Techniques for Conducting Effective Concept Design and Design-to-Cost Trade Studies

National Defense Industry Association
17th Annual Systems Engineering Conference
27-30 Oct 2014

David A. Di Pietro
Senior Systems Engineer
NASA Goddard Space Flight Center
Mission Systems Engineering Branch, Code 599
Greenbelt MD 20771
david.a.dipietro@nasa.gov, ddipietro@erols.com
301 286-0240

Today's Presentation

- ***Illustrates some key strategic aspects of conducting effective concept design & design-to-cost trade studies***

  - *What concept design is & why it's important*
  - *Fidelity needed in concept design solution*
  - *Techniques in designing mission level trade space*
  - *Challenges in determining credible design convergence*
  - *Recommended practices*

Important Note

- ***Concept design may be conducted using variety of methods***
  - *This presentation describes selected aspects of <u>one</u> method for conducting a concept design study*
    - *Uses a space observatory example*
  - *Method best suited to immature mission concepts that advance state of the art or that have high design uncertainty*

What Concept Design is
&
Why it's Important

Concept Design is Exploratory Process to Determine System Level Design Baseline

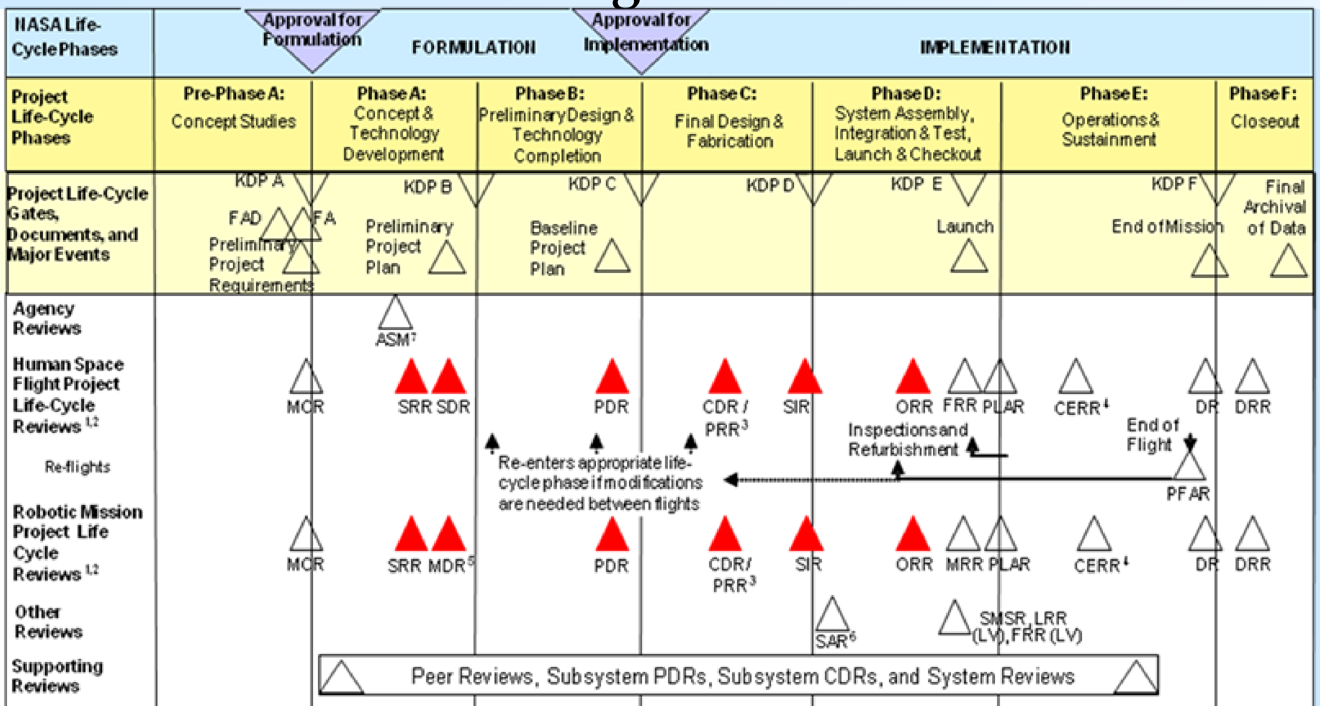
- ***Conducted in pre-Phase A & Phase A of Project Life Cycle to provide "feasible" system design baseline for new concept***

- ***As much an investigation of requirements as of design***
  - *Concurrent investigation of:*
    - *Concept of operations*
    - *Requirements*
    - *Design*
    - *Performance*
    - *Technology development*
    - *Verification approach*
    - *Flight dynamics*
    - *Ground segment (ground stations, mission & science ops centers)*
    - *Launch interface*
    - *Cost*
    - *Schedule*
    - *Risks, etc.*

