Integration of a Portfolio-based Approach to Evaluate Aerospace R&D Problem Formulation Into a Parametric Synthesis Tool

by

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Project Summary

The focus of this study is to improve R&D effectiveness towards aerospace and defense planning in the early stages of the product development lifecycle. Emphasis is on: correct formulation of a decision problem, with special attention to account for data relationships between the individual design problem and the system capability required to size the aircraft, understanding of the meaning of the acquisition strategy objective and subjective data requirements that are required to arrive at a balanced analysis and/or “correct” mix of technology projects, understanding the meaning of the outputs that can be created from the technology analysis, and methods the researcher can use at effectively support decisions at the acquisition and conceptual design levels through utilization of a research and development portfolio strategy.

The primary objectives of this study are to: (1) determine what strategy should be used to initialize conceptual design parametric sizing processes during requirements analysis for the materiel solution analysis stage of the product development lifecycle when utilizing data already constructed in the latter phase when working with a generic database management system synthesis tool integration architecture for aircraft design , and (2) assess how these new data relationships can contribute for innovative decision-making when solving acquisition hardware/technology portfolio problems. As such, an automated composable problem formulation system is developed to consider data interactions for the system architecture that manages acquisition pre-design concept refinement portfolio management, and conceptual design parametric sizing requirements. The research includes a way to:

- Formalize the data storage and implement the data relationship structure with a system architecture automated through a database management system.

- Allow for composable modeling, in terms of level of hardware abstraction, for the product model, mission model, and operational constraint model data blocks in the pre-design stages.
- Allow the product model, mission model, and operational constraint model to be cross referenced with a generic aircraft synthesis capability to identify disciplinary analysis methods and processes.
- Allow for matching, comparison, and balancing of the aircraft hardware portfolio to the associated developmental and technology risk metrics.
- Allow for visualization technology portfolio decision space.

The problem formulation architecture is finally implemented and verified for a generic hypersonic vehicle research demonstrator where a portfolio of technology hardware are measured for developmental and technology risks, prioritized by the researcher risk constraints, and the data generated delivered to a novel aircraft synthesis tool to confirm vehicle feasibility.

Nomenclature

A&D	Aerospace and Defense industry
ACD&P	Advanced component development and prototype
AD2	Advancement degree of difficulty
AFRL	Air Force Research Laboratory
ATD	Advanced technology development
AVM	Architecture variability model
CCM	Components capability model
CD	Conceptual design
CE	Configuration evaluation
CL	Configuration layout
CPM	Capability performance model
CPM	Capability performance model
CPR	Capabilities portfolio review
CV	Candidate vehicle
CVRL	Concept vehicle readiness level
DBMS	Database management system
DoD	Department of Defense
DSM	Design structure matrix
DTR	Developmental and technology risk
DTRts	Developmental and technology risk tables
FCSM	Functional capabilities system model
GHV	Generic hypersonic vehicle
IPA	Innovation portfolio architecture
IPM	Innovation portfolio management
IRL	Integration readiness level

IT	Information technology
KBS	Knowledge-based system
KPP	Key performance parameters
KSA	Key System Attributes
M&S	Modeling and simulation
MDA	Multidisciplinary analysis
MMT	Matrix mapping tool
MRL	Manufacturing readiness level
MSA	Materiel solution analysis
PALMA	Portfolio analysis machine
PAT	Portfolio analysis tool
PFSM	Problem formulation simulation model
PortMan	Portfolio management method
PPM	Product portfolio model
PPM	Product portfolio model
PRD	Product
PS	Parametric sizing
PV	Project vehicle
R&D	Research and Development
RDT&E	Research, development, test and evaluation
SAM	Structural architecture model
SE	Systems engineering
SRL	System readiness level
START	Strategic assessment of risk and technology
TRL	Technology readiness level

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Chapter 1 – Introduction

1.1 Background

The Aerospace and Defense (A&D) industry is facing an uncertain future that will likely change the structure and dynamics of the industry for years, if not decades, to come. As in previous periods of major change, it will be those civil and military groups who are adequately prepared to adapt to the new acquisition and fiscal reality landscapes that will find themselves positioned to grow and take advantage. *"To gain market share, companies need to constantly improve themselves and thus reach the market quicker and reduce lead-time to get ahead of the competition."* [173] Those groups that cannot learn to adapt or unlearn will struggle to remain relevant and may be doomed to fail. In this context, innovation and product research and development (R&D) are a constant target for time-to-value improvements. For example, Deloitte Consulting provided several near-term trends likely to affect new products decision-making at A&D companies [1]:

- Flat or declining defense spending budgets
- Increased efforts to competitors to drive into established market segments
- Increased globalization and realignment in some product segments
- Expected ramp-up of commercial product demand
- Emergence of new entrants into the commercial market space to challenge from emerging economies, disruptive technology, and new business models.

While each of these scenarios is unique and presents its' own set of challenges and problems, the goal in each situation remains the same: to *"explain away the uncertainty in the demand stream for each product* [as effectively as possible]" [2].

This means a researcher investigating the innovation and product lifecycles must: (1) rationalize a decision-making process or (2) request product development capabilities from specialists that capture the relevant and support acquisition decisions [174] and can *"ensure that ideas with the highest return are selected for investigations, that the risk-return profile matches the objectives…, and that the projects address the correct mix of market areas"* [3] At issue now is what does the "correct" acquisition decisions (cost, performance, schedule, etc.) and "correct" mix of products mean?

1.1.1 R&D Effectiveness and the A&D Planning Gap

In terms of R&D effectiveness, Cooper, Edgett, and Kleinschmidt found that this "correctness" generally intends to converge "three overarching objectives: strategic alignment, strategic balance, and maximum return."[4] Menke explains by saying:

> *"Strategic alignment is necessary to enhance the probability that the potential value created by R&D will be realized. R&D does not produce value directly—it only creates assets and capabilities that can be used in downstream organizations (such as manufacturing, marketing, sales, and customer service) to deliver value. If the projects are not aligned with the organization's strategy, the chance that they will be successfully implemented to deliver value is greatly reduced. In a similar vein, strategic balance seeks to balance higher return against higher risk, longer time frames, and other factors, to ensure that simplistic financial projections do not dominate the project selection process. Thus, both strategic alignment and strategic balance are used to help ensure that the most value is delivered from R&D efforts, ensuring that the portfolio doesn't simply contain the projects with the highest potential financial return without proper consideration of the various risks associated with each project."* [5]

Without this convergence there exists the increased risk of a R&D planning gap that starts at the innovation (pre-design acquisition stages) and compounds as it approaches manufacturing and production stages to slow product development, extend time-to-market, constrain competitiveness. [6] In pursuing product acquisition, a combination of cost, schedule, and performance should be in balance to consider the portfolio optimal.

This decision climate is as persist for the A&D Industry today as it was in 1964 when McMillan speaking about the state of technology acquisition within the United States Air Force observed:

> *"The gap I refer to is the planning gap - - our failure to answer adequately the question I just asked … 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?*" [7]

In this sense, the A&D has always taken a cautious attitude towards product development and new technology decisions. Long lead times and high costs lead to technology evolving step-by-step and it is not uncommon to see the implementation of technology lag behind the opportunity to arrive at an operational capability. [174] According to Peter Hollingsworth, from Value-Driven Design Institute, recent history has shown that the Department of Defense (DoD) with a state-of-the-art product development framework sees cost and schedule overruns of 78% and 63% respectively, with the likelihood of trending worse. [8] Consequently, it appears that while organizations can build a strategy and organize products into a portfolio, it still lacks the ability to answer *"what portfolio quality is and how it can act*ually be measured." [9] Dacus and Hagel go on to comment, *"if the only guidance provided to analysts is to do their best to* *minimize cost and time to field while maximizing performance, then making tradeoffs will rely on professional military judgement at best or become arbitrary at worst.*" [10]

To resolve the requirements for effective R&D and A&D planning, a decision-maker could have to quantify a *n*-dimensional mission opportunity roadmap, Figure 1, in order to understand and manage technology risks. To achieve a "correct" portfolio of projects, an end-to-end system capability would require organizations to pass core business and technical information and data from the ideation phase through the product development lifecycle to the consumer. Surely, this is a bottleneck that merits study by researchers. Obviously, this information bottleneck is more indicative of a symptom of the problem of managing A&D R&D, but the potential value-added to organizations that strengthen their decision-making practices and processes is high.

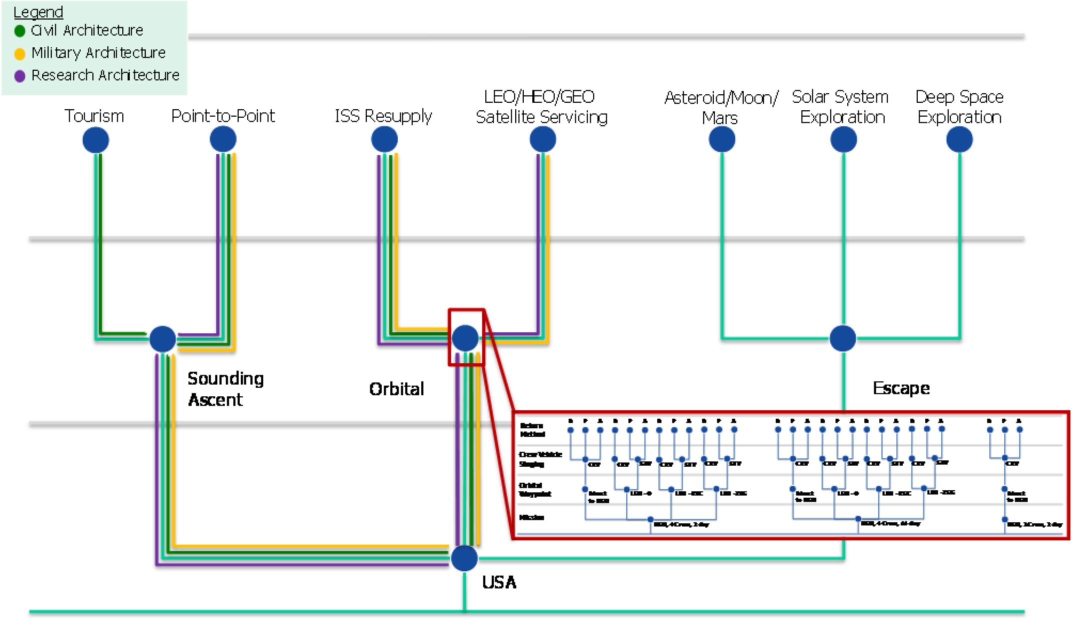


Figure 1-1 *n*-dimensional mission solution space

1.2 Research Scope

This is not a trivial problem that will be solved within the scope of this writing. Nor is it the intention. Instead, the goal is to study the dynamics of this acquisition landscape and propose a system analysis capability that is low cost, short on cycle time, and high on operational flexibility to integrate decision-making solution spaces, Figure 1-2, that can be used to custom create, prioritize, and visualize any number of developmental and technology risk concerns. This capability would allow decision-makers to manage business and technical data and experiment more effectively to better inform the selection of “correct” portfolio projects and products. Successful implementation would enable engineering and/or science –driven processes to be better represented in the business and acquisition data environments. Thus, enabling engineering to proactively participate in the acquisition process. To begin a discussion of the simulation dimensions required, it helps to identify the perspectives that are involved: systems engineering in defense acquisition, conceptual design and the product development life-cycle, and product R&D forecasting tools. Each viewpoint places a varying degree of emphasis on the cost, time, and performance objectives experienced when building a product development analysis tool.

