	Raymer, D.P.	***Aircraft Design*** **:** ***A Conceptual Approach*** **,** AIAA Education Series, AIAA, Reston, VA, 2012.
AVD 4	**Chapter 20**	Gudmundsson, S.	***General Aviation Aircraft Design: Applied Methods and Procedures*** **,** 1st Ed., Butterworth-Heinemann, September 2013.
AVD 13	**Chapter 15**	Schaufele, R.D.	***The Elements of Aircraft Preliminary Design*** **,** Aries Publications, 2000.
AVD 21	**Chapter 4**	Jenkinson, L.R., and Marchman, J.F.	***Aircraft Design Projects for Engineering Students*** **,** Co-published by AIAA, Reston, VA, 1999

NOTE: See Appendix in Overview CM