NASA Project Life Cycle
NASA Procedural Requirements 7120.5E

Figure 1

Concept Design Occurs in Pre-Phase A & Phase A of Project Life Cycle



FOOTNOTES

1. Flexibility is allowed as to the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the Project Plan.
2. Life-cycle review objectives and expected maturity states for these reviews and the attendant KDPs are contained in Table 2-5.
3. PRR is needed only when there are multiple copies of systems. It does not require an SRB. Timing is notional.
4. CERRs are established at the discretion of program.
5. For robotic missions, the SRR and the MDR may be combined.
6. SAR generally applies to human space flight.
7. Timing of the ASM is determined by the MDAA. It may take place at any time during Phase A.

ACRONYMS

ASM - Acquisition Strategy Meeting
CDR - Critical Design Review
CERR - Critical Events Readiness Review
DR - Decommissioning Review
DRR - Disposal Readiness Review
FA - Formulation Agreement
FAD - Formulation Authorization Document
FRR - Flight Readiness Review
KDP - Key Decision Point
LRR - Launch Readiness Review
LV - Launch Vehicle
MCR – Mission Concept Review
MDR - Mission Definition Review
MRR - Mission Readiness Review
ORR - Operational Readiness Review
PDR - Preliminary Design Review
PFAR - Post-Flight Assessment Review
PLAR - Post-Launch Assessment Review
PRR - Production Readiness Review
SAR - System Acceptance Review
SDR - System Definition Review
SIR - System Integration Review
SMSR - Safety and Mission Success Review
SRB - Standing Review Board
SRR - System Requirements Review

Red triangles represent life-cycle reviews that require SRBs. The Decision Authority, Administrator, MDAA, or Center Director may request the SRB to conduct other reviews.

Preliminary Design Occurs in Phase B
Detailed Design Occurs in Phase C

D.A. Di Pietro
Goddard Space Flight Center

Concept Design Plays Central Role in Project Success

- *Earliest life cycle phases have most leverage over life cycle cost (LCC)*
  - *Concept design product effectively locks (or renders unchangeable) ~70% of system LCC*
    - *Per ref. (a) & ref. (b)*

- ***Such extraordinary leverage presents business case for conducting concept design in pragmatic & rigorous fashion***
  - *Particularly important for immature mission concepts that advance state of the art or that have high design uncertainty*

D.A. Di Pietro
Goddard Space Flight Center
Published and used by NDIA with permission

Concept Design Plays Central Role in Project Success (Cont'd)

- ***Done well, provides executable system level design baseline for project teams in Phase B & later phases***

- ***Not done well, can subject project teams in Phase B & later phases to system level redesign – in some cases, to multiple system level redesigns accompanied by:***

  - *Fluid technical baselines with ever-decreasing capabilities*
  - *Cost overruns & recurring schedule delays*
  - *Contract disputes & cancellations*
  - *Challenges in retaining trained personnel*

Pre-Phase A / Phase A Offer Unique Venue for System Level Trades

- ***Teams small, agile, closely coordinated***
  - *Typically operate absent many formalities of later project phases*
    - *e.g., typically no prime contracts, system level requirements not under configuration control until late in phase A*
  - *Can accommodate high rate of change in system level "requirements" & design characteristics (R&DC)*
    - *Enables broad investigation of trade space in relatively short time*

- ***Note:***
  - *"requirements" in quotes denotes interim reference capabilities used to guide evaluation of point designs in trade space*
  - *System level requirements aren't baselined until SRR for a final concept design that meets technical & programmatic (including cost & schedule) constraints*

Phase B & Later Development Phases Not Well Suited for System Level Trades

- ***In Phase B, system level design is more difficult & expensive to change, e.g.,***
  - *Teams typically larger & more distributed*
  - *Prime contracts typically in place*
  - *System level requirements typically under configuration control*
  - *Preliminary design work assumes system level design complete*

- ***In Phases C & D, system level changes even more difficult & expensive to change***
  - *Teams typically even larger than in Phase B*
  - *System & subsystem level requirements typically under configuration control*
  - *Detailed design work either underway or has been completed*

Fidelity Needed in Concept Design Solution

A Proposed Definition for "Feasible"

- **The term "feasible" is used frequently in concept design, but its use is often problematic**
  - *Often left undefined & subject to interpretation*

- **This presentation uses "feasible" mission concept to mean:**
  - *Technical, cost, & schedule characteristics for a single, baseline mission concept design have been credibly converged to the 1st order by the end of Phase A,*
  - *such that the design may be developed, launched, operated, & decommissioned by a competent project team starting in Phase B within customary technical & programmatic margins*

D.A. Di Pietro
Goddard Space Flight Center

A Proposed Metric for Level of Convergence (1 of 2)