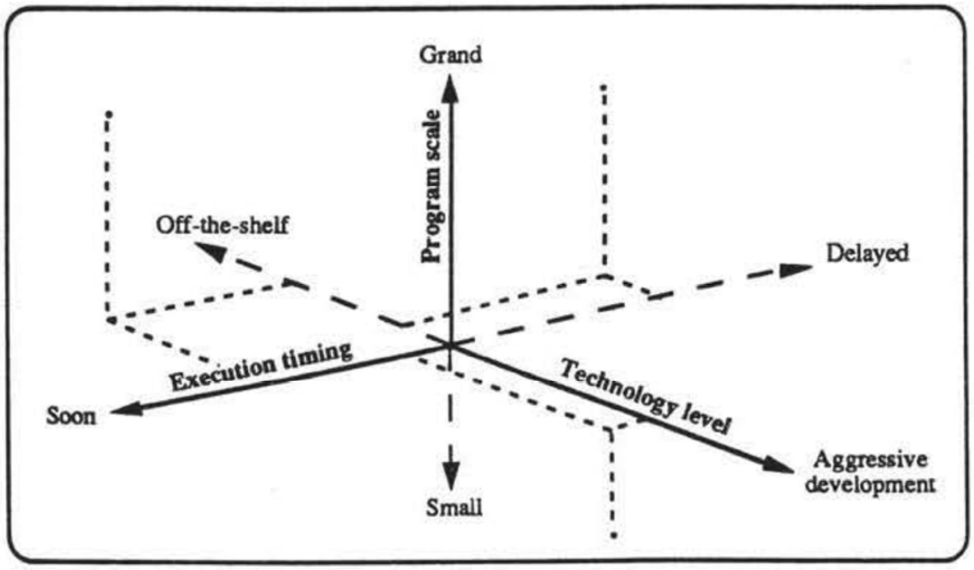


Figure 1-2 Technology Implementation Decision-making Solution Space [11]

1.2.1 Systems Engineering in Defense Acquisition

The systems engineering structure for the defense acquisition systems engineering life-cycle is presented in Figure 1-3. Current defense industry framework is reflected in third column of processes [12]. The primary takeaway from this breakdown indicates that three steps (stakeholder requirements definition, requirements analysis, and architecture design) allow for the "translation of a user's needs into a definition of the system and its architecture through an iterative process that results in an effective design." [13]. Redshaw defines these phases as:

- Stakeholder requirements definition – "establishes a firm baseline for system requirements and constraints" to be met and define 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" [14]

Proper application of the systems engineering process is meant to assure a "robust design with sufficient flexibility and adaptability to facilitate successful completion of the remaining steps and the project." [14] By doing so, stakeholders can identify relationship and attributes, requirements interdependencies, and set criteria to assess attribute value.

Towards this end, study of A&D tools to simulate all or parts of the defense acquisition lifecycle has led the author to observe two distinct lines of thought to accomplish the above drive for value-added described in the previous section: (1) to focus on existing system capability and implement them such that the time and cost associated with making decision becomes more efficient, and (2) investigate new system capabilities to analyze technology options. Both system capability development efforts benefit from improved R&D effectiveness by reducing overlapping and duplicated processes. However, they do not allow for the data generated in the early stages of product development lifecycle to interface directly with the pre-design stages such that the engineering practices can be proactively represented.

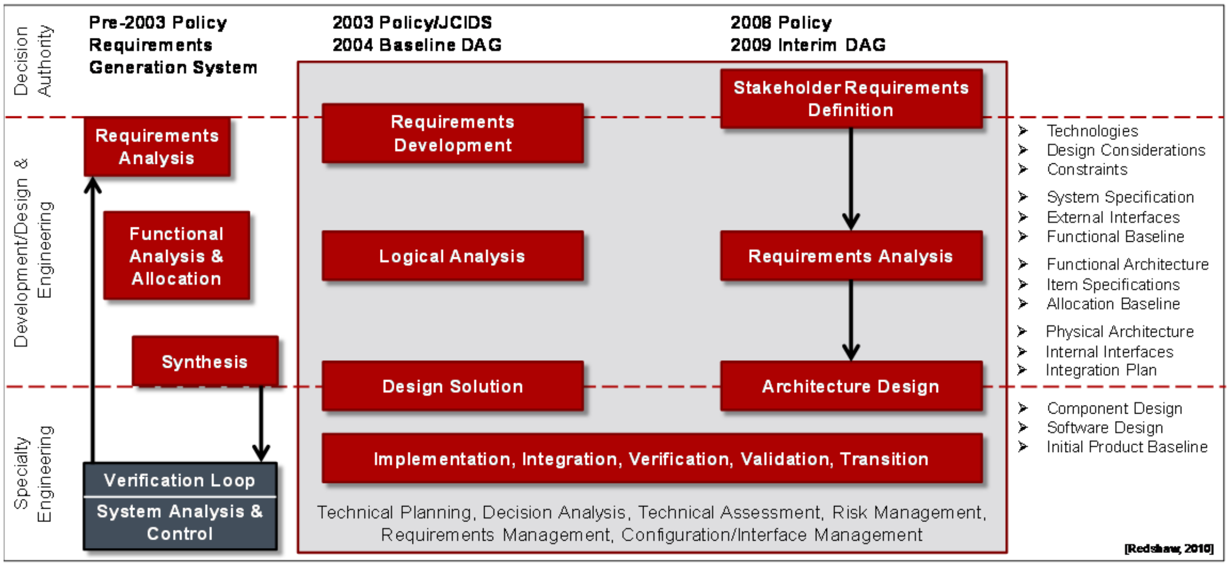


Figure 1-3 Defense Acquisition Systems Engineering Lifecycle (adapted from [14])

This shift in decision strategy would provide an opportunity (i.e. new data relationships) for well-established and verified technical R&D processes to manage requirements, investments, schedules, and risks upfront prior to the conceptual design (CD) stage of the product life-cycle where design freedom is at the maximum. This is in contrast to work traditionally done in the CD stage and onwards that is positioned to be reactive to input from the pre-design phases where the decision-making freedom of what product to design is at the greatest.

1.2.2 Acquisition Requirements, Conceptual Design, and the Product Lifecycle

Traditionally, CD is where the first engineering processes are enacted in the aircraft design process. Relative to the defense acquisition life-cycle (Figure 1-3), and specifically applied to aircraft design, the systems engineering needs are described as the *“the act of designing the aircraft or a segment of it. … Hence, synthesis* [or early stage product development] *is a collection of steps which occur throughout the systems engineering process.”* [15] Torenbeek concisely describes the primary CD activities as:

1. An evaluation of technology that enable an aircraft to be certified for flight worthiness.
2. Technology assessments and comparisons to determine the configuration arrangement of an aircraft design.
3. Identification of the figures-of-merit and/or decision-making variables to prioritize to arrive at an economically superior aircraft. [16]

The process allows various alternatives and possible solutions to be compared and iterated until a product that best meets the design requirements is available. Thus, aircraft CD *“is the evaluation of the level of vehicle performance needed in order to solve a given problem, and/or satisfy a problem-specific objective function. Aircraft synthesis tries to answer the question of ‘how well, if at all’ can you do the things you are required to do.*” [17]

Analytically, there are any number of ways a researcher can go about building a toolset for CD. However, it is the capability of the system to capture different product configurations, technology, and R&D objectives will determine the robustness, flexibility, and fidelity of the aircraft design space to interpretation. Here, robustness refers to the capability of an aircraft design system to simulate multidisciplinary design effects. Flexibility is the task to custom tailor the simulation to the user’s wants within a known time and cost. Fidelity refers to the accuracy of the prediction tool relative to system uncertainty (i.e. approximate empirical aerodynamic methods vs. computational fluid dynamics). While there is a *“vast amount of work concerning the analysis, design, integration of aerospace vehicle systems, there is no standard for this data and knowledge should be combined in order to create a synthesis system [aircraft sizing tool].*” [17] Hence, there is no single “best-practice” or standard on how the CD processes and tools should be assembled and executed. It largely reacts to the needs of the user to determine how-to and how-well a tool can be developed to solve the problem at hand. This scenario is not ideal and is still far away from a standard to design and/or decision-making that a closer investigation of the dynamics within CD is required. In turn, this better understanding will illustrate what contributions can be made to the pre-design acquisition stages.

First, from a systems engineering point-of-view, CD must be able to effectively capture multidisciplinary data requirements within a product development toolset. These data requirements are generally structured and communicated by the acquisition problem in pre-design and result in the simulation inputs and R&D priorities for the researcher. With this knowledge, the conceptual designer will make decisions on what independent and dependent variables to build into the design tool, an objective function that controls the convergence of the design points to explore the design space, a multidisciplinary design analysis process to capture the robustness of the tool in terms of architecture planning, mission selection, technology assessment, vehicle feasibility and balance the resources available to capture the appropriate fidelity of the methods to be selected.[18] Figure 1-4 illustrates this relationship relative to the product development lifecycle. In this example, Mission Definition (Pre-Design) specifies the aircraft operational characteristics, mission constraints, and hardware requirements and CD phase translates the desired states into design alternatives.

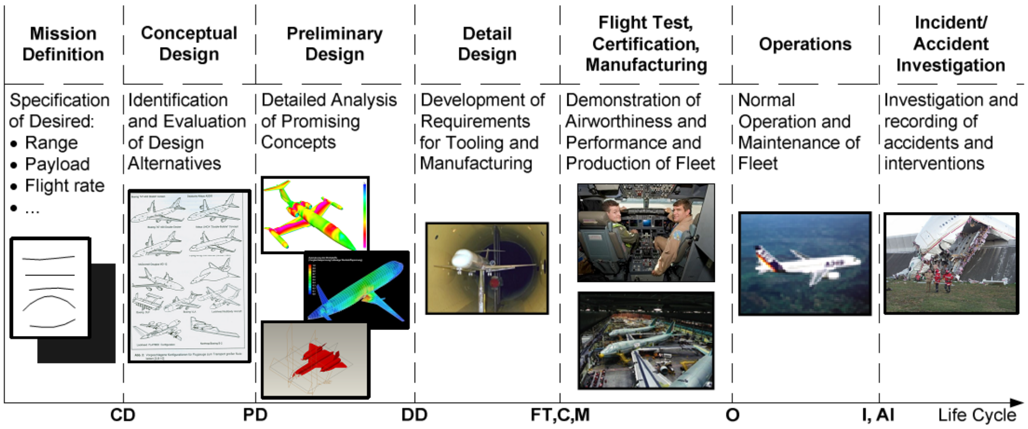


Figure 1-4 Aircraft Product Development Life Cycle [19]

Secondly, with regards to aerospace planning activities during CD, it is interesting to observe that qualitatively there is a noticeable change in product development vehicle sizing tool capability that spans the major eras of technology change, Figure 1-5. Space technology in particular, due to its' historically disruptive potential and cyclical nature, sees the robustness of the system tool capability or the ability to study various aircraft designs and technology implementations decrease just as the multidisciplinary data relationships or variables (i.e. data interactions between geometry, propulsion, aerodynamics, structures, weights, performance, cost, etc.) modelled are reduced, Figure 1-5. Additionally, this latter behavior corresponds to a significant decrease in uncertainty built into the tool. Both tool design approaches have strengths and weaknesses, but it is all the more interesting that they are meant solve a similar space architecture planning problem. In the Apollo-Era decisions were made with large solution spaces, where space architectures options are traded and optimized for cost performance, and technology growth. CD tools are shown to be more robust in simulating vehicles, technologies, and mission deterministic relationships, provided the flexibility to quickly change or update the simulation based on changing circumstances, and could balance the fidelity of the methods used as required. The SLS-Era sees more focused design spaces with limited robustness in application, flexibility limited to problem at hand with longer lead times, and a higher fidelity of methods to minimize the risks as much as allowable. If these trends from holistic correctness to detail analysis accuracy continue, it could signal a challenge to formulate a problem for innovation and R&D to be done effectively. Again, it is hard to argue which tool capability is best, though this notion does highlight that CD sizing tools have always found a way to adapt with the resources available and decision-making situations.

