

**COMPLEX MULTIDISCIPLINARY SYSTEMS DECOMPOSITION FOR
AEROSPACE VEHICLE CONCEPTUAL DESIGN AND
TECHNOLOGY ACQUISITION**

by

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ABSTRACT

COMPLEX MULTIDISCIPLINARY SYSTEMS DECOMPOSITION FOR AEROSPACE VEHICLE CONCEPTUAL DESIGN AND TECHNOLOGY ACQUISITION

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Although, the Aerospace and Defense (A&D) industry is a significant contributor to the United States' economy, national prestige and national security, it experiences significant cost and schedule overruns. This problem is related to the differences between technology acquisition assessments and aerospace vehicle conceptual design. Acquisition assessments evaluate broad sets of alternatives with mostly qualitative techniques, while conceptual design tools evaluate narrow set of alternatives with multidisciplinary tools. In order for these two fields to communicate effectively, a common platform for both concerns is desired. This research is an original contribution to a three-part solution to this problem. It discusses the decomposition step of an innovation technology and sizing tool generation framework. It identifies complex multidisciplinary system definitions as a bridge between acquisition and conceptual design. It establishes complex multidisciplinary building blocks that can be used to build synthesis systems as well as technology portfolios. It also describes a Graphical User Interface Designed to aid in decomposition process. Finally, it demonstrates an application of the methodology to a relevant acquisition and conceptual design problem posed by the US Air Force.

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Chapter 1

INTRODUCTION

1.1 Motivation of Research Topic

The Aerospace and Defense (A&D) industry is a significant contributor to the United States' economy, national prestige and national security. In 2014, the industry made \$408.5 billion in revenue (Deloitte 2015), part of which was \$78.7 billion in aerospace export-import trade balance which led to the employment of about 700,000 people (DoC 2015). In addition, recent successes of the *SpaceX Falcon 9*, *ULA Atlas* and *Blue Origin New Shepard* launches have rekindled interests in the Space travel. Furthermore, there have been significant investments in high-speed technologies, such as *Hypersonic Test Vehicle (HTV)*, *XS-1* and *SR-72* to improve U.S. defense systems from global threats.

Although the A&D industry as a whole reported increased profits in 2014, defense subsector revenues have seen a down turn. The sector saw a \$5.4 billion decline in revenue in 2014 and is expected to reach an all-time low in 2015 (Deloitte 2015). Steinbock explains that the challenges the US defense faces are cost pressures endangered by sequestration, limited budgets, bias for short-term defense policies at the expense of investments in longer term higher risk activities, challenges of defense acquisitions, shift from defense spin-offs to consumer market spin-ons, hollowing out of the defense industrial base, erosion of competitive inter-service pressures, lower defense contractor R&D intensity and rising foreign defense (Steinbock 2014).

The major sources of the revenue decline are cost overruns and schedule delays experienced by DOD and A&D companies. In "Can We Afford Our Own Future?" Deloitte predicts that the average program cost overruns may exceed 46 percent by 2019 (Deloitte 2009). The root causes of the problem are identified as:

- Project management – Activities such as planning, sourcing, assurance, staffing, finance and integration have increased budget overruns without improving development cycle time. In addition, managers rely heavily on assumptions about system requirements, technology, and design maturity, which are consistently too optimistic.
- Politics – Acquisition decisions are biased towards political expediency and not necessarily performance results. This has resulted in fund shifting to and from programs in order to hide bad news reports. Thus, undermining well-performing programs to pay for poorly performing ones.
- Supply Chain – Original equipment manufacturers (OEMs) and large platform contractors are shedding more their manufacturing and subsystem assembly work and streamlining their supplier base to create greater economies of scale. This has led to increased supplier dependency and risk of supply bottlenecks.
- Technical Complexity – Increasing performance requirements and desire for the newest technologies that apply the latest theories has led to the design of more complex vehicles. This has translated to over 500% increase in development lifecycles since the 60's.
- Talent Shortage – Baby boomers and older workers comprise 70% of the DoD and civilian AT&L workforce. Coupled with the fact that the US is producing fewer qualified scientist and engineers and the baby boobers heading for retirement, causes concern about the talent availability in A&D industry. In addition, A&D contractors experience shortage of experienced employees with a broad understanding of systems integration in an industry that is heading toward more system integration and complexity. This has had a direct effect on cost overruns and delays.

These problems highlight the following motivating problems with technology forecasting:

- The need for increase in design efficiency to balance out waste in the development chain.
- The need for increase in design capability to improve correctness and drive optimism towards realism.
- The need to Increase in design transparency to reduce acquisition decision bias.
- The need for a methodology that can be adapted for various system integration environments to allow easier knowledge transfer to incoming engineers.
- The need for a platform that allows for communication between different levels of the development life cycle and supply chain.

1.2 Background of Research topic

1.2.1 Acquisition Lifecycle

The defense acquisition system exists to manage the nation's investments in technologies, programs and product support necessary to achieve the National Security (Brown 2010). It involves the use of systems engineering (SE) processes by government and industry entities to provide a framework and methodology to plan, manage, and implement technical activities throughout the acquisition life cycle (DAU 2013, SMC 2010; USAF 2011; OSD 2015; MSFC 2012). Redshaw (2009) explains that the acquisition system evolved from system engineering approaches because programs for developing complex systems exhibit the same features that formalized the systems engineering process (Redshaw 2009). The evolution of the system engineering process for defense acquisition is shown in Figure 1-1. The major teams involved in the model are the decision authority, the development/design & engineering (system integrator) and specialty engineering (technologist).

In the pre-2003 model, the system engineering process only manages the tasks of the system integrator and does not consider the decision authority and the technologist (Redshaw 2009). There are two disadvantages of this model. First, the design engineer was not involved in the definition of requirements and programs were already flawed from the beginning. Nicolai explains

“ Even when the customer tries very hard to generate a credible set of requirements. Sometimes they are flawed. History is filled with flawed requirements. Some flawed requirements are discovered and changed, some flawed requirements prevail and designs are produced and some flawed requirements are ignored (this one is always risky).”

Second, the verification loop did not place emphasis on the role of test planning, testing and evaluation of results as major parts of the product development lifecycle (Redshaw, 2009). These flaws speak to the need for collaboration between the decision maker, synthesis specialist and the technologists. The steps of the 2009 model are

- Stakeholder requirements definition – *“establishes a firm baseline for system requirements and constraints..., thus defining project scope”*.
- Requirements analysis – *“examine user’s needs against available technologies, design considerations, and external interfaces to begin translating operational requirements into technical specifications”*.
- Architecture design – *develop a “functional architecture to achieve required capabilities across scenarios from the operational concept; developing a physical architecture, internal interfaces, and integration plan, synthesizing alternative combinations of system components; and selecting the optimal design that satisfies and balances all requirements and constraints”*.

Stake holder requirements definition is a shared responsibility between the decision maker and the system integrator while architecture design allows for the involvement of

technologists. In addition, implementation, integration, verification, validation and transition are explicitly mentioned in the model.

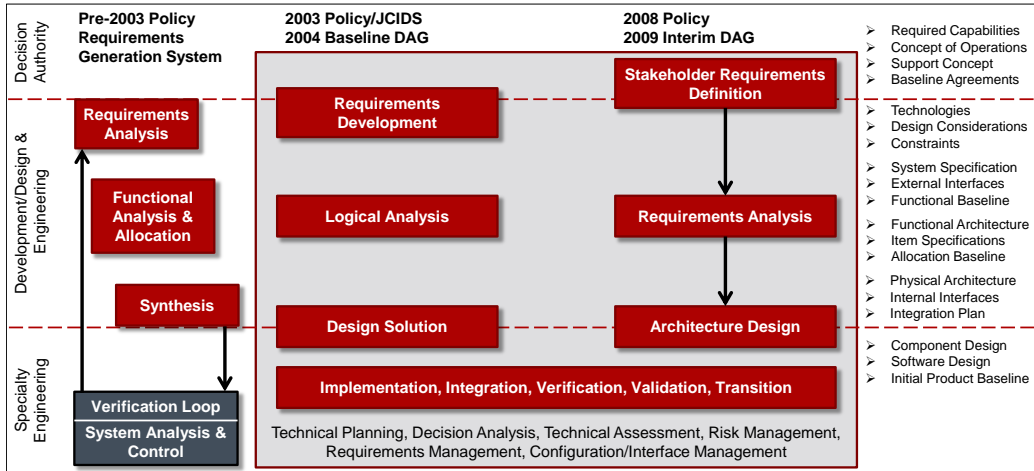


Figure 1-1 Defense Acquisition Systems Engineering Lifecycle (Redshaw 2009)

1.2.2 Acquisition and Conceptual Design

The 2009 acquisition system correlates with the aircraft product development lifecycle. The aircraft design lifecycle is shown in Figure 1-2. The requirements analysis phase corresponds to the mission definition where requirements are translated into the definition of the system. Architecture design corresponds to the three aircraft design phases, conceptual design (CD), Preliminary Design (PD) and Detail Design (DD). The implementation step corresponds with flight test, Certification and Manufacturing. The conceptual design phase determines the feasibility of meeting requirements with a credible aircraft design (Nicolai, 2010). The CD phase is critical in design because there is most freedom to change the design without incurring a lot of cost, see Figure 1-2. One of the key characteristics of the conceptual design phase is synthesis. Synthesis is concerned with the systematic generation of alternatives in order to create new designs or improve existing ones (Kusiak, 1995). A wealth of synthesis systems has been developed over the last 50 years. Table 1 shows an updated comprehensive list of synthesis systems that have

been developed to aid in aircraft design as compiled by (Chudoba, 2001; Huang, 2006; Coleman, 2010).

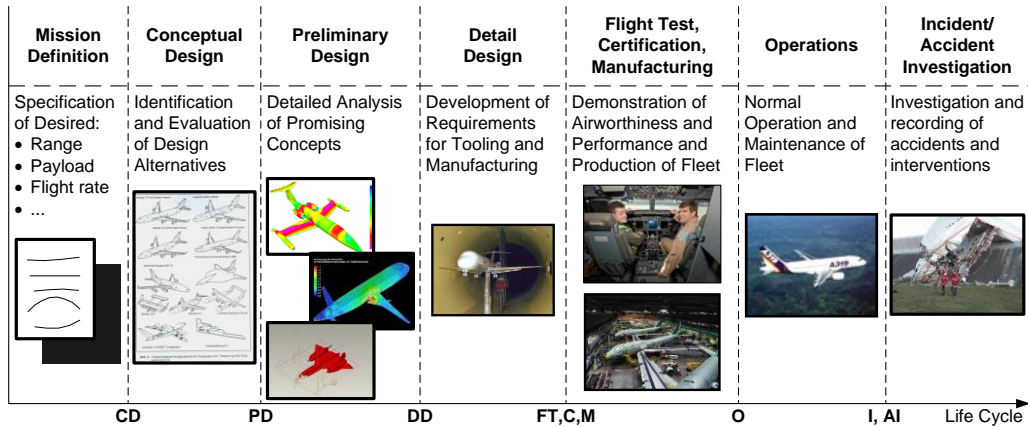


Figure 1-2 Design Lifecycle Phase (Omoragbon, 2008)

Table 1-1 Aircraft Synthesis Systems (Chudoba, 2001; Huang, 2006; Coleman, 2010)

Acronym	Full Name	Developer	Primary Application	Years
AAA	Advanced Airplane Analysis	DARcorporation	Aircraft	1991-
ACAD	Advanced Computer Aided Design	General Dynamics, Fort Worth	Aircraft	1993
ACAS	Advanced Counter Air Systems	US Army Aviation Systems Command	Air fighter	1987
ACDC	Aircraft Configuration Design Code	Boeing Defense and Space Group	Helicopter	1988-
ACDS	Parametric Preliminary Design System for Aircraft and Spacecraft Configuration	Northwestern Polytechnical University	Aircraft and AeroSpace Vehicle	1991-
ACES	Aircraft Configuration Expert System	Aeritalia	Aircraft	1989-
ACSYNT	AirCRAFT SYNThesis	NASA	Aircraft	1987-
ADAM	(-)	McDonnell Douglas	Aircraft	
ADAS	Aircraft Design and Analysis System	Delft University of Technology	Aircraft	1988-
ADROIT	Aircraft Design by Regulation Of Independent Tasks	Cranfield University	Aircraft	
ADST	Adaptable Design Synthesis Tool	General Dynamics/Fort Worth Division	Aircraft	1990
AGARD				1994
AIDA	Artificial Intelligence Supported Design of Aircraft	Delft University of Technology	Aircraft	1999
AircraftDesign	(-)	University of Osaka Prefecture	Aircraft	1990
APFEL	(-)	IABG	Aircraft	1979
Aprog	Auslegungs Programm	Dornier Luftfahrt	Aircraft	
ASAP	Aircraft Synthesis and Analysis Program	Vought Aeronautics Company	Fighter Aircraft	1974

ASCENT	(-)	Lockheed Martin Skunk Works	AeroSpace Vehicle	1993
ASSET	Advanced Systems Synthesis and Evaluation Technique	Lockheed California Company	Aircraft	Before 1993
Altman	Design Methodology for Low Speed High Altitude UAV's	Cranfield University	Unmanned Aerial Vehicles	Paper 1998
AVID	Aerospace Vehicle Interactive Design	N.C. State University, NASA LaRC	Aircraft and AeroSpace Vehicle	1992
AVSYN	?	Ryan Teledyne	?	1974
BEAM	(-)	Boeing	?	NA
CAAD	Computer-Aided Aircraft Design	SkyTech	High-Altitude Composite Aircraft	NA
CAAD	Computer-Aided Aircraft Design	Lockheed-Georgia Company	Aircraft	1968
CACTUS	(-)	Israel Aircraft Industries	Aircraft	NA
CADE	Conceptual Aircraft Design Environment	McDonnell Douglas Corporation	Fighter Aircraft (F-15)	1974
CAP	Configuration Analysis Program	North American Rockwell (B-1 Division)	Aircraft	1974
CAPDA	Computer Aided Preliminary Design of Aircraft	Technical University Berlin	Transonic Transport Aircraft	1984-
CAPS	Computer Aided Project Studies	BAC Military Aircraft Division	Military Aircraft	1968
CASP	Combat Aircraft Synthesis Program	Northrop Corporation	Combat Aircraft	1980
CASDAT	Conceptual Aerospace Systems Design and Analysis Toolkit	Georgia Institute of Technology	Conceptual Aerospace Systems	late 1995
CASTOR	Commuter Aircraft Synthesis and Trajectory Optimization Routine	Loughborough University	Transonic Transport Aircraft	1986
CDS	Configuration Development System	Rockwell International	Aircraft and AeroSpace Vehicle	1976
CISE	(-)	Grumman Aerospace Corporation	AeroSpace Vehicle	1994
COMBAT	(-)	Cranfield University	Combat Aircraft	
CONSIZ	CONfiguration SIzING	NASA Langley Research Center	AeroSpace Vehicle	1993
CPDS	Computerized Preliminary Design System	The Boeing Company	Transonic Transport Aircraft	1972
Crispin	Aircraft sizing methodology	Loftin	Aircraft sizing methodology	1980
DesignSheet	(-)	Rockwell international	Aircraft and AeroSpace Vehicle	1992
DRAPO	Définition et Réalisation d'Avions Par Ordinateur	Avions Marcel Dassault/Bréguet Aviation	Aircraft	1968
DSP	Decision Support Problem	University of Houston	Aircraft	1987
EASIE	Environment for Application Software Integration and Execution	NASA Langley Research Center	Aircraft and AeroSpace Vehicle	1992
EADS				
ESCAPE	(-)	BAC (Commercial Aircraft Division)	Aircraft	1995
ESP	Engineer's Scratch Pad	Lockheed Advanced Development Co.	Aircraft	1992
Expert Executive	(-)	The Boeing Company	?	
FASTER	Flexible Aircraft Scaling To Requirements	Florian Schieck		
FASTPASS	Flexible Analysis for Synthesis, Trajectory, and Performance for Advanced Space Systems	Lockheed Martin Astronautics	AeroSpace Vehicle	1996
FLOPS	FLight OPTimization System	NASA Langley Research Center	?	1980s-

FPDB & AS	Future Projects Data Banks & Application Systems	Airbus Industrie	Transonic Transport Aircraft	1995
FPDS	Future Projects Design System	Hawker Siddeley Aviation Ltd	Aircraft	1970
FRICITION	Skin friction and form drag code			1990
FVE	Flugzeug VorEntwurf	Stemme GmbH & Co. KG	GA Aircraft	1996
GASP	General Aviation Synthesis Program	NASA Ames Research Center	GA Aircraft	1978
GPAD	Graphics Program For Aircraft Design	Lockheed-Georgia Company	Aircraft	1975
HACDM	Hypersonic Aircraft Conceptual Design Methodology	Turin Polytechnic	Hypersonic aircraft	1994
HADO	Hypersonic Aircraft Design Optimization	Astrox	?	1987-
HASA	Hypersonic Aerospace Sizing Analysis	NASA Lewis Research Center	AeroSpace Vehicle	1985, 1990
HAVDAC	Hypersonic Astrox Vehicle Design and Analysis Code	Astrox		1987-
HCDV	Hypersonic Conceptual Vehicle Design	NASA Ames Research Center	Hypersonic Vehicles	
HESCOMP	HElicopter Sizing and Performance COMputer Program	Boeing Vertol Company	Helicopter	1973
HISAIR/Pathfinder	High Speed Airframe Integration Research	Lockheed Engineering and Sciences Co.	Supersonic Commercial Transport Aircraft	1992
Holist	?	?	Hypersonic Vehicles with Airbreathing Propulsion	1992
ICAD	Interactive Computerized Aircraft Design	USAF-ASD	?	1974
ICADS	Interactive Computerized Aircraft Design System	Delft University of Technology	Aircraft	1996
IDAS	Integrated Design and Analysis System	Rockwell International Corporation	Fighter Aircraft	1986
IDEAS	Integrated DSign Analysis System	Grumman Aerospace Corporation	Aircraft	1967
IKADE	Intelligent Knowledge Assisted Design Environment	Cranfield University	Aircraft	1992
IMAGE	Intelligent Multi-Disciplinary Aircraft Generation Environment	Georgia Tech	Supersonic Commercial Transport Aircraft	1998
IPAD	Integrated Programs for Aerospace-Vehicle Design	NASA Langley Research Center	AeroSpace Vehicle	1972-1980
IPPD	Integrated Product and Process Design	Georgia Tech	Aircraft, weapon system	1995
JET-UAV CONCEPTUAL DEISGN CODE		Northwestern Polytechnical University, China	Medium range JET-UAV	2000
LAGRANGE			Optimization	1993
LIDRAG	Span efficiency			1990
LOVELL				1970-1980
MAVRIS	an analysis-based environment	Georgia Institue of Technology		2000
MELLER		Daimler-Benz Aerospace Airbus	Civil aviation industry	1998
MacAirplane	(-)	Notre Dame University	Aircraft	1987
MIDAS	Multi-Disciplinary Integrated Design Analysis & Sizing	DaimlerChrysler Military	Aircraft	1996
MIDAS	Multi-Disciplinary Integration of Deutsche Airbus Specialists	DaimlerChrysler Aerospace Airbus	Supersonic Commercial Transport Aircraft	1996
MVA	Multi-Variate Analysis	RAE (BAC)	Aircraft	1991
MVO	MultiVariate Optimisation	RAE Farnborough	Aircraft	1973

NEURAL NETWORK FORMULATION	Optimization method for Aircraft Design	Georgia Institute of Technology	Aircraft	1998
ODIN	Optimal Design INtegration System	NASA Langley Research Center	AeroSpace Vehicle	1974
ONERA	Preliminary Design of Civil Transport Aircraft	Office National d'Etudes et de Recherches Aérospatiales	Subsonic Transport Aircraft	1989
OPDOT	Optimal Preliminary Design Of Transports	NASA Langley Research Center	Transonic Transport Aircraft	1970-1980
PACELAB	knowledge based software solutions	PACE	Aircraft	2000
Paper Airplane	(-)	MIT	Aircraft	
PASS	Program for Aircraft Synthesis Studies	Stanford University	Aircraft	1988
PATHFINDER		Lockheed Engineering and Sciences Co.	Supersonic Commercial Transport Aircraft	1992
PIANO	Project Interactive ANalysis and Optimisation	Lissys Limited	Transonic Transport Aircraft	1980-
POP	Parametrisches Optimierungs-Programm	Daimler-Benz Aerospace Airbus	Transonic Transport Aircraft	2000
PrADO	Preliminary Aircraft Design and Optimisation	Technical University Braunschweig	Aircraft and AeroSpace Vehicle	1986-
PreSST	Preliminary SuperSonic Transport Synthesis and Optimisation	DRA UK	Supersonic Commercial Transport Aircraft	
PROFET	(-)	IABG	Missile	1979
RAE	Artificial Intelligence Supported Design of Aircraft	Royal Aircraft Establishment, Farnborough	Aircraft conceptual design	Early 1970's.
RAM		NASA	geometric modeling tool	1991
RCD	Rapid Conceptual Design	Lockheed Martin Skunk Works	AeroSpace Vehicle	
RDS	(-)	Conceptual Research Corporation	Aircraft	1992
RECIPE	(-)	?	?	1999
RSM	Response Surface Methodology			1998
Rubber Airplane	(-)	MIT	Aircraft	1960s-1970s
Schnieder				
Siegers	Numerical Synthesis Methodology for Combat Aircraft	Cranfield University	combat aircraft	Late 1970s
Spreadsheet Program	Spreadsheet Analysis Program	Loughborough University	Aircraft Design Studies	1995
SENSxx	(-)	DaimlerChrysler Aerospace Airbus	Transonic Transport Aircraft	
SIDE	System Integrated Design Environment	Astrox	?	1987-
SLAM	Simulated Language for Alternative Modeling	?	?	
Slate Architect	(-)	SDRC (Eds)	?	
SSP	System Synthesis Program	University of Maryland	Helicopter	
SSSP	Space Shuttle Synthesis Program	General Dynamics Corporation	AeroSpace Vehicle	
SYNAC	SYNthesis of AirCRAFT	General Dynamics	Aircraft	1967
TASOP	Transport Aircraft Synthesis and Optimisation Program	BAe (Commercial Aircraft) LTD	Transonic Transport Aircraft	

TIES	Technology Identification, Evaluation, and Selection	Georgia Institute of Technology		1998
TRANSYN	TRANsport SYNthesis	NASA Ames Research Center	Transonic Transport Aircraft	1963- (25years)
TRANSYS	TRANsportation SYStem	DLR (Aerospace Research)	AeroSpace Vehicle	1986-
TsAGI	Dialog System for Preliminary Design	TsAGI	Transonic Transport Aircraft	1975
VASCOMPII	V/STOL Aircraft Sizing and Performance Computer Program	Boeing Vertol CO.	V/STOL aircraft	1980
VDEP	Vehicle Design Evaluation Program	NASA Langley Research Center	Transonic Transport Aircraft	
VDI				
Vehicles	(-)	Aerospace Corporation	Space Systems	1988
VizCraft	(-)	Virginia Tech	Supersonic Commercial Transport Aircraft	1999
Voit-Nitschmann				
WIPAR	Waverider Interactive Parameter Adjustment Routine	DLR Braunschweig	AeroSpace Vehicle (Waverider)	
X-Pert	(-)	Delft University of Technology	Aircraft	Paper 1992

1.2.3 Problems in Conceptual Design Relating to Acquisition

The introduction of stakeholder requirements definition as a responsibility for the conceptual designer presents new challenges for the current aerospace synthesis systems. First, typical conceptual design tools and methodologies are not designed to provide the information required for requirements definition. Figure 1-3 shows a review of selected methodologies. They each have elements for designing, building and integration architectures for analysis; however, none of them prescribe a methodology for stakeholder requirements definition. Second, requirements definition typically requires analysis of a broad range of alternatives (DAU 2013). However, most synthesis systems have a narrow range of alternatives that can be analyzed. This is because most of those decisions have already been made before the synthesis step. Finally, conceptual design methodologies need to be rapid turn-around at giving solutions to the decision makers in order to avoid incorrect assumptions and decision-making during the early project phase.

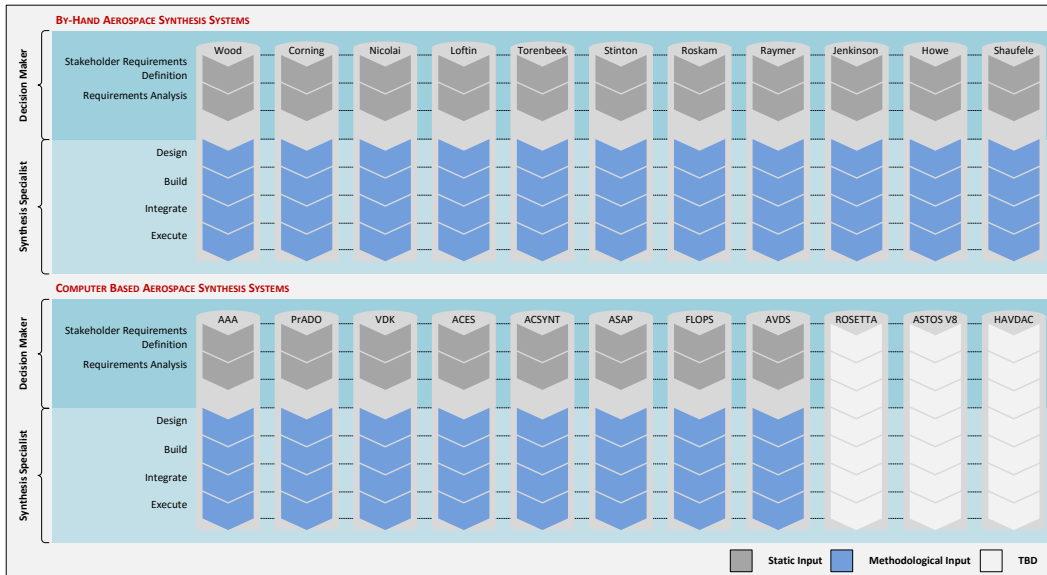


Figure 1-3 Review of Aircraft Synthesis Systems

1.2.4 Stakeholder Requirement Definition Solutions

Methodologies exist to provide the capability to evaluate technologies for defense acquisition. Azizan does a comprehensive review of the assessment approaches available and categorizes them into qualitative, quantitative and automated techniques. The qualitative techniques involve use of perceived maturity levels of technology the most common of which is Technology Readiness Level (Azzizan, 2009; Cornford, 2004; Nolte, 2004; Bilbro, 2009; Dubos, 2007; Mankins, 2007; Mankins, 2002; Ramirez-Marquez, 2009; Smith, 2009). TRL uses a 9 level scale to present the state of technology as scene in Figure 1-4. The biggest drawback of the TRL measure is that it accounts only for the maturity of individual technologies, however it doesn't capture the complexity of packaging those technologies together as would be for aerospace vehicles. Other Maturity scales have been created to capture more information than TRL and they include Manufacturing readiness level (Cundiff, 2003), Integration readiness level (Gove, 2007), TRL for non-system technologies (Graettinger, 2002), TRL for Software (DOD, 2005), Technology Transfer

Level Readiness Level (Holt, 2007), Missile Defense Agency checklist (Mahafza, 2005), Moorhouses Risk Versus TRL Metric (Moorehouse, 2002), Advancement Degree of Difficulty (AD2) (Bilbro, 2007) and Research and Development Degree of Difficulty (RD3). Qualitative techniques have the advantages of being quick and easily updatable; however, they are based on subjective knowledge and do not have a means to consider uncertainties in the knowledge.

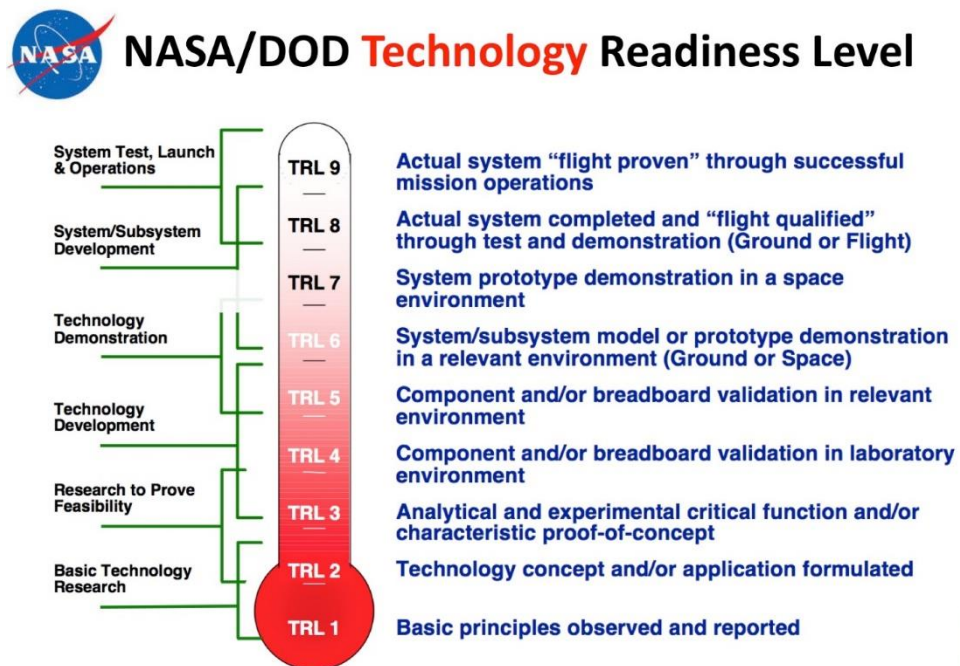


Figure 1-4 NASA/DOD Technology Readiness Level Descriptions (NASA)

Quantitative techniques are prescribed mathematical models for translating qualitative metrics into numerical data that gives more insight into the maturity of the technologies. for example, System Readiness Level developed by Sauser uses matrix manipulations to combine individual subsystem TRLs and IRLs based on the interactions with one another to describe the maturity of the subsystem technologies as a result of them combining them into a single system (Saucer 2006, 2007, 2008). Other quantitative

techniques include SRL Max (Ramirez-Marquez 2009) Technology Readiness and Risk Assessment (TRRA) (Mankins 2007), Integrated Technology Analysis Methodology (ITAM) (Mankins 2002), TRL for Non Developmental Item (NDI) Software, Technology insertion (TI) Metric (Dowling and Pardo 2005) and TRL Schedule Risk Curve (Dubos et al 2007). The quantitative techniques are very useful in giving a decision maker analytic data for fact based decision making; however, they can be difficult to understand and cause information overload if used improperly.

Automated techniques use spreadsheets or calculators to evaluate the maturity of technologies. They reduce subjective bias by converting the evaluation into smaller questions and surveys that are converted into analysis data. They include TRL calculator (Nolte 2004), MRL Calculator, Technology Program Management Model (TPMM) (SMDTC 2006) and UK MoD System Readiness Level.

The biggest drawback of these acquisition tools is that they do not prescribe a means of including vehicle mission performance information. Vehicle performance information is generally a result of sizing and synthesis. Secondly, they do not account for the supply chain problem and do not include metrics determined from business process analyses.

1.3 Research Scope and Objectives

The breath of the problems in the Aerospace & Defense industry are broad, covering acquisition lifecycle simulation, conceptual design and business processes. This writing, will not attempt to solve all these problems; instead this discussion will answer the following research questions:

[RQ1] What data relationships are required to connect existing conceptual design synthesis with acquisition assessment?

[RQ2] What are the building blocks required to make conceptual design tools adaptable to solve emerging aerospace problems in the new acquisition assessment environment?

[RQ3] How can the methodology that bridges the gap between acquisition and design decision making be used?

1.4 Research Approach and Dissertation Outline

The framework for solving the acquisition problem was too large to be solved by a single PhD; therefore, a research endeavor has been taken in conjunction with two other PhD candidates: Lex Gonzalez and Amit Oza. The unique contribution to this effort by Amen Omoragbon has been to define the building blocks for the solution architecture, while Gonzalez (2016) has been tasked to design the software interfaces for the composable architecture to tailoring tools to problems, and Oza (2016) prescribed the proper utilization of the system to solve relevant acquisition problems.

In this research thesis, Chapter 1 discusses the motivation of the research which is the need to improve technology acquisition decision-making from an aerospace conceptual designer view point. Chapter 2 explores available aerospace synthesis literature evaluating them in terms of technology adaptability, analysis capability and data/knowledge management. The result being a specification for a decomposition methodology for an aerospace decision support system. Chapter 3 describes the *Complex Multidisciplinary System (CMDS) decomposition concept* for bridging the gap between aerospace technology acquisition and aerospace vehicle conceptual design. This decomposition concept is the original contribution to aerospace science and engineering, in particular the engineering decision support system developed in collaboration with Gonzalez and Oza in the ASE Laboratory. Chapter 4 discusses the software implementation of the CMDS decomposition concept. Chapter 5 discusses the application

of the CMDS decomposition concept to a relevant acquisition and conceptual design problem posed by United State Air Force Research Laboratory. Finally, Chapter 6 summarizes the original contribution of this research effort to aerospace science and gives an outlook for future work.

Chapter 2

COMPLEX SYSTEMS, AIRCRAFT SYNTHESIS AND PORTFOLIO MANAGEMENT

Chapter 1 discussed the need for establishing the data relationships between aircraft conceptual design and acquisition lifecycle assessment. These data relationships are key in decreasing cost and schedule overruns in the acquisition lifecycle. This chapter sets the framework of the solution concept by representing aerospace vehicles as complex systems that require multidisciplinary synthesis for their design. The Innovation Portfolio is then introduced as the link between acquisition and conceptual design. This information will be used to construct the solution concept methodology in Chapter 3. The review includes a survey of complex multidisciplinary systems, synthesis tools and innovation portfolios.

2.1 Complex Systems and Complex Multidisciplinary Systems

The term 'system' has a broad meaning. Kline (1995) gives three definitions of a 'system'. First, a system is the object of study, what we want to discuss, define, think about, write about, and so forth. This means that a system is anything that we care about. Secondly, a system is a picture, equation, mental image, conceptual model, word description, etc., which represents the entity we want to discuss, analyze, think about, write about. This implies that a representation of a system is a system in itself. Thirdly, a system is an integrated entity of heterogeneous parts which acts in a coordinated way. This definition gives the idea that a system comprises unique parts that perform actions. In addition, it allows the introduction of the concept of system complexity.

2.1.1 *Complex Systems*

A complex system is defined as one that requires a lot of information in order to describe it. Bar-Yam (1997) characterizes complexity of system elements, their number,

the interactions, their strength, formation/operation and their time scales, diversity/variability, environment and its demands, activities and their objectives. Table 2-1 Boulding (1956) gives a hierarchy of system complexity based on the prevailing scientific understanding. This shows that system complexity changes with types of disciplines considered in the representation of the system. It also speaks to the multidisciplinary nature of complex systems. A simple system can be made complex if it is to be studied by taking multiple disciplinary points of view into account as shown in Figure 2-1. Complex systems retain definitions across philosophy, theory and application as show in Table 2-1. Shashank (2010) summarizes the measures of complexity as:

- Level of Abstraction: Complexity measured through “... *the visualization of system at different levels of detail ...*” such as system level (e.g. vehicle as a whole), subsystem level (e.g. wing), component level (e.g. wing spars) as shown in Figure 2-2.
- Type of representation – Complexity resulting from how the system is modeled at each level of abstraction.
- Size – Complexity based on the number of components and interactions within the system.
- Heterogeneity – Complexity based on the number of unique components and interactions. This is similar to the size measure. However, it takes into account the fact that the system with repeating components and interactions can be simplified.
- Coupling – Complexity based on the types of interactions between the components. There can be direct coupling, where the components are physically connected, or indirect coupling, where one component affects another without a physical link.