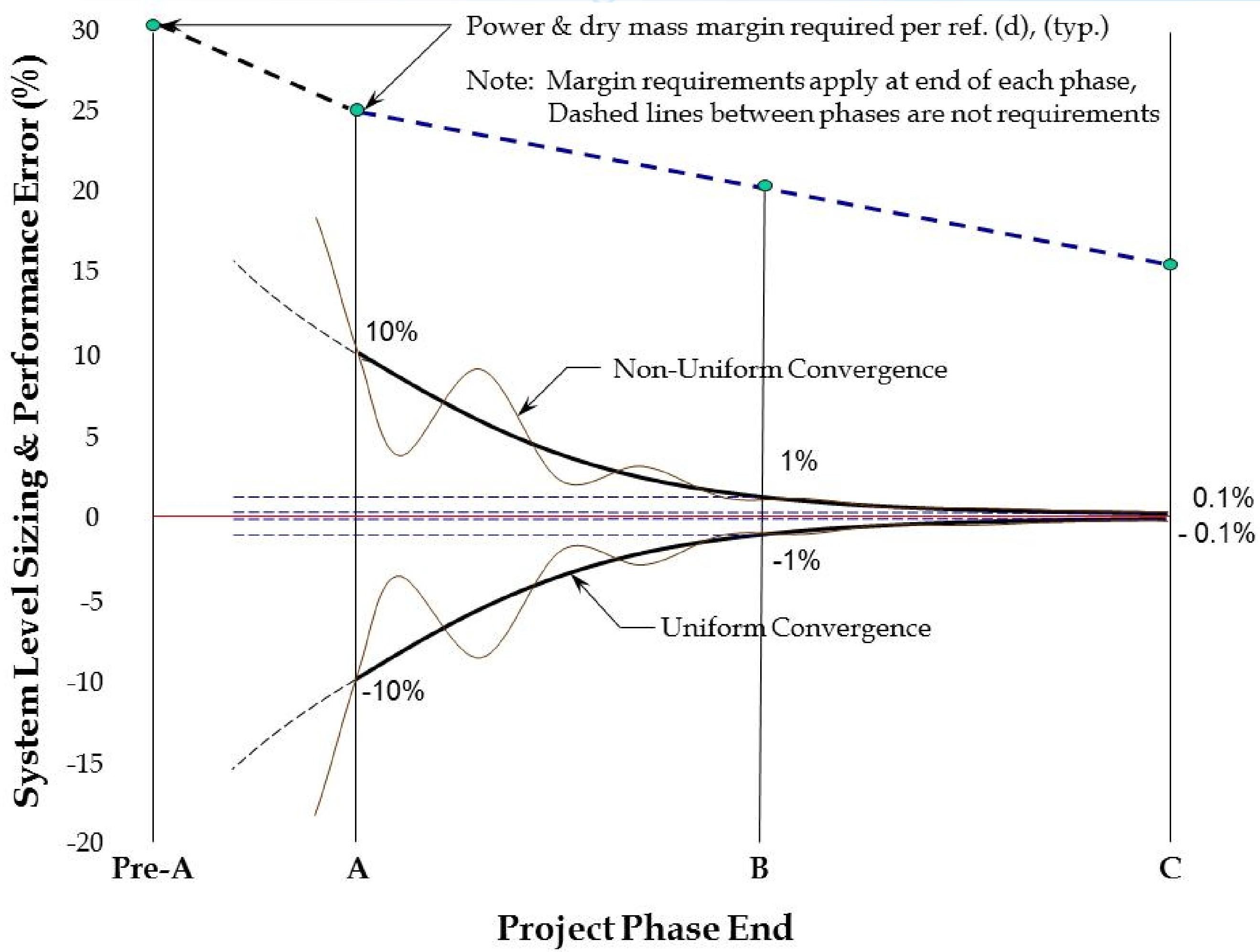
- ***Credible convergence to 1st order by end of Phase A means:***
  - *System level sizing & performance (SLSP) of mission elements is confidently determined to within 90% of SLSP when flight system is delivered*
    - *For given cost & schedule constraints*
  - *i.e., there is residual uncertainty that SLSP could change by ± ~10% between end of Phase A & launch*

D.A. Di Pietro
Goddard Space Flight Center

A Proposed Model for Product Fidelity During Design Phases (Solid Black Curve)*

Figure 2

*Adapted from ref. (c), Fig. 3-4



D.A. Di Pietro
Goddard Space Flight Center

A Proposed Metric for Level of Convergence (2 of 2)