Now the question becomes that since it is shown that CD tools possess a strong capability for multidisciplinary analytic integration, to forecast (architecture, mission, technology, and/or aircraft performance) within an environment of maximum design freedom, and minimum design data, Figure 1-6, what data synthesis tool structure is best suited to accept the information pre-design researchers use to communicate hardware, technology, and technical risk data to pass forward to the designers? (Note: At this point the business risk processes are considered well established to study strategic alignment, strategic balance, and maximum return decisions and beyond the scope of the current research.)

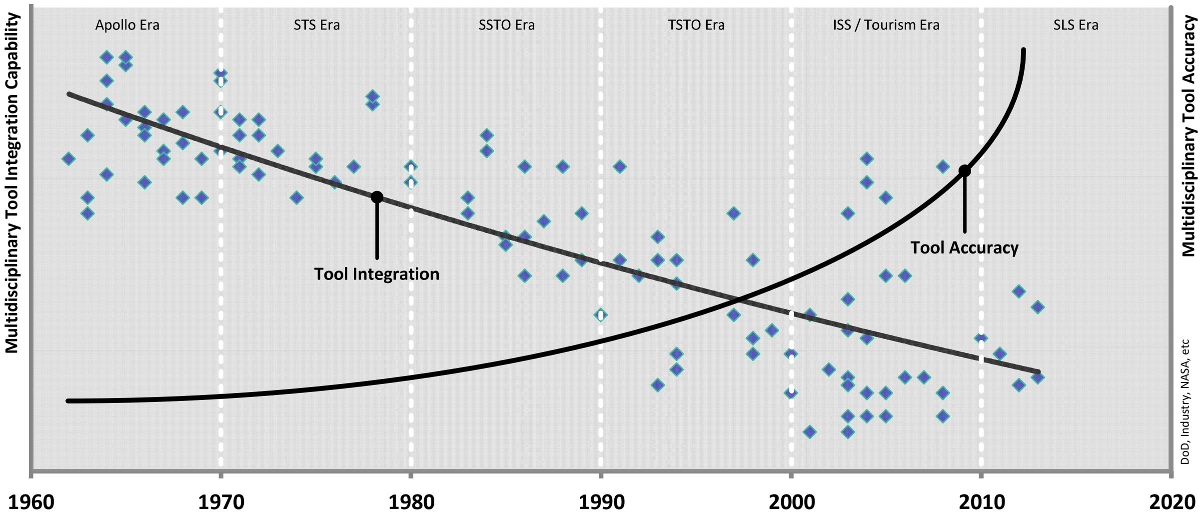


Figure 1-5 Product Development Tool Multidisciplinary Data Integration and Accuracy [20-80]

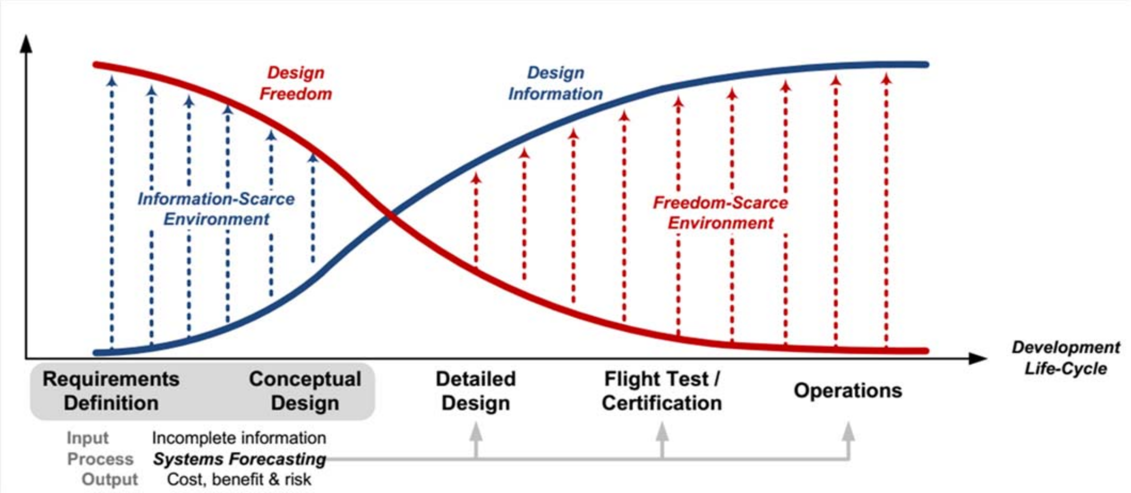


Figure 1-6 Aerospace Product Development Life Cycle [81]

It is observed, that there has not been much work found to support analytical modeling of product development risks in pre-design. What little research that has been found favors: (1) a set of scenario-based figures-of-merit (i.e. technology readiness levels) or rough-order-of-magnitudes that result in a large decision space with limited sensitivity to capture aircraft performance as described in References [3][82-85][110] or (2) high cost, high certainty data solutions that result in small decision spaces also with limited sensitivity to capture aircraft performance as shown in References [86-88]. Either way, both approaches suffer from the same problems such as inconsistent alignment of data uncertainties, low degree of multidisciplinary data integration to capture performance effects, limited ability to know what data relationships are best suited to answer R&D questions, and limited ability to directly grow the data needs as the product moves from pre-design into the design stages. Scott Mathews, innovation portfolio researcher at Boeing, says to close this knowledge gap several challenges must be overcome:

- “Concepts have little value, at least initially
- Most concepts have available only a small amount of “working” data, at least initially
- Most concepts aren’t worth pursuing very far, but all must be developed to some point in order to identify worthy concepts
- The worth of a particular concept is difficult to determine without a well-articulated strategy (which does not yet exist)
- The wide mix of concepts makes comparison challenging.” [89]

Consequently, there is a “gray zone” of opportunity, Figure 1-6, that represents a multistep change in multidisciplinary data creation capability between the Requirements Definition (Pre-Design) and CD. Bilbro explains the *“root cause of such events has often been attributed to ‘inadequate definition of requirements.’ If such were indeed the ‘root cause,’ then correcting the situation would simply be a matter of requiring better requirements definition*”, though represents only part of the problem. [90] Therefore, the potential for integration of CD aircraft synthesis processes into the acquisition stages leaves much opportunity to contribute to problem formulation. Conceptually, this capability will build a mechanism to translate CD aircraft performance data relationships into data blocks accessible in pre-design. The net value-added allows the acquisition decision-maker to holistically consider hardware, technology, mission, and operations constraints with the same analytical depth and flexibility as vested within the business practices. Thus, providing CD researchers a means to directly access and participate in conversations with acquisition decision-makers.

1.3 Solution Concept – Automation of CD Sizing Process into Pre-Design Acquisition Stages

The challenges identified through this research are driven by the desire of increasing value added to the R&D and aerospace planning processes to better support the pre-design technology acquisition decision analysis, and ultimately the CD process. The goal is to propose an integrated modeling and simulation framework to directly incorporate the multidisciplinary character and data generation tools capable of vehicle sizing to enhance innovation directly through reduced evaluation time towards product design points. An acceptable outcome will allow synthesis to better move at the pace of business in order to assist researchers to make more informed configuration, mission, technology tradeoffs. With this emphasis, the modelling and simulation (M&S) environment requires: (1) the ability to formulate the R&D problem, (2) to determine what design constraining knowledge and disciplinary information and data interactions is required to initialize the CD process, and (3) a data integration framework to interface with synthesis of CD sizing tools to accelerate information transfer. The underlying M&S capability assumption implies that the tool implementation will be capable of productivity and efficiency benefits from the automation of the environment and allocation of resources. This is not to say that existing pre-design and CD sizing tool capabilities would be abandoned but rather enhanced to enable organizations to innovate and experiment at low-cost with a quick turnover of lessons learned fail-cycles.

For this research, it is the automation of the data relationships within aircraft CD synthesis processes that is of concern. Specifically, how can modernization for information technology (IT) and an innovative implementation of multidisciplinary analysis (MDA) data relationships impact the pace of business acquisition researchers are accustomed to? Two scenarios for solution concept applications are explored towards aircraft vehicle design. However, before proceeding, the components for creating CD tools or synthesis systems is discussed. According to Gonzalez: *"Synthesis systems are comprised of disciplinary analysis modules that are [systematically organized and] run sequentially, where the outputs of a discipline may serve as inputs to one or more subsequent disciplines."* [17] Figure 1-7 illustrates a product development tool for a hypersonic vehicle design problem in in design structure matrix (DSM) form. The order of disciplinary method modules and multidisciplinary independent and dependent data relationships is paramount to determining the robustness, flexibility, and fidelity of the tool capability.

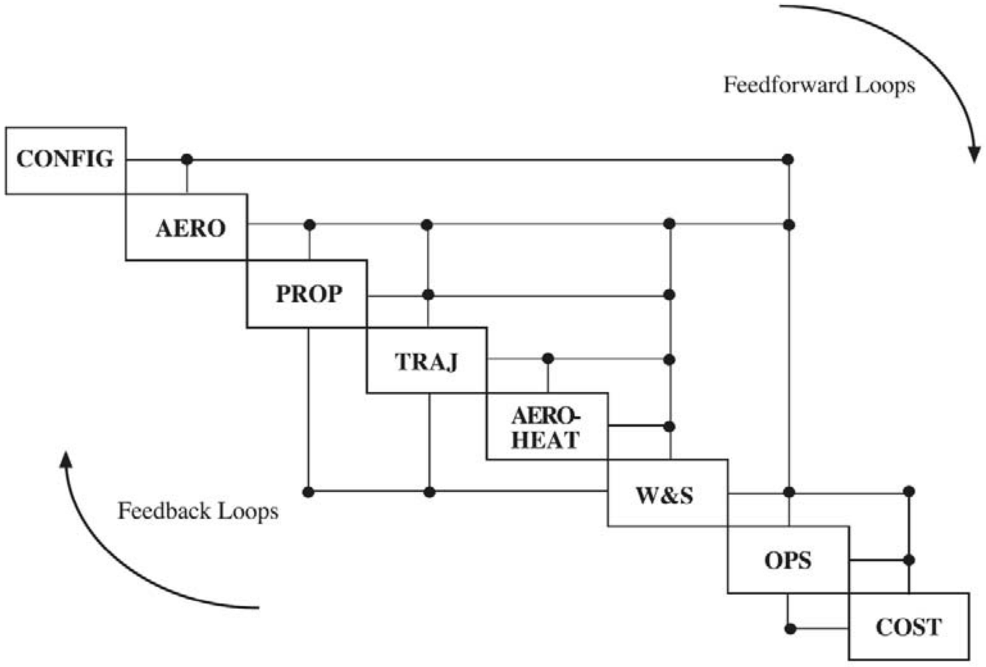


Figure 1-7 Design Structure Matrix for Hypersonic Launch Vehicle [91]

Seven aspects of CD tool system capability, as adapted from Tamaskar et al, are used to discuss the product development tool performance:

- “level of abstraction
- system representation: structure/function
- size which is indicative of number of components and interactions
- heterogeneity of components and interactions
- network topology
- dynamics involving different modes of operation
- off-design interactions” [92]

This is done to investigate the relationship between the structural (possible) versus functional (wanted) data relationships for CD sizing tools and study how crossover in design phase data interactions affect automation during strategy formulation in pre-design. The purpose being to determine how the contribution when initializing engineering practices affects the acquisition decision-making process, from a SE perspective.

At this point the research experiment is outlined to get a better feeling of the problem using two scenarios: (1) vertically integrated product development tools and (2) horizontally integrated product development tools.