- Modularity – Complexity due to a group of components coupled together in order to provide a function.
- Uncertainty – Complexity due to the potential of a system to exhibit unexpected behavior.
- Dynamics – Complexity due to the variation of system behavior over time.
- Off-Design interactions – Complexity due to the system operating outside its design range.

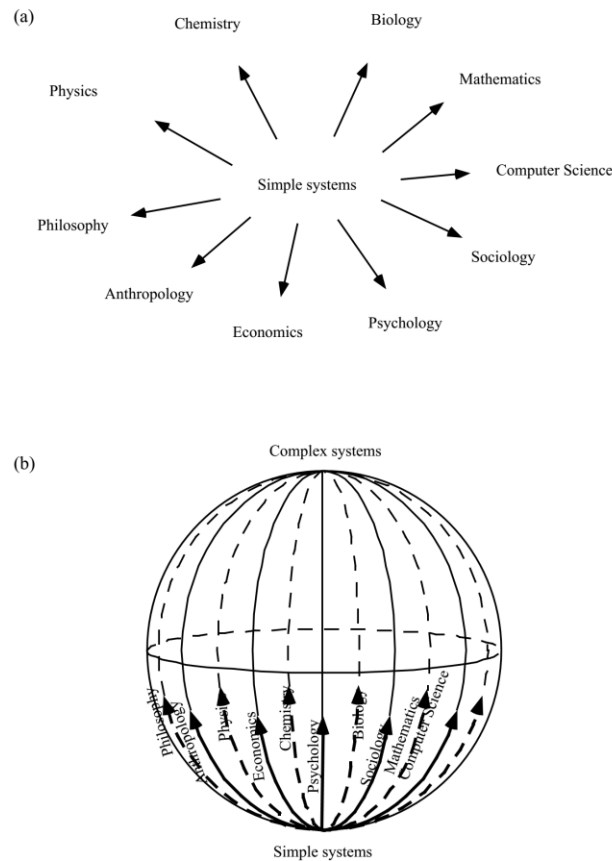


Figure 2-1 Views of complexity (Bar-Yam, 1997) (a) Simple system made complex by number of disciplines studied (b) Complexity due to multidisciplinary interactions

Table 2-1 Hierarchy Complexity (Boulding 1977)

Level	Characteristics	Examples	Relevant Discipline
1. Structure	Static	Crystals	Any
2. Clock-works	Pre-Determined motion	Machines, the solar system	Physics, Chemistry
3. Control Mechanism	Closed-loop control	Thermostats, mechanisms in organisms	Cybernetics, Control Theory
4. Open Systems	Structurally Self maintaining	Flames, biological cells	Information Theory, Biology (metabolism)
5. Lower Organisms	Organized whole functional parts, growth, reproduction	Plants	Botany
6. Animals	A brain to guide total behavior ability to learn	Birds and Beasts	Zoology
7. Humans	Self-consciousness, knowledge symbolic language	Humans	Psychology, Human Biology
8. Socio-cultural systems	Roles communication, transmission of values	Families, clubs, organizations, nations	Sociology, Anthropology
9. Transcendental systems	Inescapable unknowables	God	Metaphysics, Theology

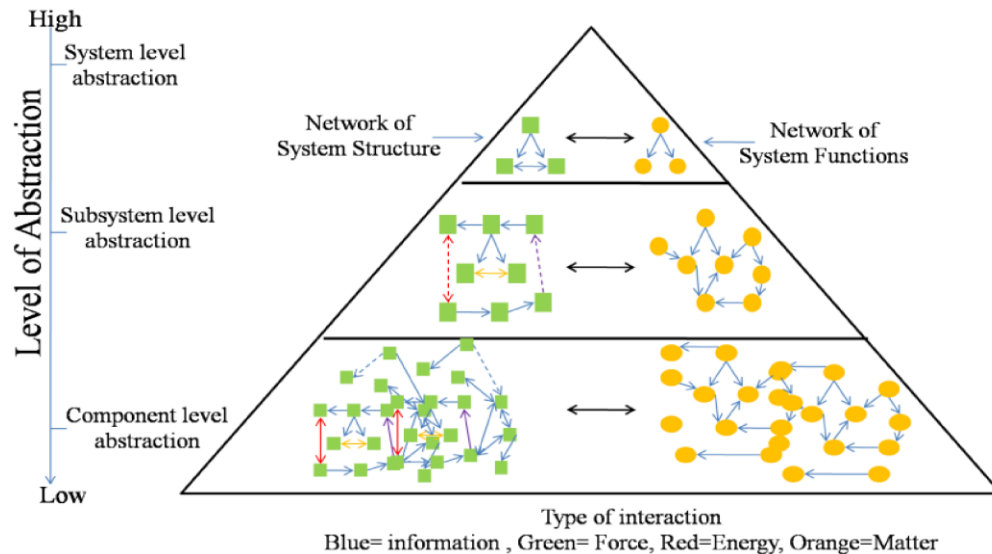


Figure 2-2 System Architecture Specification Concepts (Shashank , 2010)

Ryan has shown that Complex Systems can be used to answer a broad range of problems if a multidisciplinary approach is used to their design. He remarks that “... *of all the systems approaches, complex systems are the most tightly integrated with the natural sciences, due to an emphasis on explaining mechanism in natural systems ...*” Therefore, the representation of objects of study as complex systems gives the most suitable starting point for analysis. In the context of this research, the term complex multidisciplinary system (CMDS) is used. This is because the goal is to build a methodology for assessing the risk and value of emerging aerospace technology from an acquisition and conceptual design point of view. These systems are complex because of their limited understanding and numerous highly integrated parts. The word ‘multidisciplinary’ has been added to Complex Systems in order to emphasize that they need to be studied from more than a single-discipline perspective.

2.1.2 *Aerospace Vehicles as Complex Multidisciplinary Systems*

Aerospace Vehicles are can be represented as complex systems. They have multiple levels of abstraction, various types of representation, a large number of unique parts and interactions and experience changing dynamic behavior as they operate within and outside their design conditions. There are numerous classification scales for aerospace vehicles. These scales include the mission objectives scale, the investment sector scale, the reusability scale, the staging concept scale, the trajectory segment scale, and the aerothermodynamics scale among others. Figure 2-3 shows a spectrum of these cascading scales and sub-levels, and further options for consideration vehicle acquisition during the conceptual design of aerospace vehicles. As shown on the left side of the figure, the possible permutations of acquisition and design options rise exponentially. This multidisciplinary phenomenon requires management of the inherent complexity accordingly.

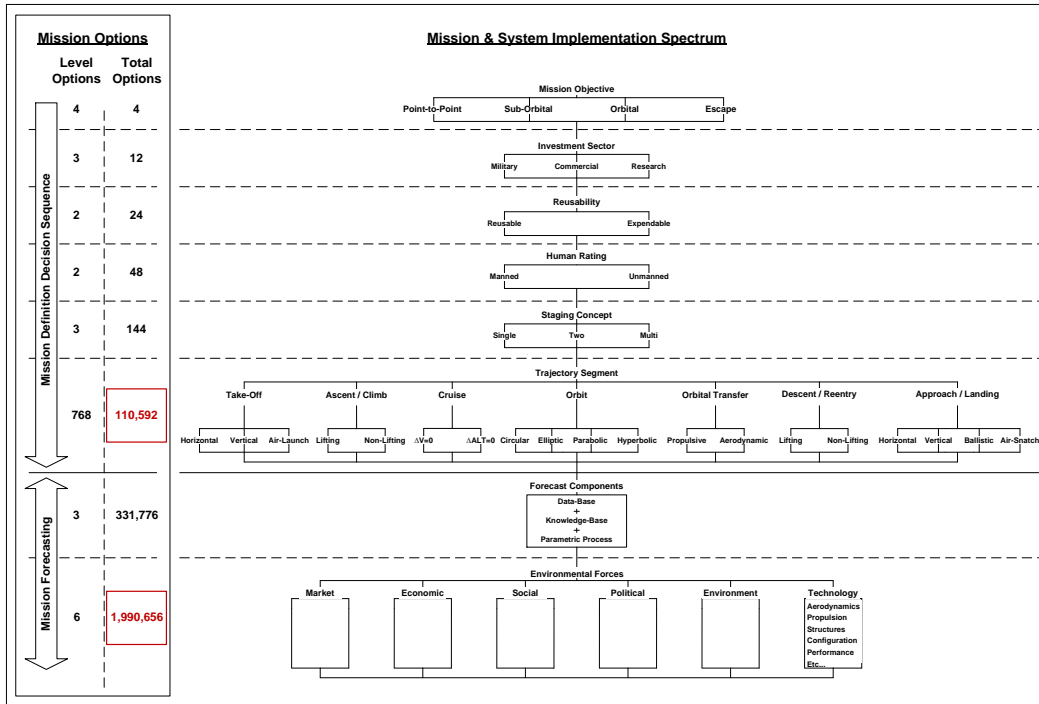


Figure 2-3 Complexity of Aerospace Vehicles Based

Complexity also tends to increase as the vehicle design speed increases. As a consequence, high speed vehicles are placing highest demands on the vehicle technologies and their respective interdisciplinary couplings. This results in vehicles that are more integrated. Figure 2-4 shows the confluence of vehicle geometry and technologies as the design cruise Mach number increases. High speed missions also introduce new disciplinary considerations, such as aerothermodynamics which are not major concerns at slow speeds. Hirschel (2008) classifies hypersonic vehicles based on the aerothermodynamics environment they experience throughout their design missions as shown in Figure 2-5. The vehicles classes are Reentry Vehicle (RV), Cruise and Acceleration Vehicle (CAV), Ascent and Reentry Vehicle (ARV) and Aeroassisted Orbital Transfer Vehicle (AOTV). RVs are vehicles which do not cruise or accelerate in a hypersonic environment; however, they decelerate from very high velocities. CAVs cruise

or accelerate in a hypersonic environment; however, they do not reach very high hypersonic velocities. ARVs accelerate to and decelerate from high hypersonic velocities. AOTVs are in-space vehicles which briefly enter the atmosphere to change orbit. Each vehicle class is configured and optimized to maximize performance in their hypersonic environments. Their design missions have to be well optimized. Most noticeably, lifting or non-lifting flight paths are selected in order to create high or low drag conditions dependent on desired cross-range and down-range requirements. In summary, the complexities of aerospace vehicles need to be managed early in the design process and this burden clearly falls on the designer and the synthesis specialists modeling the total system.

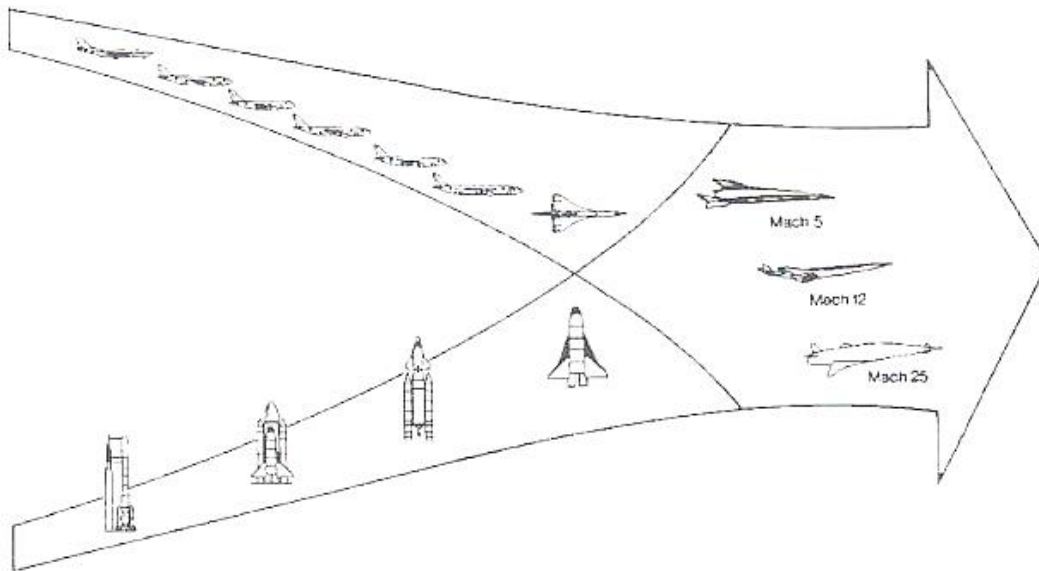


Figure 2-4 Confluence Diagram

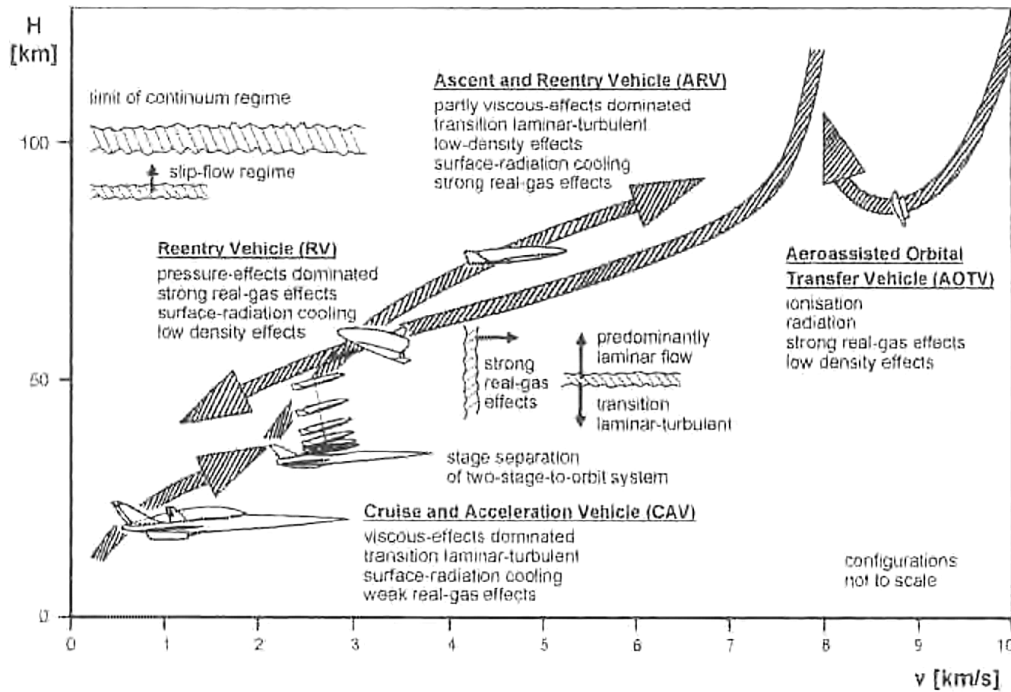


Figure 2-5: Aerothermodynamics Environment of Hypersonic Vehicles (Hirschel, 2008)

2.2 Review of Aerospace Vehicle Synthesis Systems

2.2.1 Aerospace Vehicle Design Synthesis Systems

Design synthesis involves the generation of one or more design solutions consistent with the requirements defined during the formulation of the design problem and any additional requirements identified during synthesis (Krishnamoorthy, 2000). Chudoba (2001), Huang (2006), Colman (2010) and Gonzalez (2016) review the state of the art in aerospace synthesis systems. Chudoba (2001), provides an assessment of aircraft synthesis systems, detailing specifically the change in modeling complexity as a function of time. He explains, “... *The classification scheme selected distinguishes the multitude of vehicle analysis and synthesis approaches according to their modeling complexity, thereby expressing their limitations and potential. ...*” Table 2-2 shows the characteristics of the five different classes of flight vehicle synthesis. The classes measure the chronological

implementation and integration of design knowledge with computer automation in aerospace design. Chudoba postulates that Class V synthesis capability with emphasis on the integration of multi-disciplinary effects, and the use of dedicated methods libraries as a necessity to keep up with ever changing acquisition demands and emerging technology advancements. The characteristics of this generation of synthesis systems include Generic & Physical Methods, Life-Cycle Synthesis, Knowledgebase System, Multidisciplinary Optimization, Multi-Fidelity, Design Skill, Methods Library, Integrated People Management Process.

Table 2-2 Classification of aerospace design synthesis approaches (Chudoba 2001)

Class	Design Definition	Develop Time	Characteristics
Class I	Early Dawn	Until 1905	Trial and error approach, experiment, no systematic methodology
Class II	Manual Design Sequence	1905 – 1955	Physical design transparency, parameter studies, standard aircraft design handbooks
Class III	Computer Automation	1955 – Today	Reduced design cycles, detailed exploration of the design space, discipline-specific software programs
Class IV	Multidisciplinary Integration	1960 – Today	Computerized design system, MDO, data sharing, centralizing design
Class V	Generic Design	Future Generation	Configuration independent, sophisticated design synthesis framework, detailed engineering analysis, synthesis of a user-defined aircraft, true inverse design capability, KBS

The result of this review and subsequent classification scheme has been the specification of the ‘Class V – Generic Synthesis Capability’. This breakdown places emphasis on the integration of multi-disciplinary effects, and the use of dedicated methods libraries. It is important to note that Chudoba defines Class V Synthesis as a design process NOT a design tool. This implies that more emphasis should be placed on developing the capability of a synthesis system and holistic perspective for involving the design team as opposed to the implementation of the tool itself. Chudoba specifies the attributes of a Class V system as follows: Generic & Physical Methods, Life-Cycle Synthesis, Knowledgebase System, Multidisciplinary Optimization, Multi-Fidelity, Design Skill, Methods Library, Integrated People Management Process.

- (1) Generic Design Capability:**
A generic design capability facilitates the initial configuration selection and definition phase during the conceptual design phase. Consequently, consistent SAV vehicle configuration comparisons are made possible for vehicles where the ultimate performance may hinge on numerical subtleties. It is required to consistently identify the convergence design space for total flight vehicles of different configuration concepts.
- (2) Multi-Disciplinary Design Capability:**
Effective evaluation of a design at the conceptual level requires the integration of multiple disciplines. Each discipline has to be represented as a stand-alone module. Communication between modules (disciplines) has to be organized via the data management system (DMS). Multidisciplinary design plays a key role in the three main functions of design synthesis systems: (a) Arriving at a feasible design which means that a final design concept satisfies all the physical requirements in a multidisciplinary design context. The final design concept can be built and successfully fulfill the flight mission. (b) Identifying the boundaries of the feasible design solution space by multidisciplinary design space screening, and (c) Performing multidisciplinary design optimization (MDO) with objective functions such as a minimum direct operating cost (DOC). However, most of the current synthesis systems are not capable of defining feasible design space solutions by design space screening which is difficult and challenging. In contrast, many designers start MDO before locating the feasible design space.
- (3) Dedicated SAV Conceptual Design Knowledge-Based System (SAV CD-KBS):**
This dynamic design database contains the rationale and lessons learned from fundamental flight vehicle concepts realized in the past. The SAV CD-KBS provides, in particular, design lessons learned to accelerate the conceptual design learning process leading to informed decision making.
- (4) Multi-Disciplinary Design Optimization (MDO):**
Being able to converge a single design multi-disciplinary followed by the visualization of all feasible designs in the solution space, MDO needs to be utilized as a tool using global sensitivity analysis and other MDO methods to find the best design according to a pre-defined merit function in the solution space. It reduces the number of design cycles and allows the designers to evaluate more configurations in a given time. The real-time graphical representation of the numerical solution also provides great benefits to the decision maker.
- (5) Database Management System (DMS):**
The desired data management system not only stores and manipulates numerical data belonging to physical design parameters, but it also controls the utilization of the design methods library. Additionally, it is a communication platform for the inter-discipline modules. The availability of a robust DMS facilitates data transfer, reduces data transcription errors, and allows the designer to use different computing environments and widely distributed teams.

Figure 2-7 Specification Synthesis System AVDS-SAV (Huang 2006)

Coleman (2010) investigates synthesis systems applicable to the early conceptual design for both, conventional and novel vehicle configurations. Coleman shows that, although parametric sizing is the most critical step during the conceptual design phase, it “... has stagnated or has been ignored in the current literature ...” He then introduces a specification advancing the state of the art in parametric sizing of aerospace vehicles: (1) Development of a conceptual design process library, (2) Development of a conceptual design parametric sizing methods library, (3) Development of an integrated and flexible parametric sizing program based on the process and methods library. For Coleman,

separation of the analysis processes from disciplinary methods is instrumental in his development of the Aerospace Vehicle Design System, a state-of-the-art generic aircraft parametric sizing methodology and tool.

The analytic process describes the major steps taken by the synthesis system. The process library assembled by Coleman documents the processes implemented in existing synthesis systems using Nassi-Schneiderman (NS) process diagrams and process cards. The NS diagrams visualize input, analysis, output and iteration steps for the process using color coding to show the applicability of the steps to parametric sizing, see Figure 2-8. The process card provides a written overview, application, and interpretation of the process as shown in Figure 2-9. The overview section contains indexing information including authors, publication date (both current and initial), and published references. The application of the process section provides context towards when and where the implementation should be used. The last section, interpretation', discusses how well the process answers the problem it was intended to solve.

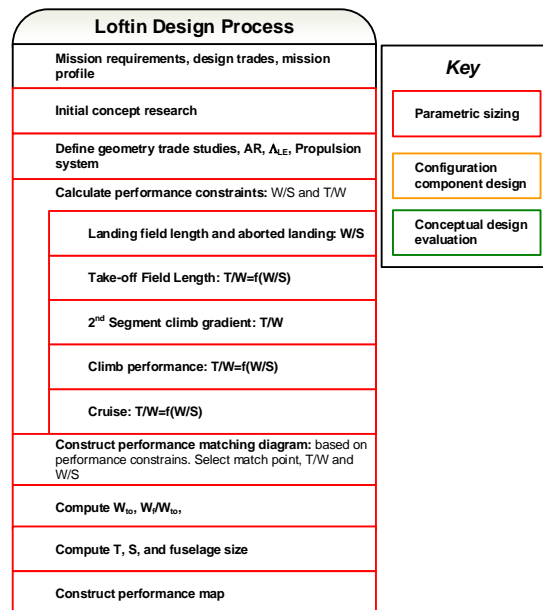


Figure 2-8 Nassi-Schneiderman diagram for the Loftin design process (Coleman 2010)

Processes Overview			
Design Phases Conceptual Design	Author Loftin	Initial Publication Date 1980	Latest Publication Date 1980
Reference: Loftin, L., "Subsonic Aircraft: Evolution and the Matching of Sizing to Performance," NASA RP1060, 1980			
Application of Processes			
Applicability Primarily focused on parametric sizing of jet powered transports and piston powered general aviation aircraft			
Objective of Processes Determine an approximate size and weight the aircraft to complete the mission from a 1 st level approximation of the design solution space			
Initial Start Point The processes begins with mission specification, possible configurations and fixed design variables such as AR.			
Description of basic execution From the mission specification statistics and basic performance relationships are used to determine relationships between T/W and W/S (Performance matching). The aircraft is then sized around this match point			
Interpretation			
CD steps Parametric Sizing	Synthesis Ladder Analysis Integrate Iteration of design Visualize design space	Similar Procedures Roskam (preliminary sizing) Torenbeek (Cat 1 methods)	
General Comments: One of the first published processes utilizing performance matching Where Nicolai compares T/W and W/S after the complete convergence and interaction of the processes, Loftin derives basic relationships between T/W up front to visualize the solution space before initial sizing. Loftin essential short cuts the Nicolai approach to derive an initial design space rather than an initial configuration.			

Figure 2-9 Example Process overview card (Coleman 2010)

Methods describe the application of disciplinary principles or empirical data to determine effects in the analysis. The 'Methods Library' consists of disciplinary methods accumulated into a compendium as either parts of a synthesis system, or as standalone analytic methods library. Each entry in the library is represented in a card detailing

assumptions, applicability, basic procedure, and experience. The accumulated disciplinary methods library allows for the documentation and storage of design experience/knowledge in a centralized location. This results in the ability of the designer to choose which method is best suited for the given problem.

Method Overview				
Discipline	Design Phase	Method Title	Categorization	Author
Aerodynamics	Parametric Sizing	Initial Drag polar estimation	Semi-Empirical	Roskam
Reference: Roskam, J., "Airplane Design Part I: Preliminary Sizing of Airplanes," DARcorporation, Lawrence, Kansas, 2003				
Brief Description The drag polar is constructed using empirical relationships for parasite drag (based on gross weight), flap and landing gear effects. A classical definition of induced drag is used.				
Assumptions Increments of flap and landing gear taken from typical values Parasite drag coefficient is a function of take-off gross weight		Applicability Homebuilt aircraft propeller aircraft, single engine propeller aircraft, twin engine propeller aircraft, agricultural aircraft, business jets, regional turboprop aircraft, transport jets, military trainers, fighters, military patrol, bomb and transport, flying boats, supersonic cruise aircraft		
Execution of Method				
Input Mission profile, type of aircraft, take-off gross weight, AR, e, S estimate				
Analysis description Estimate $S_{wet}=f(W_{TO})$ empirical based on type of aircraft Fig 3.22 Estimate $f=f(S_{wet})$ empirical based on type of aircraft Fig 3.21 Assume average value of S Select Flap and landing gear effects for each mission segment Table 3.6 $C_D = f / S + \Delta C_{Dflap} + \Delta C_{DLG} + \frac{C_L^2}{\pi AR \cdot e}$ Assume C_{Lmax} values from Table 3.1				
Output: Drag Polar				
Experience				
Accuracy Unknown		Time to Calculate Unknown		General Comments

Figure 2-10 Example Methods overview card (Coleman 2010)

2.2.2 Synthesis Systems Compatibility with Acquisition Problem

In order to understand the applicability of existing synthesis systems to the acquisition problem, a review has been conducted in conjunction with Gonzalez (2016) and Oza (2016). The synthesis systems chosen for the review are representative 'By-Hand Synthesis Methodologies' as shown in Table 2-3, and Computer-Based Methodologies' as shown in Table 2-4. The by-hand methodologies or handbook methods originate from design text books, short courses to company internal methods, while the computer-based methodologies take advantage of digital processing power.

Table 2-3 Selected By-Hand Synthesis Methodologies

Author	Year	Title
Corning	1979	Supersonic and Subsonic, CTOL and VTOL, Airplane Design
Howe	2000	Aircraft Conceptual Design Synthesis
Jenkinson	1999	Civil Aircraft Design
Loftin	1980	Subsonic Aircraft: Evolution and the Matching of Size to Performance
Nicolai	2010	Fundamentals of aircraft and airship design Volume 1, Aircraft design
Raymer	1999	Aircraft Design: A Conceptual Approach
Roskam	2004	Airplane Design, Parts I-VIII
Schaufele	2000	The Elements of Aircraft Preliminary Design
Stinton	1998	The Anatomy of the Airplane
Torenbeek	1982	Synthesis of Subsonic Airplane Design
Wood	1963	Aerospace Vehicle Design Vol. 1, Aircraft Design

Table 2-4 Selected Computer-Based Synthesis Systems

Acronym	Year	Full name	Developer
AAA	1991-	Advanced Airplane Analysis	DARcorporation
ACSYNT	1987-	AirCRAFT SYNThesis	NASA
AVDS	2010	Aerospace Vehicle Design System	Aerospace Vehicle Design Laboratory
CADE	1968	Computer Aided Design Evaluation	McDonnell Douglas
FLOPS	1994-	FLight OPTimization System	NASA Langley Research Center
Model Center	1995-	Model Center Integrate - Explore - Organize	Phoenix Integration Inc
pyOPT	2012-	Python-based object-oriented framework for nonlinear constrained optimization	Royal Military College of Canada
PrADO	1986-	Preliminary Aircraft Design and Optimisation	Technical University Braunschweig

The synthesis methodology capability review assesses the ability of synthesis systems to characterize, analyze, and solve classical and new/novel aerospace problems. The assessment criteria are shown in Table 2-5. (1) Integration and connectivity is related to ability of the system to model vehicles at the subsystem level of abstraction with multidisciplinary considerations. (2) Interface maturity studies the ability of the synthesis system to combine hardware pieces together and analyze multidisciplinary effects resulting from interfacing them. (3) The scope displays the conceptual design activity and the type of product (aerospace vehicle) to which each synthesis is applicable. (4) Influence of New Components or Environments explores the adaptability of the synthesis systems to emerging technologies and requirements. (5) Prioritization of Technology development efforts shows the flexibility of the system to match changing fidelity and data requirements during the product lifecycle. (6) Methodological problem requirement indicates if the synthesis system provides a methodology for the problem of stakeholder requirements and requirements analysis. The results of the survey are shown in Figure 2-11 to Figure 2-15 and Table 2-6 to Table 2-9.

Table 2-5 Literature Survey Criteria – System Capability

<u>System Capability</u>	
1. Integration & Connectivity	
a	Can assess each hardware technology independently
b	Can assess multiple disciplinary effects for each hardware
2. Interface Maturity	
a	Can combine hardware technologies to form a vehicle
b	Can combine hardware technology disciplinary effects
3. Scope of Applicability	
a	Conceptual design phase applicability
b	Product applicability
4. Influence of New Components or Environment	
a	Modular hardware technologies
b	Modular mission types
c	Modular disciplinary analysis methods
5. Prioritization of Technology Development Efforts	
a	Able to match hardware technology disciplinary models to problem requirements
b	Data management capability
6. Problem Input Characterization	
a	Methodological problem requirements

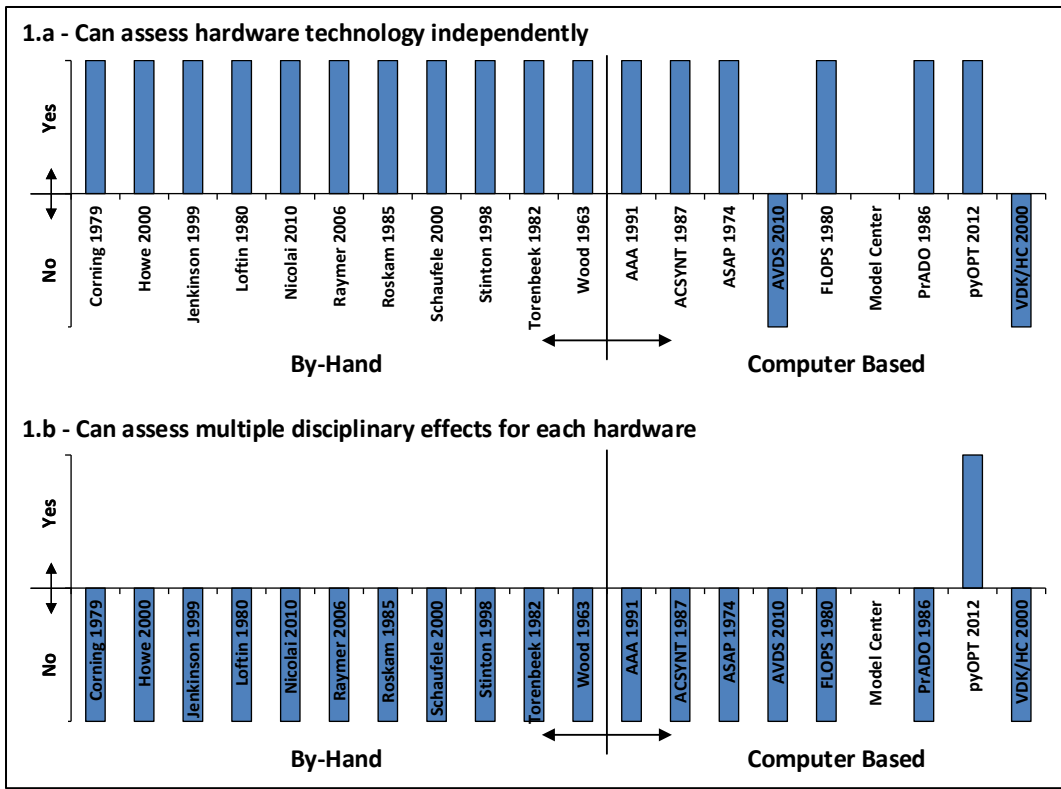


Figure 2-11 Integration and Connectivity

Figure 2-11 shows that the by-hand methods all have the capability to analyze individual hardware components outside of the synthesis process loop. This is because of the freedom to use various texts/sources as the designers see fit. On the other hand, computer systems have more integrated methodologies with prescribed order of operations that must be followed. AVDS and VDK/HC (Czysz and Vandekerckhove, 2001) especially are not set up to run individual hardware performance outside of the main design loop. *Model Center* (Davies, 2015) is an open platform which initially does not contain any vehicle-specific methodology, the user has to develop a custom design framework by integrating user specified methods.

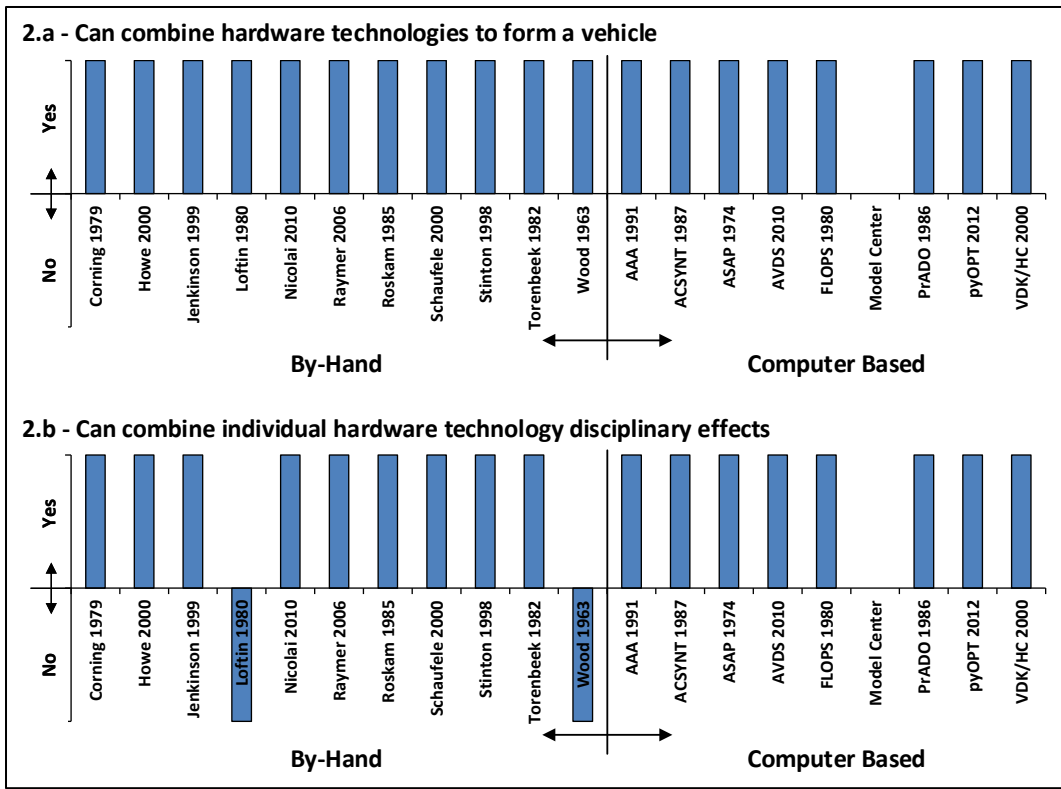


Figure 2-12 Interface Maturity

Figure 2-12 shows that all the by-hand and computer-based systems have the capability to use buildup methods towards vehicle hardware. Each system represents the vehicle as a composition of hardware pieces. All of the systems surveyed are able to combine the effects of hardware pieces to solve for the total vehicle effect. Loftin and Wood are unable to represent vehicle disciplinary effects as a composition of individual hardware effects because both methodologies solely use empirical methods for disciplinary analysis.