- ***Solid black curve in Fig. 2 (uniform convergence) shows allowable SLSP error decreases as design moves from Phases Pre-A through C***
  - *End Phase A: 1^{st} order, or 90% (accurate to 1 digit, ~ ± 10% error)**
  - *End Phase B: 2^{nd} order, or 99% (accurate to 2 digits, ~ ± 1% error)*
  - *End Phase C: 3^{rd} order, or 99.9% (accurate to 3 digits, ~ ± 0.1% error)*

- ***Metrics for SLSP error are <u>approximate guidelines only</u>***
  - *Coarse model that depicts an idealized trend of fidelity in each phase*
  - *Assume calculations done properly, but with incomplete or incorrect information / assumptions*

- **** read as 9 x 10^1 %, accurate to 1 significant digit***

Example SLSP Error Convergence for Mass

- ***For a 4,000 kg space observatory, system level mass should be known to:***

  - *End Phase A: Within ~ ± 10%, or ~ ± 400 kg of final launch mass*
  - *End Phase B: Within ~ ± 1%, or ~ ± 40 kg of final launch mass*
  - *End Phase C: Within ~ ± 0.1%, or ~ ± 4 kg of final launch mass*

Role of (Selected) Resource Margins on Required Convergence

- ***Solid black curve in Fig. 2 must be within allowable margins***
  - *Power & Dry Mass Margin requirements (per ref. (d)) are shown in Fig. 2*
    - *End Phase A: ≥ 25%*
    - *End Phase B: ≥ 20%*
    - *End Phase C: ≥ 15%*
- ***Cost (not shown in Fig. 2) serves as design constraint***
  - *Cost margin (per ref. (e))*
    - *Cost through Phase D: ≥ 30% (guideline at Phase B start)*
    - *Cost through Phase D: ≥ 25% (requirement at Phase C start)*
- ***Other programmatic margin requirements apply as well, e.g.,***
  - *Schedule margin (per ref. (e)), not shown in Fig. 2*

Importance of Concept Design Convergence to Project Manager

- **_Project Manager at start of Phase B holds 25% margins for power & dry mass resources (Fig. 2)_**
  - *<u>Can accommodate</u> concept design credibly converged to within 10% of flight sizing & performance values for power & dry mass*
    - *Even if 10% error occurs in direction of needing more resources*
  - *<u>Can't accommodate</u> concept design credibly converged to within 30% of flight sizing & performance values for power & dry mass*
    - *if 30% error occurs in direction of needing more resources*
    - *Design de-scope likely required*

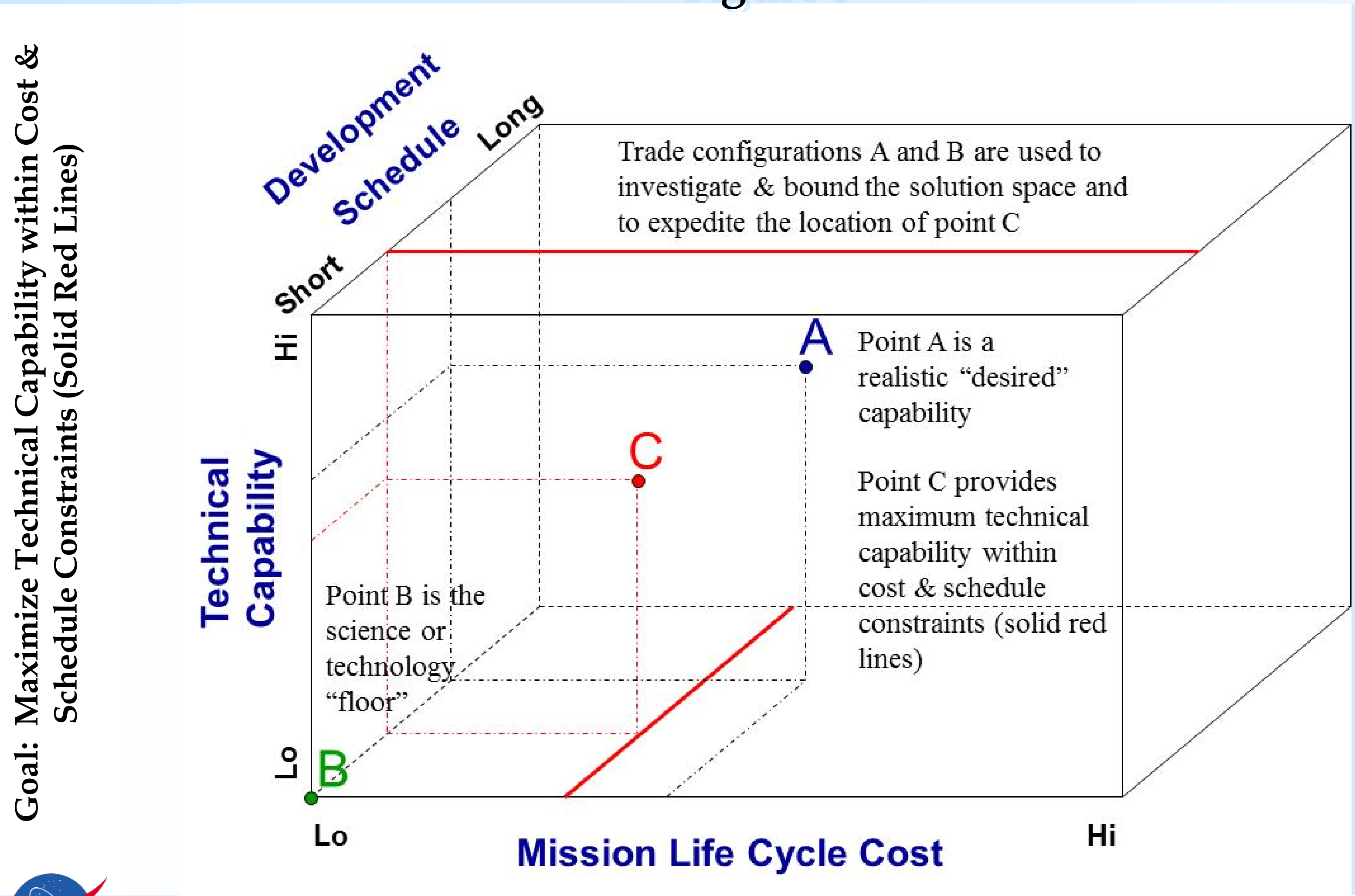
D.A. Di Pietro
Goddard Space Flight Center