1.3.1 Vertically Integrated CD Synthesis Tool

A vertically integrated toolset is described as a system that specializes in answering a specific engineering question. Sopheon Consulting, an innovation management and new product development performance group, attributes this “silo” behavior to eras of technology change, and periods of rapid innovation where the availability of time, effort, and access to resources being high, Figure 1-8. [94] To this end, Chudoba, Huang, Coleman, Gonzalez have identified 126 unique Product Development Sizing Tools for aircraft synthesis developed over the last 50 years, Table 1-1.[17][21][94][95] Recall that during the CD phase, each of these tools is developed as a closed system architecture that will be restricted to the multidisciplinary data dynamics and uncertainties desired by the researcher. While this makes the R&D problem solvable, in terms of robustness, flexibility, and fidelity the system data integrations remain static or fixed. Unfortunately, this heterogeneous structure of product, process, and disciplinary method implementation, combined with disparate data interactions leaves some vulnerabilities.

1. Dependability, predictability, and correctness are key factors that researchers rely on to control the information requirements, and contain cost and schedule in design. However, each system architecture has been built with whatever system engineering implementation seemed appropriate. To solve a new problem or new disciplinary functions within the same architecture becomes difficult to scale.
2. This scaling concept is best described as system complexity and characterized for aircraft as "levels of abstraction, type of representation, size, heterogeneity of components and interactions, network topology factors such as coupling, modularity, modes of operation and off-design interactions." [92] In general, as an existing tool is modified, layers of data interactions can build in an unstructured fashion with varying degrees of uncertainty until to becomes unusable.
3. Each layer of complexity increases the friction and effort required to unify the multidisciplinary variables, and decreases the speed by which the new requirements for system architecture is operational. Consequently, the iterative implementations of new topology structures can impact the potential and/or limit of R&D value-added in comparison to the resources allocated for CD tool development.
4. Unifying the multidisciplinary dynamics into a new custom system architecture is an agreeable approach when the time is available but can limit the ability to reduce cycle-times, innovate, and compete in the Aerospace Industry. This does not necessarily

cancel the vertically integrated approach but can that leads to a technology development strategy that overlooks opportunities.

Of interest presently is what opportunity is afforded to characterize vertically integrated product development tool circumstances within the pre-design decision space?

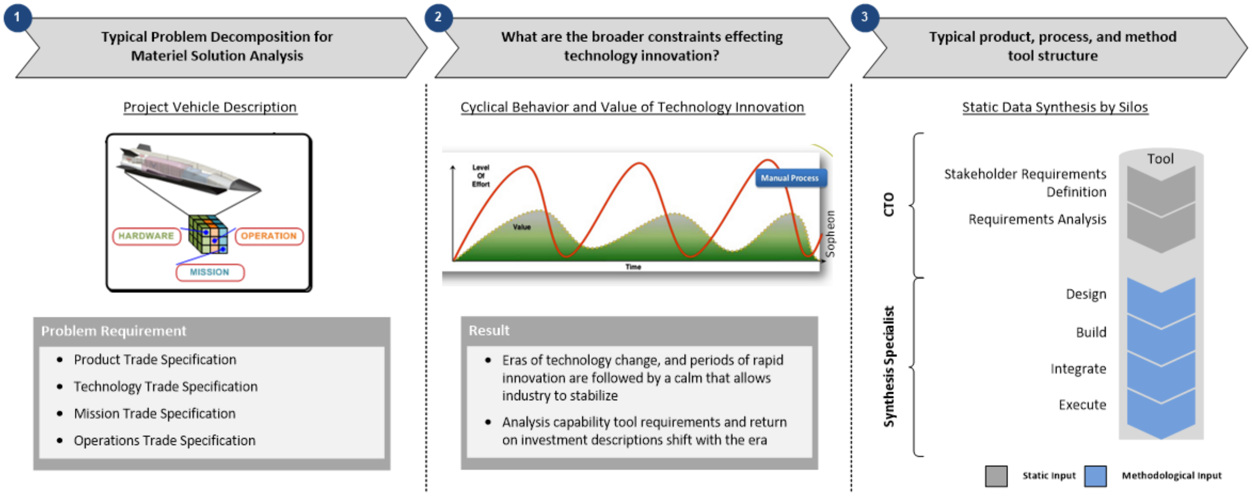


Figure 1-8 Vertically Integrated Product Development Tool Breakdown (middle picture [93])

Table 1-1 Aircraft Synthesis Systems [21][94][95]

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

AircraftDesign	(-)	University of Osaka Prefecture	Aircraft	1990
APFEL	(-)	IABG	Aircraft	1979
Aprog	Auslegungs Programm	Dornier Luftfahrt	Aircraft	
CADE	Aircraft Synthesis and Analysis Program	Vought Aeronautics Company	Fighter Aircraft	1974
ASCENT	(-)	Lockheed Martin Skunk Works	AeroSpace Vehicle	1993
ASSET	Advanced Systems Synthesis and Evaluation Technique	Lockheed California Company	Aircraft	Before 1993
Altman	Design Methodology for Low Speed High Altitude UAV's	Cranfield University	Unmanned Aerial Vehicles	Paper 1998
AVID	Aerospace Vehicle Interactive Design	N.C. State University, NASA LaRC	Aircraft and AeroSpace Vehicle	1992
AVSYN	?	Ryan Teledyne	?	1974
BEAM	(-)	Boeing	?	NA
CAAD	Computer-Aided Aircraft Design	SkyTech	High-Altitude Composite Aircraft	NA
CAAD	Computer-Aided Aircraft Design	Lockheed-Georgia Company	Aircraft	1968
CACTUS	(-)	Israel Aircraft Industries	Aircraft	NA
CADE	Conceptual Aircraft Design Environment	McDonnel Douglas Corporation	Fighter Aircraft (F-15)	1974
CAP	Configuration Analysis Program	North American Rockwell (B-1 Division)	Aircraft	1974
CAPDA	Computer Aided Preliminary Design of Aircraft	Technical University Berlin	Transonic Transport Aircraft	1984-
CAPS	Computer Aided Project Studies	BAC Military Aircraft Devision	Military Aircraft	1968
CASP	Combat Aircraft Synthesis Program	Northrop Corporation	Combat Aircraft	1980
CASDAT	Conceptual Aerospace Systems Design and Analysis Toolkit	Georgia Institute of Technology	Conceptual Aerospace Systems	late 1995
CASTOR	Commuter Aircraft Synthesis and Trajectory Optimization Routine	Loughborough University	Transonic Transport Aircraft	1986
CDS	Configuration Development System	Rockwell International	Aircraft and AeroSpace Vehicle	1976
CISE	(-)	Grumman Aerospace Corporation	AeroSpace Vehicle	1994
COMBAT	(-)	Cranfield University	Combat Aircraft	
CONSIZ	CONfiguration SIZing	NASA Langley Research Center	AeroSpace Vehicle	1993
CPDS	Computerized Preliminary Design System	The Boeing Company	Transonic Transport Aircraft	1972
Crispin	Aircraft sizing methodology	Loftin	Aircraft sizing methodology	1980
DesignSheet	(-)	Rockwell international	Aircraft and AeroSpace Vehicle	1992
DRAPO	Définition et Réalisation d'Avions Par Ordinateur	Avions Marcel Dassault/Bréguet Aviation	Aircraft	1968
DSP	Decision Support Problem	University of Houston	Aircraft	1987
EASIE	Environment for Application Software Integration and Execution	NASA Langley Research Center	Aircraft and AeroSpace Vehicle	1992
EADS				
ESCAPE	(-)	BAC (Commercial Aircraft Devision)	Aircraft	1995
ESP	Engineer's Scratch Pad	Lockheed Advanced Development Co.	Aircraft	1992
Expert Executive	(-)	The Boeing Company	?	
FASTER	Flexible Aircraft Scaling To Requirements	Florian Schieck		
FASTPASS	Flexible Analysis for Synthesis, Trajectory, and Performance for Advanced Space Systems	Lockheed Martin Astronautics	AeroSpace Vehicle	1996

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

NEURAL NETWORK FORMULATION	Optimization method for Aircrat Design	Georgia Institute of Technology	Aircraft	1998
ODIN	Optimal Design INtegration System	NASA Langley Research Center	AeroSpace Vehicle	1974
ONERA	Preliminary Design of Civil Transport Aircraft	Office National d'Etudes et de Recherches Aérospatiales	Subsonic Transport Aircraft	1989
OPDOT	Optimal Preliminary Design Of Transports	NASA Langley Research Center	Transonic Transport Aircraft	1970-1980
PACELAB	knowledge based software solutions	PACE	Aircraft	2000
Paper Airplane	(-)	MIT	Aircraft	
PASS	Program for Aircraft Synthesis Studies	Stanford University	Aircraft	1988
PATHFINDER		Lockheed Engineering and Sciences Co.	Supersonic Commercial Transport Aircraft	1992
PIANO	Project Interactive ANalysis and Optimisation	Lissys Limited	Transonic Transport Aircraft	1980-
POP	Parametrisches Optimierungs-Programm	Daimler-Benz Aerospace Airbus	Transonic Transport Aircraft	2000
PrADO	Preliminary Aircraft Design and Optimisation	Technical University Braunschweig	Aircraft and AeroSpace Vehicle	1986-
PreSST	Preliminary SuperSonic Transport Synthesis and Optimisation	DRA UK	Supersonic Commercial Transport Aircraft	
PROFET	(-)	IABG	Missile	1979
RAE	Artificial Intelligence Supported Design of Aircraft	Royal Aircraft Establishment, Farnborough	Aircraft conceptual design	Early1970's.
RAM		NASA	geometric modeling tool	1991
RCD	Rapid Conceptual Design	Lockheed Martin Skunk Works	AeroSpace Vehicle	
RDS	(-)	Conceptual Research Corporation	Aircraft	1992
RECIPE	(-)	?	?	1999
RSM	Response Surface Methodology			1998
Rubber Airplane	(-)	MIT	Aircraft	1960s-1970s
Schnieder				
Siegers	Numerical Synthesis Methodology for Combat Aircraft	Cranfield University	combat aircraft	Late 1970s
Spreadsheet Program	Spreadsheet Analysis Program	Loughborough University	Aircraft Design Studies	1995
SENSxx	(-)	DaimlerChrysler Aerospace Airbus	Transonic Transport Aircraft	
SIDE	System Integrated Design Environment	Astrox	?	1987-
SLAM	Simulated Langauge for Alternative Modeling	?	?	
Slate Architect	(-)	SDRC (Eds)	?	
SSP	System Synthesis Program	University of Maryland	Helicopter	
SSSP	Space Shuttle Synthesis Program	General Dynamics Corporation	AeroSpace Vehicle	
SYNAC	SYNthesis of AirCraft	General Dynamics	Aircraft	1967
TASOP	Transport Aircraft Synthesis and Optimisation Program	BAe (Commercial Aircraft) LTD	Transonic Transport Aircraft	
TIES	Technology Identification, Evaluation, and Selection	Georgia Institute of Technology		1998
TRANSYN	TRANsport SYNthesis	NASA Ames Research Center	Transonic Transport Aircraft	1963- (25years)

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

1.3.1.1 Implementing R&D Data Automation Strategy for Pre-Design

For a vertically integrated toolset, the nature of data automation is examined by using a practical example. Suppose that the acquisition researchers are looking to advance hypersonic vehicle technology areas for aerodynamics, propulsion, thermodynamics, and stability and control alternatives.. They range from evolutionary adaptations based on an existing knowledge-base to more innovative options that do not have an established expertise. The objective is to recognize which technology options are most feasible towards building a high-speed infrastructure and understanding the technology design risks within a 5-year time period.