Table 2-6 Scope of Applicability to CD Phase

	By-Hand											Computer								
	Corning 1979	Howe 2000	Jenkinson 1999	Loftin 1980	Nicolai 2010	Raymer 2006	Roskam 1985	Schaufele 2000	Stinton 1998	Torenbeek 1982	Wood 1963	AAA 1991	ACSynt 1987	ASAP 1974	AVDS 2010	FLOPS 1980	Model Center	PrADO 1986	pyOPT 2012	VDK/HC 2000
Parametric Sizing	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Configuration Layout	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No
Configuration Evaluation	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	No

Table 2-7 Scope of Applicability to Aerospace Product Types

	By-Hand											Computer								
	Corning 1979	Howe 2000	Jenkinson 1999	Loftin 1980	Nicolai 2010	Raymer 2006	Roskam 1985	Schaufele 2000	Stinton 1998	Torenbeek 1982	Wood 1963	AAA 1991	ACSynt 1987	ASAP 1974	AVDS 2010	FLOPS 1980	Model Center	PrADO 1986	pyOPT 2012	VDK/HC 2000
Homebuilt	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Single Engine	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Twin Engine	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Agricultural	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Business Jet	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Regional TBP's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Transport Aircraft	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Mil. Trainers	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Fighters	No	No	No	No	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	No	Yes	No	No	Yes	No
Mil. Patrol, bombers, transport	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Flying boats, Amphibious	No	No	No	No	No	Yes	Yes	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No
Supersonic Cruise	Yes	No	No	No	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No
Hypersonic P2P	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No
Launcher (Rocket)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
Launcher (A/B)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
Reentry	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No
In-Space	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No

Table 2-6 shows that all systems have methodologies for the parametric sizing step of the conceptual design phase, except Model Center which is a blank canvas and PRADO which is designed for the later conceptual design steps. Table 2-7 shows the applicability to different aerospace vehicle missions. Most systems are suitable for commercial transports, only VDK is applicable to launchers and no system covers the entire mission spectrum.

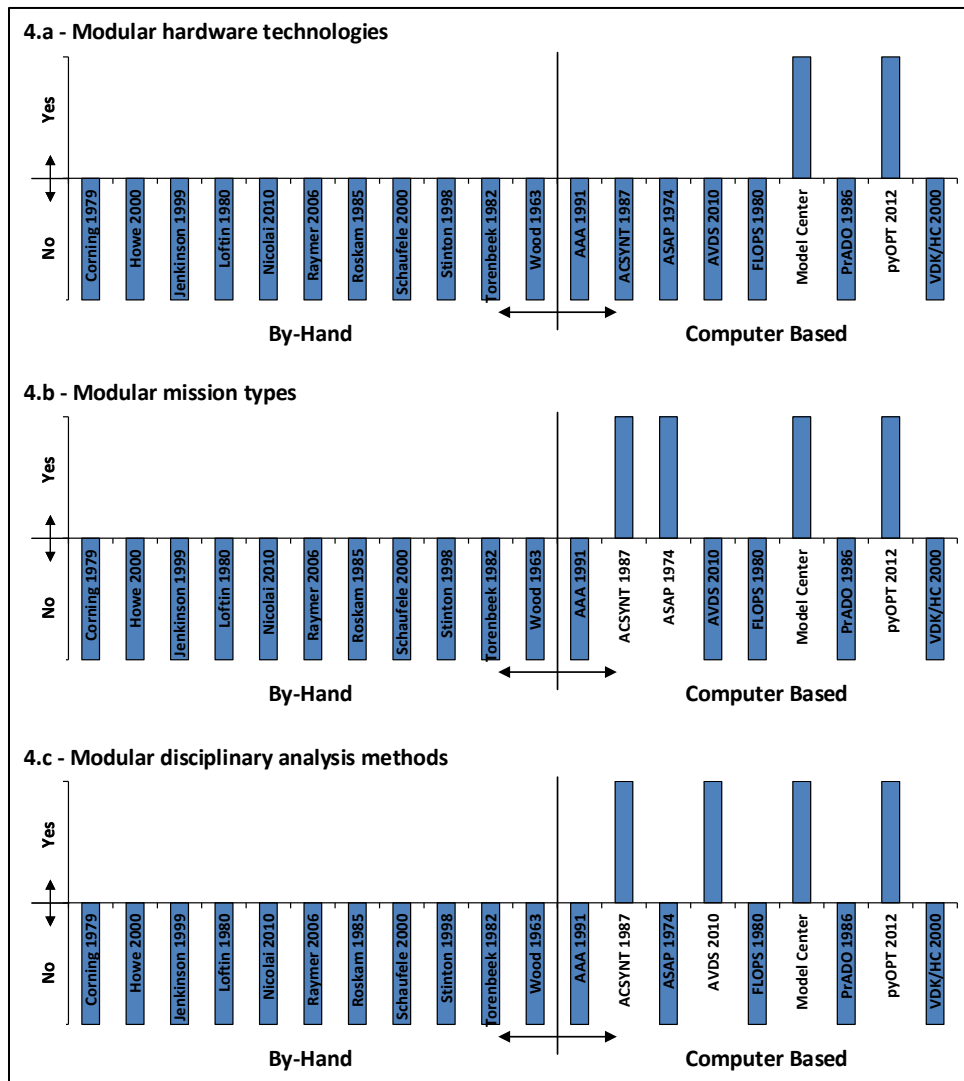


Figure 2-13 Influence of New Components or Environment

Figure 2-13 shows one of the major deficiencies in the systems that have been reviewed. Only Model Center and pyOPT have the capability to add new hardware, mission types, and disciplinary analysis methods. The other systems require significant source code modifications to adapt to new problems. ACSYNT is an early attempt at a ‘problem-flexible’ system, consisting of disciplinary analysis modules created at NASA Langley integrated through an early Model Center framework; however, it is no longer in use. AVDS, in contrast, has the ability to integrate a stand-alone methods library into a synthesis system. However, it has a fixed process that cannot be easily adapted as requirements change.

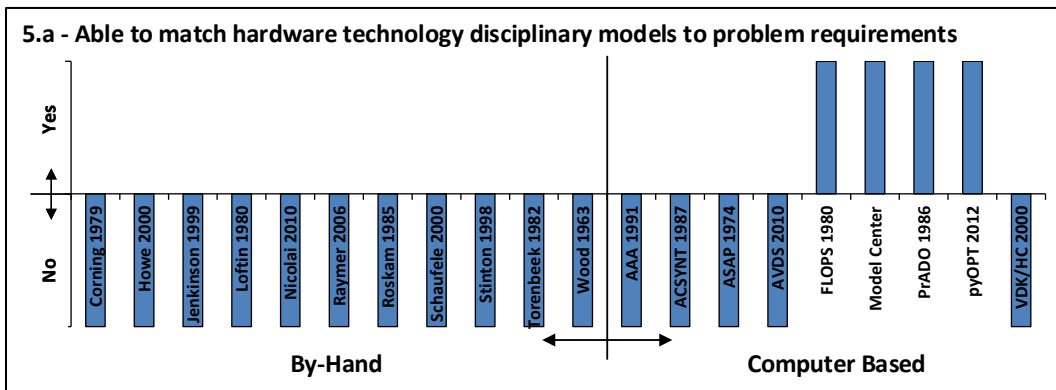


Figure 2-14 Prioritization of Technology Development Efforts

Figure 2-14 shows that FLOPS, Model Center, PrADO and pyOPT allow the user to adjust the level of disciplinary fidelity based on the given problem. This is a significant attribute because as the problem advances to later stages in the design cycle life-cycle, there is need to increase fidelity of the solutions in order to provide guidance to the design team. As previously discussed, Huang emphasized the importance of a Database Management System for Conceptual Design synthesis. Table 2-8 shows the data management survey criterion for evaluating the synthesis systems and Table 2-9 shows the results. Model Center meets all the requirements of a good DBMS except the

connection to a Knowledge base system. pyOPT also has good database management characteristics because of its object oriented programming design.

Table 2-8 Data Management Survey Criterion

Data Management Criterion	
a	Easy to create, change, delete, and view projects and project data.
b	Accommodates all project types and project information
c	Supports entry of annotative comments and appending documents, images, and links for project
d	Accommodates hundreds/thousands of projects
e	Supports data import from your existing systems and databases
f	Supports data export to your existing systems and databases
g	Supports dependency links among projects
h	Provides data cut-and-paste, project cloning, and data roll-over
i	Provides completeness/error checks and data warnings
j	Allows multiple portfolios and portfolio hierarchies (parent-child links)
k	Allows dynamic portfolios (portfolios defined based on latest project data)
l	Provides search, filter, and sort
m	Provides data archiving
n	Provides statistical analysis of historical data (e.g., trend analysis)

Table 2-9 Data Management Capability

	AAA 1991	ACSYNT 1987	ASAP 1974	AVDS 2010	FLOPS 1980	Model Center	PrADO 1986	pyOPT 2012	VDK/HC 2000
a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
b	No	No	No	No	No	Yes	No	Yes	No
c	No	No	No	No	No	Yes	No	Yes	No
d	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
e	No	Yes	No	No	No	Yes	No	Yes	No
f	No	Yes	No	No	No	Yes	No	Yes	No
g	No	No	No	No	No	Yes	No	No	No
h	No	No	No	No	No	Yes	No	Yes	No
i	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
j	No	No	No	No	No	Yes	No	No	No
k	No	No	No	No	No	Yes	No	No	No
l	No	No	No	No	No	Yes	No	No	No
m	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
n	No	No	No	No	No	No	No	No	No
	4 of 14	6 of 14	4 of 14	3 of 14	3 of 14	13 of 14	4 of 14	9 of 14	4 of 14

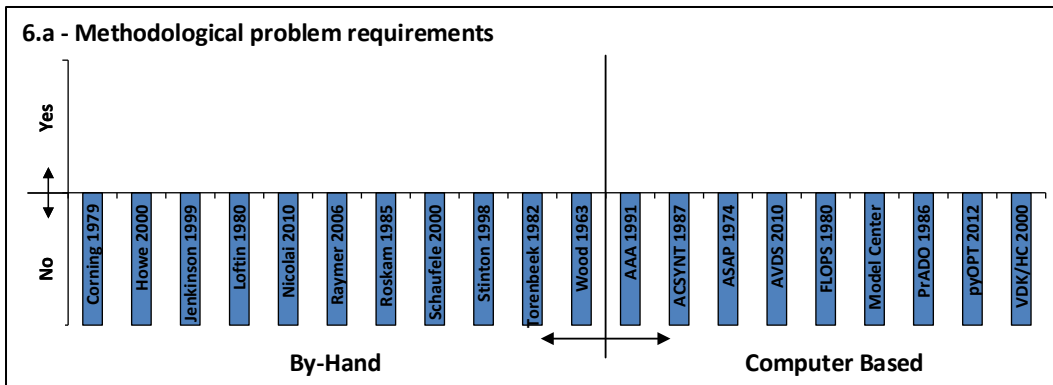


Figure 2-15 Problem Input Characterization

Figure 2-15 shows that all of the systems reviewed do not provide any methodology for requirements definition. This is because all these systems are designed to proceed from the point after the requirements have already been established. The outcome of this disintegrated approach to the problem definition is the lack of a feedback loop between the problem definition and the problem solution. This eliminates the ability of the decision maker to assess if a problem should be solved, or if the problem definition in itself has been ill-formed. The solution to this problem requires an understanding of acquisition approaches and the required flexibility to adapt synthesis systems to them.

2.2.3 Concepts for Advanced Synthesis Systems

The previous section indicated the deficiencies in representative aerospace forecasting methodologies that are either too rigidly tailored to a specific type of problem, or they are too open ended without providing any guidance on how problems should be solved. Krishnamoorthy (2000) identifies 3 synthesis approaches that can benefit from utilizing the Class V synthesis elements of KBS, DBS and Method Libraries proposed by Chudoba (2001), Huang (2006) and Coleman (2010):

- Synthesis by Problem Decomposition-Solution Recomposition – this involves the reduction of the design problem into the lowest level of abstraction for analysis.

Then the individual solutions are recomposed into coherent whole solutions. This approach relies heavily on understanding of the problem and ability to represent them using blocks in the KBS and DBS.

- Synthesis by Case-Based Reasoning – This involves using knowledge and solutions of past cases and examples to solve present design problems. The success of this method depends heavily on the availability of similar problems in the KBS and DBS system.
- Synthesis by Transformation Approach – This involves using rules and generalizations from previous design studies to draw conclusions and solutions on a current problem. This system relies on the DBS and KBS System having similar problems converted into rules that can be matched to the current problem.

A modification of the synthesis paradigm has been initiated by utilizing the problem decomposition-solution recomposition approach as the primary hypothesis for the current research undertaking. This approach is flexible to adapt to the range of design problems whilst offering uncompromised transparency due to the decomposition blocks and strategy.

2.3 Portfolio Planning for Technology Acquisition

The remedy to the dichotomy between the conceptual design tasks during the product development lifecycle and the stakeholder requirements definition during the acquisition lifecycle can be broken down into two parts. The first is the determination of a methodology for assessing stakeholder interests and resources. The second is the creation of a conceptual design methodology that is compatible with the acquisition solutions. Oza (2016) addresses the earlier with project portfolio management, while, Gonzalez answers the later with custom synthesis tool composition. This research is a bridge between these two solution concepts.

2.3.1 Portfolio Planning Management

Portfolio refers to a company's body of projects, ideas, technologies and resources. In order to make decisions on the direction a company should follow, it is important to (1) take stock of the company portfolio and the knowledge attached to them, and to (2) prioritize the portfolio elements available for the given acquisition problem. Oza proposes the use of Project Portfolio Management to bridge the gap between the conceptual design and the stakeholder requirements definition of the acquisition lifecycle (Oza 2016). Matthews (2010) explains that "... the project portfolio is focused on execution and delivery, the innovation portfolio concerns itself with the development of a coherent portfolio strategy and the maturation and selection of project candidates ...". Merkhofer (2015) adds that project portfolio management involves the evaluation, prioritization and selection of new projects in addition to the acceleration, reprioritization and termination of existing projects in order to allocate or reallocate resources to maximize productivity. Figure 2-16 shows an example of the Project Portfolio structure which allows streamlining of resources, analysis capabilities and technology options over the acquisition lifecycle.

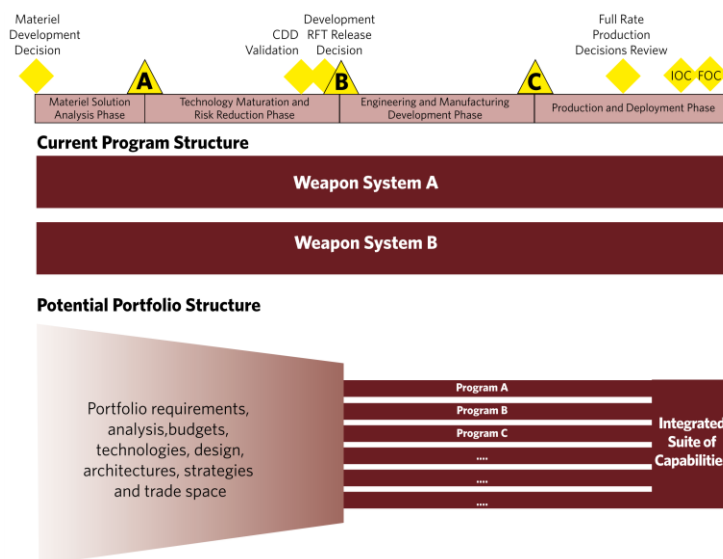


Figure 2-16 Comparison of Program vs Portfolio Approach to R&D (Janiga, 2014)

Oza (2016) postulates a semantically composable modeling platform system for managing the following steps shown Figure 2-17:

1. Required inputs are identified and communicated by the acquisition researcher.
2. Inputs are processed and decomposed following the data logic strategy in the system architecture.
3. The product portfolio model (PPM) is formulated into a technology portfolio to the appropriate level of abstraction for the problem and is used to data-mine/assess the portfolio's performance.
4. The required developmental and technology risk tables (DTRTs) are retrieved by the PPM from a DBMS and managed according to the rationale in the inference engine.
5. The DTRTs library has been previously generated and used to describe the capability performance model (CPM) for the technology portfolio.
6. Outputs are used to decide the processes to initialize for product sizing with the zero silo DBMS approach.

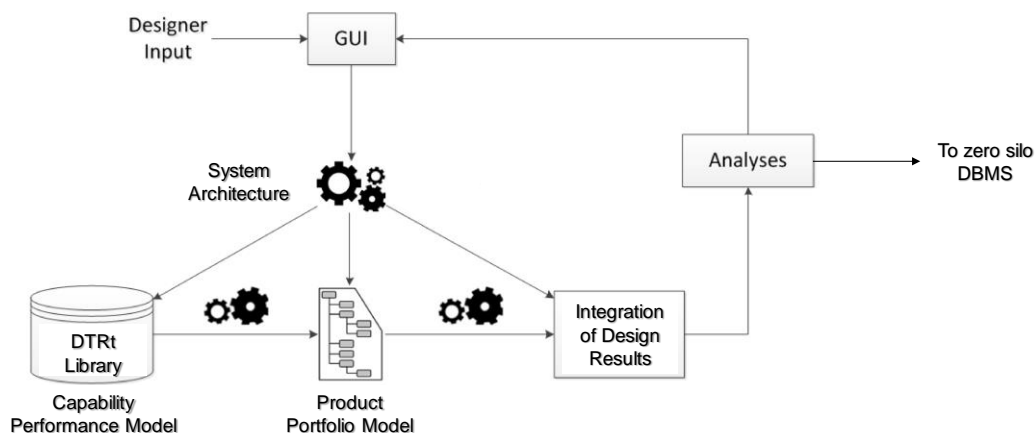


Figure 2-17 Problem Formulation Data Automation Process (Oza 2016)

The advantage of the PPM methodology is that it allows for low value and minimal initial datasets associated with most concepts [to] be addressed by keeping early-phase evaluations cheap and fast to minimize expenditures. In addition, the interface methodology can assess each hardware technology independently, utilizing any level of system abstraction with the aim to prioritize technology development to handle by qualitative and quantitative metrics. Finally, the portfolios can be linked to company or external databases systems and knowledge-base systems to provide additional insights related to the problem at hand, such as supply chain information.

2.3.2 *Synthesis Tool Composition*

Gonzalez (2016) specifies a synthesis tool generation framework that is compatible with the project portfolio management solution (Gonzalez 2016). The framework utilizes syntactic and semantic composability principles to tailor make synthesis systems to user problem requirements. Syntactic composability ensures that the composition components can be and are connected properly as shown in Figure 2-18. Semantic composability addresses whether the composed models are meaningful in terms results and problem applicability. The synthesis tool generator achieves syntactic composability by using a database management system to automatically generate interfaces between the selected synthesis system composable components. It partially enforces semantic composability by using a Graphical User Interface (GUI) that coordinates the selection of meaningful composable components while, it is able to flag potential modeling deficiencies.

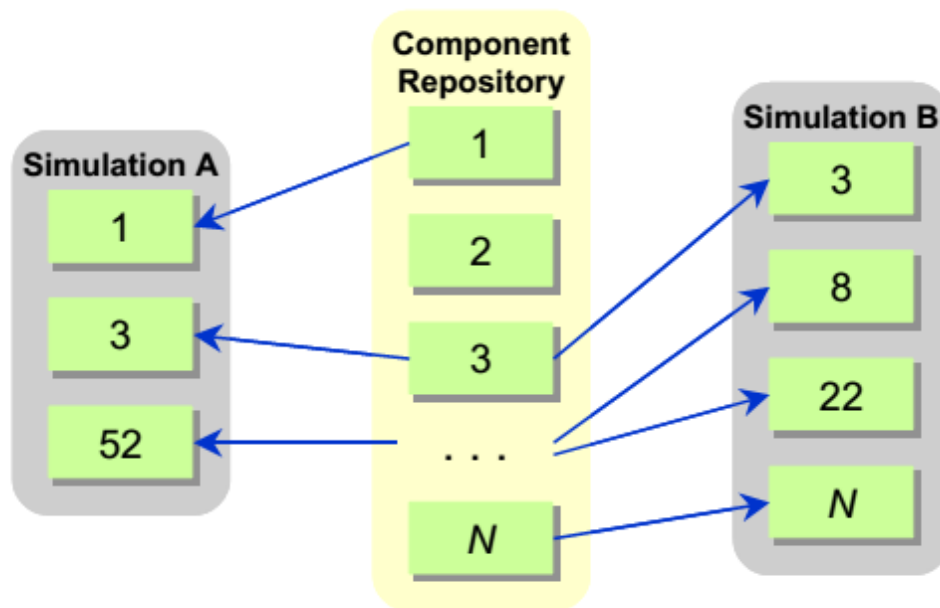


Figure 2-18 Notional Example of Composability (Petty and Weisel 2003)

The advantage of the AVD^{DBMS} methodology is its flexibility to both model old design problems and adapt to new requirements. In addition, it takes advantage of the lessons learned from many years of studying synthesis systems and leverages advancements in computing technology to mitigate identified deficiencies. This has allowed the creation of a system that is flexible to respond to stake holder requirement alternative, structured to give new users guidance, quick to allow re-evaluations as new problem information is received whilst being transparent enough to provide the decision-maker confidence. This research contributes by defining the basic pieces of the AVD^{DBMS}.

2.4 Chapter Summary and Solution Concept Specification

The project portfolio management methodology and the was invented as a collaborative effort between Omoragbon (2016), Gonzalez (2016) and Oza (2016). The original contribution of this author's writing to these efforts is the definition of the building

blocks for each system, as well as the establishment of the data relationships between them. This leads to the following solution concept specifications. The solution concept is required to

- utilize the concept of problem decomposition and system recomposition for problem solving;
- define building blocks for modeling aerospace vehicles as complex multidisciplinary systems;
- define building blocks for composable synthesis tool generation architecture for aerospace vehicle conceptual design;
- define building blocks for the project portfolio management architecture for aerospace technology acquisition assessment;
- Identify interfaces between the composable system architecture and the project portfolio management architecture.

Chapter 3

COMPLEX MULTIDISCIPLINARY SYSTEM DECOMPOSITION CONCEPT

The objective of this research endeavor is to bridge the gap between aerospace technology acquisition problems and aerospace vehicle conceptual design parametric sizing. This involves the merger of considerations for stakeholder requirement definition and an already complicated conceptual design synthesis processes. The stakeholder requirements determine what aerospace design problems to solve, while the conceptual design is concerned with determining the feasibility of the possible solutions to the design problem. Chapter 1 discussed the problem that current technology acquisition analyses tend to be qualitative and do not consider the added physical insight that parametric sizing provides. Chapter 2 showed that typical conceptual design synthesis tools have been developed to solve predefined design problems and are not easily adaptable to changing stakeholder requirements. In order to leverage the existing knowledge and techniques from stakeholder technology portfolio management together with a state-of-the-art existing synthesis system, a composable technology innovation and sizing architecture has been created in conjunction with (Oza 2016) and (Gonzalez 2016).

The technology innovation and sizing architecture is the culmination of research done at the Aerospace Systems Engineering (ASE) Laboratory at the University of Texas at Arlington. This research, amongst others, have been motivated by the following:

- assessment of technologies for advancing commercial transports (Chudoba, 2009a);
- evaluation of trust vectoring technologies (Chudoba 2009b; Omoragbon, 2013);
- performance sizing of electric aircraft technologies (Chudoba. 2011);
- creation of a high-speed technology investment databases (Haney 2013; Chudoba, 2015);

- technical feasibility assessment of a novel rotorcraft technologies (Chudoba,2014),
- solution space screening of an air-launched hypersonic demonstrator (Chudoba, 2015b).

Figure 3-1 shows an overview of the primary steps defining the framework. The first step is the decomposition of existing technologies and synthesis systems into building blocks. The next step is the composition of these blocks into system models as given acquisition or design problems require. The final step is the exploration of the different system models for the best solutions to the problem.

The original contribution of the current research by the author Omoragbon to the innovation and sizing framework is the prescription of the decomposition methodology and the identification of the building blocks required for this framework to function. This chapter discusses the CMDS decomposition solution concept for combining technology acquisition with conceptual design.

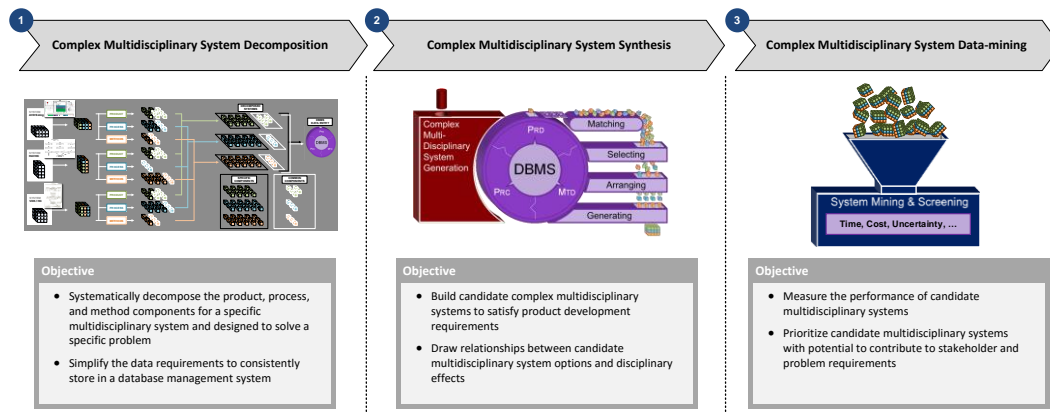


Figure 3-1 Technology Innovation and sizing framework

3.1 Decomposition into CMDS Blocks

Complex Multidisciplinary System (CMDS) is the primary block managing data-logic in the technology innovation and sizing Framework. In Chapter 2, the concept of

viewing aerospace vehicles as complex multidisciplinary systems has been discussed. The importance of CMDS is that it provides a common foundation for any object that can be observed or modeled for any purpose. Finger and Dixon (1989a, 1989b) categorize two considerations for modeling in design: (1) the description of the attributes of the design artifact, and (2) the description of how the design artifact is designed. In order to account for complexities arising from analysis by the CMDS from multiple disciplines, the second consideration can be further divided into the analysis process and disciplinary methods used for analysis.

Figure 3-2 shows CMDS decomposition blocks. The product block represents the object that is to be studied. The analysis process block prescribes the major steps to following evaluating the product. The disciplinary methods block describes the application of disciplinary principles or empirical data to obtain results for the different steps in the analysis process. This CMDS representation is consistent with both technology acquisition and conceptual design problems. In acquisition problems, technology assessment processes and methods are used to determine which products are best to pursue. For example, as discussed in Chapter 1, the TRL calculator is a tool used determine technologies that are the furthest along in development. In conceptual design problems, synthesis tools and methodologies are used to either determine the performance of given technologies or determine the vehicle size required for the technology to achieve a given performance level. For example, Coleman (2010) discusses the analysis processes and methods that different conceptual design synthesis systems use in designing aerospace vehicles. The identification and documentation of the CMDS decomposition blocks provides the tools necessary to quickly understand how both acquisition and conceptual designs can be solved. The following sections discuss the decomposition of these CMDS blocks.

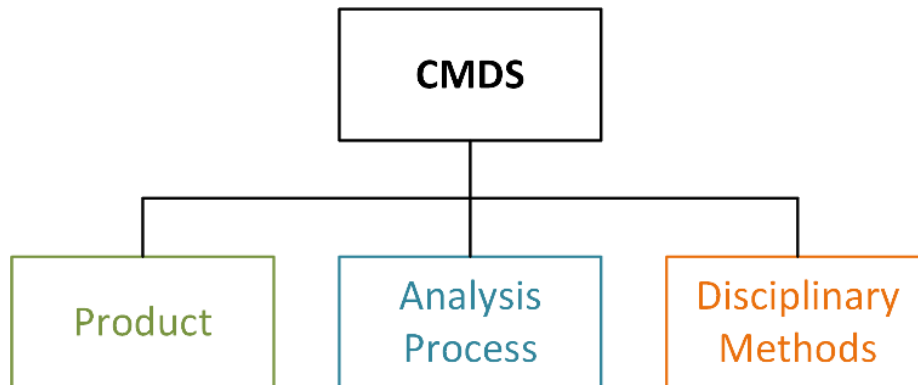


Figure 3-2 CMDS Decomposition Blocks

3.2 Decomposition into Product Blocks

The product block describes the physical characteristics of the artifact that is to be designed or acquired. There are three considerations that describe the product: (1) what it does, (2) when it does it, and (3) the limitations or requirements for its operation. Figure 3-3 shows the product decomposition blocks based on these descriptions. Functional subsystem decomposition is one of the common means of product decomposition in the literature. However, operational events and operational requirements are introduced here. The product decomposition block is important to both, acquisition assessment and conceptual design. It creates a template description of technologies that are to be acquired. It also defines the parameters of the object that is to be designed.



Figure 3-3 Product Block Decomposition

3.2.1 Subsystem Decomposition

Product decomposition in literature involves reducing the artifact into a hierarchical network of subsystems and attributes until it reaches a desired level of abstraction conducive for solving a given problem (Krishnamorthy 1996). For example, consider an aircraft as the product shown in Figure 3-4. One of the subsystems is a wing and one of the wing's subsystems is a spar. If the problem requires the stress analysis of the aircraft, the aircraft can be decomposed further into individual elements. Attributes are then used to describe the properties of that subsystem at a given level of abstraction. In the previous example, attributes could include the shape of the element and its material. As discussed in Chapter 2 and (Shashank 2011, 2014), complexity increases with the number of levels of abstraction and the type of analysis done at each level. It is imperative to increase the levels of abstraction only as needed. However, there is a risk of loss of information about the subsystem. In order to preserve subsystem information, subsequent levels of abstraction can be stored as attributes. For example, if the problem only requires the aerodynamic analysis of the wing, one of its attributes can be the type of wing sweep (forward or backward).

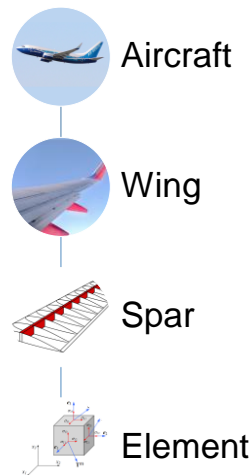


Figure 3-4 Example of hierarchal product decomposition

There are two major product decomposition schemes; the (1) structural or form decomposition, and the (2) functional or modular decomposition. Structural decomposition involves breaking the domain into various physical components that are used to construct the solution (Krishnamoorthy, 2000). In other words, it is the decomposition of the product according to its physical form. Figure 3-5 shows an example of the structural decomposition of an aircraft. The benefit of structural decomposition is that it preserves the representation of dependencies between assemblies, subassemblies and parts. Every node represents an assembly level while every line represents a dependency. One drawback of structural decomposition is that it may not produce a consistent representation across similar product types. For example, the structural representation of aircraft with wing mounted engines is different from that of fuselage aft-mounted engines. The product decomposition scheme used in this research is the functional decomposition scheme discussed in the next section.

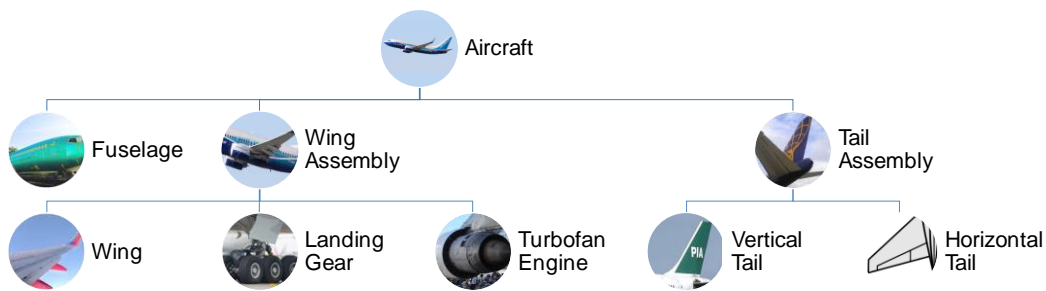


Figure 3-5 Example of structural decomposition

3.2.1.1 Functional Decomposition

Functional decomposition, on the other hand, involves the resolution of the product into constituent parts based on the primary functions they serve. In this scheme, the primary functions at each abstraction level are identified and the subsystem that satisfy these functions are grouped into modules. Figure 3-6 shows an example of functional decomposition of an aircraft. In this decomposition scheme, the engine is not a sub

assembly of the wing assembly. It is a subsystem of its own because it serves a separate function. The benefit of functional decomposition is that it gives a consistent representation of similar product type and shows points that can benefit from standardization and interchangeability. The drawbacks, however, are that information about the assembly of the product is lost in this representation and subsystems with multiple functions may not be properly represented.

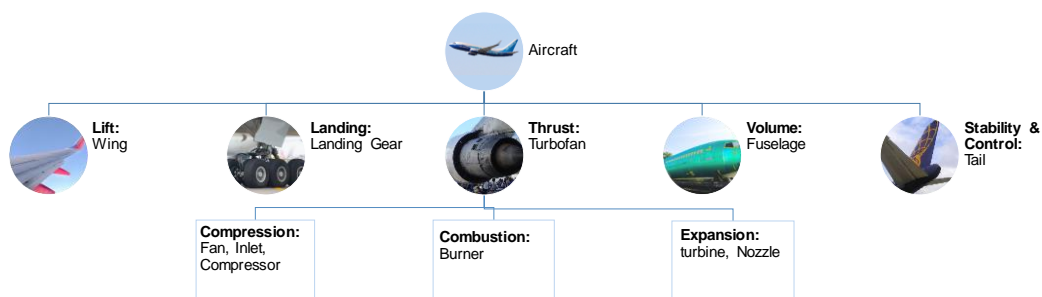


Figure 3-6 Example of functional decomposition

Functional decomposition is a popular technique in literature. It is a primary step in the system engineering process (DAU 2013, SMC 2010; USAF 2011; OSD 2015; MSFC 2012) and analysis of large complex systems (Courtois, 1985). It can be used to arrive at product families based on modularity (Martin and Ishii 1997) and component standardization (Kota and Sethuraman 1998), customer demands (Gonzalez–Zugasti et al. 1998, 1999). Advanced methods have been developed for configuration design, based on functional decomposition using design structure matrices (Newcomb et al. 1998), Artificial Intelligence (AI) (Soininen et al., 1998), constraint satisfaction (Mittal & Falkenheiner, 1990), resources (Heinrich & Jungst, 1991), evolutionary methods (Gero et al. 1997; Rosenman & Gero, 1997), rewrite rules methods (Agarwal & Cagan, 1998; Agarwal et al., 1999), heuristic rule methods (Kolodner, 1993), fuzzy neural network (Kusaik and Huang 1996), design negotiation (Kusaik et al 1996) and design guided methods (Corbett and D.W. Rosen 2004).