Techniques in Designing Mission Level Trade Space

Concept Design Mission Level Trade Space

Selecting Trades to Expedite Convergence – 3 Cycle Example

Figure 3



D.A. Di Pietro
Goddard Space Flight Center

Concept Design Mission Level Trade Space
Selecting Trades to Expedite Convergence – 3 Cycle Example (Cont'd)

- ***Approach in Fig. 3 deduces R&DC for C design by interpolating on results from A & B designs (bounding cases)***
  - *Technical capability of point C isn't known at outset of study*
- ***More like root finding algorithm than like successive refinement design process typically used in Phases B & C***
  - *In Phases B & C, each design is refinement of "baseline" system level design from prior phase*
  - *In concept design process discussed here, typically there isn't a "baseline" system level design until concept design is complete*
- ***Purposely views design problem from multiple perspectives***
  - *Illuminates aspects that otherwise may have remained hidden*
    - *Helps stimulate creative thinking & mitigate biases*
    - *Helps discover "unknown unknowns" (UUs)*

Why Selecting Bounding Cases is Important

- ***Failure to select bounding cases may cause extrapolation to determine R&DC for final solution***
  - *Adds risk in technical, cost, & schedule estimates*
  - *May result if both A & B designs exceed cost & schedule constraints*
    - *Implies R&DC for B design didn't identify "true" science or technology floor (presumes a solution exists)*
- ***Or, may cause need for more design cycles***
  - *Deadline may not permit, or may drive significant team overtime*
- ***Optimistic A designs & "false" science floors for B designs are common***
  - *Customer's vision often isn't cost / schedule constrained*
  - *Customer may resist identifying "true" science or technology floor*
- ***Teams that recognize, or adapt to, these considerations pragmatically & quickly fare better than teams that don't***

Selecting R&DC (Typical Case)

- ***Typical Approach***
  - *A Design: Most* parameters reflect realistic desired capability*
  - *B Design: Most* parameters reflect science or technology floor*
  - *C Design: Most* parameters are between A & B capabilities*

    ** but not necessarily all*

- ***R&DC for B design reevaluated after A design to assure solution space bounded***
  - *Presumes A design done first*

- ***Many parameters varied concurrently due to need to cover broad solution space in limited time*****
  - *Experience shows teams can sufficiently understand parameter sensitivities*

    *** after approach originally used by Mr. John Oberright, NASA / GSFC Emeritus, for Space Technology-5 concept design study (1999)*