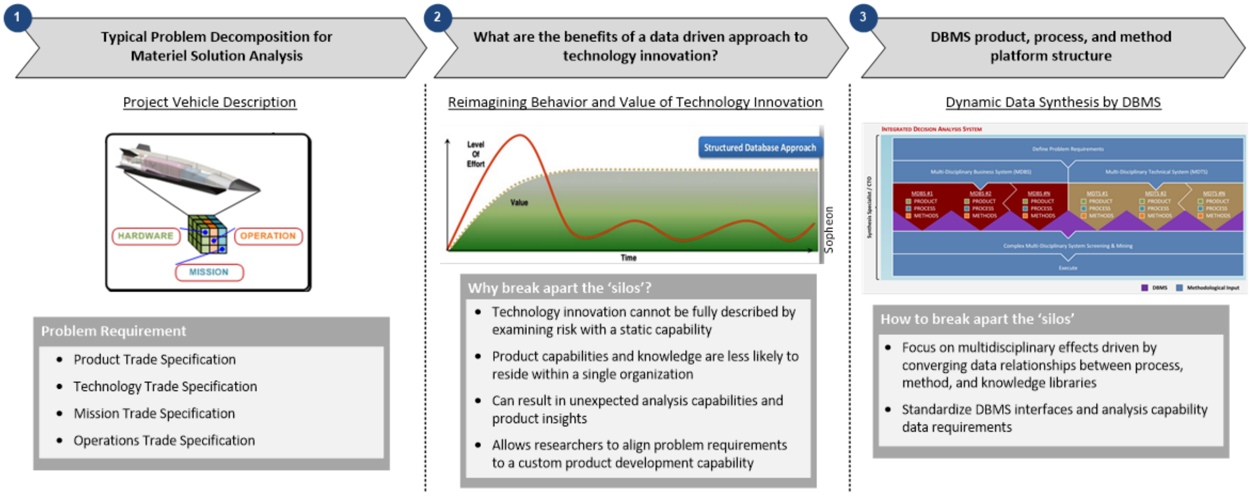
Using the silo based approach, no one sizing tool can solve this problem, however a cluster of tools can be available to reinforce the knowledge gaps and integrate the technology as an aircraft. The burden now becomes to sort out the varying degrees of robustness, flexibility, and fidelity to arrive at the data needs to initialize the CD tools. As Figure 1-5 demonstrates and by taking the criteria developed by Tamaskar et al into account(level of abstraction**,** system structure and function, number of components and interactions, heterogeneity of components and interactions, and network topology), each sizing tool will require a contrasting set of inputs.[92] Thus, to unify these numerous metrics into a singular approach that can make R&D

processes more effective is clearly limited since the CD tools must be executed in silos during the data generation phase. Consequently while the tools are capable, the automated solution to formulate the problem data would be unusable for pre-design since the information requirements are inconsistent, incomplete and/or incapable of scalability and maintainability from an IT perspective.

1.3.2 Horizontally Integrated CD Synthesis Tool

Compared to the vertically integrated approach, the horizontally integrated product development tool enables researchers to reduce costs by eliminating redundant processes that slow R&D planning. The focus is on moving from tools with separate silos with a classic IT infrastructure to a semantically composable tool construction with an open ended IT structure for systematic update (i.e. product and methods) and scalability (problem formulation). Oster defines composable system design as a "systems architecture and development concept focusing on composing new systems from known components, designs, product lines and reference architectures as opposed to focusing on 'blank sheet' designs based on requirements decomposition alone." [Oster PhD96] Ideally, for aircraft sizing there is a desire to capitalize on the large investments in the IT space in order to shift the silo dominated strategy to a platform-based database management system (DBMS), see Figure 1-9, for the purpose of automating the solution of building sizing tool capabilities. The DBMS allows for the capture of system variability features a reference architecture that decomposes design rules into components that are cataloged and supports reuse by ensuring data interfaces are compatible.

The resulting R&D sizing capability provides an objective means of balancing technology inputs to the aircraft design problem and provides an advantage in reduction in cycle time and costs towards tool execution. Whereby deciding the level of abstraction**,** system structure and function, number and heterogeneity of components are tailored to the CD researcher needs, and number and heterogeneity of data interactions, and network topology are aligned are specified by the DBMS. However, Straub cautions that a “problem with increased automation is a loss of visibility of the adequacy and accuracy of the inputs and this factor should remain paramount as the synthesis systems [sizing tools] grow in size and complexity.”[97]



Problem Requirement

- Product Trade Specification
- Technology Trade Specification
- Mission Trade Specification
- Operations Trade Specification

Why break apart the ‘silos’?

- Technology innovation cannot be fully described by examining risk with a static capability
- Product capabilities and knowledge are less likely to reside within a single organization
- Can result in unexpected analysis capabilities and product insights
- Allows researchers to align problem requirements to a custom product development capability

How to break apart the ‘silos’

- Focus on multidisciplinary effects driven by converging data relationships between process, method, and knowledge libraries
- Standardize DBMS interfaces and analysis capability data requirements

Figure 1-9 Horizontally Integrated Product Development Tool Breakdown (middle picture [93])

To this end, the problem of CD product synthesis system justification relies on an ability to demonstrate inherent benefits. Two approaches are recognized which promote a horizontally integrated architecture: (1) hybrid-silo DBMS and (2) zero-silo DBMS.

Recently there has been effort formulate the hybrid silo DBMS by Kraft [98] at the United States Air Force, Carty [99] and Oster [100] for Lockheed Martin (Figure 1-10), and Heinze from the University of Braunschweig [101]. Value is derived from an architecture that exists as a data integration layer outside the vertically integrated silos and acts as a “cross-domain common digital surrogate” [98] to connect existing sizing tools. As such, the capability is still bounded by whatever robustness, flexibility, and fidelity available to the simulation. This means the digital surrogate might require more information than the problem has available. Though, since the data relationships and topology are well understood, the opportunity exists to remove process redundancies, manage the common data requirements, and with some effort correct R&D problem specific multidisciplinary effect knowledge gaps.

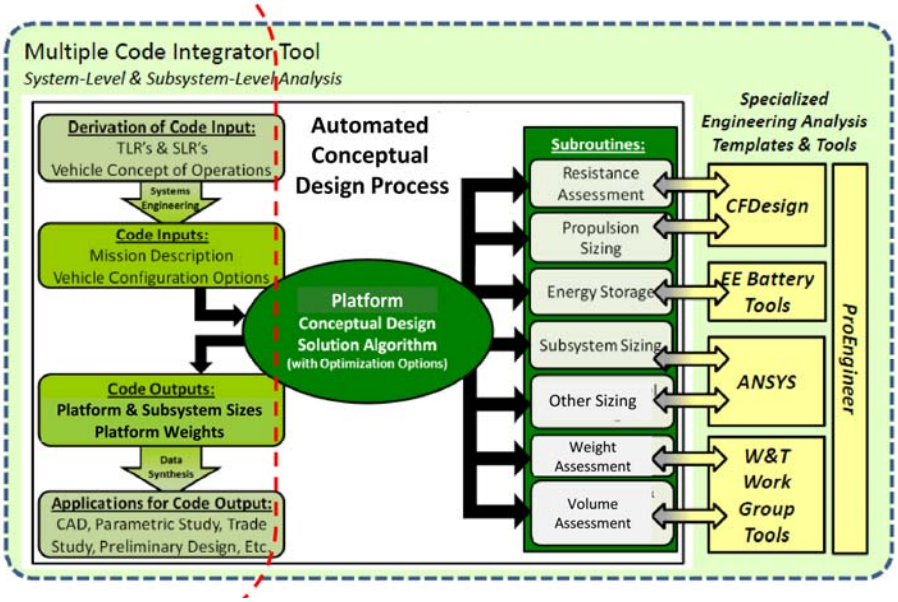


Figure 1-10 Horizontally Integrated Hybrid Silo DBMS Sizing Tool - Lockheed MBDE Digital Tapestry [100]

By contrast, the zero silo DBMS, such as AVDS DBMS [17] and pyOFT [102], benefits from the composable platform being created from the ground up. According to Gonzalez, *"[t]his means that the synthesis system has a framework where methods can be chosen, and interfaces created based on those choices. In this setting the synthesis environment is providing methods for the user to choose, and once chosen is directing their integration* into a single system." [17] Upfront setup costs will initially penalize this approach since it requires a design methodology to automate the DBMS data interfaces and retooling of the technology disciplinary methods to match the DBMS. However, once implemented in concert with the removal of process redundancies and unified management of the common data blocks, the robustness, flexibility, and fidelity are free to adapt to the researcher needs. Ultimately the opportunity for reuse will pay dividends once the system grows and only methods for new innovation problems need to be added.

1.3.2.1 Implementing R&D Data Automation Strategy for Pre-Design

Referring back to the vignette at the start of Section 1.3.2.1, the acquisition phase R&D data automation strategy is considered for horizontally integrated sizing tools.

Study of the hybrid silo DBMS strategy reveals that to a lesser degree it faces many of the same problems towards automation as experienced by vertically integrated tools. Specifically, the inconsistency and incapability in pre-design data input scalability is partially resolved. There is still concern the data interfaces can be entangled by layers of system complexity that request of the acquisition researcher information that is unavailable in pre-design unless an alternative silo based tool option is added. Whereby the data-automation data-interfaces would have to be regularly updated once the new product development tool is integrated.

For the zero silo DBMS option, analysis has shown the concept to generate sufficient parametric design robustness, flexibility, and fidelity as to complement pre-design decisions within a DBMS. Though the system is currently in the prototype stages, conversations with Gonzalez and the Aerospace Systems Engineering Lab at the University of Texas at Arlington have shown advantageous reciprocity between this research and the zero silo DBMS. [103] For instance, this framework has the widest application of any of the options reviewed and while. Data requests are consistent and adaptable based on problem formulation whilst being capable of execution and system scaling in a structured manner. In short, zero silo DBMS benefits from an ability to adjust the interactions of disciplinary modules to suit the needs of the acquisition researcher. In pursuing this strategy, a saving in time and properly guided manpower resources can provide an outlet for faster design innovation.

1.4 Research Questions

Preliminary qualitative results show the relevance of the proposed framework, see Figure 1-11. The first purpose of the current research is to establish a modeling methodology to "Define Problem Requirements" in order to effectively communicate design, technology, mission, and operation decisions from the pre-design stages. Subsequent efforts will continue to advance the data relationship automation logic to provide a broader scope of application and ease of modification for increased structural and functional system visibility. A second aim is to study if and how the problem formulation models can be included in the acquisition pre-design framework and still size an aircraft. Finally, this thesis intends to address the concurrent use of current technology portfolio risk methods (standard for pre-design evaluation) be a cost effective means to support R&D decision-making and strategy maturation. The research questions are formulated as follows:

[RQ1] How should a problem formulation model be built to be suitable for acquisition strategic alignment and sizing tool design to automate data relationships?

[RQ2] Is it possible to design a data integration or composable system architecture with reference to pre-design problem formulation and multidisciplinary effects modeling?

[RQ3] Which composable problem decomposition methodology could enable data reuse and scalability?

[RQ4] How could the concurrent use of technology and developmental risk methods support R&D innovation strategy portfolio maturation?

