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

by

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I pray that the good Lord rewards you all in multiple folds in Jesus name, Amen.

September 9, 2016
ABSTRACT

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Amen Omoragbon, PhD

The University of Texas at Arlington, 2016

Supervising Professor: Bernd Chudoba

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 polices at the expense of investments in longer term higher risk activities, challenges of defense acquisitions, shift from defense spin-offs too 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 boomers 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”.

Stakeholder 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)

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Name</th>
<th>Developer</th>
<th>Primary Application</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAA</td>
<td>Advanced Airplane Analysis</td>
<td>DARcorporation</td>
<td>Aircraft</td>
<td>1991-</td>
</tr>
<tr>
<td>ACAD</td>
<td>Advanced Computer Aided Design</td>
<td>General Dynamics, Fort Worth</td>
<td>Aircraft</td>
<td>1993</td>
</tr>
<tr>
<td>ACAS</td>
<td>Advanced Counter Air Systems</td>
<td>US Army Aviation Systems Command</td>
<td>Air fighter</td>
<td>1987</td>
</tr>
<tr>
<td>ACDC</td>
<td>Aircraft Configuration Design Code</td>
<td>Boeing Defense and Space Group</td>
<td>Helicopter</td>
<td>1988-</td>
</tr>
<tr>
<td>ACDS</td>
<td>Parametric Preliminary Design System for Aircraft and Spacecraft Configuration</td>
<td>Northwestern Polytechnical University</td>
<td>Aircraft and AeroSpace Vehicle</td>
<td>1991-</td>
</tr>
<tr>
<td>ACES</td>
<td>Aircraft Configuration Expert System</td>
<td>Aeriaitalia</td>
<td>Aircraft</td>
<td>1989-</td>
</tr>
<tr>
<td>ACSYNT</td>
<td>Aircraft SYNThesis</td>
<td>NASA</td>
<td>Aircraft</td>
<td>1987-</td>
</tr>
<tr>
<td>ADAM</td>
<td>Auslegungs Programm</td>
<td>McDonnell Douglas</td>
<td>Aircraft</td>
<td>1994</td>
</tr>
<tr>
<td>ADAS</td>
<td>Aircraft Design and Analysis System</td>
<td>Delft University of Technology</td>
<td>Aircraft</td>
<td>1988-</td>
</tr>
<tr>
<td>ADROIT</td>
<td>Aircraft Design by Regulation Of Independent Tasks</td>
<td>Cranfield University</td>
<td>Aircraft</td>
<td>1990</td>
</tr>
<tr>
<td>ADST</td>
<td>Adaptable Design Synthesis Tool</td>
<td>General Dynamics/Fort Worth Division</td>
<td>Aircraft</td>
<td>1990</td>
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<td>AGARD</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>AIDA</td>
<td>Artificial Intelligence Supported Design of Aircraft</td>
<td>Delft University of Technology</td>
<td>Aircraft</td>
<td>1999</td>
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<td>AircraftDesign</td>
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<td>University of Osaka Prefecture</td>
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<td>1990</td>
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<td>Auslegungs Program</td>
<td>Dornier Luftfahrt</td>
<td>Aircraft</td>
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<td>ASAP</td>
<td>Aircraft Synthesis and Analysis Program</td>
<td>Vought Aeronautics Company</td>
<td>Fighter Aircraft</td>
<td>1974</td>
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<tr>
<td>Name</td>
<td>Description</td>
<td>Owner/Developer</td>
<td>Year</td>
<td>Notes</td>
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<td>ASCENT</td>
<td>Advanced Systems Synthesis and Evaluation Technique</td>
<td>Lockheed Martin Skunk Works</td>
<td>1993</td>
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<td>ASSET</td>
<td>Design Methodology for Low Speed High Altitude UAV's</td>
<td>Cranfield University</td>
<td>Before 1993</td>
<td></td>
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<td>AVSYN</td>
<td>Aerospace Vehicle Interactive Design</td>
<td>N.C. State University, NASA LaRC</td>
<td>1992</td>
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<td>BEAM</td>
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<td>Boeing</td>
<td>1974</td>
<td>NA</td>
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<td>CAAD</td>
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<td>Lockheed-Georgia Company</td>
<td>1968</td>
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<td>CAP</td>
<td>Configuration Analysis Program</td>
<td>North American Rockwell (B-1 Division)</td>
<td>1974</td>
<td>Aircraft</td>
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<td>CAPDA</td>
<td>Computer Aided Preliminary Design of Aircraft</td>
<td>Technical University Berlin</td>
<td>1984</td>
<td>Transonic Transport</td>
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<td>CAPS</td>
<td>Computer Aided Project Studies</td>
<td>BAC Military Aircraft Division</td>
<td>1968</td>
<td>Military Aircraft</td>
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<td>CASP</td>
<td>Combat Aircraft Synthesis Program</td>
<td>Northrop Corporation</td>
<td>1980</td>
<td>Combat Aircraft</td>
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<td>CASDAT</td>
<td>Conceptual Aerospace Systems Design and Analysis Toolkit</td>
<td>Georgia Institute of Technology</td>
<td>late 1995</td>
<td>Aquaspace Systems</td>
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<td>CASTOR</td>
<td>Commuter Aircraft Synthesis and Trajectory Optimization Routine</td>
<td>Loughborough University</td>
<td>1986</td>
<td>Transonic Transport</td>
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<td>CDS</td>
<td>Configuration Development System</td>
<td>Rockwell International</td>
<td>1976</td>
<td>Aircraft and Aerospace Vehicle</td>
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<td>CISE</td>
<td>(--)</td>
<td>Grumman Aerospace Corporation</td>
<td>1994</td>
<td>Aerospace Vehicle</td>
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<tr>
<td>COMBAT</td>
<td>(--)</td>
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<td>NASA Langley Research Center</td>
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<td>CPDS</td>
<td>Computerized Preliminary Design System</td>
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<td>Avions Marcel Dassault/Breguet Aviation</td>
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<td>DSP</td>
<td>Decision Support Problem</td>
<td>University of Houston</td>
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<td>EASIE</td>
<td>Environment for Application Software Integration and Execution</td>
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<td>Aircraft and Aerospace Vehicle</td>
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<td>EADS</td>
<td>(--)</td>
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<td>ESCAPE</td>
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<td>BAC (Commercial Aircraft Division)</td>
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<td>ESP</td>
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<td>(--)</td>
<td>The Boeing Company</td>
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<td>FASTER</td>
<td>Flexible Aircraft Scaling To Requirements</td>
<td>Florian Schieck</td>
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<td>FLOPS</td>
<td>FLight OPtimization System</td>
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<td>FPDS</td>
<td>Future Projects Design System</td>
<td>Hawker Siddeley Aviation Ltd</td>
<td>1970</td>
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<td>FRICTION</td>
<td>Skin friction and form drag code</td>
<td></td>
<td>1990</td>
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<td>FVE</td>
<td>Flugzeug VorEntwurf</td>
<td>Stemme GmbH &amp; Co. KG</td>
<td>1996</td>
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<td>GASP</td>
<td>General Aviation Synthesis Program</td>
<td>NASA Ames Research Center</td>
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<td>GPAD</td>
<td>Graphics Program For Aircraft Design</td>
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<td>Hypersonic Aircraft Conceptual Design Methodology</td>
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<td>Astrox</td>
<td>1987-</td>
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<td>Hypersonic Aerospace Sizing Analysis</td>
<td>NASA Lewis Research Center</td>
<td>1985, 1990</td>
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<td>Hypersonic Astrox Vehicle Design and Analysis Code</td>
<td>Astrox</td>
<td>1987-</td>
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<td>HCDV</td>
<td>Hypersonic Conceptual Vehicle Design</td>
<td>NASA Ames Research Center</td>
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<td>HESCOMP</td>