Challenges in Determining Credible Design Convergence

Convergence Indicators Difficult to Define Objectively

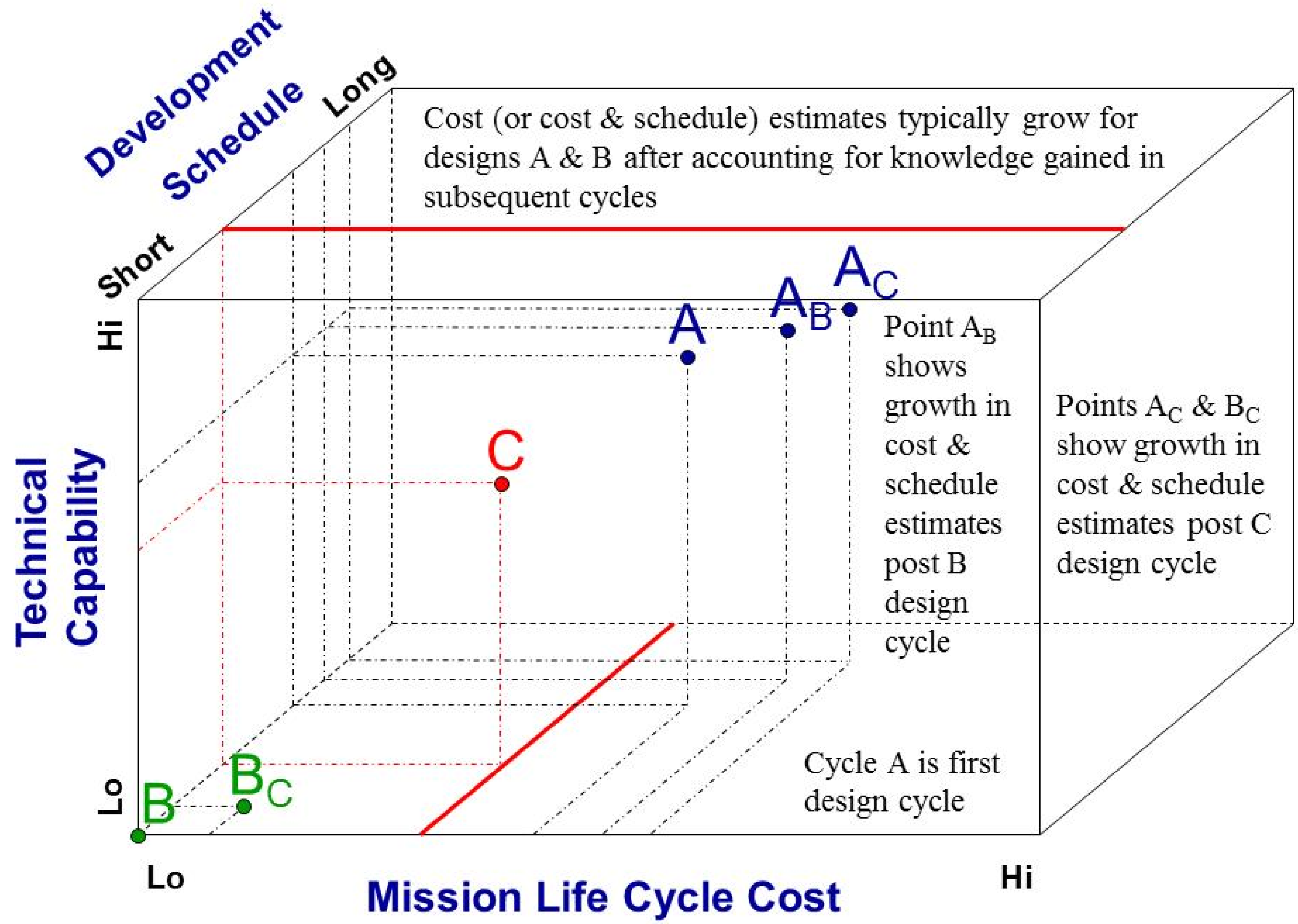
- ***Concept design is inherently an exploratory process with relatively high uncertainty***

- ***Concept design teams learn at high rate***
  - *Early assumptions & conclusions may be invalidated by later findings or by unpredictable discovery of UUs*
    - *Convergence can appear non-uniform (see copper line in Fig. 2)*

- ***Yet, indicators are desired to help avoid inferring convergence prematurely, e.g., due to:***
  - *Insufficient rigor*
  - *Study funds or time being exhausted*
  - *Pressure to meet a milestone deliverable, etc.*
  - *Biases*

Convergence Determinations Often Evident Only in Hindsight

Figure 4



Why Early Cost Estimates Tend to be Optimistic

- ***A common characteristic of concept design is costs for a given design tend to increase with each design cycle***
  - *Particularly true for immature mission concepts that advance state of the art or that have high design uncertainty*

- ***As teams progress through cycles, they learn more of what may have been omitted / incorrectly assumed in prior cycles***
  - *After B cycle, cost of A design may increase*
  - *After C cycle, cost of A design may increase again, & cost of B design may increase*
    - *Causes A & B points to move to right in Fig. 4*
  - *When accompanied by schedule increases, A & B points also move into page*
  - *After C cycle, learning tapers off for most designs*
    - *Occasionally, a D cycle is needed (or may be planned from outset)*

D.A. Di Pietro
Goddard Space Flight Center

Why Early Cost Estimates Tend to be Optimistic (Cont'd)