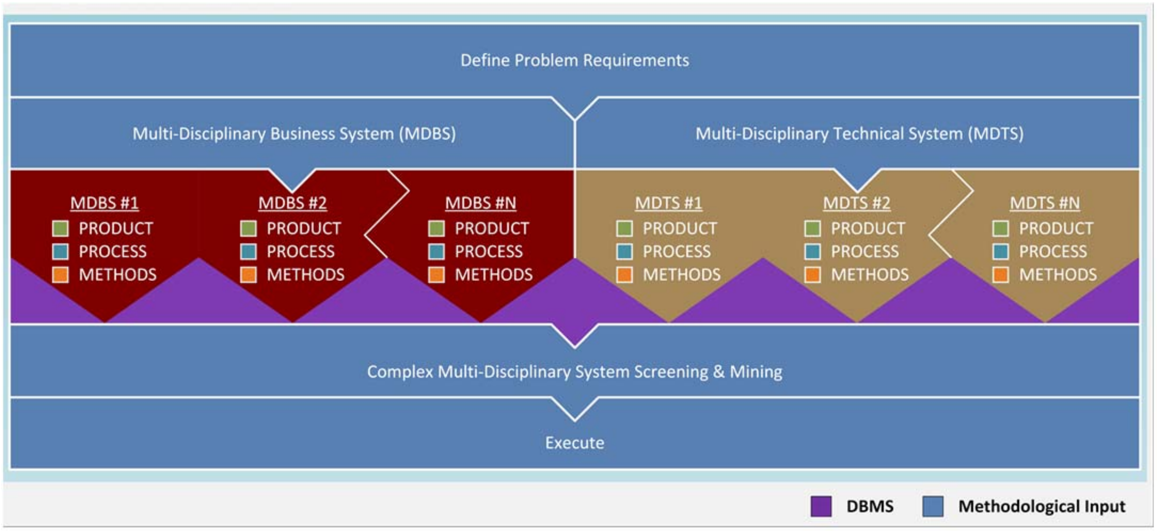
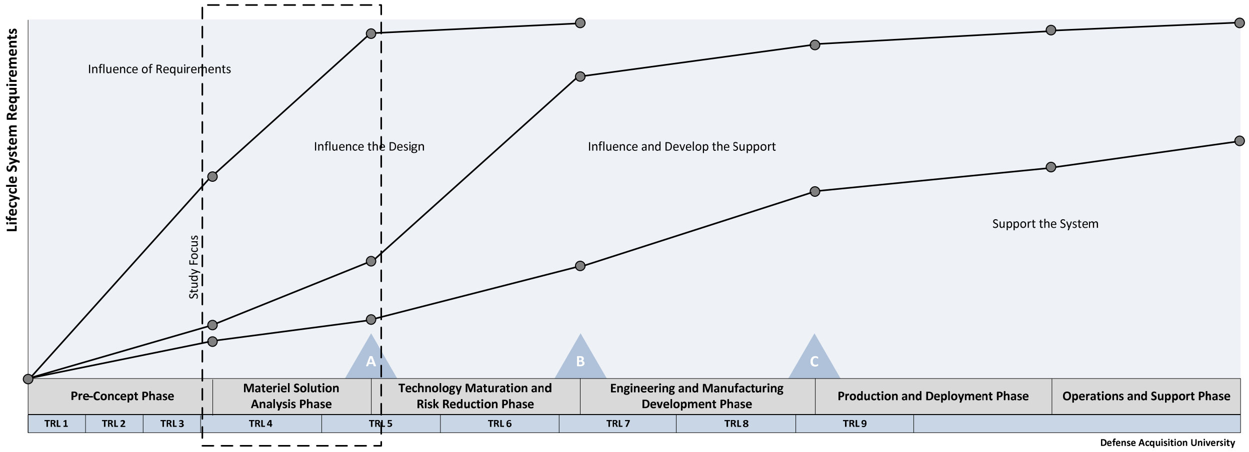


Figure 1-11 Problem Requirements Interface with Zero Silo DBMS Approach

Chapter 2 – Strategies for Problem Formulation Automation

Automation of the of the pre-design acquisition data relationships for CD sizing tool building is no trivial task. Figure 2-1 shows all of the decision spaces that must be resolved to meet defense acquisition systems engineering requirements relative to the current priority of the Materiel Solution Analysis (MSA) Phase, see the dashed-line box. During the MSA Phase, researchers are tasked for *“analysis and other activities needed to choose the concept for the product that will be acquired, to begin translating validated capability gaps into system-specific requirements, including the Key Performance Parameters (KPPs) and the Key System Attributes (KSAs), and to conduct planning to support a decision on the acquisit*ion strategy of the product.*”* [DAU. [104] Moreover, the MSA scope provides most decision freedom to balance concerns that influence the vehicle requirements (pre-design) and influence the design (CD). The challenge is to determine how best to deploy a problem decomposition and formulation strategy to take advantage of zero silo DBMS vehicle sizing within the MSA environment.



Defense Acquisition University

Figure 2-1 Defense Acquisition Life-cycle vs Life-cycle Systems Engineering Requirements (adapted from [104])

It has been proposed in this research that developing and implementing systems engineering practices is a resource intensive and time-consuming activity. Tetlay and John contend that *“system maturity and readiness during the life-cycle of development is imperative to the overall success of the system.”* [105] Thus, enabling automation of as many common or repeating processes in a structured manner indicates a key means to produce products more aligned to technology roadmaps, reduce cycle times, and cost. Mathews, from Boeing, continues that *“*[too] *often technologists and engineers endeavor mightily to design and propose leading-edge concepts, only to have them left unfunded and on the shelf as a result of a seemingly injudicious b*usiness-case analysis.” [106] Consequently, automation allows for the commoditization of process workflow to redistribute resources available and opportunity to increase focus on developing more innovative and/or more complex technology solutions. In this context, this chapter will study: problem formulation data relationship automation, pre-design acquisition and CD data domain needs, and alternative product development sizing tool data interfaces.

2.1 Zero-Silo DBMS-Based Problem Formulation Data Relationship Automation

The idea of data automation has been mentioned a number of times already, though the application of the concept yet to be properly discussed. To begin with, there are multiple degrees of automation and different interpretations of problem formulation to solve the MSA Phase problem. Regrettably, a literature survey reveals the lack of a comprehensive capability to automate problem decomposition. Many articles have been written about modelling problem requirements, however, the roadmap towards developing a syntactically composable topology of pre-design outputs to automate product development tool design would be considered prospective. This is particularly true given that the zero silo DBMS for aircraft synthesis is innovative and any system engineering work designed to contribute towards its’ advancement will add to the novelty. In this manner, business and engineering practices work jointly and simultaneously to support technology solutions.

Generally speaking, Amadori refers to data automation as a *“system that is able to perform a design task in an automatic fashion. The system includes a model that is able to transform inputs (in the form of design requirements) into desired outputs.”* [107] Relative to the present research, data automation requires a system capability as determined by Tamaskar et al (level of abstraction**,** system structure and function, number of components and interactions, heterogeneity of components and interactions, and network topology) [92] where the degree of robustness, flexibility, and fidelity is comparable to the zero silo DBMS with which it will interface. Hence, given a basic technology problem definition: 1. Custom design constraining outputs are established through a singular DBMS platform and 2. The DBMS platform will manage data to measure technology and development portfolio risks.

In the present study, problem formulation automation refers to a consistent and traceable process that possesses the composability to deconstruct and control data relationships of the product at hand. The hope is for this framework to evolve into a semantically composable automation framework compatible with learning algorithms once this fundamental research is in place. Therefore, the modelling platform presented in Chapter 3 is conceptually constructed to operate as follows, see Figure 2-2:

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 system architecture.

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.

Using this structure, the data relationships, processing, and analyses can vary with the type of technology acquisition problem to produce the output for product development sizing tool building. However, the data requirements for portfolio building and aircraft sizing need to be better understood.

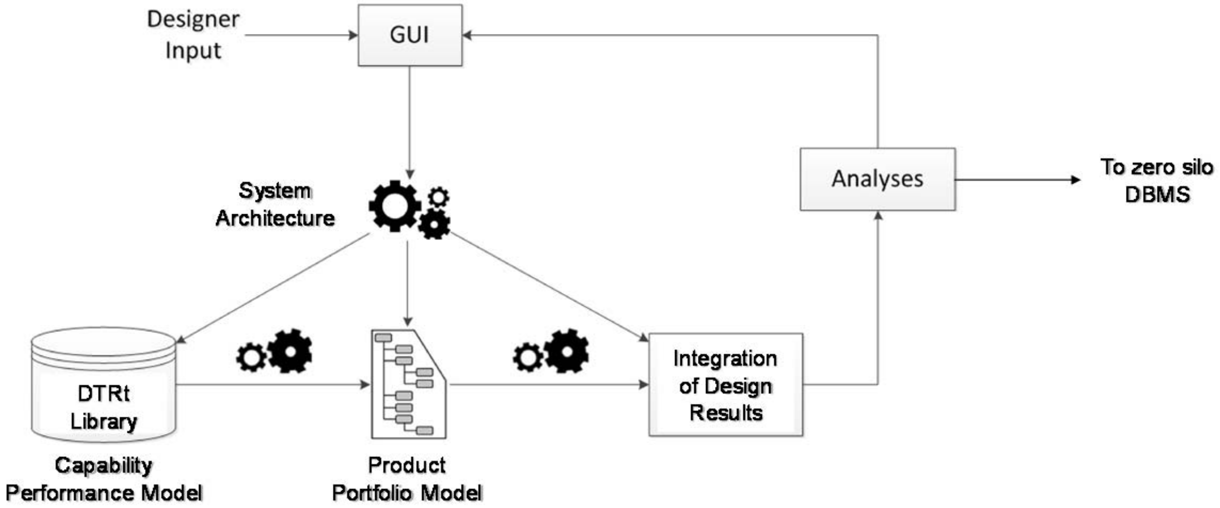


Figure 2-2 Problem Formulation Data Automation Concept (adapted from [107])

2.2 Pre-design Materiel Solution Analysis Data Requirements

To foster greater levels of business process integration, it is necessary to enable a perspective for how acquisition researchers consider product or technology development options. Along these lines, Janiga and Modigliani, from Mitre Corporation, recommend a portfolio management environment for the A&D Industry with *"robust portfolio enterprise architectures and notional designs* [that] *would outline how each capability fits within the portfolio suite* … [Whereby] *Designing enterprise-level technical and business architectures* *would optimize portfolio performance over the program-centric designs used today."* [108] Smith and Sonnenblick, from Enrich Consulting, add that by adopting this mindset, organizations enhance their R&D decision processes such that "*the portfolio [is aligned] with [researchers] long-term strategic objectives and shifted [the decision] focus from selecting the best projects to selecting the best set of projects that would meet the strategic objectives."*.[109] Observably, the MSA Phase of a traditional program would have a broader application of solution spaces, see Figure 2-3, and allows the researcher to better balance perform, cost, and technology potential, see Figure 2-4.