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<td>Boeing Vertol Company</td>
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<td>High Speed Airframe Integration Research</td>
<td>Lockheed Engineering and Sciences Co.</td>
<td>1992</td>
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<td>Holst</td>
<td>?</td>
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<td>1996</td>
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<td>IDEAS</td>
<td>Integrated DEsign Analysis System</td>
<td>Grumman Aerospace Corporation</td>
<td>1967</td>
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<tr>
<td>IKADE</td>
<td>Intelligent Knowledge Assisted Design Environment</td>
<td>Cranfield University</td>
<td>1992</td>
<td></td>
</tr>
<tr>
<td>IMAGE</td>
<td>Intelligent Multi-Disciplinary Aircraft Generation Environment</td>
<td>Georgia Tech</td>
<td>1988</td>
<td></td>
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<tr>
<td>IPAD</td>
<td>Integrated Programs for Aerospace-Vehicle Design</td>
<td>NASA Langley Research Center</td>
<td>1972-1980</td>
<td></td>
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<tr>
<td>IPPD</td>
<td>Integrated Product and Process Design</td>
<td>Georgia Tech</td>
<td>1995</td>
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<td>Medium range JET-UAV</td>
<td>2000</td>
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<tr>
<td>LAGRANGE</td>
<td>Span efficiency</td>
<td></td>
<td>1990</td>
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<td>LOVELL</td>
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<td></td>
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<td>an analysis-based environment</td>
<td>Georgia Institute of Technology</td>
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<td></td>
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<td>1998</td>
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<td>MacAirplane</td>
<td></td>
<td>Notre Dame University</td>
<td>1987</td>
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<td>MIDAS</td>
<td>Multi-Disciplinary Integrated Design Analysis &amp; Sizing</td>
<td>DaimlerChrysler Military</td>
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<td>MIDAS</td>
<td>Multi-Disciplinary Integration of Deutsche Airbus Specialists</td>
<td>DaimlerChrysler Aerospace Airbus</td>
<td>1996</td>
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<td>MVA</td>
<td>Multi-Variate Analysis</td>
<td>RAE (BAC)</td>
<td>1991</td>
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<td>MVO</td>
<td>MultiVariate Optimisation</td>
<td>RAE Farnborough</td>
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<td>NEURAL NETWORK FORMULATION</td>
<td>Optimization method for Aircraft Design</td>
<td>Georgia Institute of Technology</td>
<td>Aircraft</td>
<td>1998</td>
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<td>--------------------------------------</td>
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<tr>
<td>ODIN</td>
<td>Optimal Design Integration System</td>
<td>NASA Langley Research Center</td>
<td>AeroSpace Vehicle</td>
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<td>ONERA</td>
<td>Preliminary Design of Civil Transport Aircraft</td>
<td>Office National d'Etudes et de Recherches Aerospatiales</td>
<td>Subsonic Transport Aircraft</td>
<td>1989</td>
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<td>PACELAB</td>
<td>knowledge based software solutions</td>
<td>PACE</td>
<td>Aircraft</td>
<td>2000</td>
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<td>Paper Airplane</td>
<td>(·)</td>
<td>MIT</td>
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<td>PASS</td>
<td>Program for Aircraft Synthesis Studies</td>
<td>Stanford University</td>
<td>Supersonic Commercial Transport Aircraft</td>
<td>1992</td>
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<td>Supersonic Transport Aircraft</td>
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<td>Lissys Limited</td>
<td>Transonic Transport Aircraft</td>
<td>2000</td>
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<td>POP</td>
<td>Parametrisches Optimierungs-Programm</td>
<td>Daimler-Benz Aerospace</td>
<td>Airbus</td>
<td>1986-</td>
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<td>PiADO</td>
<td>Preliminary Aircraft Design and Optimisation</td>
<td>Technical University</td>
<td>Braunischweig</td>
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<td>PreSST</td>
<td>Preliminary SuperSonic Transport Synthesis and Optimisation</td>
<td>DRA UK</td>
<td>Transport Aircraft</td>
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<tr>
<td>PROFET</td>
<td>(·)</td>
<td>IABG</td>
<td>Missile</td>
<td>1979</td>
</tr>
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<td>RAE</td>
<td>Artificial Intelligence Supported Design of Aircraft</td>
<td>Royal Aircraft Establishment, Farnborough</td>
<td>Aircraft conceptual design</td>
<td>Early 1970's</td>
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<td>RAM</td>
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<td>NASA</td>
<td>geometric modeling tool</td>
<td>1991</td>
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<td>RDS</td>
<td>(·)</td>
<td>Conceptual Research Corporation</td>
<td>Aircraft</td>
<td>1999</td>
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<td>RECIPE</td>
<td>(·)</td>
<td>?</td>
<td>?</td>
<td>1999</td>
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<td>Rubber Airplane</td>
<td>(·)</td>
<td>MIT</td>
<td>Aircraft</td>
<td>1960s-1970s</td>
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<td>Schnieder</td>
<td></td>
<td>Cranfield University</td>
<td>combat aircraft</td>
<td>Late 1970s</td>
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<td>Loughborough University</td>
<td>Aircraft Design Studies</td>
<td>1995</td>
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<td>SENSxx</td>
<td>(·)</td>
<td>Daimler-Chrysler Aerospace Airbus</td>
<td>Transonic Transport Aircraft</td>
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<td>SIDE</td>
<td>System Integrated Design Environment</td>
<td>Astrox</td>
<td>?</td>
<td>1987-</td>
</tr>
<tr>
<td>SLAM</td>
<td>Simulated Language for Alternative Modeling</td>
<td>?</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Slate Architect</td>
<td>(·)</td>
<td>SDRC (Eds)</td>
<td>?</td>
<td></td>
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<td>SSP</td>
<td>System Synthesis Program</td>
<td>University of Maryland</td>
<td>Helicopter</td>
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<td>SSSP</td>
<td>Space Shuttle Synthesis Program</td>
<td>General Dynamics Corporation</td>
<td>AeroSpace Vehicle</td>
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<td>SYNAC</td>
<td>SYNthesis of AirCraft</td>
<td>General Dynamics</td>
<td>Aircraft</td>
<td>1967</td>
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<td>TASOP</td>
<td>Transport Aircraft Synthesis and Optimisation Program</td>
<td>BAE (Commercial Aircraft) LTD</td>
<td>Transonic Transport Aircraft</td>
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<td>Abbreviation</td>
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<td>Organization</td>
<td>Year</td>
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<tr>
<td>TIES</td>
<td>Technology Identification, Evaluation, and Selection</td>
<td>Georgia Institute of Technology</td>
<td>1998</td>
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<td>TRANSYN</td>
<td>TRANsport SYNthesis</td>
<td>NASA Ames Research Center</td>
<td>1963-2018</td>
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<td>TRANSYS</td>
<td>TRANsportation SYStem</td>
<td>DLR (Aerospace Research)</td>
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<td>TsAGI</td>
<td>Dialog System for Preliminary Design</td>
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<td>VASCOMPII</td>
<td>V/STOL Aircraft Sizing and Performance Computer Program</td>
<td>Boeing Vertol Co.</td>
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<td>VDEP</td>
<td>Vehicle Design Evaluation Program</td>
<td>NASA Langley Research Center</td>
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<td>VDI</td>
<td>V/STOL Aircraft</td>
<td>Aerospace Corporation Space Systems</td>
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<td>VizCraft</td>
<td>Waverider Interactive Parameter Adjustment Routine</td>
<td>Virginia Tech</td>
<td>1999</td>
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<td>Voit-Nitschmann</td>
<td>Waverider Interactive Parameter Adjustment Routine</td>
<td>DLR Braunschweig</td>
<td>Paper 1992</td>
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</tbody>
</table>