- ***Cost analysis is normally performed using multiple methods***
  - *One method is "grass roots" - uses relatively detailed work breakdown structure (WBS)*
- ***WBS dictionary for most space mission elements is relatively well known & largely existing, e.g.,***
  - *Spacecraft, launch, ground systems, etc.*
- ***Conversely, WBS dictionary for new instruments is unique***
  - *Design dependent, evolves as instrument design evolves*
  - *Key aspect for designs dominated by new instruments*
- ***Multiple cost cycles typically needed to develop well understood WBS free of significant gaps & overlaps***
  - *Cost fidelity improves with understanding of design <u>and</u> WBS*
  - *Gaps common in design & cost in early cycles as team learns*

Subjective Criterion for Convergence Determination – Significant Surprises

- ***One subjective criterion for credible convergence is whether team has experienced significant surprises***
- ***Team that hasn't experienced at least a few significant surprises should be cautious of its results***
- ***Lack of surprises may indicate:***
  - *Team hasn't progressed sufficiently down learning curve*
  - *Team didn't sufficiently exercise trade space or mitigate biases*
  - *Concept design study objective wasn't sufficiently challenging*

Recommended Practices

General Guidance

- ***Treat design cycles as precious resource***
  - *Essential, but in limited supply due to time & resources available*
- ***Don't retrofit A & B designs with insights from later cycles***
  - *Time better spent just applying learning to final design*
- ***Document design results in reports (not briefings) at end of each cycle (see rationale in backup charts)***
  - *Reports (functional, not pristine) are record documents*
  - *Briefings, if needed, are built exclusively from approved reports*
- ***Focus on what "should" be done vs. what "can" be done***
  - *Address 1st order items that demand attention early*
    - *Defer lower order items to later phases*
  - *Focus team efforts on developing product, omit peripheral tasks*

Analogy for 1st Order Level of Analysis Depth in Concept Design

- **Pre-Phase A & Phase A teams evaluate multiple designs in broad trade space in relatively short period**
  - *Analysis tools used typically are 1st order precision, agile enough to adapt to frequent / significant system level changes*
    - *Analogy: "Hacksaw"*
- **By comparison, analysis tools typically used in:**
  - *Phase B are 2nd order precision, assume system level design stable*
    - *Analogy: "File"*
  - *Phase C are 3rd order precision, assume both system & subsystem level designs stable*
    - *Analogy: "Polisher"*

D.A. Di Pietro
Goddard Space Flight Center

Analogy for 1^{st} Order Level of Analysis Depth in Concept Design (Cont'd)

- ***Team using "hacksaw" in Phase C has done something wrong***
  - *Didn't credibly converge 1^{st} order solution by end of Phase A*
  - *Re-doing concept design work late & out of sequence*

- ***Team using "polisher" in Phase A is doing something wrong***
  - *Won't move quickly or broadly enough to rough-out & credibly converge 1^{st} order solution**
    - *Recognize some design elements may not even exist in final concept design*

* *Some high risk elements may selectively warrant added scrutiny*

Avoid Significant Rounding Errors

- ***To avoid masking resource margins, bookkeep design & performance calculations to 3 significant digits & report out to 2 significant digits***

  - *Should not be taken to imply there is 3-digit accuracy in concept design work -- there usually is not*

  - *Simply a numerical safeguard to avoid propagating rounding errors that could overwhelm ability to adequately determine design or performance margins*

  - *See margin example in backup charts*

Recognize Typical (but Unofficial) Phases of Concept Design

- ***Concept design teams developing immature mission concepts that advance state of the art often experience four phases of work***
  - *1) Unbridled Optimism*
  - *2) Shock*
  - *3) Denial*
  - *4) Acceptance*
- ***The quicker a team moves through phases 1,2, & 3 and arrives at Phase 4, the better that team will fare***
  - *See backup charts for additional discussion*

Closing Thoughts

Closing Thoughts (1 of 2)

- ***Concept design phases have extraordinary leverage over project success, it's important they be:***
  - *Conducted in rigorous & pragmatic fashion*
    - *Particularly for immature mission concepts that advance state of the art or that have high design uncertainty*
  - *Credibly converged to 1st order prior to Phase B*
    - *Project Manager relies upon this*

- ***Unknowns dominate for designs that advance state of art***
  - *Be cautious of early results, they may not be as initially appear*
  - *Use bounding trades to help discover major UUs & mitigate biases*
  - *Look for evidence of significant surprises / unexpected findings*
    - *Indicate team progressing down learning curve, results becoming more credible*
  - *Don't let first cost estimate be final cost estimate*

Closing Thoughts (2 of 2)

- ***Concept design phases provide unique venue to facilitate exploring & converging system level design***
  - *Use the opportunity in these phases well*
  - *Not used well, the work of these phases usually will have to be re-done*
    - *The later this realization occurs, the more expensive the resulting redesign is likely to be*

