Value Based Decision-Making: The Missing Element in MBE and MBSE

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Biosketches of Dr. Daniel P. Schrage and Dr. Dimitri N. Mavris

Dr. Daniel P. Schrage, Professor Emeritus, Georgia Tech
- Professor and Director of the Georgia Tech Vertical Lift Research Center of Excellence (VLRCOE), 1984-2018; Director of the Georgia Tech Center for Aerospace Systems Engineering (CASE), 1994-2018
- Engineer, Manager and Senior Executive with the US Army Aviation Research and Development Command (AVRADC0M), 1974-1984
- Active Duty Army Aviator and Commander in South Vietnam, 1970-71, and Field Artillery Missile Battery Commander in Germany, 1968-69
- Education: BS USMA, West Point; MSAE Georgia Tech; MBA Webster U.; D.Sc ME, Washington U. (Saint Louis, MO)

Dr. Dimitri N. Mavris, Boeing Advanced Systems Analysis Professor;
- Regents Professor, School of AE, Georgia Tech
- Director, Aerospace Systems Design Laboratory (ASDL), School of AE, 1992-Present; G
- Education: BSAE, MSAE, and PhD, School of AE, Georgia tech
The Georgia Tech Graduate Program in Aerospace Systems Design is the largest of its kind in the world with ~ 200 grad students, 35 research engineers & 10 faculty.

- Two major laboratories, the Aerospace Systems Design Laboratory (ASDL) and The Space Systems Design Laboratory (SSDL), support substantial research and education programs with industry and government.
- As illustrated in the Figure on the right; a Practice-Oriented MS Program with required Courses are identified; Most Aerospace Systems and System of Systems are addressed; Includes Integrated Product/Process Development (IPPD) Methods/Techniques/Tools/Infrastructure.
The Aerospace Systems Design Laboratory (ASDL) and The Space Systems Design Laboratory (SSDL) are the Major Support Laboratories
Evolution of Georgia Tech Aerospace Systems Design IPPD Research during the 1990s
• Review of Systems Engineering Fundamentals from the 1960s-70s
• Review Development of IPPD through Robust Design Simulation (RDS) in the 1990s-2000s to address the Risk and Uncertainty in Decision-Making
• Review the Establishment of the Integrated Product Life-cycle Engineering (IPLE) Laboratory for including Product Lifecycle Management (PLM) Methods/Tools in a Computer Integrated Environment through a Strategic Alliance with Dassault Systems and Professional Education with Boeing
• Positioning Georgia Tech, through ASDL and SSDL, to become a world leader in Global Product Data Interoperability through Digital Transformation
• Systems Engineering activities are illustrated and focused in the Systems Engineering Process iterative flow between Requirements Analysis, Functional Analysis and Synthesis

• However, System Analysis and Control is where Design Trades and Optimization are used for Value Based decision-making but are often not addressed
Systems Engineering Fundamentals from 1960s-70s

- System Analysis through Optimization & Control should be based on Value-Based Decision-Making
- Multi-Attribute Decision Making (MADM) tools, as a Minimum can assist in Successful Trade Studies

Measure progress and effectiveness; assess alternatives; manage configuration, interfaces, data products and program risk

Requirements Loop

Understand the requirements and how they affect the way in which the system must function.

Design Loop

Identify a feasible solution that functions in a way that meets the requirements

Verification Loop

Show that the synthesized design meets all requirements

Systems Analysis Optimization & Control
For Value Based Decision-Making

Requirements Analysis

Functional Allocation

Synthesis/Design
Top Down Design Decision Support Process Drives Value Based Decision Making

Quality Engineering:
- Provides the Bottom Up Re-composition Approach from On-Line Quality Statistical Process Control
- Is Process Design Driven
- Can provide Robust Design Assessment & Optimization, often Using experimental Based tools.
- Provides the necessary Translation of the Voice of The Customer into Key Product & Process Requirements Using Quality Function Deployment (QFD)

Traditional Systems Engineering:
- Provides the Top Down Decomposition Approach needed
- Is Product Design Driven
- Provides System Synthesis through Multi-disciplinary Design Optimization (MDO), often using gradient based tools
- Provides Product Input for System Analysis and Control