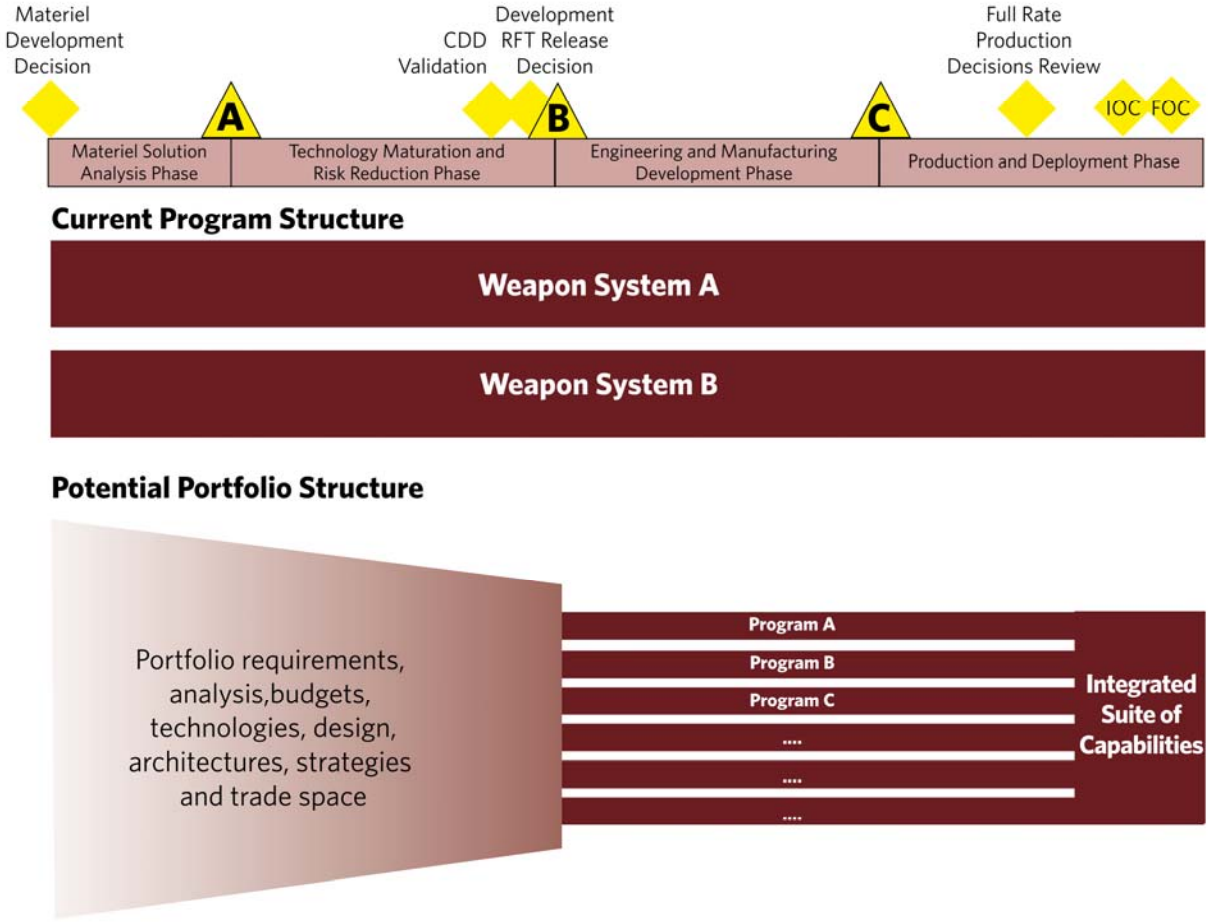


Figure 2-3 Comparison of Program vs Portfolio Approach to R&D [108]

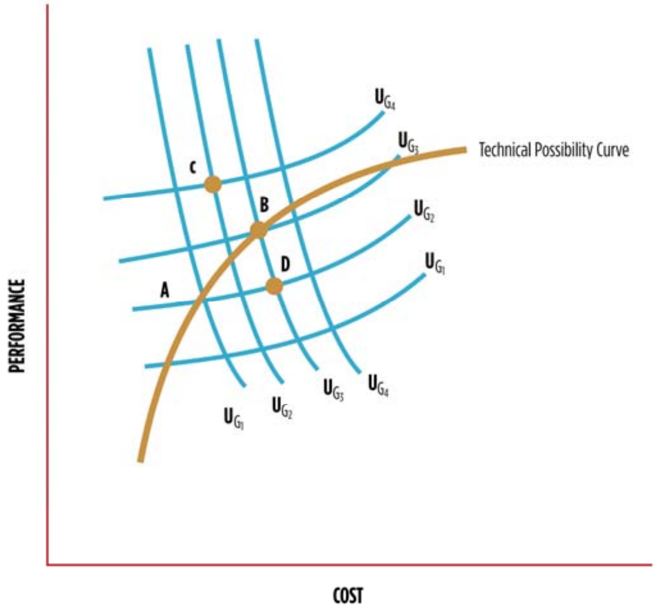


Figure 2-4 Portfolio Approach for Balancing Performance, Cost, and Technology Potential [10]

The U.S. Army uses a version of technology portfolio management designated as capabilities portfolio review (CPR). It operates with the intent to: (1) *“establish the ability to examine and modify investment portfolios,”* (2) *“develop an understanding of requirements driving investment, procurement, and sustainment,”* (3) *“reconcile requirements across portfolios,”* (4) “*validate, modify, and terminate investment and/or procurement strategy upon the reconciliation of requirements, with the goal of the reconciliation piece to ensure that funds are programmed, budgeted, and executed against validated requirements, cost, and risk-informed alternatives.”* [111] However, the priority for tool construction supports system and method development for technology and hardware implementation towards force prediction. The RAND Corporation invested the portfolio management method (PortMan) and portfolio analysis tool (PAT), and Mitre Corporation the portfolio analysis machine (PALMA) and matrix mapping tool (MMT). [112-115] Additionally Bond et al, make a case for parametric portfolio capability assessment where “risk-informed trade space” are developed to enable scenario-based acquisition decisions.[116] As such, while the application of the analysis techniques are not directly relatable to this study, the robust approach for system development and flexible CPR strategy should be emulated. For this reason, the acquisition data requirements need to be better understood to foster the appropriate system capability development.

Evans and Johnson, and Mathews, from Lockheed Martin and Boeing respectively, are in the minority to tackle portfolio management with a focus on innovation, A&D technology factors, and business development.[3][89][117] This is not to say that they are alone in exploring this subject matter or that Lockheed Martin and Boeing do not have alternative methods for innovation, but rather that other R&D processes used by other A&D companies were unavailable. The primary benefit of their research shows, whereas *"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 … The innovation portfolio, then, connects existing ideation events, where ideas are born, and project portfolios, where matured concepts are developed into products and services."* [89] Figure 2-5 illustrates this portfolio management approach. Both implementations differ in focus and scope. To solve this problem, Evans and Johnson have taken a qualitative organization-wide implementation, while Mathews has taken a structured quantitative approach to more directly support acquisition decisions.[3][89][117] This latter methodology, named Innovation Portfolio Architecture (IPA), can be leveraged to develop the problem formulation data requirements conducted research along the product portfolio track at Boeing, which resulted in innovation of portfolio management techniques.

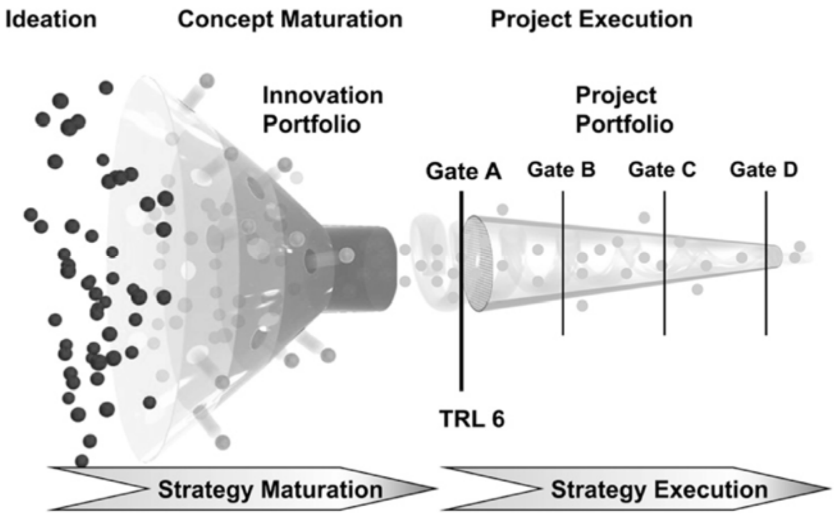
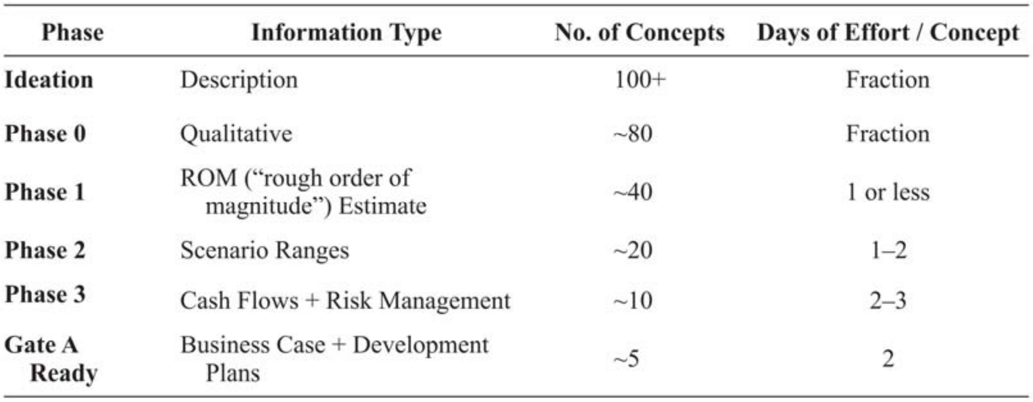


Figure 2-5 Innovation Portfolio Management Ideation Approach [89]

IPA allows for *“low value and minimal initial dataset associated with most concepts* [to] *be addressed by keeping early-phase evaluations cheap and fast to minimize expenditures … The earliest phases of the portfolio expenditure involve qualitative and rough order of magnitude estimates. The difficulty of aligning concepts with a strategy that is still emergent can be ameliorated by clustering early-stage* [product or technology] *concepts around particular strategic thrusts; as a strategy emerges, those cluster not aligned with it can be eliminated. And, as the strategy matures, concept clusters can be scrutinized with* increasing detail.*”* [IPA – Part 1” [89] or fidelity. Mathews identifies five successive stages that enable an aircraft technology to mature towards a viable investment, see Table 2-1. Each step of the IPA process carefully assigns sufficient data requirements to match the relative uncertainty in decision-making and limit need for undue resources.

Table 2-1 Innovation Portfolio Architecture Data Requirements [89]



Phase	Information Type	No. of Concepts	Days of Effort / Concept
Ideation	Description	100+	Fraction
Phase 0	Qualitative	~80	Fraction
Phase 1	ROM (“rough order of magnitude”) Estimate	~40	1 or less
Phase 2	Scenario Ranges	~20	1–2
Phase 3	Cash Flows + Risk Management	~10	2–3
Gate A Ready	Business Case + Development Plans	~5	2

Corresponding to problem formulation, the data relationships, minus the time and cost measures, of interest emerge at Phase 1 and continue into Phase 2. In Phase 1 *“… the bounds of the* [innovation technology] *‘bucket’ are values mapped to a numerical scale associated with the qualitative NASA Technology Readiness Levels* [TRL]*. Since technologists can readily assess the TRL of a technology project, … this mapping provides another rapid, inexpensive method of arriving at an initial* concept valuation.” [89] Furthermore, in Phase 2 *“… the focus is on better understanding of the risks and opportunities that are implicit in the assumptions. The analyst adds more detail to the ROM estimate by specifying optimistic and pessimistic scenario values, resulting in* [a range of scenarios].” [89] Consequently, designers and technologists can specify risk values from exposure to the product development lifecycle from the CD phase onwards.

2.2.1 Data Relationships Towards Automation

The IPA framework provides an option to directly “bridge” the data needs between the pre-design business practices and engineering environments. The interface methodology is sufficiently mature and validated by Mathews that it can assess each hardware technology independently, the scope of applicability is broad enough that any level of system decomposition is possible, the framework allows new hardware components and/or mission environment for consideration, and the prioritization of technology development efforts can handle by qualitative and quantitative metrics.[89] However, the data relationships of significance for this research do not extend beyond naming TRL values along, what is likely, a product specific system breakdown. Whereby, the lack of a consistent data topology limits the opportunity to integrate and connect the data into CD sizing tool inputs. The characterization of hardware technology, to make use of this new understanding, requires a better grasp of synthesis tool inputs as a necessity.