3.2.1.2 Applicability to Acquisition and Conceptual Design

The functional decomposition scheme has been adopted for this research because it is conducive to both acquisition and conceptual design problems. Company technology portfolios are typically based on some representation functional modules. That means, this scheme provides a line of connection to data-bases and knowledge-bases in order to support decision-making. In addition, technology assessment methods described in Chapter 1, such as the TRL calculator, can be used on each module at that different levels of abstraction. Finally, new product families can be generated from combining modules by using the many configuration generation techniques available. Conceptual design benefits because the scheme provides a template for judging the applicability of a synthesis tool to a given design problem. In addition, it helps to identify analysis gaps that should be addressed in the flexible synthesis system by showing which parts of the product the tools do not analyze.

Table 3-1 shows some major subsystem functions for aerospace vehicles and some hardware examples. Hardware is used interchangeably with functional subsystem because for aerospace vehicle conceptual design, subsystems are physical hardware not abstract forms such as software modules or sub-functions. Although some hardware functions are related to traditional disciplines, such as aerodynamics and propulsion, the subsystems are not chosen based on discipline (e.g. aerodynamic subsystems). This is because functions describe as the cause' why subsystems exist, while disciplines assess the 'effects' of having them as a consequence. For example, even though engines are providing thrust, they have aerodynamic effects such as drag.

Table 3-1 Description of Hardware Function Categories

Function	Purpose of Hardware	Example(s)
Drag Source	Provide drag force	Parachute, Autogyro, etc
Landing System	Provide capability to land/recover	Tricycle Gear, Skids, etc
Lift Source	Provide lift force	Wing, Wing Flap, Lifting Body, etc
Stability & Control	Provide stability and/or control	Aileron, Elevon, etc
Thermal Protection	Provide thermal protection	Ablator, Heat Shingle, Heat Pipe, etc
Thrust Source	Provide thrust force	Turbojet, Turbofan, Scramjet, etc
Volume Supply	Supply internal volume	Fuselage, Fuel Tank, Pod, etc

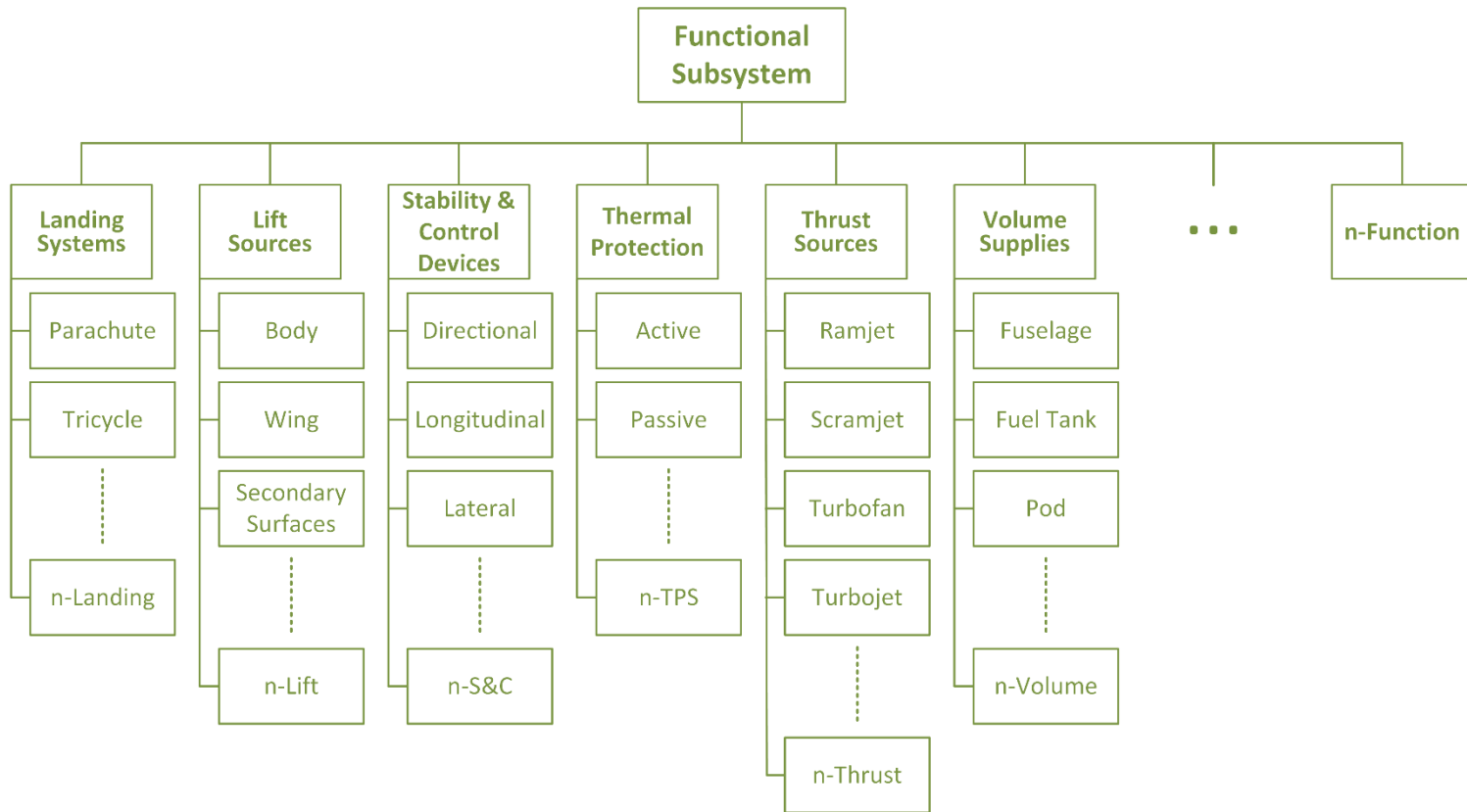


Figure 3-7 Functional Subsystem Block Decomposition

3.2.1.3 Hardware Attributes Definition

Figure 3-7 shows a functional decomposition tree for aerospace conceptual design. The number of functions and subsystems can vary depending on the design problem. In this research, one level of abstraction has been chosen in order to reduce the complexity of the conceptual design problem. That is, only one level of decomposition is used. As previously mentioned, there is risk of loss of information about subsequent levels in this scheme. In order to avoid this loss, hardware attributes have been defined to preserve detail information about the subsystem. Table 3-2 shows some examples of hardware attributes that can be used.

Table 3-2 Hardware Attribute Examples

Function	Hardware	Attribute	Attribute Options
Lift Source	Body	<i>Waverider Features</i>	Yes, No
		<i>Nose Bluntness</i>	Sharp, Spherical Bluntness
		<i>Nose Shape</i>	Cone, Spatula
		<i>Under Body</i>	Round Bottom, Flat Bottom
		<i>Cross Section</i>	Circular, Elliptic, Rectangular, FDL-8H
		<i>TPS Material</i>	T.D. NiCr, Radiation Shingle (Superalloys), Carbon-Carbon, TUF1/AETB, Haynes, BLA-S, BLA-HD, BRI-16, FRSI, SIP
		<i>Structure Material</i>	Tungsten, Inconel, Titanium, Aluminum, Steel, Composite hot structure
	Wing	<i>Waverider Features</i>	Yes, No
		<i>Planform</i>	Trapezoidal Tapered, Delta, Double Delta, Cropped Delta
		<i>Dihedral</i>	Dihedral, Anhedral, gull, Inverted gull, Channel, Cranked
<i>Position</i>		High, Mid, Low	
<i>Aspect Ratio</i>		High, Mid, Low	
	<i>Sweep</i>	Back Swept, Forward Sweep, No Sweep	
	<i>TPS Material</i>	T.D. NiCr, Radiation Shingle (Superalloys), Carbon-Carbon, TUF1/AETB, Haynes, BLA-S, BLA-HD, BRI-16, FRSI, SIP	
	<i>Structure Material</i>	Tungsten, Inconel, Titanium, Aluminum, Steel, Composite hot structure	

Thrust Source	<i>Scramjet</i>	<i>Inlet</i>	2-D Planar, 3-D Inward Turning
		<i>Isolator</i>	2-D, 3-D, 2-D to 3-D
		<i>Combustor</i>	2-D, 3-D
		<i>Nozzle</i>	SERN, 3-D, 2-D
		<i>RamJet</i>	2-D Planar, 3-D Inward Turning
		<i>Inlet</i>	
		<i>Combustor</i>	2-D, 3-D
		<i>Nozzle</i>	SERN, 3-D, 2-D
		⋮	

3.2.1.4 Hardware Shell and Implementation Blocks

Hardware shells and implementations have been defined to reconcile conceptual design products and acquisition products. Conceptual design subsystem attributes do not need to be well defined or based on existing products. They can be conceptual and analyzed as long as the abstractness of the model is acceptable. The shell hardware representation is a designation for hardware without defined attributes. They can be combined together to form different shell vehicle configurations without the constraint of matching attributes. Figure 3-8 shows 6 different shell vehicle packages created 10 shell hardware.







Function	Shell Package #1	Shell Package #2	Shell Package #3	Shell Package #4	Shell Package #5	Shell Package #6
						
Lift Source	All-Body	All-Body	Blended Body	Blended Body	Wing Body	Wing Body
Stability & Control	X-Tail	X-Tail	Twin Tail & Elevons	Twin Tail & Elevons	Twin Tail & Elevons	Twin Tail & Elevon
Thrust Source	SCRAMjet	SCRAMjet	SCRAMjet	SCRAMjet	SCRAMjet	SCRAMjet
Landing System	Tricycle	Parachute	Tricycle	Parachute	Tricycle	Parachute
Thermal Protection System	Passive	Passive	Passive	Passive	Passive	Passive

Figure 3-8 Example Shell Vehicle Packages

In contrast to conceptual design subsystems, acquisition subsystems need to be based on existing or well defined technologies. This is because the key performance parameters of cost, time and uncertainty are easier to determine for products with historical backing. Hardware implementation is the designation for subsystems based on existing technologies. Hardware implementations can be created by decomposing existing vehicles or identifying subsystems from public domain to proprietary or secret literature. Figure 3-9 shows the decomposition of X-51A into hardware implementations. The Hytech engine is the resulting implementation of scramjet hardware. Subsequent analysis using this implementation can assume TRL levels, costs, supply chain information and other attributes of the Hytech engine. Another application of hardware implementation is the combination with shell vehicle packages to create innovative portfolios of candidate vehicles. For example, the shell vehicles shown in Figure 3-8 can be permuted with hardware implementations for each shell hardware to form new results.

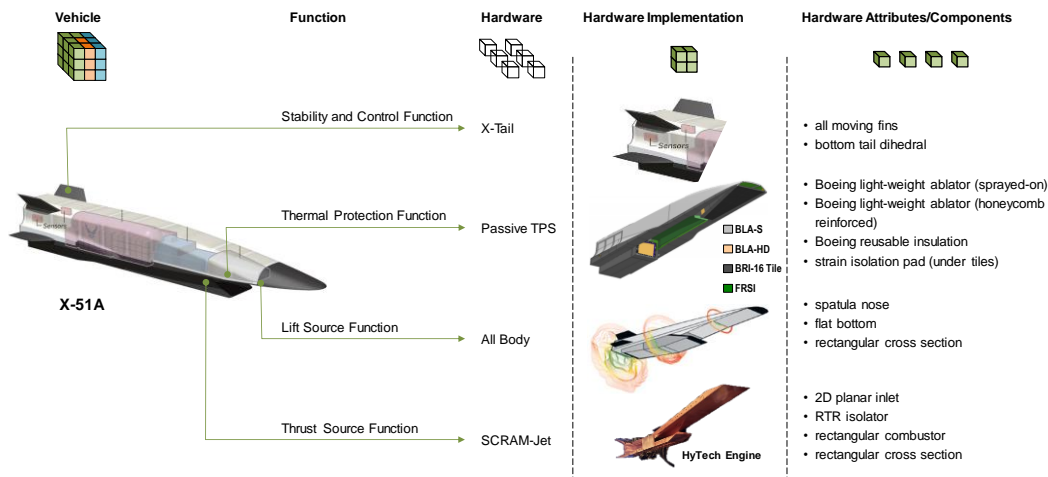


Figure 3-9 X-51A decomposition into hardware implementations

3.2.2 Operational Event Decomposition

Operational events describe how the product is designed to be used. They are the characteristics of the product that explain how it behaves overtime. Operational events are

used to define how the product performance should be simulated. For aerospace vehicles, the operational events define the vehicle mission. The decomposition of the aircraft mission into flight segments is common practice in flight mechanics texts (Vinh, 1995; Philips, 2010; Stengel 2004; Miele, 1962), flight trajectory simulation codes (Powell, 2003; Paris et al, 1996) and trajectory optimization techniques (Vinh, 1981). They are used for stability investigations, control law designs, performance estimations, flying and handling qualities evaluation of aircraft. Figure 3-10 shows the decomposition blocks used in this research.

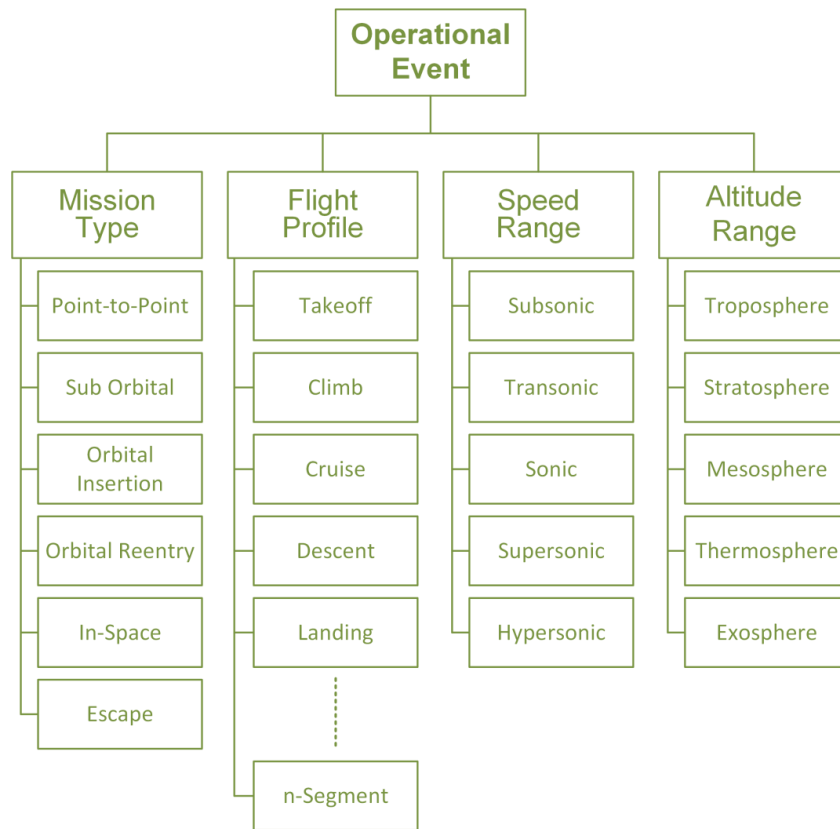


Figure 3-10 Operational Event Decomposition Block

3.2.2.1 Mission Type

The mission type describes the vehicle objective of the vehicle based on its start and end points in space. Table 3-3 shows the basic mission types, descriptions and some vehicle examples. Point-to-point (P2P) missions involve the vehicle flying from one point on earth to another point on earth. The design objective of this mission could either be for the vehicle to meet a design range or a design endurance (mission duration). In a suborbital mission, the vehicle flies to a design altitude outside the earth's atmosphere. However, its maximum velocity is not enough to sustain orbit. For orbital insertion missions, the vehicle flies from earth into a design orbit defined by an insertion altitude, velocity and flight path angle. Conversely, reentry missions begin at an altitude, velocity and flight path angle in orbit then end on the earth surface. Finally, in escape missions, the vehicle exits the atmosphere and reaches escape velocities required to leave the earth gravitational field.

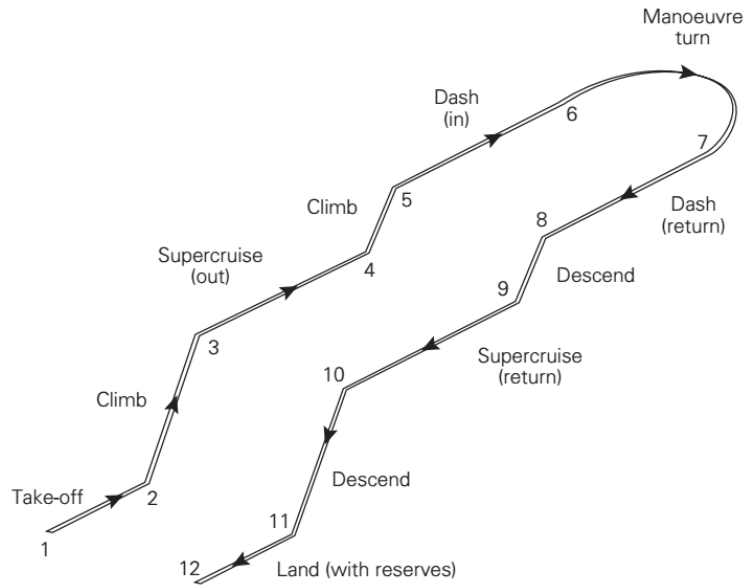
Table 3-3 Description of Mission Types

Type	Objective of Vehicle	Example Vehicles
Point-to-Point	Move vehicle or payload from one point to another	B747, A320, F22, C-5
Sub Orbital	Reach space (>100 km) without sufficient energy to complete one orbital revolution	Spaceship 2
Orbital Insertion	Reach space (>100km) with sufficient energy to remain at a specific altitude for more than one orbital revolution	Saturn V, Falcon 9
Orbital Reentry	Enter from orbital altitude through planet's atmosphere	Apollo Capsule, Dragon Capsule
In-Space	Perform mission objectives in planetary orbit	ISS
Escape	Provide sufficient energy to escape planetary gravity well	Voyager 1&2

3.2.2.2 Flight Profile

The flight profile describes the path the vehicle takes between the start and end points defined by the mission type. The flight profile is decomposed into separate flight phases for further analysis (Vinh, 1981). These flight phases or segments form blocks that can be used to build various flight profiles. Figure 3-11 shows example flight profile of a

two-place advanced deep interdicator aircraft. It is a P2P mission with both, a combined range and endurance objective.



Segment	Description	Height	Speed	Distance/duration
1-2	Warm-up, taxi and take-off	Sea level		NATO 8000 ft, icy
2-3	Climb to best supercruise alt.			
3-4	Supercruise to conflict area	Opt. alt.	M1.6	1000 nm
4-5	Climb to 50 000 ft			
5-6	Dash to target	50 000 ft	M1.6	750 nm
6-7	Turn and weapon release	50 000 ft		180°
7-8	Dash out	50 000 ft	M1.6	750 nm
8-9	Descend to supercruise alt.			
9-10	Supercruise return	50 000 ft	M1.6	1000 nm
10-11	Descend to base			
11-12	Land (with reserve fuel*)			NATO 8000 ft, icy

*Diversion and hold at sea level with 30 min fuel at economical flight conditions.

Figure 3-11 Example Flight Profile (Jenkinson, 2003)

3.2.2.3 Function Modes and Flight Segments

Not all functional subsystems serve their functions for the entirety of the operation of the product. In some cases, products switch between multiple subsystems during their operational phases. Function modes are introduced to describe the different ways each function is satisfied during product operation. Table 3-4 shows example thrust source modes for a vehicle with a rocket for acceleration and a scramjet for cruise. Function modes

can also be used to describe configuration changes. Consider the XB-70 shown in Figure 3-12. It droops its wings during supersonic flight to reduce wave drag by morphing into a waverider, ultimately riding the shock wave for compression lift. This change in configuration can be modelled using two lift source modes. The first to represent the drooped wing for supersonic flight phases. The second to represent the regular configuration for the other (mostly low-speed) flight phases. Modes can be defined for every function to simulate various scenarios including engine-out conditions, landing gear deployment and dual mode scramjet ramjet-to-scramjet mode transition.

Table 3-4 Example thrust function modes for a vehicle

Function Mode	Hardware in Use	Flight Segment	Description
Thrust Source Mode 1	Rocket	Ascent/Climb	Rocket used for acceleration
Thrust Source Mode 2	Rocket, Scramjet	Transition	Transition between rocket and scramjet
Thrust Source Mode 3	Scramjet	Cruise	Scramjet used for cruise
Thrust Source Mode 4	None	Glide	Engines off for glide

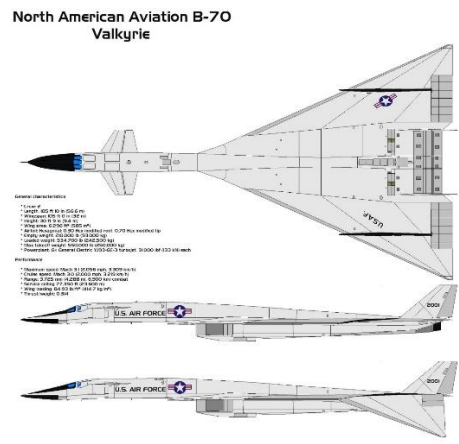


Figure 3-12 Artist rendering of North American XB70 (Bagera, 2008)

3.2.2.4 Speed and Altitude decomposition blocks

The speed and altitude decomposition blocks define the environment the vehicle will experience during its flight. As discussed in Chapter 2, the environment significantly

affects the complexity of the vehicle design. Molecular dissociation at hypersonic speed, thermal soak during reentry and ultraviolet radiation at high altitudes are some of the phenomenon that occur at extreme environments. The altitude and speed range building blocks are meant to give a representation of flow phenomenon the vehicle is expected to encounter. Mach number flow regimes shown in Table 3-5 are used as the speed range decomposition blocks. And the decomposition blocks for the altitude range are the Earth atmospheric layers shown in Table 3-6. In both cases, multiple selections can be made according to the expected flight profile and mission type of the vehicle.

Table 3-5 Mach Number Flow Regimes

Mach Regime	Mach Number
Subsonic	<0.8
Transonic	0.8-1.0
Sonic	1.0
Supersonic	1.0-5.0
Hypersonic	5.0-10.0
High Hypersonic	>10.0

Table 3-6 Earth atmospheric layers used as altitude range blocks

Earth Atmospheric Layers	Altitude Range
Exosphere	700 to 10,000 km (440 to 6,200 miles)
Thermosphere	80 to 700 km (50 to 440 miles)
Mesosphere	50 to 80 km (31 to 50 miles)
Stratosphere	12 to 50 km (7 to 31 miles)
Troposphere	0 to 12 km (0 to 7 miles)

3.2.3 Operational Requirement Decomposition

Operational requirements describe regulations, limits and boundaries on the utilization of the products. Figure 3-13 shows the operational requirement decomposition blocks. Regulatory bodies impose standards that must be met in order to maintain safety of operation. For aircraft, these regulations include airworthiness standards and noise

standards such as Federal Aviation Regulation (FAR) 23 (US 1900) for general aviation and FAR 25 (US, 1900) for commercial transport. Other operational requirement considerations are specifications that dictate non-functional or mission design choices that define the product. Examples include human rating, propellant type, pollution limits etc. The inclusion of operational requirements in the definition of CMDS do complete the holistic description of the product. They help in acquisition problems by giving a means to communicate organizational design philosophies and stakeholder requirements to the designer. They also provide additional parameters that differentiate competing technologies.

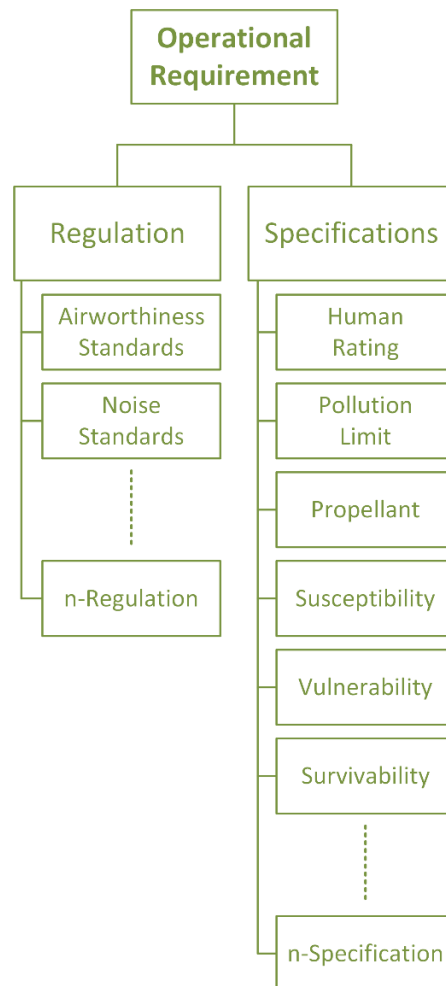


Figure 3-13 Operational Requirement Decomposition Blocks

3.3 Decomposition into Analysis Process Blocks

The Analysis Process Block is the second branch of the CMDS decomposition. It shows the coordination of analysis activities and procedures during for the design of the product. The number and types of interactions between activities described by analysis process are good indicators of product complexity. Process decomposition is a means to manage the complexity of the product design (Johnson and Benson, 1984) and business processes (Huang et. Al., 2010). The design structure matrix is a powerful tool developed to represent processes during decomposition (Steward, 1981). Figure 3-14 shows an example of a design structure matrix. The flow of information from the column index to the row index is marked with “*” while “+” shows a diagonal. After decomposition, design processes can be improved using techniques such as partitioning algorithm (Rogers, 1989; Sobieszczanski-Sobieski, 1982, 1989), Cluster Identification algorithms (Kusiak and Chow, 1987) and Branch-and-Bound algorithm (Kusiak and Cheng 1990). They can help identify events that can run concurrently, minimize number of overlapping parts, decrease resource usage and maximize measures of effectiveness.

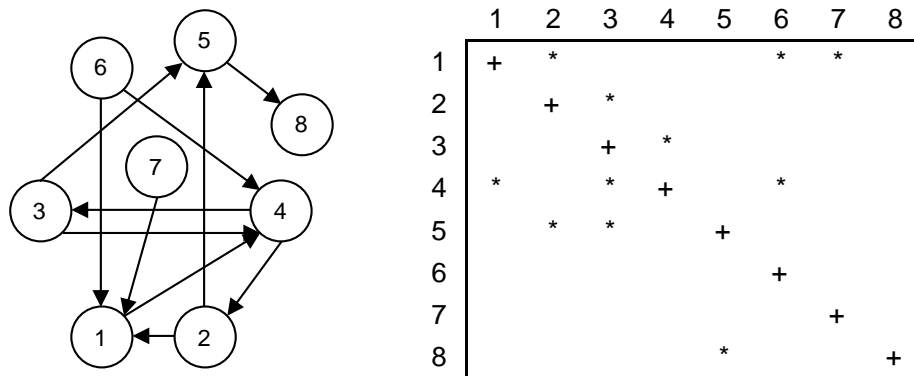


Figure 3-14 Design Structure Matrix representation of a process (Kusiak 1999)

Figure 3-15 shows the analysis process decomposition blocks used in this research. It is applicable to CMDS decomposition for both acquisition and conceptual design problems. The blocks have been chosen based on the principle that decomposition process modules should have high cohesion within themselves, but low coupling with other modules (Kusiak, 1999). They are also based on the description of conceptual design synthesis systems processes identified by Coleman (2010). There are two parts to the decomposition: (1) System Elements, and (2) Disciplinary Elements.

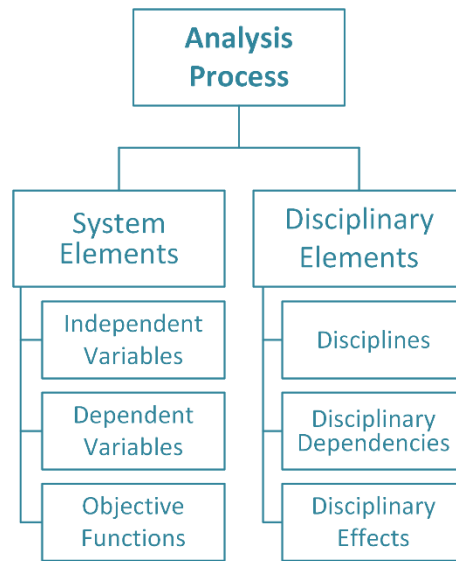


Figure 3-15 Analysis Process Decomposition Blocks

3.3.1 System Analysis Blocks

The system analysis blocks describe the formulation of the overarching problem. Analysis problems can be posed as function evaluations, system of equation solutions or objective function optimizations. These types of problems can be constructed from a set of independent and dependent variables. A dependent variable is selected from any output of a module (step) in the process. An independent variable is selected from inputs to process modules which are not outputs from other modules. The objective function block

is used to create relationships between independent and dependent variables which specify the type problem (evaluation, solution or optimization).

3.3.2 *Disciplinary Analysis Blocks*

The Disciplinary Analysis Blocks describe the overarching steps in the analysis process. In this research, the analysis process is constructed such that each process step is a module containing all the analysis performed by a single discipline. Discipline, in this context, refers to a formal branch of knowledge where the scientific method is used to generate empirical data or theories to explain phenomena that are observed. The choice to isolate disciplinary analysis to modules is based on the principle by Kusiak (1999), that decomposition process modules should have high cohesion within themselves but low coupling with other modules. A result of a disciplinary analysis is termed 'disciplinary effect'. Effects are represented as variables in the process. For example, total drag is a disciplinary effect evaluated by the aerodynamic discipline and it can be represented as D . The disciplinary effects block is used to define effects that are key performance parameters, inputs to other disciplines or used as dependent variables in the objective function. Disciplinary dependencies blocks are input parameters that define the degrees of freedom of a disciplinary analysis module. For example, if the aerodynamics module dependencies are altitude, velocity and angle of attack, then all aerodynamic effects are only applicable to 3DOF simulations. The analysis process formulation is intentionally decoupled from the product, so that it does not contain any product information.

3.4 Decomposition into Disciplinary Method Blocks

Disciplinary methods are sets of empirical, numerical or analytical functions or equations used to determine disciplinary effects of a product or its subsystems. Disciplinary methods populate the disciplinary modules defined in the analysis processes. Figure 3-16

shows the three aspect of disciplinary methods identified in this research effort. The product model block uses the hardware, mission and operation decomposition blocks explained in Section 3.2. As opposed to product decomposition, where the entire product is described, the product model blocks describe only parts of the product and their relation to given method models. The variables block contains variables used as method dependencies (inputs), as method effects (output) or method constraints. Constraint variables describe quantifiable ranges of applicability of a method. For example, a Mach number range, $0.8 < M < 1.0$, expresses the boundaries of a transonic aerodynamics method. The analysis block contains the computation details of the method. The discipline describes the formal branch of knowledge from which the method is created. The assumptions are qualitative concessions made during the derivation of the analysis equations.

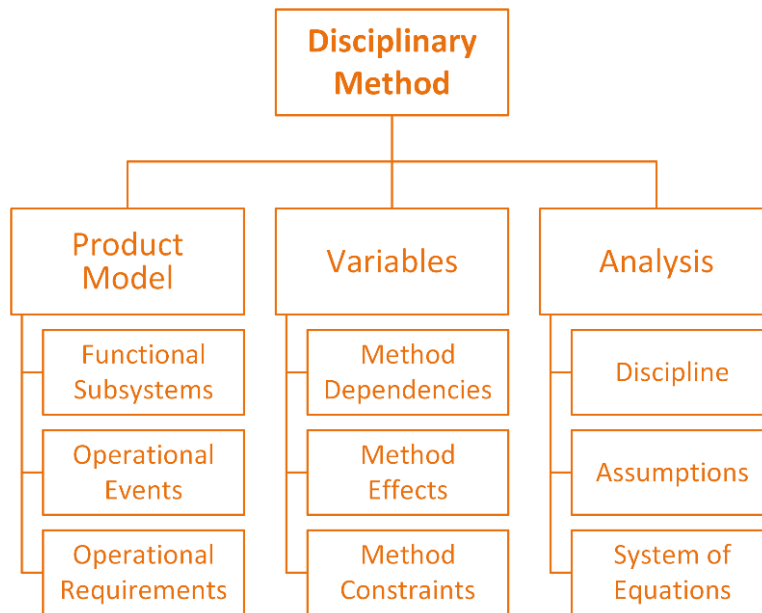


Figure 3-16 Disciplinary Method Block Decomposition

3.5 Chapter Summary

This Chapter discusses the Complex Multidisciplinary System Decomposition (CMDS) solution. The CMDS is the first of a three step process in the composable technology innovation and sizing architecture. The architecture created in conjunction with (Oza 2016) and (Gonzalez 2016) leverages existing knowledge and techniques from stakeholder technology portfolio management as well as existing aerospace synthesis systems. The CMDS decomposition blocks represent a generic means to manage system complexity. The product decomposition blocks, analysis process blocks, decomposition blocks and disciplinary method blocks are the main parts of the CMDS decomposition scheme identified, developed and software-implemented in this research. The biggest benefit of the formulation presented is the fact that it enables both, aerospace technology acquisition portfolio management and conceptual design parametric sizing tool customization.

Chapter 4

COMPLEX MULTIDISCIPLINARY SYSTEM DECOMPOSITION TOOL

The Complex Multidisciplinary System Decomposition (CMSD) concept described in Chapter 3 is designed for use in a database management framework. The prototype Database management framework developed to this end is the AVD^{DBMS}. It has been created in conjunction with Oza (2016) and Gonzalez (2016) for the purpose of validating the proposed innovation technology and parametric sizing solution concept. The decomposition branch of this framework allows the user to systematically decompose CMDS for improving understanding and storing CMDS attribute for later reuse. AVD^{DBMS} has three layers: (1) Graphical User Interface (GUI) layer, (2) database layer, and (3) analysis layer. Table 4-1 shows the software and corresponding programming languages comprising AVD^{DBMS}. Figure 4-1 shows the 3 layer architecture. The GUI Layer is the means by which the user interacts with AVD^{DBMS}. It is created using MS Access forms that initiate VBA commands that control the database. The database layer contains SQL commands which manage data transfer between the GUI and database. It is also used to generate custom CMDS synthesis tools. The analysis layer, in the MATLAB environment, is where the CMDS synthesis tools are executed. This chapter discusses the CMDS decomposition methodology as well as CMDS decomposition tools available in the AVD^{DBMS} framework.