Computer Integrated Environment Provides the Data Exchange as Indicated by Arrows
Process Re-composition Trades
- Should be included initially in Product/System Trades using QFD
- Biggest leverage can be made during Component Process Trades
- Reduction in Part/LRU Trades should be possible if Product/System and Component Product & Process Trades
- .The Development Time line from Conceptual Design to Manufacturing Can be greatly reduced through IPPD
- .Other Life Cycle Processes, such as Operations and Support can also be greatly reduced by their inclusion In the IPPD Trade Study Process

Global Product Data Interoperability is a Key for this Computer Integrated Environment
Use a Multi-Attribute Decision Making (MADM) for Down Selection

QFD tool translates customer desires into engineering factors (Columns of TOPSIS)

Matrix of Alternatives and literature search identify concepts for the Rows of TOPSIS.

Characteristics Calculator

TOPSIS Mathematical Method

<table>
<thead>
<tr>
<th>Rank</th>
<th>Alternative</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type II (same engine)</td>
<td>100.00%</td>
</tr>
<tr>
<td>2</td>
<td>theatre II 1st stage</td>
<td>99.77%</td>
</tr>
<tr>
<td>3</td>
<td>Type II w/ new 1st stage and mod Stage 2 engines</td>
<td>92.65%</td>
</tr>
<tr>
<td>4</td>
<td>Other existing missile w/ RCO2 engines</td>
<td>91.41%</td>
</tr>
<tr>
<td>5</td>
<td>Type III w/ prop w/ both mod engines</td>
<td>88.21%</td>
</tr>
</tbody>
</table>
Interactive Reconfigurable Matrix of Alternatives (IRMA) used for Scoping Intractable Problems

- The Interactive Reconfigurable Matrix of Alternatives helps scope an intractable problem space to a manageable one
- Qualitative method that often uses quantitative analyses for multi-attribute decision making
- Enumerates all possible combinations and their dependencies

IRMA Takes Morphological Matrix and Makes it Interactive
**Product Development**
- Begins with Requirements Analysis To Define the Problem Establish the Value
- Product Data sent to Virtual Product Data Mgt
- Selected Concept(s) Synthesized and Sent for Preliminary Design Iteration Through MDAO
- Physics Based Models are integrated into MDAO w/ Model Center Design Structure Matrix
- Preliminary Design Results sent for Revised Preliminary Design

**Process Development**
- Begins with Data from Virtual Product Data for Manufacturer Processes
- Receives Data from Pre-Vehicle Design Config Geom for Vehicle Assembly Processes; Support Processes; Vehicle Operations Safety Processes; and FAA Certification
- Updates Revised Preliminary Design which feeds LLC and the Overall Evaluation Criterion (OEC)
Terminology for a Model and Model Based Engineering
(Laura E. Hart Lockheed Martin, IS&GS, Presented at the Delaware Valley INCOSE Chapter Meeting July 30, 2015)

Terminology

- **Model:**
  - A simplified version of a concept, phenomenon, relationship, structure or system
  - A graphical, mathematical or physical representation
  - An abstraction of reality by eliminating unnecessary components
  - The objectives of a model include:
    - to facilitate understanding
    - to aid in decision making, examine ‘what if’ scenarios
    - to explain, control, and predict events

“Model-Based Engineering (MBE): An approach to engineering that uses models as an integral part of the technical baseline that includes the requirements, analysis, design, implementation, and verification of a capability, system, and/or product throughout the acquisition life cycle.”

Final Report, Model-Based Engineering Subcommittee, NDIA, Feb. 2011
Terminology and Definition for Model Based Systems Engineering (Laura E. Hart ibid)

• **MBSE**: Model Based Systems Engineering
  - Those aspects of MBE specifically associated with SE
  - includes behavioral analysis, system architecture, requirement traceability, performance analysis, simulation, test, etc.

“Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.”