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.
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 (Azizan, 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 Saucer 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 breadth 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)

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

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.
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
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)

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

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.
Huang (2006) assesses 115 aerospace synthesis systems meant for the design of aircraft, helicopters, missiles and launch vehicles. He evaluates a cross-section of the year 2004 state-of-the-art synthesis systems through a systematic evaluation process, providing an overview of each system with detail about its applicability towards the Space Access Problem as shown in Figure 2-6. Huang categorized each system according to its ability to perform the following: Mathematical Modelling, Multidisciplinary Analysis and Optimization, Knowledge-Based System, and Generic Concepts. The result showed a discrepancy in the ability of the then state of the art, circa 2004, to adequately address the Space Access Vehicle (SAV) problem in the early stages of conceptual design. This led him to the following specifications for a synthesis system for SAV, see Figure 2-7. Of note in Figure 2-7 is the inclusion of a ‘Database Management System’. This addition to the ‘Class V Synthesis’ specification reveals the necessity of the system to not only connect design parametric data but to also to ‘control utilization of the design methods library’.

Figure 2-6 Evaluation Process of Design Synthesis Systems (Huang 2006)
(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-Schniederman (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)
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

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

<table>
<thead>
<tr>
<th>Processes Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Phases</strong></td>
</tr>
<tr>
<td>Conceptual Design</td>
</tr>
</tbody>
</table>


**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 1st 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**

<table>
<thead>
<tr>
<th>CD steps</th>
<th>Synthesis Ladder</th>
<th>Similar Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parametric Sizing</td>
<td>Analysis</td>
<td>Roskam (preliminary sizing)</td>
</tr>
<tr>
<td></td>
<td>Integrate</td>
<td>Torenbeek (Cat 1 methods)</td>
</tr>
<tr>
<td></td>
<td>Iteration of design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Visualize design space</td>
<td></td>
</tr>
</tbody>
</table>

**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.
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 |


**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 $S_{wind}=f(W_{to})$ empirical based on type of aircraft Fig 3.22
- Estimate $f=f(S_{wind})$ 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

\[ C_D = f / S + \Delta C_{D_{flap}} + \Delta C_{D_{LG}} + \frac{C_i^2}{\pi AR \cdot e} \]

Assume $C_{L_{max}}$ values from Table 3.1

**Output:**
- Drag Polar

**Experience**

<table>
<thead>
<tr>
<th><strong>Accuracy</strong></th>
<th><strong>Time to Calculate</strong></th>
<th><strong>General Comments</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown</td>
<td>Unknown</td>
<td></td>
</tr>
</tbody>
</table>

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

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

Table 2-4 Selected Computer-Based Synthesis Systems

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Year</th>
<th>Full name</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAA</td>
<td>1991-</td>
<td>Advanced Airplane Analysis</td>
<td>DARcorporation</td>
</tr>
<tr>
<td>ACSYNT</td>
<td>1987-</td>
<td>AirCraft SYNthesis</td>
<td>NASA</td>
</tr>
<tr>
<td>AVDS</td>
<td>2010</td>
<td>Aerospace Vehicle Design System</td>
<td>Aerospace Vehicle Design Laboratory</td>
</tr>
<tr>
<td>CADE</td>
<td>1968</td>
<td>Computer Aided Design Evaluation</td>
<td>McDonnell Douglas</td>
</tr>
<tr>
<td>FLOPS</td>
<td>1994-</td>
<td>Flight OPtimization System</td>
<td>NASA Langley Research Center</td>
</tr>
<tr>
<td>Model Center</td>
<td>1995-</td>
<td>Model Center Integrate - Explore - Organize</td>
<td>Phoenix Integration Inc</td>
</tr>
<tr>
<td>pyOPT</td>
<td>2012-</td>
<td>Python-based object-oriented framework for nonlinear constrained optimization</td>
<td>Royal Military College of Canada</td>
</tr>
<tr>
<td>PrADO</td>
<td>1986-</td>
<td>Preliminary Aircraft Design and Optimisation</td>
<td>Technical University Braunschweig</td>
</tr>
</tbody>
</table>
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

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

<table>
<thead>
<tr>
<th>Aeroprop</th>
<th>By-Hand</th>
<th>Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corning</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Howe</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Jenkinson</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Loftin</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Nicolai</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Raymer</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Roskam</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Schaufele</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Stinton</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Torenbeek</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Wood</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>AAA</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ACSYNT</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ASAP</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>AVDS</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>FLOPS</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Model Center</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>PrADO</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>pyOPT</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>VDK/HC</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Table 2-7 Scope of Applicability to Aerospace Product Types

<table>
<thead>
<tr>
<th>Aeroprop</th>
<th>By-Hand</th>
<th>Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homebuilt</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Single Engine</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Twin Engine</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Agricultural</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Business Jet</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Regional TBP's</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Transport Aircraft</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Mil. Trainers</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Fighters</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Mill. Patrol, bombers, transport</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Flying boats, Amphibious</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Supersonic Cruise</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hypersonic P2P</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Launcher (Rocket)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Launcher (A/B)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Reentry</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>In-Space</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

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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.

<table>
<thead>
<tr>
<th>5.a - Able to match hardware technology disciplinary models to problem requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>No</td>
</tr>
</tbody>
</table>

By-Hand Computer Based

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to create, change, delete, and view projects and project data.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Accommodates all project types and project information</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Supports entry of annotative comments and appending documents, images, and links for project</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Accommodates hundreds/thousands of projects</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Supports data import from your existing systems and databases</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Supports data export to your existing systems and databases</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Supports dependency links among projects</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Provides data cut-and-paste, project cloning, and data roll-over</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Provides completeness/error checks and data warnings</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Allows multiple portfolios and portfolio hierarchies (parent-child links)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Allows dynamic portfolios (portfolios defined based on latest project data)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Provides search, filter, and sort</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Provides data archiving</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Provides statistical analysis of historical data (e.g., trend analysis)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2-9 Data Management Capability
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.
The advantage of the AVD\textsuperscript{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 stakeholder 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\textsuperscript{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

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](image)

### 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.
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.
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 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](image)

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 (Klodner, 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

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

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

<table>
<thead>
<tr>
<th>Function</th>
<th>Shell Package #1</th>
<th>Shell Package #2</th>
<th>Shell Package #3</th>
<th>Shell Package #4</th>
<th>Shell Package #5</th>
<th>Shell Package #6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift Source</td>
<td>All-Body</td>
<td>All-Body</td>
<td>Blended Body</td>
<td>Blended Body</td>
<td>Wing Body</td>
<td>Wing Body</td>
</tr>
<tr>
<td>Stability &amp; Control</td>
<td>X-Tail</td>
<td>X-Tail</td>
<td>Twin Tail &amp; Elevons</td>
<td>Twin Tail &amp; Elevons</td>
<td>Twin Tail &amp; Elevons</td>
<td>Twin Tail &amp; Elevons</td>
</tr>
<tr>
<td>Thrust Source</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
</tr>
<tr>
<td>Landing System</td>
<td>Tricycle</td>
<td>Parachute</td>
<td>Tricycle</td>
<td>Parachute</td>
<td>Tricycle</td>
<td>Parachute</td>
</tr>
</tbody>
</table>

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](image)

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](image-url)
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

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

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 interdictor aircraft. It is a P2P mission with both, a combined range and endurance objective.