Table 4-1 AVD^{DBMS} Layers

Layer	Software	Programming Language
GUI Layer	Microsoft Access	Microsoft Visual Basic with Applications (VBA)
Database Layer	Microsoft Access	Search Query Language (SQL)
Analysis Layer	MATLAB	MATLAB Script

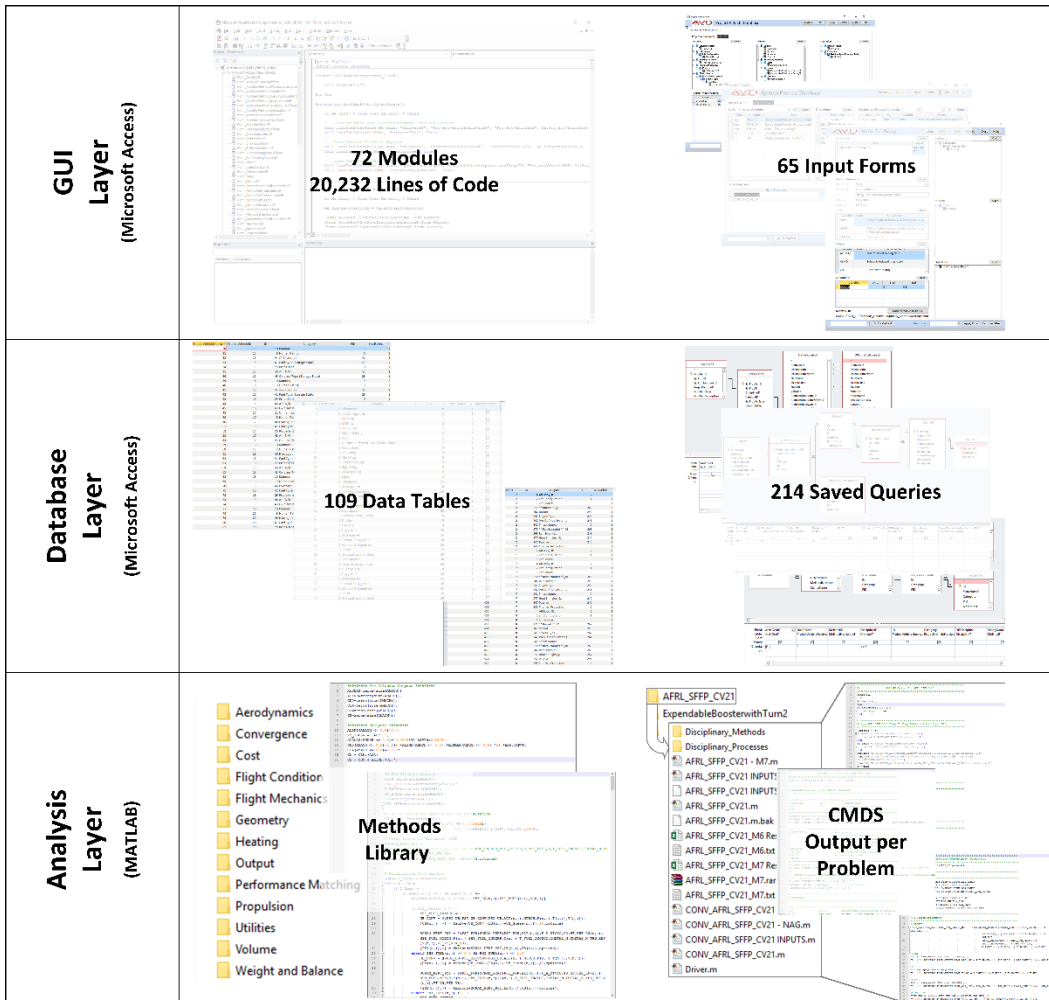


Figure 4-1 AVD DBMS Three Layer Architecture

4.1 CMDS Decomposition Methodology

Complex Multidisciplinary Systems (CMDS) Decomposition is a powerful tool for defining the technology acquisition portfolio and evaluating the applicability of a conceptual design synthesis system to a design problem. As discussed in Chapter 2, a CMDS is any body of knowledge aimed at describing or analyzing a system. That is, it has a broad range of embodiments. Reference texts that discusses technologies and parametric sizing tools for vehicle synthesis are CMDS examples. Figure 4-2 shows the decomposition

methodology for the aerospace CMDS developed in this context. First, a given CMDS is decomposed into product, process and method blocks. Then these blocks are examined to identify common components that already exist in the database, followed by specific components that are unique to the CMDS. Finally, all the CMDS information is stored using AVD^{DBMS}. Using this methodology, the understanding of existing problems and capability to solve new problems increase as more CMDS are decomposed.

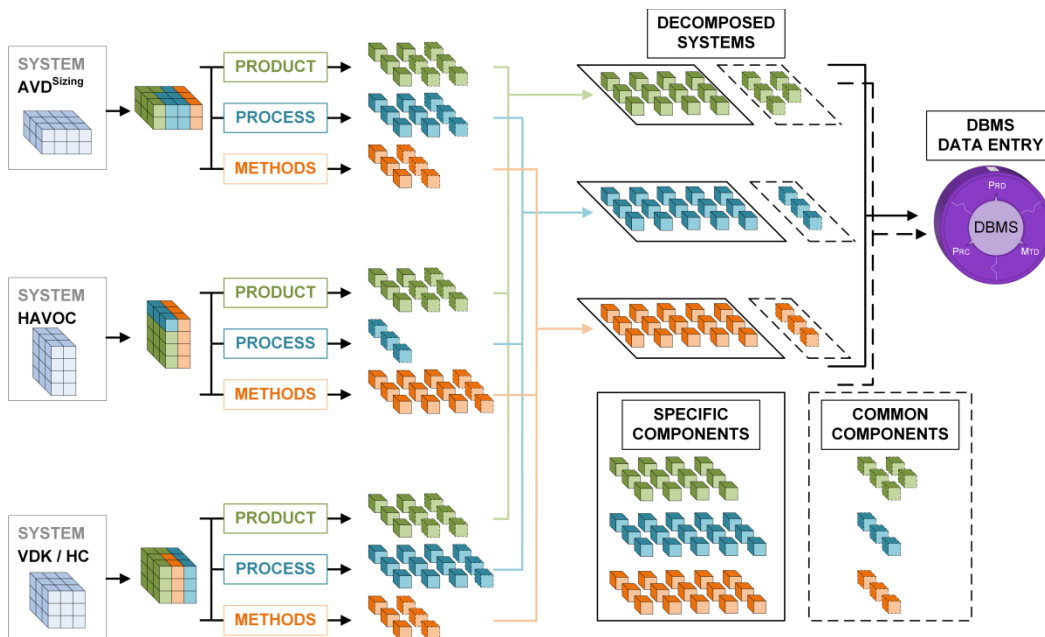


Figure 4-2 Methodology for CMDS Decomposition

4.2 CMDS Decomposition Input Forms

AVD^{DBMS} decomposition input forms are used to execute the aerospace CMDS decomposition methodology. There are three decomposition forms: (1) product input form, (2) analysis input form, and (3) disciplinary method input form.

4.2.1 Product Input form

Figure 4-3 shows the product input form. It is a card that describes the CMDS product decomposition blocks described in Section 3.2. The top half represents the

hardware, mission (operational event) and operational requirement blocks. Hardware are grouped by function, mission is grouped by altitude range, mission type, speed, and flight segment. The operational requirements are human rating, propellant type, regulations and other non-hardware specifications. The bottom half of the card is used to map hardware to function modes and function modes to flight segments as discussed in Section 3.2.2.3. Function modes are different ways a group of hardware are used to satisfy a function. For example, thrust modes for aircraft with both rockets and scramjets are: (1) all engines on, (2) rocket only, (3) scramjet only, (4) all engines off. The trajectory segment mapping is used to specify when each function mode is used. For example, all engine off is used for the glide segment.

The screenshot shows the 'Project Vehicle Database' interface for 'AFRL CV 10'. It features three main tree views: Hardware, Mission, and Operation. Below these are two mapping tables.

Hardware Tree:

- Landing System
 - Tricycle_01
- Lift Source
 - Blended Body_01
- Stability & Control
 - Twin Tail & Elevons_01
- Thermal Protection
 - Passive
 - ** Passive **_01
- Thrust Source
 - Pre-Defined Systems
 - Engine Type
 - Scramjet
 - ** Scramjet **_01

Mission Tree:

- Speed
 - Hypersonic
 - Subsonic
 - Supersonic
 - Transonic
- Trajectory Segment
 - Climb
 - Constant Q Climb_01
 - Cruise
 - Constant Mach Endurance Cruise_01
 - Constant Mach Endurance Cruise_02
 - Descent
 - Gliding Descent_01
 - Takeoff
 - Booster Launch_01
 - Turning Flight

Operation Tree:

- Human Rating
 - Unmanned
- Propellant
 - Oxidizer Type (Storage State)
 - Air (N/A)

Function Mode Mapping Table:

Function	Mode Name	Hardware
Lift Source	Lift Source 1	Blended Body_01
Thrust Source	Thrust Source 1	** Scramjet **_01

Trajectory Segment Mapping Table:

Trajectory Segment	Function	Function Modes
Booster Launch_01	Lift Source	Lift Source 1
Booster Launch_01	Thrust Source	Thrust Source 1
Constant Mach Endurance Cruise_01	Lift Source	Lift Source 1
Constant Mach Endurance Cruise_01	Thrust Source	Thrust Source 1
Constant Mach Endurance Cruise_02	Lift Source	Lift Source 1
Constant Mach Endurance Cruise_02	Thrust Source	Thrust Source 1
Constant Q Climb_01	Lift Source	Lift Source 1
Constant Q Climb_01	Thrust Source	Thrust Source 1
Gliding Descent_01	Lift Source	Lift Source 1
Gliding Descent_01	Thrust Source	
Steady Level Turn_01	Lift Source	Lift Source 1
Steady Level Turn_01	Thrust Source	Thrust Source 1

Figure 4-3 Product Input Form

4.2.2 Analysis Process Input Form

Figure 4-4 shows the analysis process input form. This card is used to record the CMDS analysis decomposition block information described in Section 3.3. The form has 5 sections: (1) System Variables, (2) Discipline, (3) Disciplinary Process Variable, (4) Error Function, and (5) Dependent Variable Check. *System variables* consist of independent variables and dependent variables which are selected from all the variables available in the database. They are variables that are used to specify the objective function as discussed in Section 3.3.1. The *discipline* section is used to specify the disciplines involved in the analysis process as well as the order they are run. The *disciplinary process variable* section dictates the key effects of each discipline. For each discipline, only variables that are known to be outputs of that discipline can be selected. The *error function* section shows the objective function of the analysis process. Finally, the *dependent variable check* section ensures the dependent variables selected in the system variable section are actually dependent. That is, variables that are marked as disciplinary effects and are directly used in the objective function.

System Process Database

Process Name: AFRLSFPD.GHV

Type	Variable	Name
Dep	OWE_V	Operational Weight Empty based
Dep	OWE_W	Operational Weight Empty based
Dep	TOGW	Take-off Gross Weight
Ind	SPLN	Planform area
Ind	WS	Wing loading (i.e. TOGW/S)

Discipline	Type	Variable	Name
Geometry	Output	AKW	Ratio of wetted surface area to p
Geometry	Output	AL	Vehicle length
Geometry	Output	BPLN	Span of the vehicle
Geometry	Output	MDOTO_X	Engine Massflow Rate Scale (MD
Geometry	Output	SF	Frontal Area
Geometry	Output	SFSPLN	Ratio of frotal area to planform a
Geometry	Output	SPLN_SF	Planform Geometric Scale Factor
Geometry	Output	SWET	Wetted surface area
Geometry	Output	TAU	Küchemann's tau
Geometry	Output	TAU_SF	TAU Scale Factor
Geometry	Output	VP	Volume of propulsion system
Geometry	Output	VTOTAL	Volume of total vehicle
Aerodynamic: Input		ALT	Flight Altitude

Error Function	Edit	Delete
WS-TOGW/SPLN	Edit	Delete
OWE_V-OWE_W	Edit	Delete

Variable	Used in Error Function	Output From Discipline
OWE_V	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
OWE_W	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
TOGW	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Go To Process

Figure 4-4 Analysis Process Input Form

4.2.3 Disciplinary Method Input Form

Figure 4-5 shows the disciplinary method input form. This card has 9 sections for describing CMDS disciplinary method decomposition blocks discussed in Section 3.4. (1) The first section is the reference section. It is used to keep track of page numbers of all references used in constructing the method. It is also linked to the AVD^{DBMS} reference library for more detail. (2) The method information gives the details of the method such as discipline, method ID, title date created and date update. (3) The 'more button' on that section provides additional detail about the method including assumptions made. (4) The input section displays variable inputs used by method, while, the (5) output section is for disciplinary effects (variable outputs) calculated in the method. The (6) constraint section specifies quantitative limits of method applicability. The (7) hardware mission (operational event) and (8) operation sections are used to describe aspects of the product that is modeled by the method. Finally, the (9) analysis section links the method card to the

analysis platform. AVD^{DBMS} uses the MATLAB environment for analysis. Therefore, the method analysis steps are written in a MATLAB script as shown in Figure 4-6.

The screenshot displays the AVD Methods Library interface. The main window is titled 'Methods Input Form' and 'Methods Library'. It features a navigation bar with buttons for 'Previous', 'Next', 'New', 'Delete', 'Close', and 'Help'. The interface is divided into several sections:

- References:** A table with columns 'Title' and 'Page #'. One entry is 'Hypersonic Convergence' with page numbers '241, 244, 258'.
- Method Information:** Fields for Discipline (AERO), Method ID (AERO_MD0001), Title (Lifting Body Subsonic Aerodynamics), Created (12/3/2014), and Updated (5/5/2015).
- Input:** A table with columns 'Variable', 'Units', and 'Variable Name'.

Variable	Units	Variable Name
AKW		Ratio of wetted surface area to planform area
AKW0		Ratio of wetted surface area to planform area of vehicle without spatula
AMACH		Mach number
- Output:** A table with columns 'Variable', 'Units', and 'Variable Name'.

Variable	Units	Variable Name
ALDMAX		Maximum lift to drag ratio
ALIND		Subsonic induced drag factor
CD		Coefficient of drag
- Constraints:** A table with columns 'Variable', 'Units', 'Start', and 'End'.

Variable	Units	Start	End
AMACH		0	0.8
- Hardware:** A tree view showing 'Lift Source' and 'Lift Configuration' (All Body).
- Mission:** A tree view showing 'Speed' (Subsonic).
- Operation:** A section titled 'All Operational Reqs'.

At the bottom, there is an 'Analysis File' section with a file path: X:\AVDS\AVD_ABE\Methods_Library\Disciplinary_Methods\Aerodynamic. Below this are buttons for 'Go To Method', 'Discipline:', 'Apply Filter', and 'Remove Filter'.

Figure 4-5 Disciplinary Method Input Form


```

1  ##### Pre-Allocate Outputs #####
2  ALDMAX=zeros(size(AMACH));
3  ALIND=zeros(size(AMACH));
4  CD0=zeros(size(AMACH));
5  CLA=zeros(size(AMACH));
6  CL=zeros(size(AMACH));
7  CD=zeros(size(AMACH));
8
9  ##### Analysis #####
10 ALIND(AMACH <= 0.8)=0.7;
11 V2_3SPLN = TAU^1.5;
12 ALDMAX(AMACH <= 0.8)=-9.0625*V2_3SPLN+6.5375;
13 CD0(AMACH <= 0.8)=1./(4.*ALIND(AMACH <= 0.8).*ALDMAX(AMACH <= 0.8).^2).*AKW./AKW0;
14 CLA(AMACH <= 0.8)=0.020;
15 CL = CLA.*AOA;
16 CD = CD0 + ALIND.*CL.^2;

```

Figure 4-6 Example Methods Library Entry MATLAB m-file (AERO_MD0001.m)

One key to the AVD^{DBMS} implementation is the re-structuring of analysis file data input and output requirements. When writing a new analysis file for a new method, it is not necessary to include the description of any input variables in the analysis file. Any new analysis method is made with the assumption that any input variable that has been selected using the disciplinary method input form exists in the workspace for that file. This means that when writing a new method file, it is only necessary to include lines of code dealing with the analysis meant to be performed. In other words, the burden of tracking where input variables have been created, or how they are connected in the system, is not placed on the user/creator of the method but rather the onus is on the system itself to correctly track and implement these connections.

4.3 Chapter Summary

This chapter discussed the implementation of the CMDS decomposition methodology. The AVD^{DBMS} is the tool developed for this effort. It is a database management software programmed in MS Access and the MATLAB environment using VBA, SQL and MATLAB script languages. CMDS decomposition is executed using the decomposition forms available in AVD^{DBMS}. The forms include product input, process input and disciplinary method input forms. CMDS have a broad range of embodiments ranging

from reference texts to parametric sizing tools. As more CMDS are decomposed, both understanding of existing problems and capability to solve new ones increase.

Chapter 5

COMPLEX MULTIDISCIPLINARY SYSTEM DECOMPOSITION CASE STUDY

5.1 Case Study Objectives

The objective of this research has been to bridge the gap between technology acquisition and conceptual design. The CMDS decomposition methodology developed has been identified as a vital piece creating the bridge between the two domains. The purpose of this case study is to demonstrate the application of this methodology to a relevant acquisition and design problem. The problem selected is the solution space screening study of air-launched hypersonic demonstrators. It was done in 2015 in conjunction with Bernd Chudoba, Lex Gonzalez, Amit Oza under the Summer Faculty Fellowship Program (SSFP) at Wright-Patterson Air Force Base. The case study problem required the contribution of this research thesis as well as (Oza 2016) and (Gonzalez 2016). This chapter discusses the problem, research strategy, strategy execution and study results.

5.2 Case Study Problem – AFRL GHV

The US Air Force Science and Technology Research plan (USAF, 2011) highlights US interests in hypersonic technologies. These technologies enable operational high-speed weapons and aircraft platforms that are vital increasing warfighting capabilities. They also contribute to intelligence, surveillance, reconnaissance and other mission objectives. The Air Force projects these systems to be operational by 2030 (Norris, 2012). In order to ensure the success of these systems there is a need to determine the best high-speed technologies. Improper planning has been the bane of many research projects in the past as expressed by former Undersecretary of the Air Force, Brockway McMillian (Morgenthaler, 1964):

We don't spend enough time, energy, or talent in deciding how to deploy our technological resources - - in other words, in deciding what to develop out of the products of our research. Just as our research and development program must match the risks that we face in the international arena, so also must our planning of that program be commensurate with the commitments we are making. ...How much effort should we expend to be sure we are committing these resources toward a product that we really need and one that we can really use?

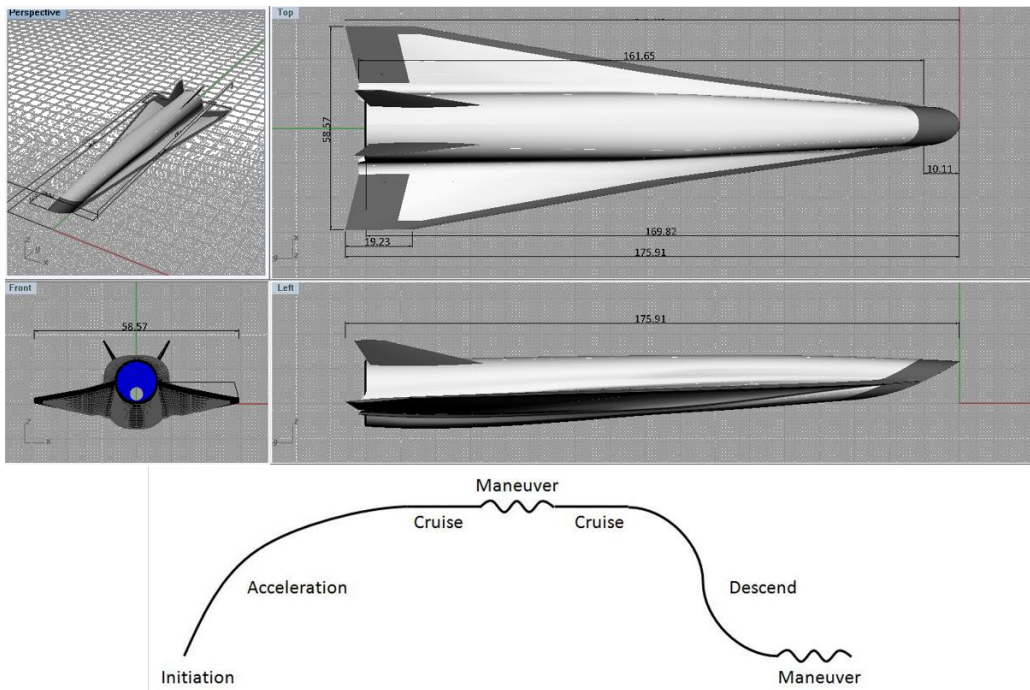
Another hindrance to hypersonic vehicle research is its sensitive nature to national defense. International Trade in Arms Regulations (ITAR) guidelines and industry proprietary technology considerations have restricted the amount of information that can be accessed and published in academia. However, the benefit of collaboration between multiple bodies to solve these problems is unquestionable. In response to this need, the Air Force Research Laboratory (AFRL) has provided a setting for collaboration between aerospace hypersonic research partners working in government, industry or academia. This avenue for collaboration is the generic hypersonic vehicle (GHV) study. Ruttle (2012) describes the study thus:

Due to proprietary or ITAR restrictions, AFRL cannot readily provide most data or designs to researchers who are not in the US Government or associated contractor community. It was decided that a family of in-house designs should be created which would be publicly releasable and relevant to current hypersonic projects. AFRL would then be able to share these designs and any data derived from them with other government, academic or industry partners and thereby foster greater collaboration within the area.

The objective of this study was to create a family of generic hypersonic vehicles (GHV) completely in-house using design tools either owned by or licensed to AFRL. The GHV would have to be based upon the state of the art in hypersonic engine design so that it would be valuable for studies of operability, controllability, and aero-propulsion integration. It was agreed early on that the vehicle would need to have a blended wingbody configuration, 3D inlet and nozzle, an axisymmetric scramjet combustor, and a metallic structure with a thermal protection coating. The GHV would cruise at Mach 6 within a dynamic pressure range of 1000 to 2000 psf, and maneuver at a maximum loading factor of approximately 2G.

For the sake of the current research endeavor, the GHV study is posed as an acquisition and conceptual design problem. Figure 5-1 shows the configuration and mission description of the GHV study. The case study questions to be answered are:

- Acquisition: What relevant technology packages satisfy the GHV type mission?
- Acquisition: What technology package gives the least acquisition risks?
- Conceptual Design: What is the configuration of the least risk technology package?
- Conceptual Design: What is the technical feasibility of the technology package?



	Mach	Lift/Weight	Dynamic Pressure (psf)
Initiation (booster separation)	4 – 5	1	2500 – 1500
Acceleration and Climb	4 – 6	>1	2500 – 1500
Cruise	6	1	2000 – 1000
Maneuver (#1 or #2)	~6	~2	2000 – 1000
Cruise	6	1	2000 – 1000
Descend (powered)	6 – 4	<1	2000 – 3000
Descend (unpowered)	4 – 3	<1	2500 – 5000
Maneuver (unpowered)	~3	>1	~5000

Figure 5-1 Generic Hypersonic Vehicle Study Description (Ruttle et al., 2012)

5.3 Case Study Research Strategy

The strategy adopted balances the acquisition and conceptual design challenge. The acquisition challenge is to determine the technologies to invest in. The conceptual design challenge is to evaluate the technical feasibility of the technology investments and address identified pitfalls. Primary emphasis has been placed on the utilization of existing hypersonic vehicle knowledge at the UT Arlington Aerospace Systems Engineering (ASE) Laboratory and execution of the technology innovation and sizing framework developed in conjunction with Gonzalez (2016) and Oza (2016). This involves the prioritization of a hypersonic demonstrator vehicle portfolio and producing parametric flight vehicle technical feasibility solution spaces. The study is executed in two parts:

Part 1: Technology Acquisition Portfolio Prioritization

Part 2: Conceptual Design Parametric Sizing

5.4 Part 1: Technology Acquisition Product Portfolio Prioritization

The initially wide-open trade space of hypersonic technologies is refined successively and constrained to trades of immediate relevance to the GHV type mission. The range of past-to-present hypersonic demonstrators is assessed in order to deliver a small, yet reasonable number of design attributes directly addressing the immediate critical mission-operation-hardware path or need. The overall trade-space consists of combinations of: (a) *mission* (endurance, payload, speed), (b) *operation* (carrier system, booster system, landing system), (c) *hardware* (thrust source: 2D and 3D scramjet; lift source: blended-body and wing-body). Figure 5-2 shows the technology acquisition portfolio prioritization road map. The strategy is summarized as

- Reference vehicle identification from AVD Database;
- Reference vehicle decomposition into technology portfolio;

- Candidate vehicle composition from technology portfolio;
- Candidate vehicle portfolio assessment;
- Project vehicle selection.

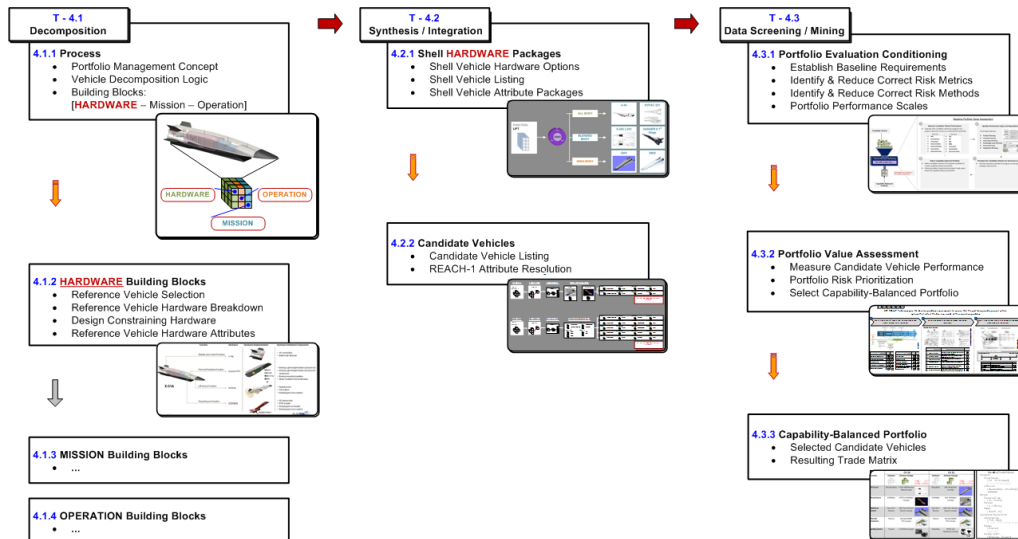


Figure 5-2 Technology Acquisition Portfolio Prioritization Roadmap (Chudoba, 2015)

5.4.1 Reference Vehicle Identification from AVD Database

A primary literature search has been conducted to identify relevant past and present data and knowledge related to the planning and development of hypersonic technology demonstrators. A systematic literature survey, has been an ongoing effort throughout the existence of the ASE Laboratory. Source for accessing normal and radical design data and knowledge have been (a) public domain literature, (b) organization internal sources, and (c) expert advice. For efficient handling of design related data and information, a dedicated computer-based aircraft conceptual design data-base (AVD-DB) has been developed (Haney 2016). This system handles disciplinary and inter-disciplinary literature relevant for conceptual design (methodologies, flight mechanics, aerodynamics, etc.), interview-protocols, flight vehicle case study information (descriptive-, historical-, numerical information on conventional and unconventional flight vehicle configurations),

simulation and flight test information, etc. The overall requirement for the creation of the AVD-DB has been simplicity in construction, maintenance, and operation, to comply with the underlying time constraints.

The system has been used to identify a listing of reference vehicle with technologies relevant to the GHV type mission. The vehicles chosen have suitably selected, structured, and condensed flight vehicle conceptual design data and information. The research goal, to develop an air-breathing hypersonic technology demonstrator requires accounting for as many design-related interactions as necessary, since the rationale for the evolution of aircraft is diverse as a quick browse through aviation history reveals. In order to decrease the overall risks towards a failing acquisition program, it is important to select technologies with successful track records or high potential. Figure 5-3 shows the reference vehicle list selected from the AVD-DB. The feasibility era represents vehicles that have had previous engineering and/or flight test success, while the maturation era identifies vehicles with potential towards the next generation of hypersonic flight demonstrators.

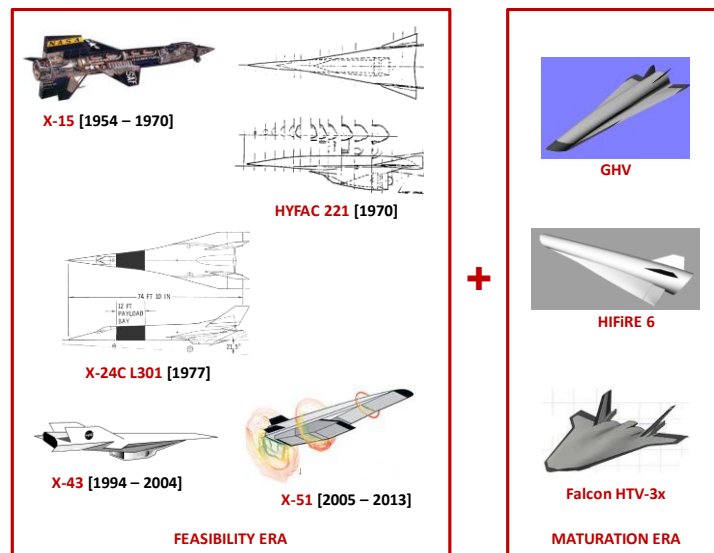


Figure 5-3 Vehicle Decomposition – Reference Vehicle Listing

5.4.2 Reference Vehicle Decomposition into Technology Portfolio

The reference vehicles are used to build the technology portfolio for acquisition assessment. Figure 5-4 shows the decomposition methodology for defining the technology portfolio. This methodology is based on the product decomposition blocks defined in the current research undertaking. The primary focus of the portfolio being defined is technology hardware. The primary hardware function types used to define the portfolio are: (1) lift source, (2) stability & control device, (3) thrust source, (4) landing system, and (5) thermal protection System (TPS). AVD^{DBMS} is utilized to decompose the reference vehicles into their constituent hardware technologies. Figure 5-5 shows the resulting technology portfolio. Table 5-1 shows the attributes of the lift and thrust source technologies.

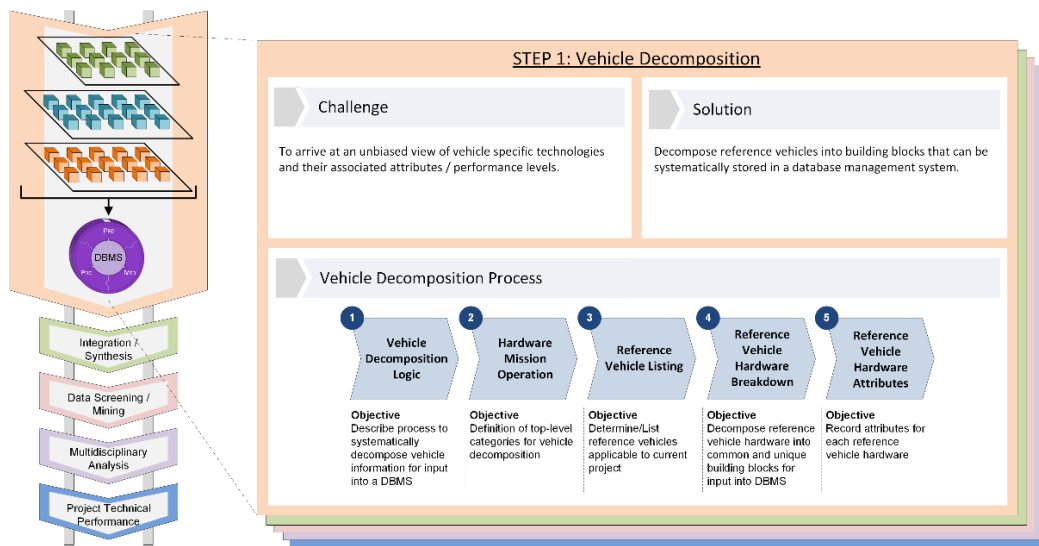


Figure 5-4 Reference Vehicle Decomposition Methodology

Function	Hardware	Reference Vehicle Decomposition								Total
		GHV	X-24C-L301	HYFAC 221	Sanger II	X-43 C	X-51A Cruiser	HIFIRE 6	Falcon HTV-3x	
Lift Source	All-Body									3
	Blended Body									3
	Wing Body									2
Stability & Control	Twin Tail									5
	X-tail									3
	Elevons									5
Thrust Source	Rocket									1
	Ramjet									1
	SCRAMjet									5
	DMSJ									0
	Turbo-Ramjet									2
Landing System	Tricycle Gear									2
	Chute									1
Thermal Protection	Active									0
	Passive									8

Figure 5-5 Reference Vehicle Decomposition into functional hardware

Table 5-1 Lift and Thrust Source Technology Portfolio Attributes

Function	HW	Attribute	GHV	X-24C-L301	HYFAC 221	X-43 C	X-51A Cruiser	HIFIRE 6	HTV-3x
Lift	Body	Waverider	No	No	No	No	No	No	No
		Nose Blunt		Spherical	Spherical	Sharp	Sharp		
		Nose Shape		Cone	Cone	Spatula	Spatula		
		Under Body	Flat	Round & Flat	Flat Bottom	Flat Bottom	Flat Bottom	Flat	
		Cross Section	Circular	FDL-8H	Elliptic	Rectangular	Rectangular	Circular	
		TPS Material			T.D. NiCr, radiation shingle	Carbon-Carbon, TUF1/AETB, Haynes	BLA-S, BLA-HD, BRI-16, FRSI, SIP		
		Structure		LockAlloy	Aluminum	Tungsten, Steel, Aluminum	Tungsten, Inconel, Titanium, Aluminum, Steel, Composite hot structure		
	Wing	Waverider	Yes	No				Yes	No
		Planform	Cropped Delta	Cropped Delta				Cropped Delta	Double Delta
		Position	Low	Low				Low	Low
		Aspect Ratio	Low	Low				Low	Low
		Sweep Structure	Swept Back	Swept Back				Swept Back	Swept Back
Thrust	Scramjet	Engine Name				HyTech	HyTech		
		Inlet	3-D Inward Turning	2-D		2-D Planar	2-D Planar	3-D Inward Turning	
		Isolator	3-D			2-D	2-D	3-D	
		Combustor	3-D			2-D	2-D	3-D	
		Nozzle	3-D	2-D		2-D	2-D	3-D	
	Ramjet	Engine Name			MA145				
		Inlet			2-D				
		Combustor			3-D				
	Rocket	Engine Name		LR-105, LR-101					

5.4.3 Candidate Vehicle Composition from Technology Portfolio

Although the portfolio of technologies has merit in itself, the desired product of the acquisition study is a prospective hypersonic vehicle demonstrator. Consequently, these technologies need to be combined in a syntactical sound manner to compose vehicles. The resulting vehicles are candidates for acquisition. Figure 5-6 shows the methodology for composing vehicles. The concept of shell vehicles for aerospace vehicle portfolio definition is discussed in Section 3.2.1.4. The shell vehicles are used to define vehicle configurations without attribute details. After the definition of these shells, the technology portfolio is combined with the shell vehicles to form candidate vehicles. This process is automated using AVD^{DBMS} as described by Oza (2016). Table 5-2 shows the resulting shell vehicles, while, Table 5-3 and Table 5-4 show the final candidate vehicle portfolio.