INCOSE SE Vision 2020 (INCOSE-TP-2004-004-02, Sep 2007)
MBSE is Intended to Provide Life Cycle Support

(Laura E. Hart ibid)

- Formalizes the practice of systems development through the use of models

- Broad in scope
  - Includes multiple modeling domains across life cycle from SOS to component

- Results in quality/productivity improvements & lower risk
  - Rigor and precision
  - Communications among development team and customer
  - Management of complexity
Concept of An Integrated MBE/MBSE Environment

Performance, RMA, SWaP, Cost, etc.
Key Stakeholders Must be Identified for Participation in System Acquisition

Stakeholders Involved in System Acquisition

- Customers
- Developers/Integrators
- Project Managers
- Vendors
- Regulators
- Testers

Modeling Needed to Improve Communications across all Stakeholders
Current Approach: Use Civil Aircraft and Systems Development Process with Integral Processes for Development Assurance Value Based Acquisition (DAVBA)

What
- Civil Aviation Development and Certification Standards are based on worldwide consensus with Continuous on-going updates
- As illustrated in the Figure Development and Safety Assessment are closely Coupled.
- Also, software and electronic hardware have recently been integrated with Integrated Modular Avionics
- Global Product Data Interoperability is essential for Civil Aviation worldwide

Why
- The Functional Safety Management approach for Civil Transport Aircraft represents the “Holy Grail” for civil aircraft safety certification of all aircraft types
- The inclusion of Integrated Modular Avionics (IMA), DO-297, provides a new model for integrated software certification for other aircraft, both civil, military and UAS
- Global Product Data Interoperability is essential for IMA Certification
The Simplified ARP 4754A Civil Aircraft and Systems Development Process in the Figure Below
ARP 4754A Civil Aircraft and System Development Process Model including Integral Processes

INTEGRAL PROCESSES
- 5.1 SAFETY ASSESSMENT
- 5.2 DEVELOPMENT ASSURANCE LEVEL ASSIGNMENT
- 5.3 REQUIREMENTS CAPTURE
- 5.4 REQUIREMENTS VALIDATION
- 5.6 CONFIGURATION MANAGEMENT
- 5.7 PROCESS ASSURANCE
- 5.8 CERTIFICATION & REGULATORY AUTHORITY COORDINATION

CONCEPT
AIRCRAFT FUNCTION DEVELOPMENT
ALLOCATION OF AIRCRAFT FUNCTIONS TO SYSTEMS
DEVELOPMENT OF SYSTEM ARCHITECTURE
ALLOCATION OF SYSTEM REQUIREMENTS TO ITEMS
SYSTEM IMPLEMENTATION
DATA & DOCUMENTATION

AIRCRAFT/SYSTEM DEVELOPMENT PROCESS
PLANNING
The Functional Safety Management (FSM) Integral Safety Assessment for Commercial Transport Aircraft (Part 25) is Illustrated Below

System Development Process (ARP 4754A)

Aircraft Level Requirements → Allocation of Aircraft Functions to Systems → Development of System Architecture → Allocation of Requirements to Hardware & Software → System Implementation

Aircraft Functions → Fail Conditions, Effects, Classification, Safety Objectives → System Functions → Fail Conditions, Effects, Classification, Safety Objectives, Architecture Requirements → Item Requirements

Safety Assessment Process (ARP 4761)

Final Implementation → Certification
5.1 Safety Assessment

5.2 Development Assur. Level Assignments

5.3 Requirements Capture

5.4 Requirements Validation

5.5 Implementation Verification

5.6 Configuration Management

5.7 Process Assurance

5.8 Certification & Regul. Authority Coordination

- Please refer to ARP4754A Section 5 for further descriptions and information.