![Flight Profile](image)

**Figure 3-11 Example Flight Profile (Jenkins, 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 it 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

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

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

<table>
<thead>
<tr>
<th>Mach Regime</th>
<th>Mach Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsonic</td>
<td>&lt;0.8</td>
</tr>
<tr>
<td>Transonic</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>Sonic</td>
<td>1.0</td>
</tr>
<tr>
<td>Supersonic</td>
<td>1.0-5.0</td>
</tr>
<tr>
<td>Hypersonic</td>
<td>5.0-10.0</td>
</tr>
<tr>
<td>High Hypersonic</td>
<td>&gt;10.0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Earth Atmospheric Layers</th>
<th>Altitude Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exosphere</td>
<td>700 to 10,000 km (440 to 6,200 miles)</td>
</tr>
<tr>
<td>Thermosphere</td>
<td>80 to 700 km (50 to 440 miles)</td>
</tr>
<tr>
<td>Mesosphere</td>
<td>50 to 80 km (31 to 50 miles)</td>
</tr>
<tr>
<td>Stratosphere</td>
<td>12 to 50 km (7 to 31 miles)</td>
</tr>
<tr>
<td>Troposphere</td>
<td>0 to 12 km (0 to 7 miles)</td>
</tr>
</tbody>
</table>

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.
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.

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.

![Disciplinary Method Block Decomposition](image)
3.5 Chapter Summary

This Chapter discusses the Complex Multidisciplinary System Decomposition (CMSD) 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\textsubscript{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\textsubscript{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\textsubscript{DBMS}. Figure 4-1 shows the 3 layer architecture. The GUI Layer is the means by which the user interacts with AVD\textsubscript{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\textsubscript{DBMS} framework.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Software</th>
<th>Programming Language</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUI Layer</td>
<td>Microsoft Access</td>
<td>Microsoft Visual Basic with Applications (VBA)</td>
</tr>
<tr>
<td>Database Layer</td>
<td>Microsoft Access</td>
<td>Search Query Language (SQL)</td>
</tr>
<tr>
<td>Analysis Layer</td>
<td>MATLAB</td>
<td>MATLAB Script</td>
</tr>
</tbody>
</table>
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 AVDDBMS. 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

AVDDBMS 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.

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.
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 AVDDBMS 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.

Figure 4-5 Disciplinary Method Input Form
One key to the AVDDBMS 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 AVDDBMS 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 AVDDBMS. 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?

<table>
<thead>
<tr>
<th>Stage</th>
<th>Mach</th>
<th>Lift/Weight</th>
<th>Dynamic Pressure (psf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiation (booster separation)</td>
<td>4 – 5</td>
<td>1</td>
<td>2500 – 1500</td>
</tr>
<tr>
<td>Acceleration and Climb</td>
<td>4 – 6</td>
<td>&gt;1</td>
<td>2500 – 1500</td>
</tr>
<tr>
<td>Cruise</td>
<td>6</td>
<td>1</td>
<td>2000 – 1000</td>
</tr>
<tr>
<td>Maneuver (#1 or #2)</td>
<td>~6</td>
<td>~2</td>
<td>2000 – 1000</td>
</tr>
<tr>
<td>Cruise</td>
<td>6</td>
<td>1</td>
<td>2000 – 1000</td>
</tr>
<tr>
<td>Descend (powered)</td>
<td>6 – 4</td>
<td>&lt;1</td>
<td>2000 – 3000</td>
</tr>
<tr>
<td>Descend (unpowered)</td>
<td>4 – 3</td>
<td>&lt;1</td>
<td>2500 – 5000</td>
</tr>
<tr>
<td>Maneuver (unpowered)</td>
<td>~3</td>
<td>&gt;1</td>
<td>~5000</td>
</tr>
</tbody>
</table>

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](image-url)
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). AVDDBMS 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
<table>
<thead>
<tr>
<th>Function</th>
<th>Hardware</th>
<th>GHV</th>
<th>X-24C-L001</th>
<th>HYFAC-211</th>
<th>Sanger II</th>
<th>X-43C</th>
<th>X-51A Cruiser</th>
<th>HIFiRE 6</th>
<th>Falcon HTV-3x</th>
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<td></td>
</tr>
<tr>
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Figure 5-5 Reference Vehicle Decomposition into functional hardware
<table>
<thead>
<tr>
<th>Function</th>
<th>HW</th>
<th>Attribute</th>
<th>GHV</th>
<th>X-24C-L301</th>
<th>HYFAC 221</th>
<th>X-43 C</th>
<th>X-51A Cruiser</th>
<th>HIFIRE 6</th>
<th>HTV-3x</th>
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<td>2-D Planar</td>
<td>2-D Planar</td>
<td>3-D Inward Turning</td>
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<td>3-D</td>
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<td>2-D</td>
<td>2-D</td>
<td>2-D</td>
<td>3-D</td>
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<td>3-D</td>
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<tr>
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<td>2-D</td>
<td></td>
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<tr>
<td></td>
<td>Combustor</td>
<td></td>
<td>3-D</td>
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<td></td>
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</table>
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 AVDDBMS 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.
# Table 5-2 Technology Portfolio Definition Shell Vehicles

<table>
<thead>
<tr>
<th>Function</th>
<th>Shell Package #1</th>
<th>Shell Package #2</th>
<th>Shell Package #3</th>
<th>Shell Package #4</th>
<th>Shell Package #5</th>
<th>Shell Package #6</th>
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<tbody>
<tr>
<td>Lift Source</td>
<td>All-Body</td>
<td>All-Body</td>
<td>Blended Body</td>
<td>Blended Body</td>
<td>Wing Body</td>
<td>Wing Body</td>
</tr>
<tr>
<td>Stability &amp; Control</td>
<td>X-Tail</td>
<td>X-Tail</td>
<td>Twin Tail &amp; Elevons</td>
<td>Twin Tail &amp; Elevons</td>
<td>Twin Tail &amp; Elevon</td>
<td></td>
</tr>
<tr>
<td>Thrust Source</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
<td>SCRAMjet</td>
</tr>
<tr>
<td>Landing System</td>
<td>Tricycle</td>
<td>Parachute</td>
<td>Tricycle</td>
<td>Parachute</td>
<td>Tricycle</td>
<td>Parachute</td>
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</table>