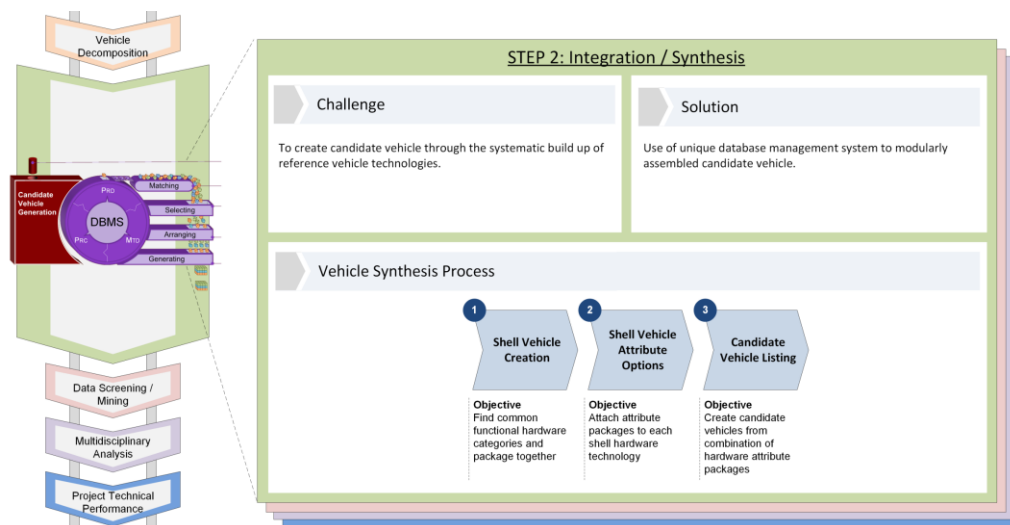


Figure 5-6 Candidate Vehicle Synthesis Methodology

Table 5-2 Technology Portfolio Definition Shell Vehicles







Function	Shell Package #1	Shell Package #2	Shell Package #3	Shell Package #4	Shell Package #5	Shell Package #6
						
Lift Source	All-Body	All-Body	Blended Body	Blended Body	Wing Body	Wing Body
Stability & Control	X-Tail	X-Tail	Twin Tail & Elevons	Twin Tail & Elevons	Twin Tail & Elevons	Twin Tail & Elevon
Thrust Source	SCRAMjet	SCRAMjet	SCRAMjet	SCRAMjet	SCRAMjet	SCRAMjet
Landing System	Tricycle	Parachute	Tricycle	Parachute	Tricycle	Parachute
Thermal Protection System	Passive	Passive	Passive	Passive	Passive	Passive

Table 5-3 Candidate Vehicle Portfolio

























Candidate Vehicle	Hardware Function				
	Lift Source Concept	Thrust Source Concept	Stability & Control Concept	Thermal Protection Concept	Landing System Concept
 CV 1	X-43C All Body Concept	GHV SCRAMjet Concept	X-51A X Tail Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 2	X-43C All Body Concept	HYTECH SCRAMjet Concept	X-51A X Tail Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 3	HYFAC 221 All Body Concept	GHV SCRAMjet Concept	X-51A X Tail Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 4	HYFAC 221 All Body Concept	HYTECH SCRAMjet Concept	X-51A X Tail Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 5	X-43C All Body Concept	GHV SCRAMjet Concept	X-51A X Tail Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 6	X-43C All Body Concept	HYTECH SCRAMjet Concept	X-51A X Tail Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 7	HYFAC 221 All Body Concept	GHV SCRAMjet Concept	X-51A X Tail Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 8	HYFAC 221 All Body Concept	HYTECH SCRAMjet Concept	X-51A X Tail Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 9	X-24C-L301 Blended Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 10	X-24C-L301 Blended Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 11	Sanger II Blended Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 12	Sanger II Blended Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	X-15 Skids Concept

Table 5-4 Candidate Vehicle Portfolio (Cont'd)

Candidate Vehicle	Hardware Function				
	Lift Source Concept	Thrust Source Concept	Stability & Control Concept	Thermal Protection Concept	Landing System Concept
 CV 13	X-24C-L301 Blended Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 14	X-24C-L301 Blended Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 15	Sanger II Blended Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 16	Sanger II Blended Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 17	GHV Wing Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 18	GHV Wing Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 19	M6M Wing Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 20	M6M Wing Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	X-15 Skids Concept
 CV 21	GHV Wing Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 22	GHV Wing Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 23	M6M Wing Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept
 CV 24	M6M Wing Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept	X-24C L301 TPS Concept	HYFAC 221 Parachute Concept

5.4.4 Candidate Vehicle Portfolio Value Assessment

The candidate vehicle portfolio defined consists of vehicles with both, high risk and low risk technologies. The acquisition problem objective is to maximize technology investment value while minimizing risks. Figure 5-7 shows the portfolio value assessment methodology described by Oza (2016). It is a combination of the technology acquisition techniques described in Chapter 1. It involves the integration of the Technology Readiness Levels (TRL), Integration Readiness Levels (IRL) and Advanced Degree of Certainty (ADC) into the technology portfolio to facilitate the composition of candidate vehicle TRL-ratings and risks. In order to manage uncertainties that may exist, best case, worst case and most

likely scenarios are considered. Figure 5-8 shows the candidate vehicle portfolio assessment results. Although candidate vehicles CV6 and CV10 have the highest composite TRLs, CV6 has a lower variance in TRL. (Oza, 2016) provides more detail about the portfolio assessment result.

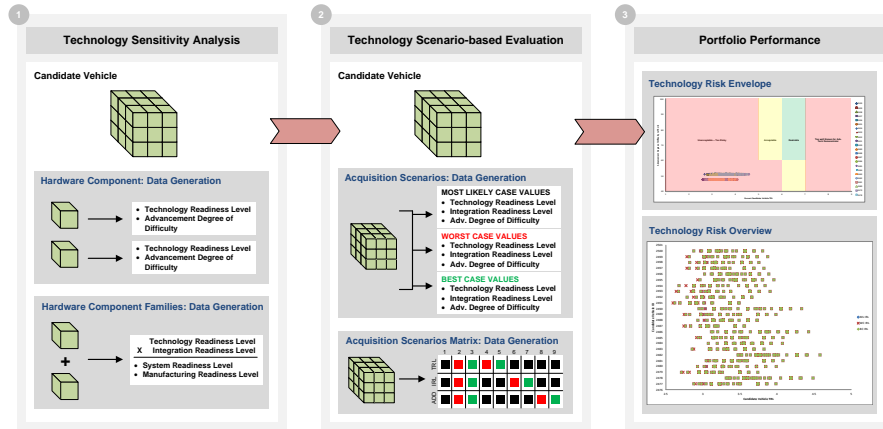


Figure 5-7 Portfolio Value Assessment Methodology

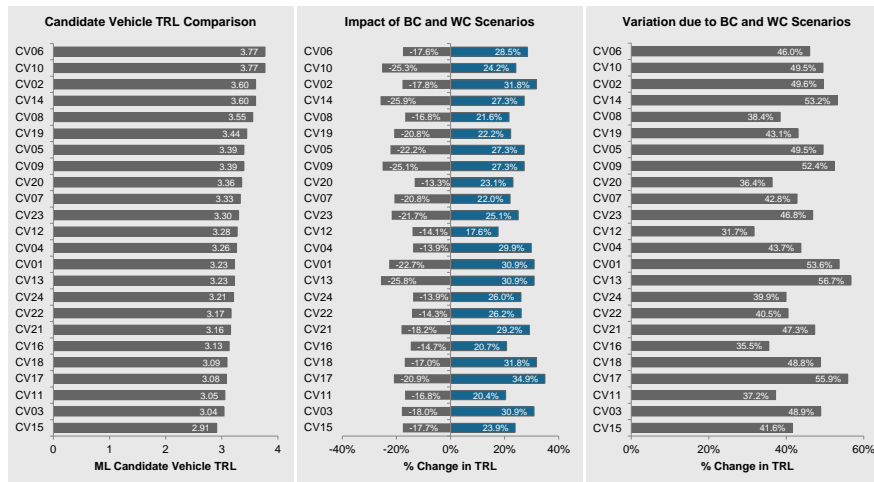


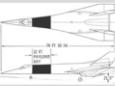

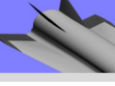



Figure 5-8 Composite Candidate Vehicle TRL for risk scenarios

5.4.5 Project Vehicle Selection

CV10 has been selected as the most desirable technology combination to develop into a flight vehicle project. This selection is based on candidate portfolio value assessment

and other considerations. Although CV6 has equal TRL and lower TRL variance than CV10, the choice of landing system hardware was the deciding factor. A landing gear system as opposed to a recovery parachute is perceived to be more conducive for vehicle reuse. Figure 5-9 shows the characteristics of CV10 and the potential feasibility space that should be explored.

Function	CV 10		
	Hardware	Attribute Package	
			~TRL: 3.77 ΔTRL: 49.5%
Lift Source	Blended Body	X-24C-L301 Blended Body Concept	
Thrust Source	SCRAMjet	HYTECH SCRAMjet Concept	
Stability & Control	Twin Tail + Elevons	GHV Twin Tail and Elevon Concept	
Thermal Protection	Passive		
Landing System	Tricycle	X-15 Skids Concept	

Resulting Trade Volume

Hardware

- Thrust Source [2-D Scramjet]
- Lift Source [Blended Body]

Mission

- Endurance Time [10 – 30 min]
- Payload [0 – 1,500 lbs]
- Speed [Mach 5 – 8]

Operational Requirements

- Carrier Vehicle [F-15 – B-52]
- Booster [External]
- Landing Option [Runway]

Figure 5-9 Characteristics of Candidate Vehicle 10

5.5 Part 2: Conceptual Design Parametric Sizing

CV10 has been chosen for a follow-on conceptual design study based on the results of the technology portfolio value assessment. The conceptual design sequence consists of three individual phases executed in sequence: (1) parametric sizing (PS), (2) configuration layout (CL), and (3) configuration evaluation (CE) (see Figure 2). For the demonstration of AVD^{DBMS}, only parametric sizing is executed aimed at exploring the feasible trade space for the technology acquisition study. The sequence of the parametric sizing study is organized as follows:

- Decomposition of synthesis systems at the ASE Laboratory;
- Composition of sizing CMDS for CV10;
- Visualization of CV 10 feasibility solution space.

5.5.1 Decomposition of Synthesis Systems at ASE Laboratory

The purpose of the synthesis system decomposition is to increase the AVD^{DBMS} sizing capability by populating it with products, processes and methods from existing synthesis systems. The ASE Laboratory has access to a range of synthesis systems based on years of building a parametric process library (Coleman 2010). Figure 5-10 shows one of the synthesis systems available, AVDS. It is a best-practice design-to-mission sizing process capable of first-order solution space screening of a wide variety of conventional and unconventional vehicle configurations (Coleman 2010). AVDS relies on a robust disciplinary methods library for analysis and a unique multi-disciplinary sizing logic and software kernel enabling data storage, design iterations, and multi-disciplinary process convergence. Figure 5-11 and Figure 5-12 show a snapshot of the products, analysis process and method libraries populated by using the AVD^{DBMS} decomposition forms discussed in Section 4.2.

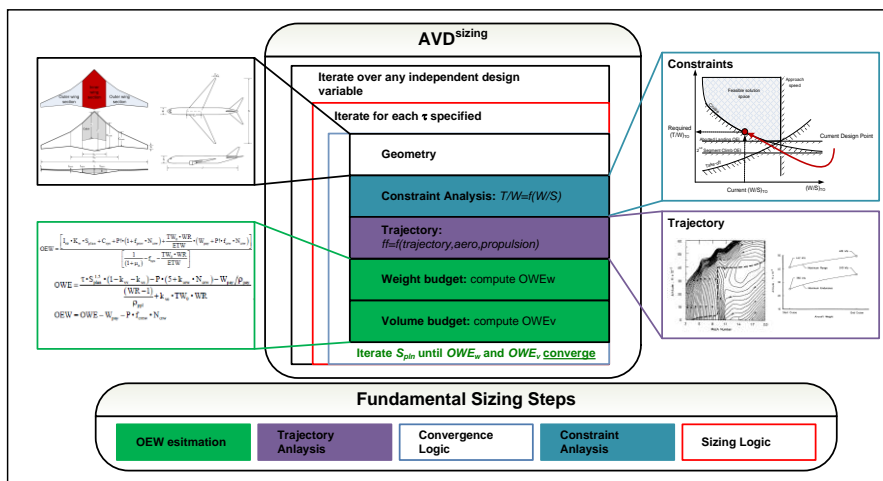


Figure 5-10 Overview of AVDS Synthesis System (Coleman 2010)

5.5.2 Composition of Sizing CMDS for Candidate Vehicle 10

Gonzalez (2016) describes the capability of AVD^{DBMS} to compose the custom sizing CMDS for given conceptual design problems. In the context of the 2015 SFFP study, CV10 has been chosen for the parametric sizing study based on results from the technology portfolio value assessment in Section 5.4. CV10 is based on the X-24C (L-301) lift source technology and X51A thrust source technology. A literature search identified the characteristic dimensions of the vehicles including, fuselage length, height and width, planform, root/tip chord, sweep angle and incidence angle. Based on this understanding, the AVD^{DBMS} CMDS composition form is executed. The composition steps are

- Matching disciplinary methods to the given product and process;
- Selecting most appropriate disciplinary methods from the matched list;
- Arranging selected product, process and methods into CMDS blue print;
- Generating customized CMDS executable.

The CV10 project vehicle and the AVDS analysis process were input into the AVD^{DBMS} CMDS composition form as product and process respectively. Table 5-5 shows the objective function for AVDS process. The AVDS process poses an equation solution problem to determine the planform area, S_{pln} , and Wing loading, W/S , required for operating weight estimates based on volume calculations, $(OWE)_V$, to equal operating weight estimates based on weight calculations, $(OWE)_W$. AVD^{DBMS} provides a list of matching disciplinary methods for the parametric sizing problem.

Process Blocks	Variable / Problem Type	Equation/Symbol
Independent Variable	Planform Area, ft ²	S_{pln}
Independent Variable	Wing Loading, N/ft ²	$\frac{W}{S} = \frac{TOGW}{S_{pln}}$
Dependent Variable	Operating Weight Based on Weights Budget, N	$(OWE)_V = \frac{W_{Fix} + W_{Eng} + W_{TPS}}{1 + \mu_a} - \frac{W_{str}}{OEW} - F_{Wsys} + W_{payload}$

Dependent Variable	Operating Weight Based on Volume Budget, N	$(OWE)_v = \frac{V_{Total} - V_{Systems} - V_{Eng} - V_{Str} - V_{TPS} - V_{Void}}{\frac{WR - 1}{\rho_{ppt} * g_0}}$
Objective Function	Equation Solution Problem	$(OWE)_v - (OWE)_w = 0$ $\left(\frac{W}{S}\right)_{Guess} - \frac{TOGW}{S_{pln}} = 0$

Table 5-6 shows the disciplinary methods selected from the matching list of method. In the arranging step, Aero Methods 5, 6, 7 were arranged to execute during the subsonic, transonic-supersonic and hypersonic flight regimes respectively. Figure 5-13 shows a Design Structure Matrix (DSM) of the resulting CV10 sizing CMDS blueprint. It describes the flow of information during the execution of the CMDS.

Table 5-5 AVDS Analysis Process Objective Function Block

Process Blocks	Variable / Problem Type	Equation/Symbol
Independent Variable	Planform Area, ft ²	S_{pln}
Independent Variable	Wing Loading, N/ft ²	$\frac{W}{S} = \frac{TOGW}{S_{pln}}$
Dependent Variable	Operating Weight Based on Weights Budget, N	$(OWE)_v = \frac{W_{Fix} + W_{Eng} + W_{TPS}}{1 + \mu_a} + W_{payload}$ $\frac{W_{str}}{OEW} - F_{Wsys}$
Dependent Variable	Operating Weight Based on Volume Budget, N	$(OWE)_v = \frac{V_{Total} - V_{Systems} - V_{Eng} - V_{Str} - V_{TPS} - V_{Void}}{\frac{WR - 1}{\rho_{ppt} * g_0}}$
Objective Function	Equation Solution Problem	$(OWE)_v - (OWE)_w = 0$ $\left(\frac{W}{S}\right)_{Guess} - \frac{TOGW}{S_{pln}} = 0$

Table 5-6 Disciplinary methods selected for composing CV10 Sizing CMDS

Discipline	Sizing Name	Method Title	Reference
Flight Condition	FLTCON_MD0001	Atmospheric Model	(MINZNER et al. 1959)
Geometry	GEO_MD0002	Hypersonic Air-breather Geometry (AFRL SFFP CV10).	(Chudoba 2010)
Aerodynamics	AERO_MD0005	Hypersonic Convergence Aerodynamic Estimation Method - Subsonic	(Czysz 2004; Sforza 2016)
	AERO_MD0006	Hypersonic Convergence Aerodynamic Estimation Method - Supersonic	(Czysz 2004; Sforza 2016)

	AERO_MD0007	Hypersonic Convergence Aerodynamic Estimation Method - Hypersonic	(Czysz 2004; Sforza 2016)
Propulsion	PROP_MD0008	HAP Stream Thrust SERN CEA (C2H4 - Air) Look-Up Table	(Heiser and Pratt 1994)
Performance Matching	PM_MD0001	Gliding Decent at Max L/D	(Miele 1962)
	PM_MD0003	Constant Q-Climb to an Altitude and Velocity at Small Flight Path Angles	(Miele 1962)
	PM_MD0008	Constant Mach Range Cruise at Small Flight Path Angles	(Miele 1962)
	PM_MD0009	Launch Methods using WR	(Miele 1962)
	PM_MD0010	Steady Level Turn	(Vinh 1981)
Weight & Balance	WB_MD0003	Convergence OWE Estimation for Scramjet w/ Landing skids	(Czysz 2004; Harloff 1988)

Complex Multidisciplinary System DSM Blueprint and Data Relationships		Selected Methods	Objective Function
Selected Method	GEO_MD0002		
	AERO_MD0005		
	AERO_MD0006		
	AERO_MD0007		
	PROP_MD0008		
	PM_MD0001		
	PM_MD0003		
	PM_MD0008		
	PM_MD0009		
	PM_MD0010		
Objective Function	OWE_V - OWE_W		
	WS - TOGW / SPLN		
	SPLN		
	WS		
Disciplinary Outputs Variables	AKW		
	AL		
	ALLE		
	BPLN		
	SF		
	SFSPLN		
	SPLN_SF		
	SWET		
	TAU		
	TAU_SF		
	VP		
	VTOTAL		
	CD		
	CL		
	AISP		
	FT_AVAIL		
	OF		
	FF		
	THRL_VAR_MAX		
	WR		
AIP			
AISTR			
OWE_V			
OWE_W			
TOGW			

Figure 5-13 Design Structure Matrix for CV10 sizing CMDS blueprint

5.5.3 Visualization of Candidate Vehicle CV10 Feasibility Solution Space

5.5.3.1 Solution Space Description

The objective of parametric sizing is to identify and visualize the feasibility solution space of vehicles that satisfy a particular mission. A solution space is a dashboard visualization of vehicle metrics in order to aid in decision-making. It is constructed by plotting resulting metrics of fixed-mission sized vehicles with prescribed vehicle parameter

variation. Figure 5-14 shows a sample solution space. it is constructed from vehicle gross weight + booster weight in the y-axis and the vehicle planform area in the x-axis. Each point on the space represents a vehicle converged to satisfy the objective function defined in the analysis process. This continuum map shows the effect of increasing cruise time, t , vehicle slenderness parameter, τ , and payload weight, W_{pay} .

Constraint lines can be added to the solution spaces to provide more interpretation with respect to constraints and limitations. Figure 5-15 shows a sample solution space constrained by maximum weights allowable by various carrier vehicles. The F-15 limit is the maximum weight for a vehicle carried underneath an F-15. The B-52 limit is for under the wing of a standard B-52 while the NB-52 A/B limit is for a modified B-52 with a structurally reinforced wing. The NB-52 A/B limit is grayed out as the vehicle is no longer in service. Figure 5-16 shows a sample solution space constrained by length and span limits for vehicles carried under B-52H wing. These solution spaces constraints discussed define the feasibility boundaries for the parametric sizing study.

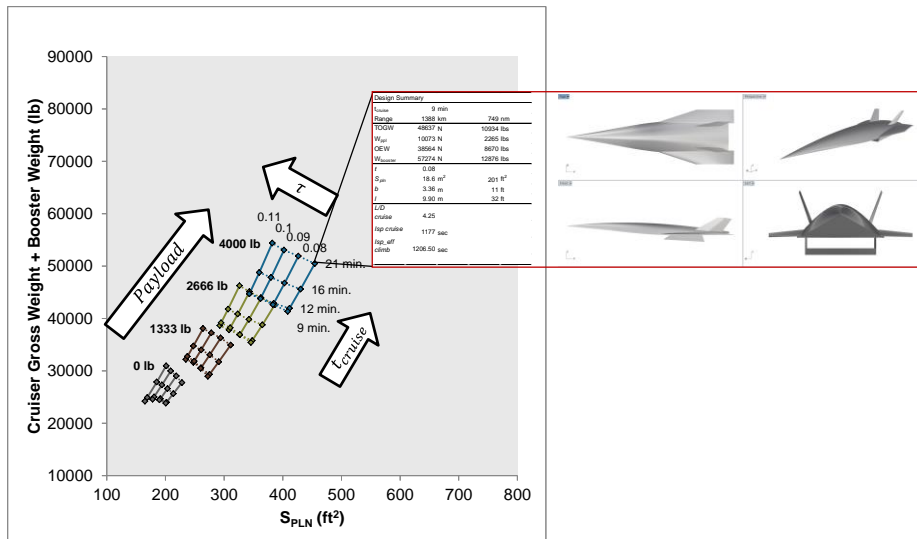


Figure 5-14 Sample fixed-mission solution space

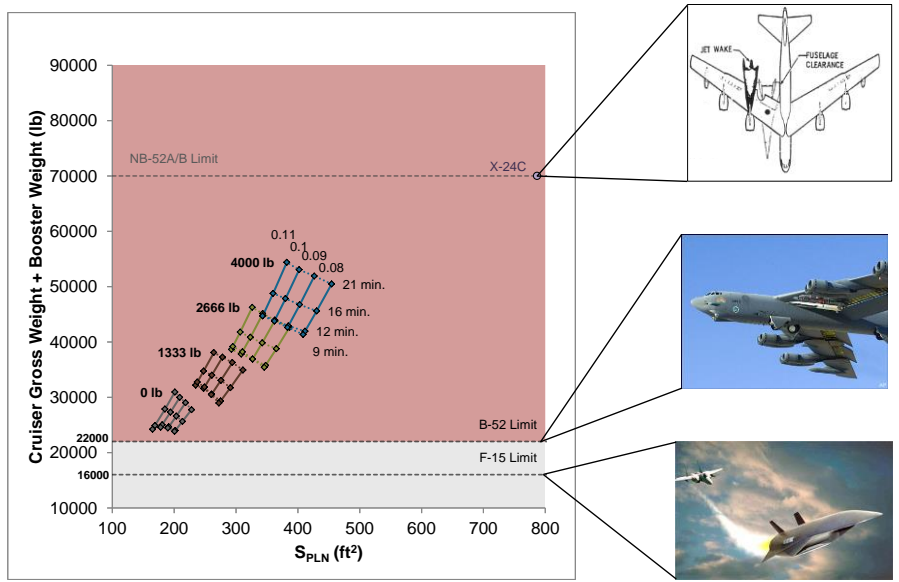


Figure 5-15 Sample fixed mission solution space with carrier weight constraints

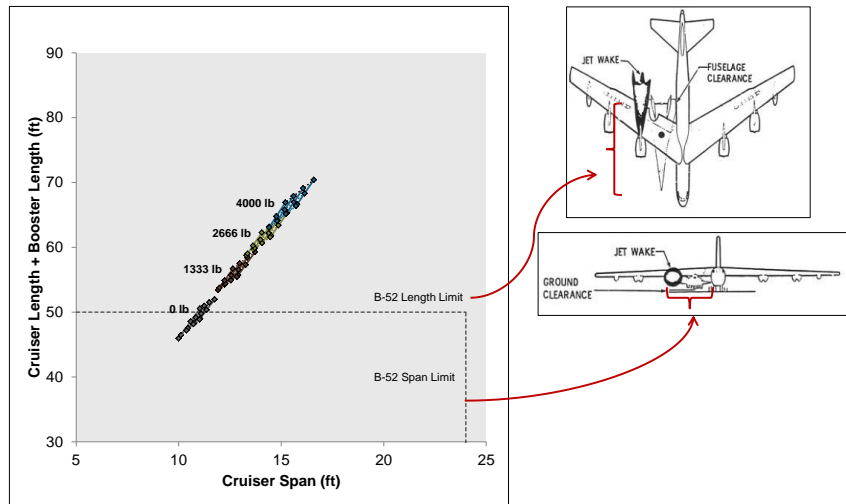


Figure 5-16 Sample fixed mission solution space with carrier packaging constraints

5.5.3.2 CV10 Sizing Solution Space Results

Figure 5-17 shows the design mission parameters used in sizing CV10. After airdrop, the vehicle climbs at a constant dynamic pressure of 1,500 lb/ft² until it reaches the cruise altitude for the design Mach number. The vehicle then cruises at design Mach

number for a specified endurance time, between 0 and 500 s. Afterwards, the vehicle performs a 2 g turn towards base and cruises for the previously specified cruise endurance. Finally, the vehicle glides at a constant altitude to decelerate to the equilibrium glide velocity and equilibrium glides to landing altitude. The overshoot of base ensures that the vehicle has sufficient fuel margin to return. Two design speeds, M6 and M7, have been considered for this sizing study. Feasibility solution spaces are generated by varying cruise time, t , vehicle slenderness parameter, τ , and payload weight, W_{pay} for each design.

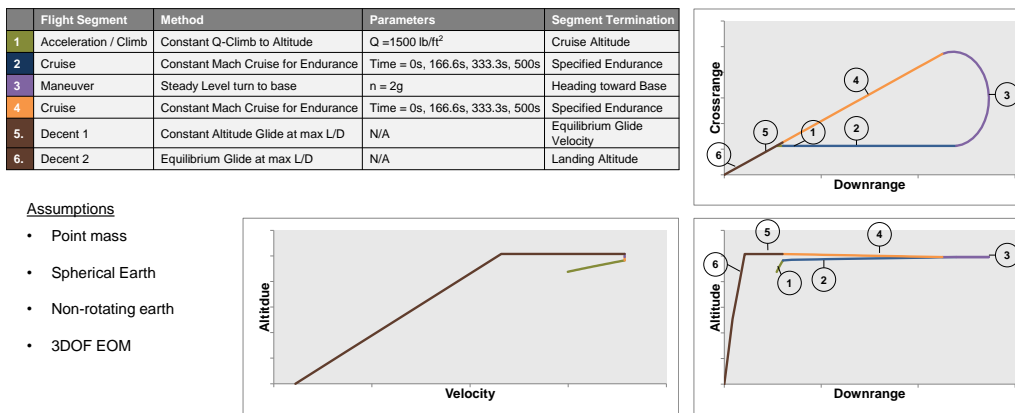


Figure 5-17 Design mission for CV10 solution space

Figure 5-18 and Figure 5-19 show the carriage weight feasibility space for a family of M6 and M7 CV10 vehicles. These results show that all the booster mounted vehicles are too heavy to be carried by existing carriage vehicles. Feasibility only exists if the B52H is recommissioned or a new carriage vehicle is developed. Figure 5-20 and Figure 5-21 show the landing feasibility of the vehicle families. The results show that all M6 vehicles can land on a runway, while all but the stout, $\tau = 0.11$, M7 vehicles can safely land. Finally, Figure 5-22 and Figure 5-23 show the carriage size feasibility solution spaces. These results indicate that only some of the booster mounted M6 CV10 vehicles are small enough to fit under the carrier vehicle wing (geometry limitation). It is shown that no M7 Vehicles can fit the carrier vehicle.

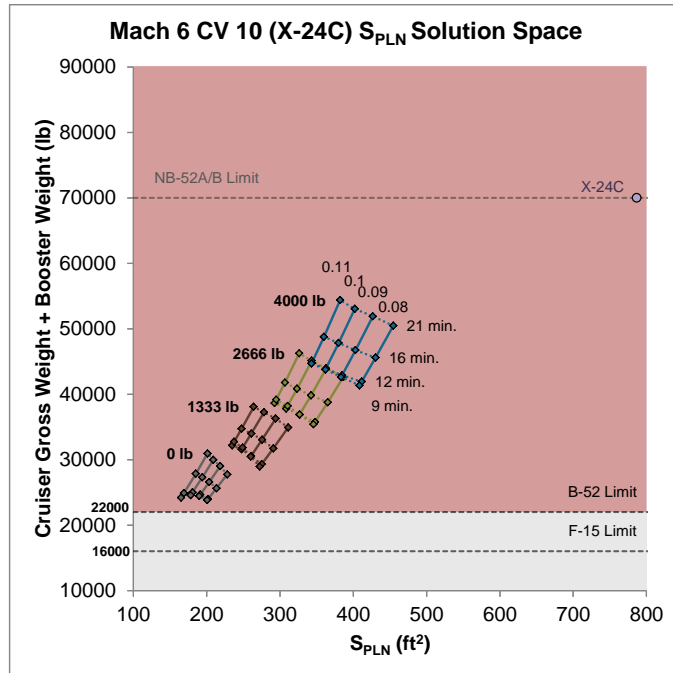


Figure 5-18 M6 CV10 carriage weight solution space

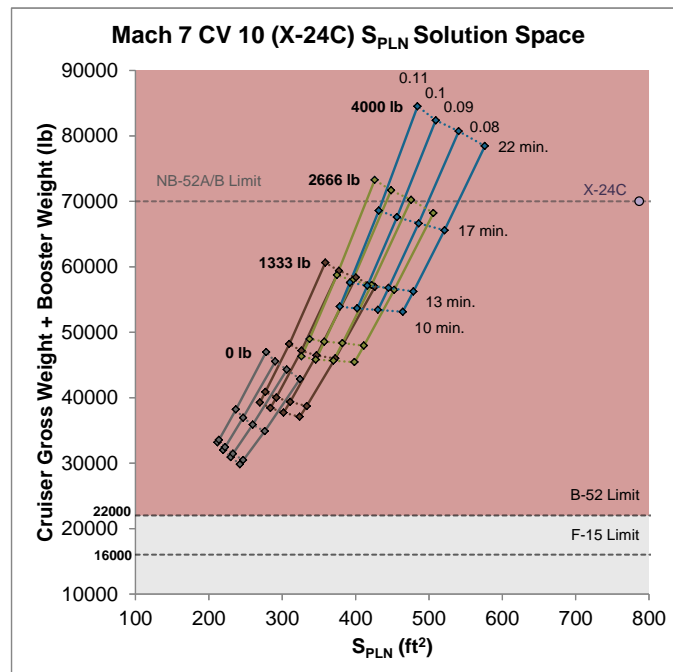


Figure 5-19 M7 CV10 carriage weight solution space

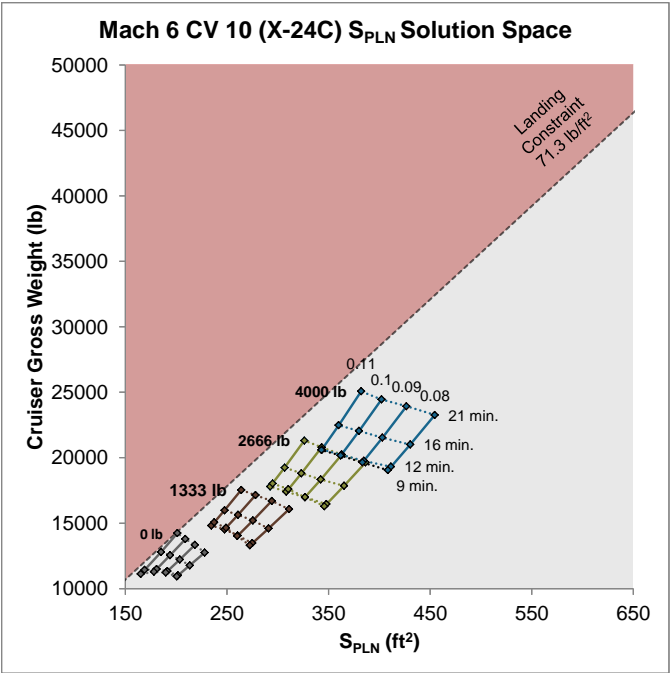


Figure 5-20 M6 CV10 gross weight landing solution space

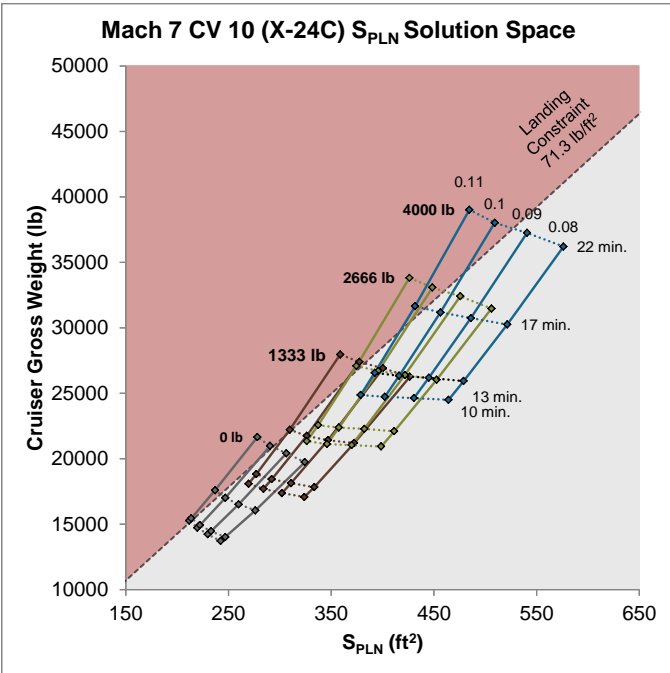


Figure 5-21 M7 CV10 gross weight landing solution space

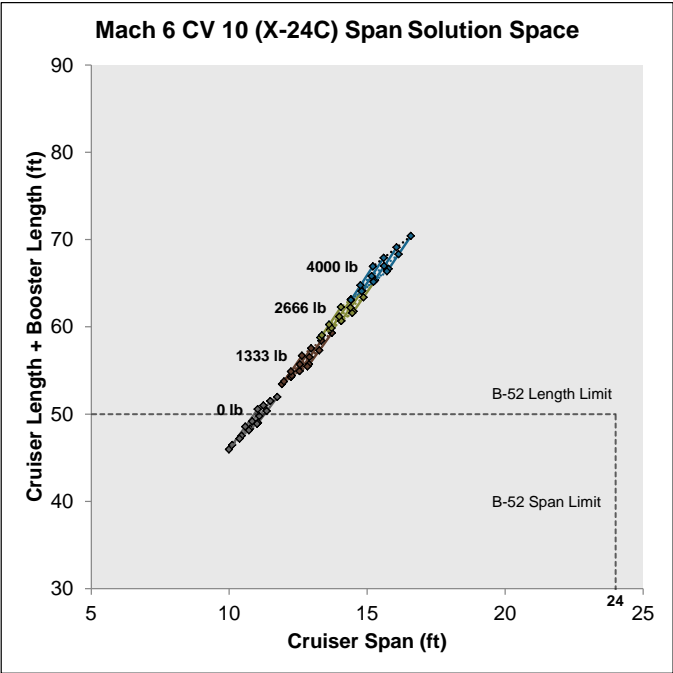


Figure 5-22 M6 CV10 carriage size solution space

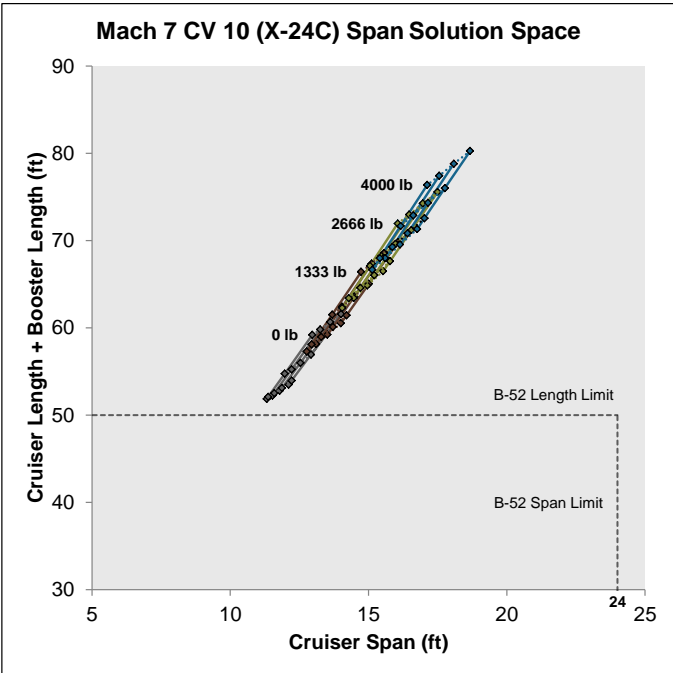


Figure 5-23 M7 CV10 carriage size solution space

5.6 Case Study Conclusion

The case study presented is an excerpt from a comprehensive research effort by the ASE (Chudoba et al. 2015). Over the course of that study, ASE introduces a unique product development capability to support decision makers at the acquisition and technology maturation levels. Three types of solution spaces have been presented including variations of two mission concepts, thirty-two operational scenarios and two design speeds, two hardware (two lift sources, two thrust sources, two landing systems, and two stability and control arrangements) package combinations. This has led to design and technology relationships being established between 256 sized vehicles. Still, this composes only a fraction of the mission, operation, and hardware combinations that should be studied prior to an acquisition decision being made.