System Safety

Systems Engineering

CM

Systems

PM
ARP 4754A Civil Aircraft and Systems Development Vee Diagram
Proposed Development Assurance Value Based Acquisition (DAVBA) Technical Approach for Future Vertical Lift (FVL)

- Take the Georgia Tech Integrated Product and Process Development (IPPD) through Robust Design Simulation (RDS) approach to provide a DAVBA Airworthiness Qualification and Specification Compliance Environment
- Build off of the Civil Aircraft Consensus Best Practices as identified in SAE ARP 4754A and apply them where applicable for the DAVBA Virtual Stochastic Prototyping (VSP) using the Dassault Systemes RFLP and PCC MBE methods
- Develop DAVBA Environment in two new ADSs with VSP of baseline FVL medium aircraft, e.g. UH-60M & notional advanced FVL medium aircraft concepts
- Provide the two new Draft ADSs as Deliverables for Consensus Building among the Vertical Lift community
Example of Value Based Decision Decision Making Approach Using MBSE

2015 NRTC Year End Review

- Project Title: Development Assurance Value-Based Acquisition (DAVBA) Approach for Airworthiness Qualification and Specification Compliance
- Project Number: NRTC-FY15-W-01
- Principal Investigator: Daniel P. Schrage
  School of AE, Georgia Tech
  P.(404) 395-4456 F.(404) 894-2760
  Daniel.Schrage@ae.gatech.edu
- Team Members: University of Alabama at Huntsville
  Clausewitz Technology
  Dassault Systemes Government Solutions

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Why is a New Army Aircraft Aeronautical Design Standard (ADS) Based on a DAVBA MBSE Approach Required?

- Military Safety and Airworthiness Qualification standards provide a traditional Qualification Assurance approach, e.g. at the end of development, rather than a Development Assurance Level (DAL) at the beginning of Aircraft Development.
- Cyber Physical Vehicle Systems (CPVS) require Co-Design of Cyber and Physical Systems which requires aircraft guidance for implementing a next generation Integrated Modular Avionics (IMA) standard which includes Reconfiguration and Multi-core processors Certification.
- No equivalent to ARP 4754A exists in the military standards; last update of military airworthiness qualification was ADS-51-HDBK in 1996.
- Contiguous Example required for explicit description on how to apply the DAL Approach from Aircraft Functional Development Assurance Level (FDAL) to Software/Hardware Item Development Assurance Level (IDAL).
Transfer of Civil Aircraft Best Practice Guidelines to Military Aircraft
Development Assurance level (DAL) for functions, item of equipment, item of software.

- The DAL is the means for prescribing the measures to be taken in order to avoid errors during the development of onboard functions systems and items.
- The DAL definition and the allocation process is described in SAE ARP 4754A document.
- DAL is determined using the Safety/Reliability Assessment Process.
- The quality procedures to apply for the development of a function or an item depend on the DAL associated to this item. These quality procedures for the onboard systems are given in:
  - ARP 4754A/ED 19A for functions, systems, equipment development,
  - DO 178 B / ED 78B for software design,
  - DO 254 / ED 80 for electronic hardware design,
  - Aircraft manufacturer/equipment suppliers internal documentation for development and design.
Transfer from Deterministic Virtual Prototyping to Stochastic Virtual Prototyping
Proposed Notional Vee Diagram Layout for FVL DAVBA Approach

Hazard Identification/Risk Mitigation from Start to Finish

Value-Based Acquisition Overall Evaluation Criterion (OEC)

Virtual Prototype (stochastic)

Physical Prototype (VV&A)
Value Based Acquisition (VBA) Approach

\[ DAVBAMetric = \frac{SystemEffectiveness}{LCC} \]

\[ \alpha(A_{Matl}) + \beta(C_{Perf}) + \delta(D_{SysRel+Surv}) \]

\[ \phi(RDTE + PC + O & S + DC) \]

\[ A_{Oper} = \frac{MTBF}{MTBF + MTTR + ALDT} \]

\[ C_{Perf} = MCI^* = \frac{Payload_{HOGE} \times (BlockSpeed)}{W_{Empty} + W_{Fuel}} \]

\[ D_{Safety + Surv} = Functional \ Development \ Assurance \ Level \]

\[ (FDAL) + Survivability (1 - P_D \times P_H \times P_K) \]

\[ \phi LCC = \phi_1 RDTE + \phi_2 PC + \phi_3 O&S + \phi_4 DC \]