# Table 5-3 Candidate Vehicle Portfolio

<table>
<thead>
<tr>
<th>Candidate Vehicle</th>
<th>Lift Source Concept</th>
<th>Thrust Source Concept</th>
<th>Stability &amp; Control Concept</th>
<th>Thermal Protection Concept</th>
<th>Landing System Concept</th>
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</thead>
<tbody>
<tr>
<td>CV 1</td>
<td>X-43C All Body Concept</td>
<td>GHV SCRAMjet Concept</td>
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<td>X-24C L301 TPS Concept</td>
<td>X-15 Skids Concept</td>
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<td>CV 2</td>
<td>X-43C All Body Concept</td>
<td>HYTECH SCRAMjet Concept</td>
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<td>X-24C L301 TPS Concept</td>
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<td>CV 3</td>
<td>HYFAC 221 All Body Concept</td>
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<td>X-24C L301 TPS Concept</td>
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</tr>
<tr>
<td>CV 4</td>
<td>HYFAC 221 All Body Concept</td>
<td>HYTECH SCRAMjet Concept</td>
<td>X-51A X-Tail Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>X-15 Skids Concept</td>
</tr>
<tr>
<td>CV 5</td>
<td>X-43C All Body Concept</td>
<td>GHV SCRAMjet Concept</td>
<td>X-51A X-Tail Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>HYFAC 221 Parachute Concept</td>
</tr>
<tr>
<td>CV 6</td>
<td>X-43C All Body Concept</td>
<td>HYTECH SCRAMjet Concept</td>
<td>X-51A X-Tail Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>HYFAC 221 Parachute Concept</td>
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<td>CV 7</td>
<td>HYFAC 221 All Body Concept</td>
<td>GHV SCRAMjet Concept</td>
<td>X-51A X-Tail Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>HYFAC 221 Parachute Concept</td>
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<td>HYTECH SCRAMjet Concept</td>
<td>X-51A X-Tail Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>HYFAC 221 Parachute Concept</td>
</tr>
<tr>
<td>CV 9</td>
<td>X-24C-L301 Blended Body Concept</td>
<td>GHV SCRAMjet Concept</td>
<td>GHV Twin Tail &amp; Elevon Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>X-15 Skids Concept</td>
</tr>
<tr>
<td>CV 10</td>
<td>X-24C-L301 Blended Body Concept</td>
<td>HYTECH SCRAMjet Concept</td>
<td>GHV Twin Tail &amp; Elevon Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>X-15 Skids Concept</td>
</tr>
<tr>
<td>CV 11</td>
<td>Sager II Blended Body Concept</td>
<td>GHV SCRAMjet Concept</td>
<td>GHV Twin Tail &amp; Elevon Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>X-15 Skids Concept</td>
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<tr>
<td>CV 12</td>
<td>Sager II Blended Body Concept</td>
<td>HYTECH SCRAMjet Concept</td>
<td>GHV Twin Tail &amp; Elevon Concept</td>
<td>X-24C L301 TPS Concept</td>
<td>X-15 Skids Concept</td>
</tr>
</tbody>
</table>
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.

![Technology Sensitivity Analysis](image1)

**Figure 5-7 Portfolio Value Assessment Methodology**

<table>
<thead>
<tr>
<th>Candidate Vehicle TRL Comparison</th>
<th>Impact of BC and WC Scenarios</th>
<th>Variation due to BC and WC Scenarios</th>
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<tr>
<td>CV03</td>
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<td>CV04</td>
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<td>CV14</td>
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</table>
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.

Figure 5-9 Characteristics of Candidate Vehicle 10

<table>
<thead>
<tr>
<th>Function</th>
<th>CV 10</th>
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<tbody>
<tr>
<td>Lift Source</td>
<td>Blended Body X-24C-L301 Blended Body Concept</td>
</tr>
<tr>
<td>Thrust Source</td>
<td>SCRAMjet HYTECH SCRAMjet Concept</td>
</tr>
<tr>
<td>Stability &amp; Control</td>
<td>Twin Tail + Elevons GIV Twin Tail and Elevon Concept</td>
</tr>
<tr>
<td>Thermal Protection</td>
<td>Passive</td>
</tr>
<tr>
<td>Landing System</td>
<td>Tricycle X-15 Skids Concept</td>
</tr>
</tbody>
</table>

~TRL: 3.77 ΔTRL: 49.5%

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 AVDBMS, 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:

- **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]
• Decomposition of synthesis systems at the ASE Laboratory;
• Composition of sizing CMDS for CV10;
• Visualization of CV10 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)
### Product DMM

<table>
<thead>
<tr>
<th>Lift Source</th>
<th><strong>Air Bgng</strong></th>
<th><strong>Wing Bgng</strong></th>
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</thead>
<tbody>
<tr>
<td>Thermal Protection</td>
<td><strong>Heat Shingles</strong></td>
<td><strong>RAM</strong></td>
</tr>
<tr>
<td><strong>V-Shaped</strong></td>
<td><strong>Rbd/Skirted</strong></td>
<td><strong>Rbd</strong></td>
</tr>
<tr>
<td><strong>Turbine</strong></td>
<td><strong>Tubular</strong></td>
<td></td>
</tr>
<tr>
<td>Volume Supply</td>
<td><strong>Integral Tank</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### Functional Subsystems

<table>
<thead>
<tr>
<th>Mission Segment</th>
<th><strong>Air Launch</strong></th>
<th><strong>Booster Launch</strong></th>
<th><strong>Horizontal Takeoff</strong></th>
<th><strong>Vertical Takeoff</strong></th>
<th><strong>Parachute Landing</strong></th>
<th><strong>Pneumatic Landing</strong></th>
<th><strong>Depowered Landing</strong></th>
<th><strong>Gliding Decent</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Speed</td>
<td><strong>Supersonic</strong></td>
<td><strong>Subsonic</strong></td>
<td><strong>Hypermach</strong></td>
<td><strong>Hypermach</strong></td>
<td><strong>Congression Mach</strong></td>
<td><strong>Congression Mach</strong></td>
<td><strong>Congression Mach</strong></td>
<td><strong>Gliding Decent</strong></td>
</tr>
<tr>
<td>Mission Type</td>
<td><strong>Hypermach</strong></td>
<td><strong>Impulse</strong></td>
<td><strong>Hyperimpulse</strong></td>
<td><strong>Impulse</strong></td>
<td><strong>Prelaunch</strong></td>
<td><strong>Prelaunch</strong></td>
<td><strong>Prelaunch</strong></td>
<td><strong>Gliding Decent</strong></td>
</tr>
<tr>
<td>Operational Requirements</td>
<td><strong>Human Rating</strong></td>
<td><strong>Unmanned</strong></td>
<td><strong>Unmanned</strong></td>
<td><strong>Unmanned</strong></td>
<td><strong>Hypermach</strong></td>
<td><strong>Hypermach</strong></td>
<td><strong>Hypermach</strong></td>
<td><strong>Gliding Decent</strong></td>
</tr>
<tr>
<td><strong>Fuel (Storage State)</strong></td>
<td><strong>Armstrong Jet (Liquid)</strong></td>
<td><strong>Methane-Methane (Liquid)</strong></td>
<td><strong>JP-5 (Liquid)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Oxidizer (Storage State)</strong></td>
<td><strong>Nitrogen-Triklyde (Liquid)</strong></td>
<td><strong>Nitrogen (Cryogenic Liquid)</strong></td>
<td><strong>Oxygen (Cryogenic Liquid)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** This is a design mapping matrix for the AVDDBMS product library. The table above represents various parameters and their possible combinations. The matrix is designed to help in selecting appropriate configurations for different missions and operational requirements.
### Process Domain Mapping Matrix

<table>
<thead>
<tr>
<th>Process DMM</th>
<th>Process List</th>
<th>Analysis Process:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Variables</td>
<td>SPLN</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td>Disciplinary Dependencies</td>
<td>ALT</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>MARCH</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>AOA</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>THRVL VAR</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td>Disciplinary Run Order</td>
<td>AERO</td>
<td>3 3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>GEO</td>
<td>2 2 2 2 2</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>5 5 5 5 5</td>
</tr>
<tr>
<td></td>
<td>PROP</td>
<td>4 4 4 4 4</td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>6 6 6 6 6</td>
</tr>
<tr>
<td></td>
<td>AOA</td>
<td>2 2 2 2 2</td>
</tr>
<tr>
<td></td>
<td>AL</td>
<td>2 2 2 2 2</td>
</tr>
<tr>
<td></td>
<td>ALT</td>
<td>3 3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>MARCH</td>
<td>3 3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>AOA</td>
<td>4 4 4 4 4</td>
</tr>
<tr>
<td></td>
<td>THRVL VAR</td>
<td>4 4 4 4 4</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2 2 2 2 2</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>3 3 3 3 3</td>
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<tr>
<td></td>
<td>CS_CS</td>
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<tr>
<td></td>
<td>CE_CS</td>
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<td></td>
<td>FF</td>
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<tr>
<td></td>
<td>FT_AV</td>
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<tr>
<td></td>
<td>FT_MAX_HW</td>
<td>5 5 5 5 5</td>
</tr>
<tr>
<td></td>
<td>FTC</td>
<td>4 4 4 4 4</td>
</tr>
<tr>
<td></td>
<td>OF</td>
<td>6 6 6 6 6</td>
</tr>
<tr>
<td></td>
<td>OWE_V</td>
<td>6 6 6 6 6</td>
</tr>
<tr>
<td></td>
<td>OWE_W</td>
<td>6 6 6 6 6</td>
</tr>
<tr>
<td></td>
<td>RANGE</td>
<td>5 5 5 5 5</td>
</tr>
<tr>
<td></td>
<td>SPLN</td>
<td>5 5 5 5 5</td>
</tr>
<tr>
<td></td>
<td>TAU</td>
<td>2 2 2 2 2</td>
</tr>
<tr>
<td></td>
<td>THRVL TEMP</td>
<td>4 4 4 4 4</td>
</tr>
<tr>
<td></td>
<td>TOGW</td>
<td>5 5 5 5 5</td>
</tr>
<tr>
<td></td>
<td>WR</td>
<td>1 1 1 1 1</td>
</tr>
</tbody>
</table>