5.7 Chapter Summary

This chapter discussed a case study to demonstrate the application of the CMDS decomposition methodology to a USAF relevant acquisition and conceptual design problem. The design case study selected was based on the Generic Hypersonic Vehicle (GHV) project initiated by AFRL to foster hypersonic vehicle design collaboration. The acquisition problem posed was to determine the best aerospace technology investment to solve the GHV mission. The conceptual design problem was to determine the technical feasibility of the chosen technology investment. The CMDS decomposition tools amongst other tools in AVD^{DBMS} were used to arrive at a prioritized portfolio of candidate vehicle based on relevant hypersonic demonstrator technologies. Candidate vehicle CV10, which is based on X-24C lift source and X-51A thrust source technologies, was selected for investment because of its technology maturity and landing gear system.

The technical feasibility of the CV10 vehicle was evaluated through a parametric sizing study. The CMDS decomposition tools amongst other tools in AVD^{DBMS} were used

to compose a custom CV10 sizing CMDS. The CMDS generated solution spaces for families of CV10 based vehicles for Mach 6 and Mach 7 design speeds. The solution spaces were explored to check the feasibility of the vehicles to land on a runway and to be carried by existing carrier vehicle. Results indicated that none of the vehicles is small enough to be carried by existing carrier vehicles. It also shows that M6 CV10 vehicles without payload are feasible if the, now decommission, B52H is the carrier vehicle.

This case study demonstrated the benefit of the CMDS decomposition methodology to acquisition and conceptual design. First, The CMDS building blocks enabled the systematic and transparent composition of technology and candidate vehicle portfolios. The building blocks established by the decomposition allowed the use a combination of existing technology assessment techniques. Secondly, the decomposition of existing synthesis systems into the AVD^{DBMS} advanced the capability of the problem-customize-sizing-tool generator. In summary, the CMDS building blocks are instrumental in mapping the conceptual design problem to customize the sizing CMDS for the problem at hand.

Chapter 6

RESEARCH CONCLUSION, CONTRIBUTION AND OUTLOOK

6.1 Conclusion

This research endeavor has been initiated in an effort to contribute to the fields of aerospace technology acquisition and aerospace conceptual design. It is motivated by the need to mitigate acquisition schedule and cost overruns caused by program management, politics, supply chain, technical complexity and talent shortage problems. The mitigation approach chosen has been to increase collaboration and transparency between technology acquisition assessments and vehicle conceptual design synthesis. A dichotomy exists between the two fields because state-of-the-art technology assessments utilize system engineering methodologies that require conceptual designer to impute during the stakeholder requirements definition phase. However, existing conceptual design synthesis systems only accept requirements and do not offer methodologies to define them. Secondly, Acquisition studies require assessment of diverse technology options in order to arrive at design requirements. However, most synthesis systems have a narrow range of applicability with reference to flight vehicle configuration, and other perturbations that should be considered thus be analyzed. This results in the acquisition of technologies that are well vetted for investment risks but insufficiently evaluated for technical feasibility.

The solution identified to solve the research problem is the development of a common framework for technology acquisition assessment and conceptual design synthesis. Due to the enormity of the problem, this framework has been developed in conjunction with two other PhD researchers. The original contribution to this effort as documented in the present report has been in the definition of the framework building blocks. A literature survey has identified the concept of 'complex multidisciplinary systems' as the starting point to enable a general building block approach towards problem solving.

After this identification, a methodology has been developed for decomposing this block into constituent parts for both acquisition and conceptual design problems. The product decomposition blocks, analysis process decomposition block and disciplinary method blocks are the main parts of the CMDS decomposition scheme presented in this research. The biggest benefit of the formulation presented is that it enables both, aerospace technology acquisition portfolio management and conceptual design parametric sizing tool customization.

AVD^{DBMS} is the software implementation of the unified acquisition and design platforms. It is a database management software programmed in the MS Access and MATLAB environment using VBA, SQL and MATLAB script languages. CMDS decomposition is executed using the decomposition forms available in AVD^{DBMS}. The forms include product input, process input and disciplinary method input forms. Note that the CMDS have a broad range of embodiments ranging from reference texts to parametric sizing tools. As more CMDS are decomposed, the understanding of existing problems and capability to address new challenges increase.

Finally, a case study has demonstrated the application of the CMDS decomposition methodology to a relevant acquisition and conceptual design problem. Two major benefits have been highlighted. First, the CMDS building blocks enabled the systematic and transparent composition of technology and candidate vehicle portfolios. The building blocks established by the decomposition allowed the use a combination of existing technology assessment techniques. Secondly, the decomposition of existing synthesis systems into the AVD^{DBMS} advanced the ability to customize sizing tool generation capabilities. The CMDS building blocks are instrumental in mapping the conceptual design problem towards the customization of a problem-specific sizing tools.

6.2 Contributions and Benefits of CMDS Decomposition

The original contributions of this research are as follows:

- Identification of complex multidisciplinary systems as common building block for acquisition and conceptual design problems.
- Development of a decomposition scheme reducing CMDS into constituent parts.
- Design of the decomposition input forms recording CMDS in the AVD^{DBMS} framework.
- Demonstration of the applicability of CMDS decomposition to a relevant acquisition and conceptual design problem with USAF endorsement.

6.3 Future Work

The AVD^{DBMS} framework is suitable for real world problems as is. However, there are some areas can be improved for greater system capability. First, the decomposition of CMDS is, so far, a manual process. It requires advanced understanding and effort to decompose new CMDS or poorly described ones. The addition of an Artificial Intelligence (AI) system to speed up the decomposition process will help mitigate this issue. Secondly, only two levels of abstraction have been implemented in the decomposition concept in order to reduce complexity. That is, only a single subsystem decomposition level exists in addition to the system level. Therefore, if the product is an aircraft, it can only be decomposed into the hardware level (e.g. scramjet, wing body, landing gear, etc.). Although subsequent sublevels are captured as attributes, this conception is insufficient for more complex problems. For example, consider the decomposition of multistage space launcher. In this conception, the product is the complete vehicle and the subsystems are the individual vehicle stages. The specification of an actual vehicle as a subsystem instead

of the vehicle hardware will not work with the methods in the database as they exist. Further research is required to determine the best way to handle staged vehicles in the decomposition methodology that has been developed.

Appendix A

METHODS LIBRARY SOURCE CODE

A.1 Aerodynamics

A.1.1 AERO_MD0005

```
%%%%%%%%%%%% Pre-Allocate Outputs %%%%%%%%%%%%%
```

```
ALDMAX=zeros(size(AMACH));
```

```
ALIND=zeros(size(AMACH));
```

```
CD0=zeros(size(AMACH));
```

```
CLA=zeros(size(AMACH));
```

```
CL=zeros(size(AMACH));
```

```
CD=zeros(size(AMACH));
```

```
%%%%%%%%%%%% Analysis %%%%%%%%%%%%%
```

```
SWET = AKW*SPLN;
```

```
ALIND(AMACH <= 0.8)=0.45; %from fig4-19
```

```
ALDMAX(AMACH <= 0.8)= sqrt(pi.*(ECDF/4).*(BPLN./SWET)); %eq on fig 4-13, ECDF
```

from the plot = 280

```
CD0(AMACH <= 0.8)=1./(4.*ALIND(AMACH <= 0.8).*ALDMAX(AMACH <= 0.8).^2);
```

```
CLA(AMACH <= 0.8)=0.024; %from fig 4-19
```

```
CL = CLA.*AOA;
```

```
CD = CD0 + ALIND.*CL.^2;
```

```
ALD = CL./CD;
```

A.1.2 AERO_MD0006

```
%%%%%%%%%%%% Pre-Allocate Outputs %%%%%%%%%%%%%
```

```
ALDMAX = repmat(NaN,size(AMACH));
```

```
ALIND = repmat(NaN,size(AMACH));
```

```
CD0 = repmat(NaN,size(AMACH));
```

```
CLA = repmat(NaN,size(AMACH));
```

```
CL = repmat(NaN,size(AMACH));
```

```
CD = repmat(NaN,size(AMACH));
```

```
%%%%%%%%% Regression Data %%%%%%%%%%
```

```
AMACH_MAP=[1.5, 2.0, 6.0, 12.0];
```

```
TAU_MAP=[0.01118,0.041569219,0.051822958,0.064,0.076367532,0.088772738,0.10248638  
4,0.117575508, ...
```

```
0.132574507,0.147369057,0.164316767,0.181019336,0.198252364,0.216,0.234247732, ...  
0.252982213,0.272191109,0.29086856];
```

```
ALDMAX_MAP=[8.83,6.85,6.39,5.99,5.64,5.29,4.98,4.68,4.38,4.11,3.85,3.59,3.  
34,3.10,2.86,2.61,2.37,2.15;
```

```
8.83,6.85,6.39,5.99,5.64,5.29,4.98,4.68,4.38,4.11,3.85,3.59,3.34,3.10,2.86,2.61,2.37,2.15;
```

```
8.50,6.32,5.90,5.53,5.19,4.87,4.59,4.31,4.07,3.80,3.56,3.35,3.12,2.89,2.68,2.46,2.26,2.06;
```

```
5.67,4.68,4.39,4.14,3.90,3.68,3.49,3.30,3.11,2.93,2.78,2.63,2.48,2.33,2.19,2.05,1.91,1.79];
```

```
% %%%%%%%%%% Subsonic Analysis %%%%%%%%%%
```

```
SWET = AKW*SPLN;
```

```
ALDMAXS = sqrt(pi.*(ECDF/4).*(BPLN./SWET));
```

```
ALINDS = 0.45;
```

```

CD0S = 1./(4.*ALINDS.*ALDMAXS.^2);

%%%%%%%%%%%% Transonic Analysis %%%%%%%%%%%%%%

SF=SPLN*SFSPN;

if (SF/(AL^2) < 0.015)
    DCDT_MAX=(1.3862*(SF/AL^2)+0.067)*SFSPN*CDTW_COR;
else
    DCDT_MAX=(0.9536*(SF/AL^2)^3-
1.916*(SF/AL^2)^2+1.3651*(SF/AL^2)+0.1119)*SFSPN*CDTW_COR;
end

%%%%%%%%%%%% Left side of M1.2 Analysis %%%%%%%%%%%%%% Same for WB
and AB

CD0(AMACH >= 0.80 & AMACH < 1.2) = CD0S + DCDT_MAX./0.4.*(AMACH(AMACH
>= 0.80 & AMACH < 1.2)-0.8); % linear Drag rise Y = Y0 + m(x-x0)

ALDMAX(AMACH >= 0.80 & AMACH < 1.2)=0.5.*sqrt(1./(ALINDS.*CD0(AMACH >=
0.80 & AMACH < 1.2))); % (L/D)_max = sqrt(cd0/K') Approximation

%%%%%%%%%%%% Right side of M1.2 Analysis %%%%%%%%%%%%%% Same for AB and WB

CD_2M=1/(4*interp2(TAU_MAP,AMACH_MAP,ALDMAX_MAP,TAU,2.0,'spline').^2*ALINDS);

CD_12M=CD0S+DCDT_MAX;

```

```

CD0(AMACH >= 1.2 & AMACH <= 2.0)=(CD_2M-CD_12M)/0.8.*(AMACH(AMACH >=
1.2 & AMACH <= 2.0)-1.2)+CD_12M; % linear Drag function Y = Y0 + m(x-x0) from M1.2 to M2
ALDMAX(AMACH >= 1.2 & AMACH <= 2.0)=0.5.*sqrt(1./(CD0(AMACH >= 1.2 &
AMACH <= 2.0)*ALINDS));

```

```

%%%%%%%%%%%% Analysis %%%%%%%%%%%%%%

```

```

% CLA(AMACH >= 0.80 & AMACH < 1.5)=(0.022-0.02)/(1.5-0.8).*(AMACH(AMACH
>= 0.80 & AMACH < 1.5)-0.8)+0.020; %Gary (WB)

```

```

CLA(AMACH >= 0.80 & AMACH < 1.2)= 0.0052.*AMACH(AMACH >= 0.80 & AMACH
< 1.2) + 0.0202; %Linear relation from excel file

```

```

%%%%%%%%%%%% Analysis %%%%%%%%%%%%%%

```

```

%CLA(AMACH >= 1.5 & AMACH <= 2.0)=0.03./AMACH(AMACH >= 1.5 &
AMACH <= 2.0).^0.75+0.00025; %Gary (WB)

```

```

CLA(AMACH >= 1.2 & AMACH <= 2.0)=0.0098.*AMACH(AMACH >= 1.2 &
AMACH <= 2.0) + 0.0379; %Linear relation from excel file

```

```

%ALIND(AMACH >= 0.8 & AMACH <= 2.0) = 0.47; %Approx Value

```

```

ALIND(AMACH >= 0.8 & AMACH <= 2.0)= 0.0651.*(AMACH(AMACH >= 0.8 &
AMACH <= 2.0).^2) - 0.0758.*AMACH(AMACH >= 0.8 & AMACH <= 2.0) + 0.4083; %Polynomial
expression from excel file

```

```

CL = CLA.*AOA;

```

```

CD = CD0 + ALIND.*CL.^2;

```

```

ALD = CL./CD;

```

A.1.3 AERO_MD0007

```

%%%%%%%%%%%% Pre-Allocate Outputs %%%%%%%%%%%%%%

```



```
ALDMAX = repmat(NaN,size(AMACH));
```

```
ALIND = repmat(NaN,size(AMACH));
```

```
CD0 = repmat(NaN,size(AMACH));
```

```
CLA = repmat(NaN,size(AMACH));
```

```
%%%%%%%% Regression Data %%%%%%%%%
```

```
AMACH_MAP=[1.5, 2.0, 6.0, 12.0];
```

```
TAU_MAP=[0.01118,0.041569219,0.051822958,0.064,0.076367532,0.088772738,0.10248638  
4,0.117575508, ...
```

```
0.132574507,0.147369057,0.164316767,0.181019336,0.198252364,0.216,0.234247732, ...  
0.252982213,0.272191109,0.29086856];
```

```
ALDMAX_MAP=[8.83,6.85,6.39,5.99,5.64,5.29,4.98,4.68,4.38,4.11,3.85,3.59,3.  
34,3.10,2.86,2.61,2.37,2.15;
```

```
8.83,6.85,6.39,5.99,5.64,5.29,4.98,4.68,4.38,4.11,3.85,3.59,3.34,3.10,2.86,2.61,2.37,2.15;
```

```
8.50,6.32,5.90,5.53,5.19,4.87,4.59,4.31,4.07,3.80,3.56,3.35,3.12,2.89,2.68,2.46,2.26,2.06;
```

```
5.67,4.68,4.39,4.14,3.90,3.68,3.49,3.30,3.11,2.93,2.78,2.63,2.48,2.33,2.19,2.05,1.91,1.79];
```

```
%%%%%%%% Subsonic Analysis %%%%%%%%%
```

```
SWET = AKW*SPLN;
```

```
ALDMAXS = sqrt(pi.*(ECDF/4).*(BPLN./SWET));
```

```

ALINDS = 0.45;
CD0S = 1./(4.*ALINDS.*ALDMAXS.^2);

%%%%%%%%%%%%% Transonic Analysis %%%%%%%%%%%%%%

SF=SPLN*SF SPLN;
%DBCD0=interp1(C_SA,DBCD0_MAP,CS_SPAT,'spline');

%ALIND(AMACH >= 2.0)=(2.5-ALINDS)./(12.0-2.0).*(AMACH(AMACH >= 2.0)-
2.0)+ALINDS;
ALIND(AMACH >= 2.0 & AMACH <= 4.0)= 0.081.*(AMACH(AMACH >= 2.0 &
AMACH <= 4.0).^2) - 0.1515.*AMACH(AMACH >= 2.0 & AMACH <= 4.0) + 0.5199; % ?? % add
+ALINDS;
ALIND(AMACH >= 4.0)= 0.1685.*AMACH(AMACH >= 4.0) + 0.5255;

ALDMAX(AMACH >=
2.0)=interp2(TAU_MAP,AMACH_MAP,ALDMAX_MAP,TAU,AMACH(AMACH >= 2.0),'spline');
%same for WB and AB

CD0(AMACH >= 2.0 & AMACH <= 4.0)=1./(4.*ALDMAX(AMACH >= 2.0 &
AMACH <= 4.0).^2.*ALIND(AMACH >= 2.0 & AMACH <= 4.0)); % ?? %Does ALDMAX also go
from 2 to 4 even if it doesnt change from 2 to 12
CD0(AMACH >= 4.0)=1./(4.*ALDMAX(AMACH >= 4.0).^2.*ALIND(AMACH >=
4.0)); % For AB add : + DBCD0./sqrt(AMACH(AMACH >= 2.0).^2-1);

CLA(AMACH >= 2.0)=0.0001.*(AMACH(AMACH >= 2.0).^2) -
0.0029.*AMACH(AMACH >= 2.0) + 0.0243; %from excel file

```

```

CL = CLA.*AOA;

CD = CD0 + ALIND.*CL.^2;

ALD = CL/CD;

```

A.2 Propulsion

A.2.1 PROP_MD0008

```

%% Pre-Allocate HBE_LN
HBE_LN = repmat(NaN,size(THRL_VAR));

%% Pre-Allocate Outputs
AISP = repmat(NaN,size(THRL_VAR));
FT_AVAIL = repmat(NaN,size(THRL_VAR));
OF = repmat(NaN,size(THRL_VAR));
DUCT_PRESSURE = repmat(NaN,size(THRL_VAR));
F_MDOT = repmat(NaN,size(THRL_VAR));

%% Set Up Input Interpolation Arrays
PHI_FUEL = THRL_VAR.*PHI_FUEL_REF;

% Call SCRAM_PERF_LUT
[AISP(AMACH >= 4 & AMACH <= 8.0), F_MDOT(AMACH >= 4 & AMACH <= 8.0), DUCT_PRESSURE(AMACH >= 4 &
AMACH <= 8.0)] = SCRAM_PERF_LUT(ALT(AMACH >= 4 & AMACH <= 8.0), HBE_LN(AMACH >= 4 & AMACH <= 8.0),
PHI_FUEL(AMACH >= 4 & AMACH <= 8.0), V(AMACH >= 4 & AMACH <= 8.0));

% Spillage/Additive Effect of Capture Area Ratio f(AMACH)
[A0_A1_SPILLAGE] = A0_A1_Billig(DMACH, AMACH);

% Contraction Area Ratio as a Function of AOA
A1_A2_GEO = CR_GEO./cosd(AOA);

% Boundary Layer Displacement Thickness Effect of Capture Area Ratio
A2_A3_BLDISPLACEMENT = A_A0_BLDISPLACEMENT;

% Effective Capture Area
CR_EFF = A0_A1_SPILLAGE.*A1_A2_GEO.*A2_A3_BLDISPLACEMENT;

% Available Thrust
FT_AVAIL = F_MDOT.*RHO.*V.*(CR_EFF).*ACAP;

%% SubFunction
function [AISP, F_MDOT, DUCT_PRESSURE] = SCRAM_PERF_LUT(ALT, HBE_LN, PHI_FUEL, V)
    %% Load Look Up Table Array Data
    if exist('PROP_MD0008') == 0
        load C:\AVDS\AVD_ABE\Utilities\Method_Data\PROP_MD0008.mat;
    end

    %% Look-Up Table Interpolation Arrays
    PROP_ALT_MAP = PROP_MD0008.DISCPROC.PROP.OUTPUT.PROP_ALT_MAP;
    PROP_HBE_LN_MAP = PROP_MD0008.DISCPROC.PROP.OUTPUT.PROP_HBE_LN_MAP;
    PROP_PHI_FUEL_MAP = PROP_MD0008.DISCPROC.PROP.OUTPUT.PROP_PHI_FUEL_MAP;
    PROP_V_MAP = PROP_MD0008.DISCPROC.PROP.OUTPUT.PROP_V_MAP;

    % NDGRID
    [PROP_ALT_MAP, PROP_HBE_LN_MAP, PROP_PHI_FUEL_MAP, PROP_V_MAP] = ndgrid(PROP_ALT_MAP,...

```

```

PROP_HBE_LN_MAP,...

PROP_PHI_FUEL_MAP,...

PROP_V_MAP);

%% Interpolate For AISP, Specific Thrust, DUCT_PRESSURE
AISP = interpn(PROP_ALT_MAP, PROP_HBE_LN_MAP, PROP_PHI_FUEL_MAP, PROP_V_MAP, ...
PROP_MD0008.HW.Scramjet_01.PROP.OUTPUT.AISP, ...
ALT, HBE_LN, PHI_FUEL, V,'spline');

F_MDOT = interpn(PROP_ALT_MAP, PROP_HBE_LN_MAP, PROP_PHI_FUEL_MAP, PROP_V_MAP, ...
PROP_MD0008.HW.Scramjet_01.PROP.OUTPUT.F_MDOT, ...
ALT, HBE_LN, PHI_FUEL, V,'spline');

DUCT_PRESSURE = interpn(PROP_ALT_MAP, PROP_HBE_LN_MAP, PROP_PHI_FUEL_MAP, PROP_V_MAP, ...
PROP_MD0008.HW.Scramjet_01.PROP.OUTPUT.DUCT_PRESSURE, ...
ALT, HBE_LN, PHI_FUEL,
V,'spline');
end

function [A0_A1] = A0_A1_Billig(DMACH, AMACH)
DATA_S = ...
    [5.1270356      0.3717109
     5.809769      0.39194015
     6.67132       0.42053854
     7.5028367     0.44673762
     8.423623      0.4765186
    10.294952      0.53727454
    12.01722       0.59085536
    13.442756      0.63611245
    14.512325      0.67186326
    16.353342      0.7290146
    18.106201      0.7874053
    19.561771      0.8350617
    21.135534      0.883878
    22.175346      0.91843486
    23.155369      0.94939846
    24.135668      0.9815674
    25.04978       0.9824202];

AMACH_S = DATA_S(:,1);

A0_A1_S = DATA_S(:,2);

A0_A1_REF = interp1(AMACH_S,A0_A1_S,DMACH,'pchip');
A0_A1_RAW = interp1(AMACH_S,A0_A1_S,AMACH,'pchip');

A0_A1 = A0_A1_RAW./A0_A1_REF;
end

```

A.3 Performance Matching

A.3.1 *PM_MD0003*

A.3.2 *PM_MD0008*

A.3.3 *PM_MD0009*

A.3.4 PM_MD0010

```

% % PREALLOCATE VECTORS
AISP_EFF_V      = zeros(TRAJ_NSTEP,1);
AISP_V          = zeros(TRAJ_NSTEP,1);
AISP_V_HW       = zeros(TRAJ_NSTEP,length(VEHICLE_HW));
ALD_V           = zeros(TRAJ_NSTEP,1);
AMACH_V         = zeros(TRAJ_NSTEP,1);
AN_V            = zeros(TRAJ_NSTEP,1);
AOA_V           = zeros(TRAJ_NSTEP,1);
CD_V            = zeros(TRAJ_NSTEP,1);
CD_V_HW         = zeros(TRAJ_NSTEP,length(VEHICLE_HW));
CL_V            = zeros(TRAJ_NSTEP,1);
CL_V_HW         = zeros(TRAJ_NSTEP,length(VEHICLE_HW));
D_V             = zeros(TRAJ_NSTEP,1);
DGAM_V          = zeros(TRAJ_NSTEP,1);
DPSI_V          = zeros(TRAJ_NSTEP,1);
DR_V            = zeros(TRAJ_NSTEP,1);
DT_V            = zeros(TRAJ_NSTEP,1);
DUCT_PRESSURE_V = zeros(TRAJ_NSTEP,1);
DW_V            = zeros(TRAJ_NSTEP,1);
DWF_V           = zeros(TRAJ_NSTEP,1);
DWO_V           = zeros(TRAJ_NSTEP,1);
DX_V            = zeros(TRAJ_NSTEP,1);
DY_V            = zeros(TRAJ_NSTEP,1);
EDOT_V          = zeros(TRAJ_NSTEP,1);
EI_V            = zeros(TRAJ_NSTEP,1);
FT_AVAIL_MAX_V  = zeros(TRAJ_NSTEP,1);
FT_V            = zeros(TRAJ_NSTEP,1);
%FT_V_HW        = zeros(TRAJ_NSTEP,length(VEHICLE_HW));
G_V             = zeros(TRAJ_NSTEP,1);
GAMDOT_V        = zeros(TRAJ_NSTEP,1);
L_V             = zeros(TRAJ_NSTEP,1);
OF_V            = zeros(TRAJ_NSTEP,1);
OF_V_HW         = zeros(TRAJ_NSTEP,length(VEHICLE_HW));
PSIDOT_V        = zeros(TRAJ_NSTEP,1);
QBAR_V          = zeros(TRAJ_NSTEP,1);
SELECTED_V_FUNCMODE = cell(TRAJ_NSTEP,length(VEHICLE_FUNCTION));
SIGMA_V         = zeros(TRAJ_NSTEP,1);
W_V             = zeros(TRAJ_NSTEP,1);

% INITIAL POINTS FROM TRAJECTORY
I = max(I_V);

% CALCULATE CHANGE IN AMACH PER STEP
V_START = V_V(I);
ALT_START = ALT_V(I);
X_START = X_V(I);
Y_START = Y_V(I);
PSI_START = PSI_V(I)*DTR;

% ASSIGN CONTROL VARIABLES TO traj
AN_LIM = TRAJ_AN_MAX;

G = G0/(1 + ALT_START./RE).^2;
RTURN = V_START^2/sqrt(AN_LIM^2*G0^2-(G-V_START^2/(RE+ALT_START))^2);
SIGMA = acos(1/(AN_LIM*G0)*(G-V_START^2/(RE+ALT_START)));
L0 = sqrt(X_START^2+Y_START^2);
THT0 = atan2(Y_START,X_START);
if THT0 < 0
    THT0 = 2*pi+THT0;
end
THT3 = THT0+pi-(pi/2+PSI_START);
L1 = sqrt(L0^2+RTURN^2-2*L0*RTURN*cos(THT3));
THT1 = asin(RTURN/L1*sin(THT3));

```

```

THT2 = asin(RTURN/L1);
PSI_FINAL = THT0+THT1+THT2+pi;

% CALCULTE CHANGE IN ALT PER STEP
DPSI = (PSI_FINAL - PSI_START)/(TRAJ_NSTEP+1);
PSI_V(I) = PSI_V(I)+DPSI/DTR;
% ITERATE FOR EACH ENERGY LEVEL
for CT = 1:TRAJ_NSTEP %ending at E(N+1) in order to store derivatives for E(N)
    %INPUTS FROM TRAJECTORY
    I = max(I_V);
    WR = WR_V(I);
    GAM = GAM_V(I)*DTR;
    PSI = PSI_V(I)*DTR;
    V = V_V(I);%sqrt((V_V(I+1).^2 + V_V(I).^2)/2);
    ALT = ALT_V(I);%(ALT_V(I+1) + ALT_V(I))/2;

    %ANALYSIS
    FLTCOND = fltcon(ALT,0,V,0);
    QBAR=FLTCOND.QBAR; AMACH=FLTCOND.AMACH;

    W = WS*SPLN/WR;
    G = G0./(1 + ALT./RE).^2;

    GAMDOT = 0;
    L = W./(G0*cos(SIGMA)) .* (G - V.^2./(RE + ALT));
    CL_REQ = L./(QBAR*SPLN);

    AOA_OUT = fzero(@(AOA_IN) AOAFUNC(AOA_IN,ALT,V),0,optimset('Display','off','Diagnostic','off'));
    AOA = AOA_OUT;
    D = QBAR.*CD*SPLN;
    ALD = L/D;

    AN = 0;
    THRL_VAR = 1;
    FT_AVAIL_MAX = FT_AVAIL;
    FT = W*(AN + D/W + G/G0*sin(GAM)); % Thrust requirement for max acceleration

    if (FT_AVAIL_MAX < FT & INSUFF_THRUST_CHECK == 'Y')
        disp(' I ALT V GAM W FT_AVAIL_MAX FT D
G./G0.*sin(GAM)')
        disp([I ALT V GAM/DTR W FT_AVAIL_MAX FT D G./G0.*sin(GAM)])
        error('INSUFFICIENT THRUST')
    end

    THRL_VAR_OUT = fsolve(@(THRL_VAR_IN) THRL_VARFUNC(THRL_VAR_IN, AOA,ALT,V,
FT),1,optimset('Display','off','Diagnostic','off','TolFun',1e-4));
    THRL_VAR = THRL_VAR_OUT; % Change in THRL_VAR triggers code to call FT function

    FT = FT_AVAIL;
    AISP = AISP;
    OF = OF;
    DUCT_PRESSURE = DUCT_PRESSURE;
    THRL_VAR_HW = zeros(size(FT_AVAIL_HW));
    THRL_VAR_HW(FT_AVAIL_HW~=0) = THRL_VAR;

    AISP_EFF = (FT - D - W*sin(GAM))/(FT/AISP);

    ALT_NEXT = ALT;
    V_NEXT = V;
    E0 = ALT_V(I)*RE/(RE+ ALT_V(I)) + V_V(I)^2/(2*G0);
    EI = ALT_NEXT*RE/(RE+ALT_NEXT) + V_NEXT^2/(2*G0);

%% %%%%%%%%%%%
% CALCULATE DELTAS TO GET TO CURRENT POINT
EDOT = V*AN;%sqrt((V^2+V_V(I+1)^2)/2)*AN;

```

```

PSIDOT = AN_LIM*G0/V*sin(SIGMA);
XDOT = V*cos(GAM)*cos(PSI)*RE/(RE+ALT);
YDOT = V*cos(GAM)*sin(PSI)*RE/(RE+ALT);
DT = DPSI/PSIDOT;
DW = - (FT/AISP)*DT;
DWF = - DW/(1+OF);
DWO = OF*DWF;
WRNEXT = 1/(1/WR + DW/(WS*SPLN));
DX = XDOT*DT;
DY = YDOT*DT;
DR = sqrt(DX^2+DY^2);
DGAM = GAMDOT*DT;

% ASSIGN VALUES AT CURRENT POINT
I_V(I+1,1) = I+1;
ALT_V(I+1,1) = ALT;
FF_V(I+1,1) = FF_V(I) + DWF/(WS*SPLN);
GAM_V(I+1,1) = (GAM+DGAM)/DTR;
PSI_V(I+1,1) = (PSI+DPSI)/DTR;
TIME_V(I+1,1) = TIME_V(I)+DT;
RANGE_V(I+1,1) = RANGE_V(I)+DR;
V_V(I+1,1) = V;
WR_V(I+1,1) = WRNEXT;
X_V(I+1,1) = X_V(I) + DX;
Y_V(I+1,1) = Y_V(I) + DY;
FT_V_HW(I+1,:) = FT_AVAIL_HW;
DUCT_PRESSURE_V_HW(I+1,:) = DUCT_PRESSURE_HW;
THRL_VAR_REQ_V_HW(I+1,:) = THRL_VAR_HW;
TRAJSEG_V(I+1,1) = METHOD_TRAJSEG;

RANGE = RANGE_V(I+1,1);
X_RANGE = X_V(I+1,1);
ENDURANCE = TIME_V(I+1,1);
WR = WR_V(I+1,1);
FF = FF_V(I+1,1);
FT_MAX_HW = max(FT_V_HW,[],1);
DUCT_PRESSURE_MAX_HW = max(DUCT_PRESSURE_V_HW,[],1);
THRL_VAR_MAX = max(max(THRL_VAR_REQ_V_HW,[],1));

AISP_EFF_V(CT,1) = AISP_EFF;
AISP_V(CT,1) = AISP;
AISP_V_HW(CT,:) = AISP_HW;
ALD_V(CT,1) = ALD;
AMACH_V(CT,1) = AMACH;
AN_V(CT,1) = AN;
AOA_V(CT,1) = AOA;
CD_V(CT,1) = CD;
CD_V_HW(CT,:) = CD_HW;
CL_V(CT,1) = CL;
CL_V_HW(CT,:) = CL_HW;
D_V(CT,1) = D;
DGAM_V(CT,1) = DGAM/DTR;
DPSI_V(CT,1) = DPSI/DTR;
DR_V(CT,1) = DR;
DT_V(CT,1) = DT;
DUCT_PRESSURE_V(CT,1) = DUCT_PRESSURE;
%DUCT_PRESSURE_V_HW(CT,1) = DUCT_PRESSURE_HW;
DW_V(CT,1) = DW;
DWF_V(CT,1) = DWF;
DWO_V(CT,1) = DWO;
DX_V(CT,1) = DX;
DY_V(CT,1) = DY;
EDOT_V(CT,1) = EDOT;
EI_V(CT,1) = E0;
FT_AVAIL_MAX_V(CT,1) = FT_AVAIL_MAX;

```

```

FT_V(CT,1) = FT;
%FT_V_HW(CT,:) = FT_AVAIL_HW;
G_V(CT,1) = G;
GAMDOT_V(CT,1) = GAMDOT;
L_V(CT,1) = L;
OF_V(CT,1) = OF;
OF_V_HW(CT,:) = OF_HW;
QBAR_V(CT,1) = QBAR;
SELECTED_V_FUNCMODE(CT,:) = SELECTED_FUNCMODE;
SIGMA_V(CT,1) = SIGMA/DTR;
W_V(CT,1) = W;
end

PSI_V(I+1,1) = (pi+atan2(Y_V(I+1),X_V(I+1)))/DTR; % Eliminate roundoff errors

%% SubFunction
function Err = AOAFUNC(AOA_IN,ALT,V)
    AOA = AOA_IN; % Change in AOA triggers code to call CL function
    ALT = ALT;
    V = V;
    Err = CL-CL_REQ;
end

%% SubFunction
function Err = THRL_VARFUNC(THRL_VAR_IN, AOA,ALT,V, FT)
    AOA = AOA;
    ALT = ALT;
    V = V;
    THRL_VAR = THRL_VAR_IN; % Change in THRL_VAR triggers code to call CL function

    Err = abs(FT-FT_AVAIL);
endend