- \( \alpha, \beta, \delta \), are system effectiveness weighting variables determined by user-developer consensus
- \( \phi_1, \phi_2, \phi_3, \phi_4 \) are life cycle cost weighting variables determined by user-developer consensus
- The quantitative VBD/A model when defined, analyzed and optimized through Virtual Stochastic Prototyping (VSP) can become the basis for contracting
Model-Based Systems Engineering (MBSE) Approach for DAVBA
Model Based Systems Engineering (MBSE) Implementation in DS Isight
DAVBA Proof of Concepts Results for UH-60M Upgrades and Proposed FVL Approach

- 6K-95F HOGF
- 250Kts Cruise Speed
- 385Km radius
- Increase AoA

- 6K-95F HOGF
- 145Kts Cruise Speed
- 200Km radius
- Increase AoA

- RD Cost = f(Non-recurring Eng/Mfg, Testing, Training, etc)
- Prod Cost = f(weight, complexity, etc.)
- OS Cost = f(RAM, complexity, etc.)

Uncertainty associated with System Effectiveness and Cost

A more robust design trade space that informs decision makers a level of risk as organization is willing to take.

System Effectiveness

Lifecycle Cost
Value Driven Cost Capability Analysis Now Required for DoD Major Weapon System Decision-Making

- Cost and Schedule over runs and lack of achievement in performance objectives for large complex defense systems has led to the need for required Cost Capability Analysis (CCA)
- U.S. Air Force Material Command (AFMC) has introduced CCA, applied it to Pilot Projects, and now require it at all critical milestones. AFMC additional CCA initiatives:
  - Air Force Life Cycle Management Center (AFLCMC) has established a Standard Process for CCA
  - Air Force Institute of Technology (AFIT) has established a CCA Certificate Program in the Graduate School of Engineering and Management
- The U.S. Army Aviation Development Directorate awarded a one year VLC NRTC S&T contract to Georgia Tech, entitled: *A Development Assurance Value Based Acquisition (DAVBA) Approach for Airworthiness Qualification and Specification Compliance*. It included two key elements:
  - Development of a Draft Aeronautical Design Standard (ADS) entitled: *Military Aircraft & Systems Development Assurance and Value Based Acquisition*, which calls for a CCA approach
  - Development of a CCA example for the Draft ADS applying the DAVBA approach to the UH-60M as a FVL Baseline
What is Cost Capability Analysis
(Defensed Acquisition Guide – Systems Engineering, 2016)

• A Cost Capability Analysis (CCA) is an analytical tool used by Program Management to examine cost and military utility. It allows for better understanding and decision making of the effects of requirements on cost and capability. The purpose of a CCA is to support delivery of cost-effective solutions through deliberate trade-off analysis between operational capability and affordability.

• A CCA uses Multi-Objective Decision Analysis (MODA) that results in a trade space between cost and warfighting capabilities. The MODA utilizes an attribute hierarchy to assign a value score to each alternative. Alternatives then are compared based on the requirement attribute score and cost to determine which are most efficient (i.e., provide greatest performance for the cost, or lowest cost for given performance). Once these efficient alternatives are identified, it’s up to the Program Manager, working with the stakeholders, to decide the proper trade-off between cost and performance on the efficient alternatives.
3.3.3.7. Analysis of Alternatives (AoA) Study Plan—Cost-Effectiveness Comparisons

Notional Cost-Effectiveness Analysis: Display of Results

Rectangles indicate upper and lower bounds of sensitivity analyses (or bounds for distribution of results from stochastic models)

Alt 6 is more cost-effective than 5 or 4: at least as effective but at lower cost

For these Alts, question is how much is enough?
Air Force Materiel Command

Cost Capability Policy Update
DRAFT

Mr. Harry Conley
HQ AFMC/A5C
25 March 14

One Team Delivering Capabilities to Fly, Fight & Win.... Today & Tomorrow
When to Perform Cost Capability Analysis?

When to Perform It?

- Start early!
  - Works best when used at the earliest point before the ICD is developed to understand what the realm of the possible is; then throughout Life Cycle

- Reported at AFROC for AoA final report, Capability Development Document (CDD) and Capability Production Document (CPD)
When to Perform Cost Capability Analysis?