References

a) *Intermediate Systems Acquisition Course, Volume 2 Technical, Defense Acquisition University, Oct – Dec 1998, p. SE-1-24 and p. LM1-15*

b) *Fundamentals of Systems Engineering (5th Ed., day 3, chart 44), Strategy Bridge International, Inc., Academy of Program / Project & Engineering Leadership, presented 11-15 Feb 2013 at NASA / GSFC*

c) *The NASA Mission Design Process, An Engineering Guide to the Conceptual Design, Mission Analysis and Definition Phases; the NASA Engineering Management Council; 22 Dec 1992*

d) *GSFC-STD-1000F (with Administrative Changes), Rules for the Design Development, Verification, and Operation of Flight Systems*

e) *Goddard Procedural Requirements 7120.7, Schedule Margins and Budget Reserves to be Used In Planning Flight Projects and In Tracking Their Performance*

Backup

Documenting Concept Design Results in Reports at End of Each Design Cycle

- **_Provides official study record of what team did, how team did it, & what team found for present (& future) team use_**
- **_Reports are developed for each subsystem / discipline_**
  - *Built from standardized templates*
    - *Include analysis methods & example calculations*
  - *Provide coherent technical waypoints that enable team to recall designs & performance from prior cycles, often needed for scaling or comparison*
    - *High rate of design changes makes recollection difficult otherwise*
  - *Used for system level review, subsystem integration, independent review, new / follow-on team member orientation*
- **_Once approved, reports typically are under informal configuration control of Mission Systems Engineer_**
  - *Briefings can be generated quickly from approved reports*
  - *Briefings contain only information in approved reports*

Effect of Rounding Errors on Margin Determination

- ***Rounding errors can significantly affect margin determination if adequate care isn't exercised***
  - *In some cases, rounding errors can fully mask margins such as those for mass & power shown in Fig. 2*

Effect of Rounding Errors on Margin Determination (Cont'd)
Example

Case 1:	Power Available	= 200 W
	Max. Estimated Power Required	= 249 W
	Power Margin = 100 (200 W – 249 W) / 249 W	= -19.7%
Case 2:	Power Available	= 200 W
	Max. Estimated Power Required	= 151 W
	Power Margin = 100 (200 W – 151 W) / 151 W	= 32.5%

The margins for Cases 1 and 2 are -19.7% and +32.5%, respectively

Now consider a third case in which a designer rounds calculations to the first digit in Cases 1 and 2

Case 3:	Power Available	= 2 x 10^2 W
	Max. Estimated Power Required	= 2 x 10^2 W
	Power Margin = 100 (2 x 10^2 W – 2 x 10^2 W) / 2 x 10^2 W	= 0%

The margin for Case 3 is 0%

Effect of Rounding Errors on Margin Determination (Cont'd)
Example

- ***Required power margin at end of pre-Phase A is 30% (Fig. 2)***
  - *Comparing Case 3 to Case 2 shows how rounding to 1st digit can fully mask a margin of over 30%*
  - *Additional errors can accrue when combinations of rounded results are used in successive calculations*

- ***To avoid masking resource margins, bookkeep design & performance calculations to 3 significant digits & report out to 2 significant digits***

- ***Notes:***
  - *This should not be taken to imply there is 3-digit accuracy in concept design work -- there usually is not*
  - *This practice is simply a numerical safeguard to avoid propagating rounding errors that could overwhelm ability to adequately determine design or performance margins*
  - *Margin calculation method is per ref. (d), Table 1.06*

Recognize Typical (but Unofficial) Phases of Concept Design

- ***Concept design teams developing new designs that advance state of the art often experience four phases of work***

- ***1) Unbridled Optimism***
  - *This phase features unbridled, optimistic performance desires levied as “requirements” before team gains credible understanding of associated cost & schedule*
  - *Meetings often not well-focused on study objectives*
    - *Often feature unproductive, run-on advocacy discussions of why mission has best science of all competing missions & why it has best chance to win*

- ***2) Shock***
  - *This brief phase usually begins after team completes its first credible cost estimate*

Recognize Typical (but Unofficial) Phases of Concept Design (Cont'd)

- ***3) Denial***
  - *This phase features abundant rationalizations as to why models used to estimate costs weren't representative*
  - *Team points to anything but excessively high technical capability as reason costs are too high in order that science return remains compelling relative to competition*
    - *Seeks to reduce costs in areas other than technical capability / science return below normal allocations*
    - *Theorizes why partner no-cost contributions will be higher than initially planned*
    - *Argues why the request for proposal is incorrect, etc.*
- ***4) Acceptance***
  - *This phase features the ultimate realization technical capability / science return must be lowered to design a credible mission concept*
    - *One that meets cost & schedule constraints according to established independent review standards*