```

A.4 Weight & Balance

A.4.1 WB_MD0003

```

%% Analysis
if WR < 1
    WR
    error('WR < 1 vehicle gained weight over trajectory')
end

%FT_MAX_HW = max(FT_V_HW);
WOX_WF = (1-1/WR)/FF - 1;
RHO_PPL=(WOX_WF+1)/(WOX_WF/RHO_OX + 1/RHO_FUEL);

WENG_ALENG = ((1990-1210)/(100-10)*(DUCT_PRESSURE_MAX_HW/6894.75729-10) + (1210-1120)/(70-60))*(BENG/0.0254- 70)+1210)*0.45359237*G0/(3.4);
WENG = sum(WENG_ALENG*ALENG_MOD);

AKSTR=(0.317+EBAND)*TAU^0.206;
WSTR_OEW = AKSTR*SPLN^0.138;

% WEIGHT BUDGET CONSTANTS
% WCPRV=FCPRV*CREW;
% WOPER=85.0*ANCREW+FWPPRV*ANPAX; %FROM HOWE
% WOPER=FPRV*(CREW*DAYS)^1.18;
WOPER=0;

WPAX = FWPAX*ANPAX;
WCREW = FWCREW*ANCREW;
WFIX = WUN+FWMND*ANCREW;

```



```

WPAY = WPAX+WCARGO;
WLG = 0.00916*(WS*SPLN*WR/4.44822162)^1.124*4.44822162;

% WEIGHT BUDGET OEW = (1+AMUA)*(WSTR - WLG + WCHUTE + WENG + WSYS); WSYS = WFIX +
FWSYS*OEW;
OEW_W = (WFIX+WENG+WLG) / (1/(1+AMUA)-WSTR_OEW-FWSYS);
OEW_W = OEW_W+WPAY+WCREW;

if ((1/(1+AMUA)-WSTR_OEW-FWSYS) < 0.0)
    fprintf('AKSTR = %f\n',AKSTR);
    fprintf('WR = %f\n',WR);
    fprintf('1/(1+AMUA) = %f\n',1/(1+AMUA));
    fprintf('1/(1+AMUA)-WSTR_OEW-FWSYS = %f\n',(1/(1+AMUA)-WSTR_OEW-FWSYS));
    fprintf('FWSYS = %f\n',FWSYS);
    fprintf('1/(1+AMUA)-WSTR_OEW-FWSYS = %f\n',1/(1+AMUA)-WSTR_OEW-FWSYS);
    % WR
    % 1/(1+AMUA)
    % TW0WR_ETW
    % TW0WR_ETW_HW
    % FT_MAX_HW
    % AKSTR*SPLN^0.138
    % FWSYS
    % (1/(1+AMUA)-AKSTR*SPLN^0.138-FWSYS-(TW0WR_ETW))
    error('CONVERGENCE FAILURE:');
    % 1/(1+AMUA),AKSTR*SPLN^0.138
    % (TW0WR_ETW)
end

% VOLUME BUDGET OWE
% VTOTAL = TAU*SPLN^1.5;

VFIX = VUN+AKVMND*ANCREW;
VSY = VFIX+AKVS*VTOTAL;
VPAY = ANPAX*AKVPAX+(WCARGO/RHO_CARGO/G0);
VCREW = (AKVCPV+AKVCREW)*ANCREW;
VVOID = VTOTAL*AKVV;

% from VPPL = OWE_V*(WR-1)/(RHO_PPL*G0) = VTOTAL - VVOID - VSY - VENG - VPAY - VCREW
OWE_V = (VTOTAL-VSY- VP -VPAY-VCREW-VVOID)/((WR-1)/(RHO_PPL*G0));
AIP = RHO_PPL/(WR-1);

% WEIGHT AND VOLUME BREAKFORWN
OWE = OEW_W;
OEW = OEW_W;

WSTR = AKSTR*SPLN^0.138*OEW_W;
AISTR = WSTR/(SPLN*AKW);

TOGW = OWE*WR;
WPPL = TOGW*(1-1/WR);
WFUEL = TOGW*FF;
WOX = WOX_WF*WFUEL;
WP = WENG;
WSYS = WFIX + FWSYS*OEW;
AMZFW = OWE+WPAY;
AMWE = OWE-WOPER-WCREW;
WMARGIN = OEW-(WOPER+WSYS+WSTR+WP);

% VP = TW0WR_KVE*OWE;
VENG = VP;
VPPL = WPPL/RHO_PPL/9.81;
VFUEL = WFUEL/RHO_FUEL/9.81;
VOX = WOX/RHO_FUEL/9.81;

```

;

Appendix B

CV10 CMDS


```

% THRL_VAR_RES      m      Flight Altitude Resolution
% *****
Variable.SYSPROC.INPUT.ALT_RANGE = [0.1,26000];
Variable.SYSPROC.INPUT.ALT_RES = 2000;
Variable.SYSPROC.INPUT.V_RANGE = [0.1,2300];
Variable.SYSPROC.INPUT.V_RES = 300;
Variable.SYSPROC.INPUT.AOA_RANGE = [-2,12];
Variable.SYSPROC.INPUT.AOA_RES = 2;
Variable.SYSPROC.INPUT.THRL_VAR_RANGE = [0.01,9];
Variable.SYSPROC.INPUT.THRL_VAR_RES = 0.1;

% *****
% Geometry Disciplinary & Method Variables
% *****

% Method: GEO_MD0002 Hardware: TotalVehicle % *****
% ALBURNER      m      Length of Burner (X-Dir)
% ALC_AL        Ratio of length of compression surface to length of vehicle
% ALISO_HTHROAT Isolator Length to Height Ratio
% ALT_CRUISE_DESIGN m      Cruise Altitude at Design Point
% DMACH         Design Mach number
% F_A_STOIC     Stoichiometric Fuel to Air Ratio
% HF            KJ/kg     Absolute sensible enthalpy of fuel entering combustor
% HPR_FUEL      KJ/kg     Heat of reaction for the fuel
% HTHROAT       m      Height of Engine Throat
% NTECH         NTECH SCRAMJET TECHNOLOGY LEVEL: (1 = OPTIMISTIC HYDROGEN; 2 = MODERATE
HYDROGEN; 3 = KEROSENE)
% PHI_FUEL_REF  Reference Fuel Equivalence Ratio
% T_FUEL_INJECT K      Fuel Injection Temperature
% TAU           KÜchemann's tau
% THETA1_N     degrees  First nozzle angle
% THETA2_N     degrees  Second nozzle angle
% TPB_REF      K      Reference temperature to estimate the absolute static enthalpy
% VF_V3        Ratio of fuel injection total velocity to V3 (combustion inlet)
% VFX_V3       Ratio of fuel injection axial velocity to V3 (combustion inlet)
% *****
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.ALBURNER = 1.53;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.ALC_AL = 0.6;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.ALISO_HTHROAT = 20;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.ALT_CRUISE_DESIGN = 26270;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.DMACH = 7;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.F_A_STOIC = 0.06763;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.HF = 0;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.HPR_FUEL = 50291680;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.HTHROAT = 0.05;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.NTECH = 2;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.PHI_FUEL_REF = 1;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.T_FUEL_INJECT = 750;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.TAU = 0.09;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.THETA1_N = 22;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.THETA2_N = 9;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.TPB_REF = 222;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.VF_V3 = 0.5;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.VFX_V3 = 0.5;

% *****
% Aerodynamics Disciplinary & Method Variables
% *****

% Method: AERO_MD0005 Hardware: BlendedBody_01 % *****
% ECDF           Ratio of square of oswald efficiency factor to skin friction drag coefficient (e^2/CDF). (HYFAC Vol
2pt2 fig 413 use 160, 200, 240, 280 for wing Body). 280 is recommended for very efficient vehicle
% *****
Variable.HW.BlendedBody_01.AERO.BlendedBody_01_AERO_MD0005.INPUT.ECDF = 280;

```

```

%Method: AERO_MD0006 Hardware: BlendedBody_01 %*****
%CDTW_COR Transonic drag rise correction factor
%ECDF Ratio of square of oswald efeciency factor to skin friction drag coefficient (e^2/CDF). (HYFAC Vol
2pt2 fig 413 use 160, 200, 240, 280 for wing Body). 280 is recommed for very efficient vehicle
%*****
Variable.HW.BlendedBody_01.AERO.BlendedBody_01_AERO_MD0006.INPUT.CDTW_COR = 1.0;
Variable.HW.BlendedBody_01.AERO.BlendedBody_01_AERO_MD0006.INPUT.ECDF = 280;

%Method: AERO_MD0007 Hardware: BlendedBody_01 %*****
%ECDF Ratio of square of oswald efeciency factor to skin friction drag coefficient (e^2/CDF). (HYFAC Vol
2pt2 fig 413 use 160, 200, 240, 280 for wing Body). 280 is recommed for very efficient vehicle
%*****
Variable.HW.BlendedBody_01.AERO.BlendedBody_01_AERO_MD0007.INPUT.ECDF = 280;

% *****
% Propulsion Disciplinary & Method Variables
% *****

%Method: PROP_MD0008 Hardware: Scramjet_01 %*****
%A_A0_BLDISPLACEMENT Area Ratio of Viscous Captured Flow to Inviscid Captured Flow
%DMACH Design Mach number
%PHI_FUEL_REF Reference Fuel Equivalence Ratio
%*****
Variable.HW.Scramjet_01.PROP.Scramjet_01_PROP_MD0008.INPUT.A_A0_BLDISPLACEMENT = 0.95;
Variable.HW.Scramjet_01.PROP.Scramjet_01_PROP_MD0008.INPUT.DMACH = 7;
Variable.HW.Scramjet_01.PROP.Scramjet_01_PROP_MD0008.INPUT.PHI_FUEL_REF = 1;

% *****
% Performance Matching Disciplinary & Method Variables
% *****

%Performance Matching Disciplinary Process Input Variables%*****
%TRAJ_ALT_V_START m Start Point For Vector of altitudes
%TRAJ_FF_V_START Start Point For Vector of Fuel fractions
%TRAJ_GAM_V_START degrees Start Point For Vector of flight path angles
%TRAJ_PSI_V_START degrees Start Point For Vector of heading angles
%TRAJ_RANGE_V_START m Start Point For Vector of total range
%TRAJ_TIME_V_START s Start Point For Vector of trajetory time
%TRAJ_TRAJSEG_V_START Start Point For Vector of current flight segment string
%TRAJ_V_V_START m/s Start Point For Vector of vel
%TRAJ_WR_V_START Start Point For Vector of ratios of final mass at each point in the trajectory to init
%TRAJ_X_V_START m Start Point For Vector of position in x-directio
%TRAJ_Y_V_START m Start Point For Vector of position in y-directio
%*****
Variable.MISSION.INPUT.TRAJ_ALT_V_START = 21891;
Variable.MISSION.INPUT.TRAJ_FF_V_START = 0.0;
Variable.MISSION.INPUT.TRAJ_GAM_V_START = 0.0;
Variable.MISSION.INPUT.TRAJ_PSI_V_START = 0;
Variable.MISSION.INPUT.TRAJ_RANGE_V_START = 0.0;
Variable.MISSION.INPUT.TRAJ_TIME_V_START = 0.0;
Variable.MISSION.INPUT.TRAJ_TRAJSEG_V_START = {' '};
Variable.MISSION.INPUT.TRAJ_V_V_START = 1481.5;
Variable.MISSION.INPUT.TRAJ_WR_V_START = 1;
Variable.MISSION.INPUT.TRAJ_X_V_START = 0;
Variable.MISSION.INPUT.TRAJ_Y_V_START = 0;

%Method: PM_MD0009 Trajectory Segment: Booster Launch_01 %*****
%TRAJ_NSTEP Number of steps in current trajectory segment
%TRAJ_WR Ratio of final mass to initial mass for trajectory segment
%*****
Variable.TRAJSEG.BoosterLaunch_01_PM_MD0009.INPUT.TRAJ_NSTEP = 1;
Variable.TRAJSEG.BoosterLaunch_01_PM_MD0009.INPUT.TRAJ_WR = 1;

%Method: PM_MD0003 Trajectory Segment: Constant Q Climb_01 %*****

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%INSUFF_THRUST_CHECK          Check for insufficient thrust in PM
%TRAJ_ALT_END                 Altitude desired at the end of the trajectory segment
%TRAJ_AN_MAX                  g's    Maximum acceleration allowed for current trajectory segment
%TRAJ_AN_MIN                  g's    Minimum acceleration allowed for current trajectory segment
%TRAJ_NSTEP                   Number of steps in current trajectory segment
%*****
Variable.TRAJSEG.ConstantQClimb_01_PM_MD0003.INPUT.INSUFF_THRUST_CHECK = 'N';
Variable.TRAJSEG.ConstantQClimb_01_PM_MD0003.INPUT.TRAJ_ALT_END = 26270;
Variable.TRAJSEG.ConstantQClimb_01_PM_MD0003.INPUT.TRAJ_AN_MAX = 2.0;
Variable.TRAJSEG.ConstantQClimb_01_PM_MD0003.INPUT.TRAJ_AN_MIN = 0.3;
Variable.TRAJSEG.ConstantQClimb_01_PM_MD0003.INPUT.TRAJ_NSTEP = 20;

%Method: PM_MD0008 Trajectory Segment: Constant Mach Endurance Cruise_01 %
%ENDURANCE_CRUISE           s      Flight time during cruise
%INSUFF_THRUST_CHECK        Check for insufficient thrust in PM
%TRAJ_NSTEP                  Number of steps in current trajectory segment
%*****
Variable.TRAJSEG.ConstantMachEnduranceCruise_01_PM_MD0008.INPUT.ENDURANCE_CRUISE = 500;
Variable.TRAJSEG.ConstantMachEnduranceCruise_01_PM_MD0008.INPUT.INSUFF_THRUST_CHECK = 'N';
Variable.TRAJSEG.ConstantMachEnduranceCruise_01_PM_MD0008.INPUT.TRAJ_NSTEP = 20;

%Method: PM_MD0010 Trajectory Segment: Steady Level Turn_01 %*****
%INSUFF_THRUST_CHECK        Check for insufficient thrust in PM
%TRAJ_AN_MAX                 g's    Maximum acceleration allowed for current trajectory segment
%TRAJ_NSTEP                   Number of steps in current trajectory segment
%*****
Variable.TRAJSEG.SteadyLevelTurn_01_PM_MD0010.INPUT.INSUFF_THRUST_CHECK = 'N';
Variable.TRAJSEG.SteadyLevelTurn_01_PM_MD0010.INPUT.TRAJ_AN_MAX = 2;
Variable.TRAJSEG.SteadyLevelTurn_01_PM_MD0010.INPUT.TRAJ_NSTEP = 20;

%Method: PM_MD0008 Trajectory Segment: Constant Mach Endurance Cruise_02 %
%ENDURANCE_CRUISE           s      Flight time during cruise
%INSUFF_THRUST_CHECK        Check for insufficient thrust in PM
%TRAJ_NSTEP                   Number of steps in current trajectory segment
%*****
Variable.TRAJSEG.ConstantMachEnduranceCruise_02_PM_MD0008.INPUT.ENDURANCE_CRUISE = 500;
Variable.TRAJSEG.ConstantMachEnduranceCruise_02_PM_MD0008.INPUT.INSUFF_THRUST_CHECK = 'N';
Variable.TRAJSEG.ConstantMachEnduranceCruise_02_PM_MD0008.INPUT.TRAJ_NSTEP = 20;

%Method: PM_MD0001 Trajectory Segment: Gliding Descent_01 %*****
%TRAJ_ALT_END                 Altitude desired at the end of the trajectory segment
%TRAJ_NSTEP                   Number of steps in current trajectory segment
%*****
Variable.TRAJSEG.GlidingDescent_01_PM_MD0001.INPUT.TRAJ_ALT_END = 0;
Variable.TRAJSEG.GlidingDescent_01_PM_MD0001.INPUT.TRAJ_NSTEP = 5;

%*****
% Weight and Balance Disciplinary & Method Variables
%*****

%Method: WB_MD0003 Hardware: TotalVehicle %*****
%AKVCPRV                      m^3/person  Volume of provision for each crew member (Formerly VPCRW)
%AKVCREW                       m^3/person  Volume per crew member (formerly AKCRW)
%AKVMND                         m^3/person  Volume of manned fixed systems per crew member (FCREW in hypersonic convergence)
%AKVPAX                         m^3/person  Volume of each passenger space (formerly V_PAX)
%AKVS                          m^3/m^3    Volume of variable systems per total vehicle volume
%AKVV                          m^3/m^3    Volume of vehicle void space per total vehicle volume
%AMUA                           Minimum OWE weight margin
%ANCREW                          Number of crew
%ANPAX                          Number of passengers
%EBAND                          m^-0.138  Error band around the structural fraction EBAND (+/- 0.049)
%FWCREW                          N/person  Weight of each crew member (formerly WCREW)
%FWMND                          N/person  Weight fixed manned systems per crew member (formerly FMND)
%FWPAX                          N/person  Weight of each passenger (formerly WPAX)
%FWPPRV                         N/person  Weight of passenger provisions per passenger (formerly FPRV)

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%FWSYS      kg/kg      Weight of variable systems per vehicle dry weight (FSYS in hypersonic convergence)
%RHO_CARGO  kg/m^3     Density of the cargo
%RHO_FUEL   kg/m^3     Density of fuel (formerly FUEL_DEN)
%RHO_OX     kg/m^3     Density of oxidizer (formerly OX_DEN)
%VUN        m^3       Volume of unmanned fixed system
%WCARGO     N         Weight of cargo
%WUN        N         Weight of unmanned fixed systems (CUN in Hypersonic Convergence)
%*****
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.AKVCPRV = 1.5;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.AKVCREW = 1.5;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.AKVMND = 0.0;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.AKVPAX = 1.7;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.AKVS = 0.03;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.AKVV = 0.15;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.AMUA = 0.10;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.ANCREW = 0.0;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.ANPAX = 0.0;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.EBAND = 0.0;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.FWCREW = 129.0*9.81;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.FWMND = 0.0*9.81;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.FWPAX = 100*9.81;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.FWPPRV = 0.0*9.81;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.FWSYS = 0.16;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.RHO_CARGO = 240;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.RHO_FUEL = 567.65;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.RHO_OX = 1287.0;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.VUN = 2.5;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.WCARGO = 17792;
Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.WUN = 300*9.81;

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end

B.2 Results

TAU	CRUISE_T ME	WCAR GO	SPLN	WS	TOGW	F1	F2	TIME1	TIME2	TIME3	ISTR	IP	THRL_VAR_ MAX	OWE_ W
8.00E-02	5.55E+02	0	1.86E+01	2.61E+03	4.86E+04	1.80E-09	1.86E-07	0	5.55E+02	0	2.14E+02	2.17E+03	1.00E+00	3.86E+04
9.00E-02	5.51E+02	0	1.76E+01	2.83E+03	4.99E+04	3.82E-10	9.86E-08	0	5.51E+02	0	2.25E+02	1.97E+03	1.00E+00	3.87E+04
1.00E-01	5.47E+02	0	1.65E+01	3.04E+03	5.02E+04	4.01E-09	4.70E-07	0	5.47E+02	0	2.37E+02	1.88E+03	1.00E+00	3.86E+04
1.10E-01	5.44E+02	0	1.53E+01	3.22E+03	4.94E+04	0.00E+00	2.91E-11	0	5.44E+02	0	2.48E+02	1.92E+03	1.00E+00	3.81E+04
8.00E-02	7.05E+02	0	1.87E+01	2.61E+03	4.90E+04	8.64E-12	6.26E-10	1.58E+02	3.89E+02	1.58E+02	2.13E+02	2.13E+03	1.00E+00	3.87E+04
9.00E-02	7.05E+02	0	1.78E+01	2.84E+03	5.04E+04	-1.63E-09	-8.18E-08	1.58E+02	3.88E+02	1.58E+02	2.25E+02	1.92E+03	1.00E+00	3.89E+04
1.00E-01	7.04E+02	0	1.68E+01	3.05E+03	5.11E+04	5.21E-09	1.17E-06	1.58E+02	3.87E+02	1.58E+02	2.36E+02	1.81E+03	1.00E+00	3.89E+04
1.10E-01	7.02E+02	0	1.57E+01	3.24E+03	5.09E+04	4.09E-12	6.55E-11	1.58E+02	3.86E+02	1.58E+02	2.47E+02	1.79E+03	1.00E+00	3.86E+04
8.00E-02	9.80E+02	0	1.98E+01	2.64E+03	5.24E+04	5.40E-10	4.15E-08	3.17E+02	3.47E+02	3.17E+02	2.10E+02	1.79E+03	1.00E+00	3.98E+04
9.00E-02	9.80E+02	0	1.89E+01	2.88E+03	5.44E+04	-1.37E-10	-1.22E-08	3.17E+02	3.47E+02	3.17E+02	2.22E+02	1.61E+03	1.00E+00	4.02E+04
1.00E-01	9.80E+02	0	1.80E+01	3.10E+03	5.58E+04	-4.84E-09	-3.83E-07	3.17E+02	3.46E+02	3.17E+02	2.33E+02	1.50E+03	1.00E+00	4.05E+04
1.10E-01	9.79E+02	0	1.72E+01	3.31E+03	5.69E+04	3.55E-11	5.68E-09	3.17E+02	3.46E+02	3.17E+02	2.42E+02	1.41E+03	1.00E+00	4.06E+04
8.00E-02	1.28E+03	0	2.12E+01	2.68E+03	5.67E+04	-2.49E-10	-1.45E-08	4.75E+02	3.30E+02	4.75E+02	2.06E+02	1.49E+03	1.00E+00	4.11E+04
9.00E-02	1.28E+03	0	2.03E+01	2.92E+03	5.93E+04	-3.04E-10	-1.69E-08	4.75E+02	3.30E+02	4.75E+02	2.18E+02	1.35E+03	1.00E+00	4.18E+04
1.00E-01	1.28E+03	0	1.94E+01	3.16E+03	6.13E+04	-1.18E-09	-6.77E-08	4.75E+02	3.30E+02	4.75E+02	2.29E+02	1.26E+03	1.00E+00	4.23E+04
1.10E-01	1.28E+03	0	1.87E+01	3.39E+03	6.33E+04	1.31E-09	7.54E-08	4.75E+02	3.30E+02	4.75E+02	2.39E+02	1.18E+03	1.00E+00	4.27E+04
8.00E-02	5.53E+02	5.93E+03	2.53E+01	2.34E+03	5.92E+04	-1.44E-10	-1.35E-08	0	5.53E+02	0	1.82E+02	2.37E+03	1.00E+00	4.77E+04

9.00E-02		5.93E+03	2.42E+01	2.58E+03	6.24E+04	-1.78E+10	-1.38E+08	0	5.51E+02	0	1.94E+02	2.01E+03	1.00E+00	4.86E+04
1.00E-01	5.51E+02	5.93E+03	2.31E+01	2.82E+03	6.51E+04	1.62E+10	1.08E+08	0	5.48E+02	0	2.06E+02	1.79E+03	1.00E+00	4.95E+04
1.10E-01	5.46E+02	5.93E+03	2.21E+01	3.04E+03	6.70E+04	2.32E+11	1.89E+09	0	5.46E+02	0	2.17E+02	1.68E+03	1.00E+00	5.00E+04
8.00E-02	7.05E+02	5.93E+03	2.55E+01	2.35E+03	6.00E+04	-1.11E+10	-1.02E+08	1.58E+02	3.88E+02	1.58E+02	1.82E+02	2.26E+03	1.00E+00	4.79E+04
9.00E-02	7.04E+02	5.93E+03	2.42E+01	2.58E+03	6.25E+04	6.87E+11	5.44E+09	1.58E+02	3.88E+02	1.58E+02	1.94E+02	2.00E+03	1.00E+00	4.87E+04
1.00E-01	7.04E+02	5.93E+03	2.30E+01	2.81E+03	6.46E+04	-5.05E+09	-3.08E+07	1.58E+02	3.87E+02	1.58E+02	2.06E+02	1.83E+03	1.00E+00	4.93E+04
1.10E-01	7.03E+02	5.93E+03	2.18E+01	3.02E+03	6.59E+04	-2.77E+11	-2.43E+09	1.58E+02	3.87E+02	1.58E+02	2.17E+02	1.75E+03	1.00E+00	4.97E+04
8.00E-02	9.80E+02	5.93E+03	2.70E+01	2.40E+03	6.49E+04	-3.11E+09	3.77E+07	3.17E+02	3.47E+02	3.17E+02	1.79E+02	1.76E+03	1.00E+00	4.91E+04
9.00E-02	9.80E+02	5.93E+03	2.56E+01	2.64E+03	6.76E+04	1.35E+09	8.97E+08	3.17E+02	3.46E+02	3.17E+02	1.91E+02	1.60E+03	1.00E+00	4.99E+04
1.00E-01	9.80E+02	5.93E+03	2.42E+01	2.87E+03	6.96E+04	-3.07E+07	-4.47E+07	3.17E+02	3.46E+02	3.17E+02	2.03E+02	1.51E+03	1.00E+00	5.05E+04
1.10E-01	9.79E+02	5.93E+03	2.30E+01	3.09E+03	7.11E+04	1.93E+10	1.09E+08	3.17E+02	3.46E+02	3.17E+02	2.15E+02	1.45E+03	1.00E+00	5.11E+04
8.00E-02	1.28E+03	5.93E+03	2.89E+01	2.47E+03	7.15E+04	1.43E+10	9.31E+09	4.75E+02	3.30E+02	4.75E+02	1.76E+02	1.39E+03	1.00E+00	5.07E+04
9.00E-02	1.28E+03	5.93E+03	2.73E+01	2.72E+03	7.43E+04	5.41E+11	3.15E+09	4.75E+02	3.30E+02	4.75E+02	1.88E+02	1.29E+03	1.00E+00	5.16E+04
1.00E-01	1.28E+03	5.93E+03	2.58E+01	2.95E+03	7.62E+04	5.32E+11	2.68E+09	4.75E+02	3.30E+02	4.75E+02	2.00E+02	1.23E+03	1.00E+00	5.22E+04
1.10E-01	1.28E+03	5.93E+03	2.45E+01	3.18E+03	7.80E+04	1.21E+10	5.09E+09	4.75E+02	3.30E+02	4.75E+02	2.12E+02	1.19E+03	1.00E+00	5.28E+04
8.00E-02	5.46E+02	1.19E+04	3.21E+01	2.26E+03	7.25E+04	1.05E+10	1.14E+08	0	5.46E+02	0	1.62E+02	2.07E+03	1.00E+00	5.69E+04
9.00E-02	5.44E+02	1.19E+04	3.04E+01	2.49E+03	7.55E+04	-2.02E+10	-1.83E+08	0	5.44E+02	0	1.74E+02	1.83E+03	1.00E+00	5.77E+04
1.00E-01	5.41E+02	1.19E+04	2.88E+01	2.71E+03	7.83E+04	-7.14E+11	-5.49E+09	0	5.41E+02	0	1.85E+02	1.67E+03	1.00E+00	5.84E+04
1.10E-01	5.39E+02	1.19E+04	2.74E+01	2.93E+03	8.02E+04	-1.33E+10	-9.59E+09	0	5.39E+02	0	1.95E+02	1.58E+03	1.00E+00	5.90E+04
8.00E-02	7.03E+02	1.19E+04	3.23E+01	2.27E+03	7.32E+04	-1.82E+12	-1.16E+10	1.58E+02	3.87E+02	1.58E+02	1.62E+02	2.00E+03	1.00E+00	5.70E+04
9.00E-02	7.03E+02	1.19E+04	3.04E+01	2.49E+03	7.55E+04	-2.83E+10	-2.57E+08	1.58E+02	3.86E+02	1.58E+02	1.74E+02	1.83E+03	1.00E+00	5.77E+04
1.00E-01	7.02E+02	1.19E+04	2.87E+01	2.70E+03	7.74E+04	1.01E+10	8.12E+09	1.58E+02	3.86E+02	1.58E+02	1.85E+02	1.72E+03	1.00E+00	5.82E+04
1.10E-01	7.02E+02	1.19E+04	2.72E+01	2.91E+03	7.92E+04	7.32E+11	4.70E+09	1.58E+02	3.85E+02	1.58E+02	1.95E+02	1.64E+03	1.00E+00	5.88E+04

8.00E-02	9.79E+02	1.19E+04	3.39E+01	2.34E+03	7.94E+04	-3.23E-10	-2.96E-08	3.17E+02	3.46E+02	3.17E+02	1.61E+02	1.60E+03	1.00E+00	5.86E+04
9.00E-02	9.79E+02	1.19E+04	3.18E+01	2.56E+03	8.16E+04	-2.45E-10	-1.53E-08	3.17E+02	3.46E+02	3.17E+02	1.73E+02	1.50E+03	1.00E+00	5.92E+04
1.00E-01	9.79E+02	1.19E+04	3.00E+01	2.79E+03	8.37E+04	-1.44E-06	-1.09E-06	3.17E+02	3.46E+02	3.17E+02	1.84E+02	1.42E+03	1.00E+00	5.98E+04
1.10E-01	9.79E+02	1.19E+04	2.85E+01	3.00E+03	8.56E+04	5.55E-11	3.40E-09	3.17E+02	3.45E+02	3.17E+02	1.94E+02	1.36E+03	1.00E+00	6.04E+04
8.00E-02	1.28E+03	1.19E+04	3.59E+01	2.43E+03	8.73E+04	-1.13E-07	-1.36E-07	4.75E+02	3.30E+02	4.75E+02	1.61E+02	1.29E+03	1.00E+00	6.07E+04
9.00E-02	1.28E+03	1.19E+04	3.37E+01	2.67E+03	9.00E+04	-9.63E-10	-6.00E-08	4.75E+02	3.30E+02	4.75E+02	1.73E+02	1.22E+03	1.00E+00	6.14E+04
1.00E-01	1.28E+03	1.19E+04	3.19E+01	2.90E+03	9.25E+04	2.33E-10	1.42E-08	4.75E+02	3.29E+02	4.75E+02	1.84E+02	1.16E+03	1.00E+00	6.21E+04
1.10E-01	1.28E+03	1.19E+04	3.03E+01	3.13E+03	9.48E+04	2.18E-11	1.34E-09	4.75E+02	3.29E+02	4.75E+02	1.94E+02	1.11E+03	1.00E+00	6.28E+04
8.00E-02	5.40E+02	1.78E+04	3.79E+01	2.23E+03	8.47E+04	-1.26E-10	-1.66E-08	0	5.40E+02	0	1.51E+02	1.98E+03	1.00E+00	6.59E+04
9.00E-02	5.37E+02	1.78E+04	3.56E+01	2.45E+03	8.73E+04	-7.61E-10	-7.82E-08	0	5.37E+02	0	1.62E+02	1.81E+03	1.00E+00	6.65E+04
1.00E-01	5.35E+02	1.78E+04	3.36E+01	2.67E+03	8.97E+04	0.00E+00	1.12E-09	0	5.35E+02	0	1.72E+02	1.68E+03	1.00E+00	6.71E+04
1.10E-01	5.32E+02	1.78E+04	3.19E+01	2.87E+03	9.16E+04	-1.82E-12	-5.82E-11	0	5.32E+02	0	1.82E+02	1.60E+03	1.00E+00	6.76E+04
8.00E-02	7.02E+02	1.78E+04	3.82E+01	2.25E+03	8.59E+04	-1.12E-10	-1.44E-08	1.58E+02	3.85E+02	1.58E+02	1.51E+02	1.90E+03	1.00E+00	6.62E+04
9.00E-02	7.01E+02	1.78E+04	3.57E+01	2.46E+03	8.79E+04	-9.64E-11	-1.04E-08	1.58E+02	3.84E+02	1.58E+02	1.62E+02	1.77E+03	1.00E+00	6.66E+04
1.00E-01	7.01E+02	1.78E+04	3.37E+01	2.67E+03	9.00E+04	-7.41E-11	-7.17E-09	1.58E+02	3.84E+02	1.58E+02	1.72E+02	1.67E+03	1.00E+00	6.71E+04
1.10E-01	7.00E+02	1.78E+04	3.19E+01	2.88E+03	9.18E+04	-7.55E-11	-7.12E-09	1.58E+02	3.83E+02	1.58E+02	1.82E+02	1.59E+03	1.00E+00	6.76E+04
8.00E-02	9.79E+02	1.78E+04	4.00E+01	2.34E+03	9.34E+04	-1.26E-09	-1.43E-07	3.17E+02	3.45E+02	3.17E+02	1.52E+02	1.53E+03	1.00E+00	6.82E+04
9.00E-02	9.78E+02	1.78E+04	3.74E+01	2.56E+03	9.58E+04	-3.09E-10	-2.90E-08	3.17E+02	3.45E+02	3.17E+02	1.63E+02	1.44E+03	1.00E+00	6.87E+04
1.00E-01	9.78E+02	1.78E+04	3.53E+01	2.78E+03	9.80E+04	8.14E-11	5.97E-09	3.17E+02	3.45E+02	3.17E+02	1.73E+02	1.36E+03	1.00E+00	6.92E+04
1.10E-01	9.78E+02	1.78E+04	3.34E+01	2.99E+03	1.00E+05	-5.55E-11	-3.03E-09	3.17E+02	3.45E+02	3.17E+02	1.83E+02	1.31E+03	1.00E+00	6.98E+04
8.00E-02	1.28E+03	1.78E+04	4.22E+01	2.45E+03	1.03E+05	2.40E-10	2.32E-08	4.75E+02	3.29E+02	4.75E+02	1.53E+02	1.24E+03	1.00E+00	7.09E+04
9.00E-02	1.28E+03	1.78E+04	3.96E+01	2.69E+03	1.06E+05	7.59E-11	6.43E-09	4.75E+02	3.29E+02	4.75E+02	1.64E+02	1.16E+03	1.00E+00	7.16E+04
1.00E-01	1.28E+03	1.78E+04	3.74E+01	2.91E+03	1.09E+05	-3.50E-08	-6.82E-07	4.75E+02	3.29E+02	4.75E+02	1.75E+02	1.12E+03	1.00E+00	7.21E+04

1.10E-		1.78E+	3.55E+	3.14E+	1.12E+	-1.36E-	-9.02E-	4.75E+	3.29E+	4.75E+	1.85E+	1.07E+		7.29E+
01	1.28E+03	04	01	03	05	11	10	02	02	02	02	03	1.00E+00	04

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BIOGRAPHICAL INFORMATION

Amen Omoragbon is a Nigeria born God fearing follower of Jesus Christ. During his secondary school days in Nigeria, he fell in love with airplanes. Enticed by their curves and the physics behind their gravity defying motion, he made a decision learn how to design these vehicles. He began his colligate career in spring 2004 at the University of North Texas (UNT) and transferred to the University of Texas at Arlington (UTA) following year. He earned a Bachelor of Science degree in Aerospace Engineering from UTA in 2008. During his undergraduate studies, he joined various engineering honors societies, such as Tau Beta Pi and Pi Tau Sigma, and was elected as the chapter president of the Nation Society of Black Engineers. In addition to these activities, he was a member of the Autonomous Vehicle Laboratory at UTA which won multiple awards at the International AUVSI Unmanned Air Systems competitions.

He continued with his graduate studies at the University of Texas at Arlington in fall of 2008. In the following summer, he joined the Aerospace Vehicle Design (AVD) laboratory. He joined the AVD laboratory because he recognized it was a path to realize his childhood dream of designing airplanes. In 2010, He earned a Master's of Science degree in Aerospace Engineering and then embarked on this current research undertaking. As a member of the lab, he has worked on various aerospace technology and design projects including assessment of technologies for advancing commercial transports, evaluation of trust vectoring technologies, performance sizing of electric aircraft technologies, creation of a high-speed technology investment databases, technical feasibility assessment of a novel rotorcraft technology and solution space screening of an air-launched hypersonic demonstrators. He is an author to a Journal article, 5 Conference Papers, 1 Contract Report and 3 Contract Presentations. Following this Ph.D. research, he

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