**Cost Capability Analysis Decision Framework**

<table>
<thead>
<tr>
<th>Decision Points</th>
<th>AF Decision Maker*</th>
<th>Key Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AFROC</td>
<td>What are the affordable and viable military concepts to mitigating the identified capability gap? Does the AoA Study Plan adequately describe the methodology for estimating the life cycle costs and operational effectiveness of the potential concepts identified in the study guidance to close the gap identified in the ICD?</td>
</tr>
<tr>
<td>2</td>
<td>MDA</td>
<td>Does the preferred solution provide the maximum military utility for cost within affordability constraints? Do the KPPs and KSA reflect life-cycle trades between cost, schedule and performance resulting in the maximized military utility within the affordability constraints? For each KPP and KSA, what are the cost and operational impacts and resulting military utility to accepting a lower threshold value? Does the acquisition strategy reflect maximizing military utility?</td>
</tr>
<tr>
<td>3</td>
<td>AFROC</td>
<td>Can you validate the preferred solution to provide the maximum military utility for cost within affordability constraints? Do the KPPs and KSA reflect life-cycle trades between cost, schedule and performance resulting in the maximized military utility within the affordability constraints? For each KPP and KSA, what are the cost and operational impacts and resulting military utility to accepting a lower threshold value? Does the acquisition strategy reflect maximizing military utility?</td>
</tr>
<tr>
<td>4</td>
<td>MDA</td>
<td>Have changes to the program baseline been assessed to ensure the maximum military utility for cost within affordability constraints? If so, what trades were made to arrive at these values and what are the cost, schedule, technical, and operational implications?</td>
</tr>
</tbody>
</table>

* Final decision maker, other reviews may occur prior to final decision, i.e., AFRRO RDR for AF
Lessons Learned Cost/Capability Pilot Program

Cost/Capability Pilot Programs - What We’re Learning

• Trial programs for developing the analysis and capturing lessons learned:
  
  Advanced Pilot Training (T-X)
  Presidential Aircraft Recapitalization (PAR)
  Ground-Based Strategic Deterrence (GBSD)
  Global Aircrew Strategic Network Terminal (Global ASNT)
  Three-Dimensional Expeditionary Long Range Radar (3DELRR)
  F-15 Eagle Passive/Active Warning and Survivability System (EPAWSS)

  – No formal cost/capability process existed
  – Difficult to define military value/worth of a proposed capability
    • Must define military value before trades can be evaluated
  – Multi-disciplined team approach needed
    • Requirement owner/warfighter, PM, EN, cost analyst, ops research
    • Requires tight coupling of engineering and cost functions within the program office
  – Depicting results of analysis more difficult than expected
  – Industry analysis provided valuable insights to decisions
  – Cost capability methodology should be started in Development Planning (DP) and Analysis of Alternatives (AoA) timeframe and used throughout lifecycle
Results of a USAF Pilot Project on Application of CCA

F-15 EPAWSS AoA Pilot Program

F-15 EPAWSS (AFMC Pilot Program)
- ACC defined the priority—or operational value—derived from each measure under four AoA Mission Tasks
- Performing cost & effectiveness analysis at detail level
- Aggregating normalized results to compare Alternatives

- First down-selecting Alternatives that are on the "Pareto Front"
- Further down-selecting Alternatives based on affordability and minimum acceptable capability
AFMC Pilot Programs for progressive CCA Development and Evaluation

Understanding the Trade Space

AFMC pilot programs are implementing cost-capability process tailored to each program’s phase and specific needs.
Identifying the Next Steps for Integrating GPDI into MBE and MBSE

• Build off recent inclusions of GPDI in MBSE, such as Boeing is doing with its movement from the traditional Vee Diagram to a Diamond Diagram to capture the Digital Twin
• Recruit Industry-Government-Academia Stakeholders for creating a GPDI/MBE/MBSE Research and Education Consortium based on enhancing Civil Aircraft and Systems Development Guidelines for Development Assurance and Value-Based Decision-Making for other applications
• The Georgia Tech Graduate Program in Aerospace Engineering has the expertise, experience and resources to lead such a Consortium Effort
• Would be glad to work with Industry-Government and Academia pursuing this Partnership