### Method Domain Mapping Matrix

<table>
<thead>
<tr>
<th>Method DMM</th>
<th>Method List</th>
<th>Method Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product (Functional Subsystems)</td>
<td>Life Source</td>
<td>Mission Segment</td>
</tr>
<tr>
<td></td>
<td>Thrust Source</td>
<td>Mission Speed</td>
</tr>
<tr>
<td></td>
<td>Human Rating</td>
<td>Mission Type</td>
</tr>
<tr>
<td></td>
<td>Fuel (Storage State)</td>
<td>Product (Operational Requirements)</td>
</tr>
<tr>
<td></td>
<td>Lift Source</td>
<td>Condition (Storage State)</td>
</tr>
<tr>
<td></td>
<td>Thrust Source</td>
<td>Discipline</td>
</tr>
</tbody>
</table>

### Figure 5-12 Design Mapping Matrix of AVDDBMS Process and Method Libraries

94
5.5.2 Composition of Sizing CMDS for Candidate Vehicle 10

Gonzalez (2016) describes the capability of AVD\textsubscript{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\textsubscript{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\textsubscript{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, \( S_{\text{p}ln} \), and Wing loading, \( W/S \), required for operating weight estimates based on volume calculations, \( (O\text{WE})_V \), to equal operating weight estimates based on weight calculations, \( (O\text{WE})_W \). AVD\textsubscript{DBMS} provides a list of matching disciplinary methods for the parametric sizing problem.

<table>
<thead>
<tr>
<th>Process Blocks</th>
<th>Variable / Problem Type</th>
<th>Equation/Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Variable</td>
<td>Planform Area, ft(^2)</td>
<td>( S_{\text{p}ln} )</td>
</tr>
<tr>
<td>Independent Variable</td>
<td>Wing Loading, N/ft(^2)</td>
<td>( \frac{W}{S} = \frac{TOGW}{S_{\text{p}ln}} )</td>
</tr>
<tr>
<td>Dependent Variable</td>
<td>Operating Weight Based on Weights Budget, N</td>
<td>( (O\text{WE})<em>V = \frac{W</em>{\text{fix}} + W_{\text{Eng}} + W_{\text{TPS}}}{1 + \frac{W_{\text{str}}}{OE\text{W}} - F_{W_{\text{sys}}}} + W_{\text{payload}} )</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Process Blocks</th>
<th>Variable / Problem Type</th>
<th>Equation/Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Variable</td>
<td>Planform Area, ft²</td>
<td>( S_{pln} )</td>
</tr>
<tr>
<td>Independent Variable</td>
<td>Wing Loading, N/ft²</td>
<td>( \frac{W}{S} = \frac{TOGW}{S_{pln}} )</td>
</tr>
<tr>
<td>Dependent Variable</td>
<td>Operating Weight Based on Weights Budget, N</td>
<td>( (OWE)<em>V = \frac{W</em>{fix} + W_{Eng} + W_{TPS} + W_{payload}}{1 + \mu_a} - F_{Wsys} )</td>
</tr>
<tr>
<td>Dependent Variable</td>
<td>Operating Weight Based on Volume Budget, N</td>
<td>( (OWE)<em>V = \frac{V</em>{Total} - V_{Systems} - V_{Eng} - V_{Str} - V_{TPS} - V_{Void}}{WR - \frac{1}{\rho_{ppt} \ast g_0}} )</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Sizing Name</th>
<th>Method Title</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Condition</td>
<td>FLTCON_MD0001</td>
<td>Atmospheric Model</td>
<td>(MINZNER et al. 1959)</td>
</tr>
<tr>
<td>Geometry</td>
<td>GEO_MD0002</td>
<td>Hypersonic Air-breather Geometry</td>
<td>(Chudoba 2010)</td>
</tr>
<tr>
<td>Aerodynamics</td>
<td>AERO_MD0005</td>
<td>Hypersonic Convergence Aerodynamic Estimation Method - Subsonic</td>
<td>(Czysz 2004; Sforza 2016)</td>
</tr>
<tr>
<td>Aerodynamics</td>
<td>AERO_MD0006</td>
<td>Hypersonic Convergence Aerodynamic Estimation Method - Supersonic</td>
<td>(Czysz 2004; Sforza 2016)</td>
</tr>
<tr>
<td>Category</td>
<td>Code</td>
<td>Description</td>
<td>Reference</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------</td>
<td>------------------------------------------------------------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>AERO_MD0007</td>
<td>Propulsion</td>
<td>Hypersonic Convergence Aerodynamic Estimation Method - Hypersonic</td>
<td>(Czysz 2004; Sforza 2016)</td>
</tr>
<tr>
<td>PROP_MD0008</td>
<td>Performance Matching</td>
<td>HAP Stream Thrust SERN CEA (C2H4 - Air) Look-Up Table</td>
<td>(Heiser and Pratt 1994)</td>
</tr>
<tr>
<td>PM_MD0001</td>
<td>Performance Matching</td>
<td>Gliding Decent at Max L/D</td>
<td>(Miele 1962)</td>
</tr>
<tr>
<td>PM_MD0003</td>
<td>Performance Matching</td>
<td>Constant Q-Climb to an Altitude and Velocity at Small Flight Path Angles</td>
<td>(Miele 1962)</td>
</tr>
<tr>
<td>PM_MD0008</td>
<td>Performance Matching</td>
<td>Constant Mach Range Cruise at Small Flight Path Angles</td>
<td>(Miele 1962)</td>
</tr>
<tr>
<td>PM_MD0009</td>
<td>Performance Matching</td>
<td>Launch Methods using WR</td>
<td>(Miele 1962)</td>
</tr>
<tr>
<td>PM_MD0010</td>
<td>Performance Matching</td>
<td>Steady Level Turn</td>
<td>(Vinh 1981)</td>
</tr>
<tr>
<td>WB_MD0003</td>
<td>Weight &amp; Balance</td>
<td>Convergence OWE Estimation for Scramjet w/ Landing skids</td>
<td>(Czysz 2004; Harloff 1988)</td>
</tr>
</tbody>
</table>
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, \( \tau \), 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](image_url)
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, \( \tau \), and payload weight, \( W_{pay} \), for each design.

<table>
<thead>
<tr>
<th>Flight Segment</th>
<th>Method</th>
<th>Parameters</th>
<th>Segment Termination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acceleration / Climb</td>
<td>Constant Q-Climb to Altitude</td>
<td>( Q = 1500 ) lb/ft^2</td>
</tr>
<tr>
<td>2</td>
<td>Cruise</td>
<td>Constant Mach Cruise for Endurance</td>
<td>Time = 0s, 166.6s, 333.3s, 500s</td>
</tr>
<tr>
<td>3</td>
<td>Maneuver</td>
<td>Steady Level turn to base</td>
<td>( n = 2 )g</td>
</tr>
<tr>
<td>4</td>
<td>Cruise</td>
<td>Constant Mach Cruise for Endurance</td>
<td>Time = 0s, 166.6s, 333.3s, 500s</td>
</tr>
<tr>
<td>5</td>
<td>Decent 1</td>
<td>Constant Altitude Glide at max L/D</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Decent 2</td>
<td>Equilibrium Glide at max L/D</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Assumptions
- Point mass
- Spherical Earth
- Non-rotating earth
- 3DOF EOM

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<sup>DBMS</sup> 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<sup>DBMS</sup> 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 AVDDBMS 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));

%%% Analysis %%%
SWET = AKW*SPLN;

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

%eq on fig 4-13, ECDF from the plot = 280
ALDMAX(AMACH <= 0.8)= sqrt(pi.*(ECDF/4).*(BPLN./SWET));   %eq on fig 4-13, ECDF

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));
\[
\begin{align*}
CL &= \text{repmat}(\text{NaN}, \text{size}(AMACH)); \\
CD &= \text{repmat}(\text{NaN}, \text{size}(AMACH)); \\
\%
\%
\%
\%
\text{Regression Data} \%
\%
\%
\%
AMACH\_MAP &= [1.5, 2.0, 6.0, 12.0]; \\
TAU\_MAP &= [0.01118, 0.041569219, 0.05182958, 0.064, 0.076367532, 0.088772738, 0.10248638, 0.117575508, \ldots, \\
& \quad 0.132574507, 0.147369057, 0.164316767, 0.181019336, 0.198252364, 0.216, 0.234247732, \ldots, \\
& \quad 0.252982213, 0.272191109, 0.29086856]; \\
ALDMAX\_MAP &= [8.83, 6.85, 6.39, 5.99, 5.64, 5.29, 4.98, 4.68, 4.38, 4.11, 3.85, 3.59, 3.34, 3.10, 2.86, 2.61, 2.37, 2.15; \\
& \quad 8.85, 6.39, 5.99, 5.64, 5.29, 4.98, 4.68, 4.38, 4.11, 3.85, 3.59, 3.34, 3.10, 2.86, 2.61, 2.37, 2.15; \\
& \quad 8.50, 6.32, 5.90, 5.53, 5.19, 4.87, 4.59, 4.31, 4.07, 3.80, 3.56, 3.35, 3.12, 2.89, 2.68, 2.46, 2.26, 2.06; \\
& \quad 5.67, 4.68, 4.39, 4.14, 3.90, 3.68, 3.49, 3.30, 3.11, 2.93, 2.78, 2.63, 2.48, 2.33, 2.19, 2.05, 1.91, 1.79]; \\
\%
\%
\%
\%
\text{Subsonic Analysis} \%
\%
\%
\%
SWET &= AKW\times SPLN; \\
ALDMAXS &= \sqrt{\pi\times(\text{ECDF}/4)\times(\text{BPLN}/\text{SWET})}; \\
ALINDS &= 0.45;
\end{align*}
\]
CD0S = 1./(4.*ALINDS.*ALDMAXS.^2);

%%%%%% Transonic Analysis %%%%%%%
SF=SPLN*SFSPLN;

if (SF/(AL^2) < 0.015)
   DCDT_MAX=(1.3862*(SF/AL^2)+0.067)*SFSPLN*CDTW_COR;
else
   DCDT_MAX=(0.9536*(SF/AL^2)^3-1.916*(SF/AL^2)^2+1.3651*(SF/AL^2)+0.1119)*SFSPLN*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;
\[ CD_0(AMACH \geq 1.2 \& AMACH \leq 2.0) = (CD_{2M} - CD_{12M}) / 0.8 \times (AMACH(AMACH \geq 1.2 \& AMACH \leq 2.0) - 1.2) + CD_{12M}; \]

\% linear Drag function \( Y = Y_0 + m(x-x_0) \) from M1.2 to M2

\[ ALD_{MAX}(AMACH \geq 1.2 \& AMACH \leq 2.0) = 0.5 \times \sqrt{1/(CD_0(AMACH \geq 1.2 \& AMACH \leq 2.0) \times ALINDS)}; \]

\%\%\%\%\%\% Analysis \%\%\%\%\%\%\%

\% CLA(AMACH \geq 0.80 \& AMACH < 1.5) = \frac{0.022 - 0.02}{1.5 - 0.8} \times (AMACH(AMACH \geq 0.80 \& AMACH < 1.5) - 0.8) + 0.020; \%

\% Gary (WB)

\% CLA(AMACH \geq 0.80 \& AMACH < 1.2) = 0.0052 \times AMACH(AMACH \geq 0.80 \& AMACH < 1.2) + 0.0202; \%

\% Linear relation from excel file

\%\%\%\%\%\%\% Analysis \%\%\%\%\%\%\%

\% CLA(AMACH \geq 1.5 \& AMACH \leq 2.0) = 0.03 / AMACH(AMACH \geq 1.5 \& AMACH \leq 2.0) ^ 0.75 + 0.00025; \%

\% Gary (WB)

\% CLA(AMACH \geq 1.2 \& AMACH \leq 2.0) = 0.0098 \times AMACH(AMACH \geq 1.2 \& AMACH \leq 2.0) + 0.0379; \%

\% Linear relation from excel file

\% ALIND(AMACH \geq 0.8 \& AMACH \leq 2.0) = 0.47; \%

\% Approx Value

\% ALIND(AMACH \geq 0.8 \& AMACH \leq 2.0) = 0.0651 \times (AMACH(AMACH \geq 0.8 \& AMACH \leq 2.0) ^ 2) - 0.0758 \times AMACH(AMACH \geq 0.8 \& AMACH \leq 2.0) + 0.4083; \%

\% Polynomial expression from excel file

\% CL = CLA \times AOA;

\% CD = CD_0 + ALIND \times CL ^ 2;

\% ALD = CL / CD;

A.1.3 AERO_MD0007

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

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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, 0.102486384, 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; ... 8.50, 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*SFSPLN;
%DBCD0=interp1(C_SA,DBC0_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

```matlab
%% 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)
%i % Load Look Up Table Array Data
if exist('PROP_MD0008') == 0
    load C:\AVDS\AVD_ABE\Utilities\Method_Data\PROP_MD0008.mat;
end

%i % 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;

%i 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
% 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);
EL_V = zeros(Traj_NSTEP,1);
FT_AVAIL_MAX_V = zeros(Traj_NSTEP,1);
FT_V = zeros(Traj_NSTEP,1);
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

G = G0/(1 + ALT_START/RE)^2;
RTURN = V_START^2/(2*qpsg/(AN_LIM^2*G0^2*(G-V_START^2)/(RE+ALT_START))^2);
SIGMA = acos(1/(AN_LIM^2*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;
L1 = sqrt(RTURN^2+X_START^2+Y_START^2);
THT1 = atan2(RTURN*L1*cos(THT3));
THT2 = asin(RETURN/L1);
PSI_FINAL = THT0+THT1+THT2+p;

% CALCULATE 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);

if (FT_AVAIL_MAX < FT & INSUFF_THRUST_CHECK == 'Y')
    disp('            I          ALT            V          GAM            W FT_AVAIL_MAX FT D
    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_AVAIUL_HW~=0) = THRL_VAR;

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

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

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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;
E1_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

if WR < 1
    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+FWPRV*ANPAX; %FROM HOWE
%WOPER=FPVR*(CREW*DAYS)^1.18;
WOPER=0;

WPAX = FWPA*XANPAX;
WCREW = FWCREW*ANCREW;
WFIX = WUN+FWMD+ANCREW;

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\[ WPAY = WPAX + WCARGO; \]
\[ WLG = 0.00916 \times (WS \times SPLN \times WR / 4.44822162) ^ {1.124 \times 4.44822162}; \]

\% WEIGHT BUDGET
\[ OEW = (1 + AMUA) \times (WSTR - WLG + WCHUTE + WENG + WSYS); \]
\[ WSYS = WFIX + FWSYS \times OEW; \]
\[ OEW_W = (WFIX + WENG + WLG) / (1/(1+AMUA) - WSTR_OEW - FWSYS); \]
\[ OWE_W = OEW_W + WPAY + WCREW; \]
\[ if \ ((1/(1+AMUA) - WSTR_OEW - FWSYS) < 0.0) \]
\[ fprintf('AKSTR = %f
'); \]
\[ fprintf('WR = %f
'); \]
\[ fprintf('1/(1+AMUA) = %f
'); \]
\[ fprintf('1/(1+AMUA) - AKSTR*SPLN^0.138 = %f
'); \]
\[ error('CONVERGENCE FAILURE:'); \]
\[ end \]

\% VOLUME BUDGET OWE
\[ VTOTAL = TAU \times SPLN^1.5; \]
\[ VFIX = VUN + AKVMND \times ANCREW; \]
\[ VSYS = VFIX + AKVS \times VTOTAL; \]
\[ VPAY = ANPAX + AKVPAX + WCARGO / RHO_CARGO / G0; \]
\[ VCREW = (AKVCPRV + AKVCREW) \times ANCREW; \]
\[ VVOID = VTOTAL \times AKVV; \]
\% from VPPL = OWE_V \times (WR - 1) / (RHO_PPL \times G0) = VTOTAL - VVOID - VSYS - VENG - VPAY - VCREW
\[ OWE_V = (VTOTAL - VSYS - VP - VPAY - VCREW - VVOID) / ((WR - 1) / (RHO_PPL \times G0)); \]
\[ AIP = RHO_PPL / (WR - 1); \]

\% WEIGHT AND VOLUME BREAKFORWN
\[ OWE = OWE_W; \]
\[ OEW = OEW_W; \]
\[ WSTR = AKSTR \times SPLN^0.138 \times OEW_W; \]
\[ AISTR = WSTR / (SPLN \times AKW); \]
\[ TOGW = OWE \times WR; \]
\[ WPPL = TOG \times (1 - 1/WR); \]
\[ WFUEL = TOG \times FF; \]
\[ WOX = WOX_W \times WFUEL; \]
\[ WP = WENG; \]
\[ WSYS = WFIX + FWSYS \times OEW; \]
\[ AMZFW = OWE + WPAY; \]
\[ AMWE = OWE - WOPER - WCREW; \]
\[ WMARGIN = OEW - (WOPER + WSYS + WSTR + WP); \]

\% VP = TWWR_KVE \times 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
B.1 Input File

% AVD_ABE Input File For AFRL_SFFP.CV10
% function [Variable] = AFRL_SFFP.CV10(Variable)

% ArchGen: AFRL_SFFP.CV10 Control Variables

% Set X-Vector Variable for FZERO solver
% SPLN_INIT m^2 Planform area
% WS_INIT N/m^2 Wing loading (i.e. TOGW/S)
% X0 Numerical values for X-Vector

Variable.SYSPROC.INPUT.SPLN_INIT = 30;
Variable.SYSPROC.INPUT.WS_INIT = 3000;
Variable.SYSPROC.INPUT.X0 = [Variable.SYSPROC.INPUT.SPLN_INIT, Variable.SYSPROC.INPUT.WS_INIT];

% Multipoint Variation
% MODE_DESIGN Design mode
% = 0 for Single Point Without Convergence
% = 1 for Multipoint Variation Without Convergence
% = 2 for Single Point With Convergence
% = 3 for Multipoint Variation With Convergence
% MV_NAMES Variables to be traded
% MV_init Initial value of trade variables
% MV_SS Variable step sizes
% MV_NS Number of Steps

Variable.SYSPROC.INPUT.MODE_DESIGN = 2;
Variable.SYSPROC.INPUT.MV_NAMES = [
    'Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.TAU',
    'Variable.TRAJSEG.ConstMachEnduranceCruise_01_PM_MD0008.INPUT.ENDURANCE_CRUISE',
    'Variable.HW.TotalVehicle.WB.TotalVehicle_WB_MD0003.INPUT.WCARGO'
];
Variable.SYSPROC(INPUT.MV_init = [0.07,0,0];
Variable.SYSPROC INPUT.MV_SS = [0.02,166.67,5930.7];
Variable.SYSPROC INPUT.MV_NS = [3,3,3];

% Constants

% G0 m/s^2 Gravitational acceleration at sealevel
% DTR /degrees Conversion from degrees to radians
% RE m Radius of the Earth

Variable.SYSPROC.INPUT.G0 = 9.81;
Variable.SYSPROC.INPUT.DTR = pi/180;
Variable.SYSPROC.INPUT.RE = 6371e3;

% Look-Up Table Array Variables

% ALT_RANGE m Flight Altitude Range: [Start,End]
% ALT_RES m Flight Altitude Resolution
% V_RANGE m/s Flight Velocity Range: [Start,End]
% V_RES m/s Flight Velocity Resolution
% AOA_RANGE m Flight Altitude Range: [Start,End]
% AOA_RES m Flight Altitude Resolution
% THRL_VAR_RANGE m Flight Altitude Range: [Start,End]
%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 = [0.1,23000];
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  m  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.ALC_AL = 0.6;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.ALC_AL = 0.6;
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Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.ALC_AL = 0.6;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.ALC_AL = 0.6;
Variable.HW.TotalVehicle.GEO.TotalVehicle_GEO_MD0002.INPUT.ALC_AL = 0.6;

% Aerodynamics Disciplinary & Method Variables

%Method: AERO_MD0005  Hardware: BlendedBody_01
%-------------------------------------------------
%ECDQ  Ratio of square of oswald efficency factor to skin friction drag coefficient (e^2/CDF). (HYFAC Vol 2pt2 fig 413 use 160, 200, 240, 280 for wing Body). 280 is recomended for very efficient vehicle

Variable.BlendedBody_01.AERO.BlendedBody_01_AERO_MD0005.INPUT.ECDQ = 280;
%Method: AERO_MD0006 Hardware: BlendedBody_01 %****************************************
%CDTW_COR Transonic drag rise correction factor
%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_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 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_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
%********************************************************************************

%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 %**************************
%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 %************
%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.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 AKCREW)
%AKVMND  m^3/person  Volume of manned fixed systems per crew member (FCREW in hypersonic convergence)
%AKVPAX  m^3/person  Volume of each passenger (formerly VPAX)
%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  m^3/m^3  Minimum OWE weight margin
%ANCREW  Number of crew
%ANPAX  Number of passengers
%EBAND  m^3/0.138  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)
%FWSYS  kg/kg  Weight of variable systems per vehicle dry weight (FSYS in hypersonic convergence)
%RHO_CARGO  kg/m³  Density of the cargo
%RHO_FUEL  kg/m³  Density of fuel (formerly FUEL_DEN)
%RHO_OX  kg/m³  Density of oxidizer (formerly OX_DEN)
%VUN  m³  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.AKVCRV = 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_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;

end
### B.2 Results

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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 National 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
plans to pursue a career aerospace technology acquisition and conceptual design consulting.