2.3 CD Aircraft Synthesis Data Requirements

Product development sizing tools are systems dedicated to: (1) exploring the feasibility of multidisciplinary effects for technology integrated into an aircraft product, (2) the architectural design or system capability of the parametric data relationships as it relates to the user-defined disciplinary methods (i.e. uncertainty) to be integrated. Coleman divides the CD process into three continuous processes: Parametric Sizing (PS), Configuration Layout (CL), and Configuration Evaluation (CE), see Figure 2-6. [21] The first stage PS is of present interest. In this Phase, the design researcher is tasked to use the mission specification, hardware technology, and hardware configuration knowledge from pre-design (outside PS)to derive an analytical framework for assessing design solution spaces. Specifically, engineers and researchers are wanting to answer if the mission is feasible with the current industrial capability or potential future technology and what a converged aircrafts' size, scale, and shape results. [21] On the whole, however, Coleman illustrate that the PS Phase of CD has largely *"… stagnated or has been ignored in t*he *current literature."*[21] Most tools fall into similar patterns of system capability limitations observed in robustness, flexibility, and fidelity (as discussed in Chapter 1).

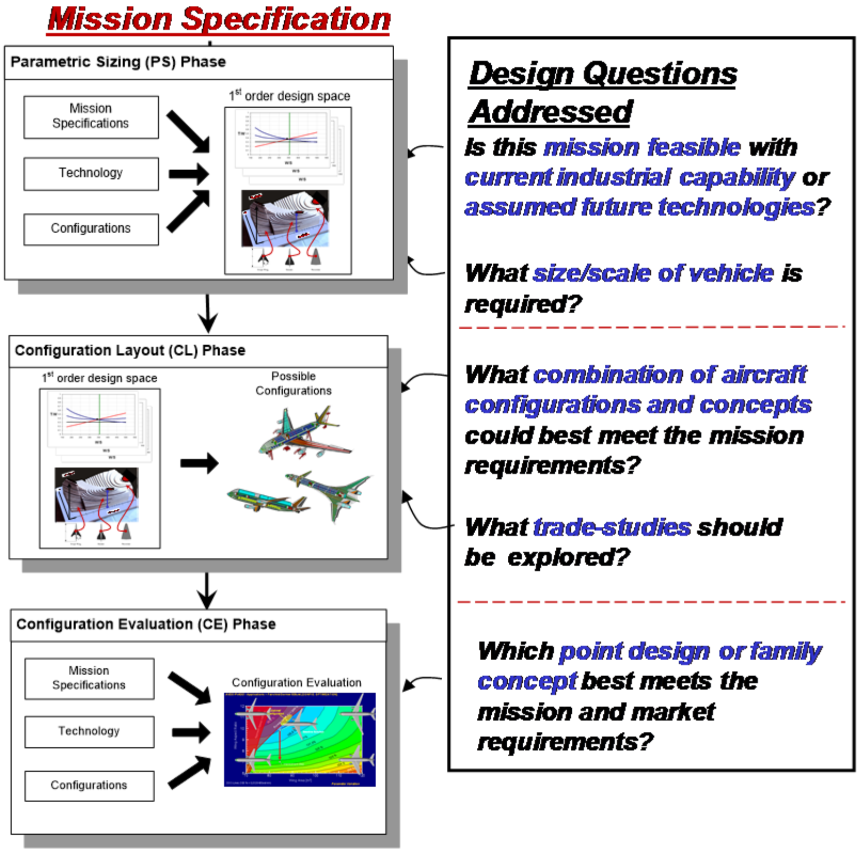


Figure 2-6 Steps to Aerospace Vehicle CD [21]

For example, consider the Loftin sizing PS methodology as a conventional example of tool data logic, see Figure 2-7. [118] The methodology itself, as described in Table 2-2, is oriented to solve subsonic aircraft development problems. It does feature integrate an informal knowledge-based system (KBS) that makes known disciplinary technology constraint factors. The multidisciplinary effects data is well integrated for this product implementation, though the handicap becomes evident when attempting to restructure the framework and modify the application towards analyzing a technology portfolio and/or innovative hardware. Resolving the data relationships for a portfolio-based approach starts with controlling the problem inputs.

Consequently, this limitation is experienced by the majority of aerospace vehicle design synthesis tools and can be traced to the programming data structure used to manage data. Whereby, the vested CD stakeholders generate analysis programs intended to emphasize a process with a set of “appropriate” methods to parameterize a solution space towards a baseline configuration. Generally, the system inputs comprise of a unique description of the baseline aircraft outer mold geometry, materials and mass properties, aerodynamic characteristics, engine performance data, and flight performance requirements. As such, these tools naturally evolve into a heterogeneous data framework that demands more robustness and flexibility though they are increasingly vertically integrated. With the current focus on zero silo DBMS sizing and an acquisition reasoning prioritizing portfolio management, what synthesis tool problem formulation inputs can be expanded into a homogeneous suite to better capture the data required to initialize CD practices alongside pre-design activities?

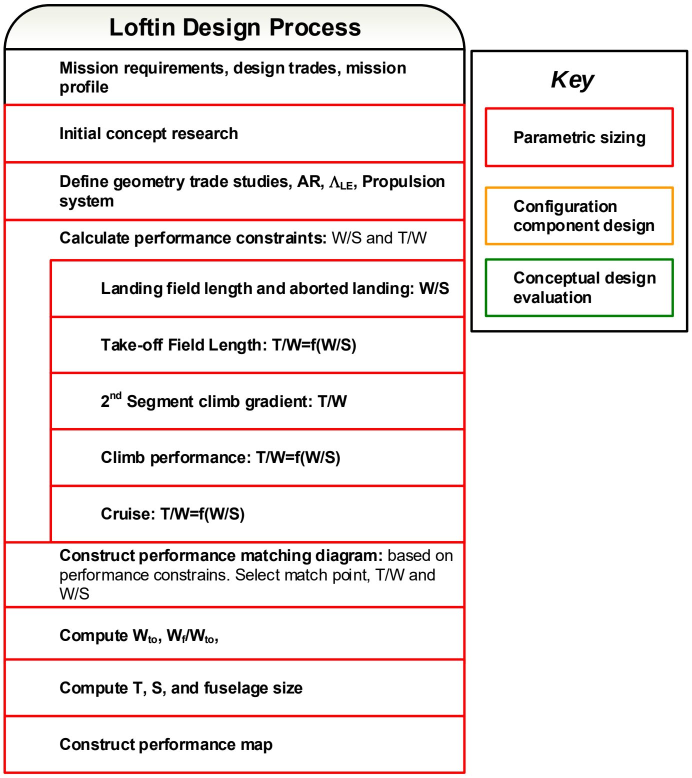


Figure 2-7 Nassi-Schneiderman diagram for the Loftin aircraft sizing process [21]

Table 2-2 Loftin Subsonic Aircraft Sizing Tool System Capability Description [21]

<table>
<tr><th colspan="12">Processes Overview</th></tr>
<tr><td colspan="3">**Design Phases**
Conceptual Design</td><td colspan="3">**Author**
Loftin</td><td colspan="3">**Initial Publication Date**
1980</td><td colspan="3">**Latest Publication Date**
1980</td></tr>
<tr><td colspan="12">**Reference:** Loftin, L., “Subsonic Aircraft: Evolution and the Matching of Sizing to Performance,” NASA RP1060, 1980</td></tr>
<tr><th colspan="12">Application of Processes</th></tr>
<tr><td colspan="12">**Applicability**
Primarily focused on parametric sizing of jet powered transports and piston powered general aviation aircraft</td></tr>
<tr><td colspan="12">**Objective of Processes**
Determine an approximate size and weight the aircraft to complete the mission from a 1^{st} level approximation of the design solution space</td></tr>
<tr><td colspan="12">**Initial Start Point**
The processes begins with mission specification, possible configurations and fixed design variables such as AR.</td></tr>
<tr><td colspan="12">**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</td></tr>
<tr><th colspan="12">Interpretation</th></tr>
<tr><td colspan="4">**CD steps**
Parametric Sizing</td><td colspan="4">**Synthesis Ladder**
Analysis
Integrate

Iteration of design
Visualize design space</td><td colspan="4">**Similar Procedures**
Roskam (preliminary sizing)
Torenbeek (Cat 1 methods)</td></tr>
<tr><td colspan="12">**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 intial sizing.
Loftin essential short cuts the Nicolai approach to derive an initial design space rather than an initial configuration.</td></tr>
</table>

Historically, the value of a synthesis tool comes its' capability to model the multidisciplinary effects that characterize the aircraft. The most dynamic of these were built and utilized in the 1960s/70s. These systems are meant to be vertically integrated and include Computerized Preliminary Design System (Boeing), Integrated Design and Analysis System (Grumman), Advanced Systems Synthesis and Evaluation Technique (Lockheed), Computer Aided Design Evaluation (McDonnell), Configuration Analysis Program (North American Rockwell), Aircraft Synthesis Analysis Program (Vought), and Integrated Programs for Aerospace Vehicle Design (NASA). All were designed to support managerial and CD decision-making. Straub discusses the functionality and basic logic of the other systems in Reference 97. Of these only the McDonnell system is available for review through conversations with Csysz [119] As such, additional notable vertically integrated methodologies are evaluated. They include a cross-section of available analog ("by-hand") and digital ("computer-based") aircraft product development sizing tools by academia and industry Table 2-3 and Table 2-4 respectively. Appendix A discusses these systems in more detail. Note that Model Center, while not a synthesis system, is included since it is a data integration platform that allows the researcher to define the system capability.

Table 2-3 Cross-section Analog Aircraft Synthesis Tools [16][18][118][120-127]

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

Table 2-4 Cross-section of Digital Aircraft Synthesis Tools [101][102][128-132]

Acronym	Year	Full name	Developer
AAA	1991-	Advanced Airplane Analysis	DARcorporation
ACSYNT	1987-	AirCraft SYNThesis	NASA
AVDS	2010	Aerospace Vehicle Design System	Aerospace Vehicle Design Laboratory
CADE	1968	Computer Aided Design Evaluation	McDonnell Douglas
FLOPS	1994-	FLight OPtimization System	NASA Langley Research Center
Model Center	1995-	Model Center Integrate - Explore - Organize	Phoenix Integration Inc
pyOPT	2012-	Python-based object-oriented framework for nonlinear constrained optimization	Royal Military College of Canada
PrADO	1986-	Preliminary Aircraft Design and Optimisation	Technical University Braunschweig
VDK/HC	2001	VDK/Hypersonic Convergence	McDonnell Douglas, Hypertec

The system capability for these tools has been qualitatively assessed, see below, using criteria developed during the course of research and conversations with Gonzalez regarding zero silo DBMS sizing.[103] Recall that system capability is defined as the robustness, flexibility, and fidelity of a system in terms of level of abstraction, system structure, number of components and interactions, heterogeneity of components and interactions, and dynamics involving modes of operation.[92] Simply put, system capability is the feasibility of the sizing tool to M&S new, conventional, and/or innovative product development problems under study. Six categories of attributes, Table 2-5, are presented: (1) data integration and connectivity, (2) data interface maturity, (3) tool scope of applicability, (4) influence of new product component, subcomponents, and operational flight environments, (5) prioritization of technology development effort to tool suitability, and (6) characterization of problem formulation input. Combined, they build a profile for how and what data is used by CD engineers.

Table 2-5 Cross-section of Digital Aircraft Synthesis Tools

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

A. Integration and Connectivity

Each system is a set of modular disciplinary blocks that model the associated hardware components. The blocks are integrated together to solve for the aircraft system by the structure of the multidisciplinary data connections. This relationship is investigated by two attributes. The capability to:

- Criteria 1.a – assess each hardware technology independently. Once the system block is decomposed into disciplinary modules, are the data inputs for each disciplinary block able to independently execute the disciplinary analysis?
- Criteria 1.b – assess multiple disciplinary effects for each technology and/or hardware. Are the decomposed disciplinary data blocks able to connect to other independent disciplinary blocks to create to create new and varied multidisciplinary effects data?

Figure 2-8 illustrates the results.

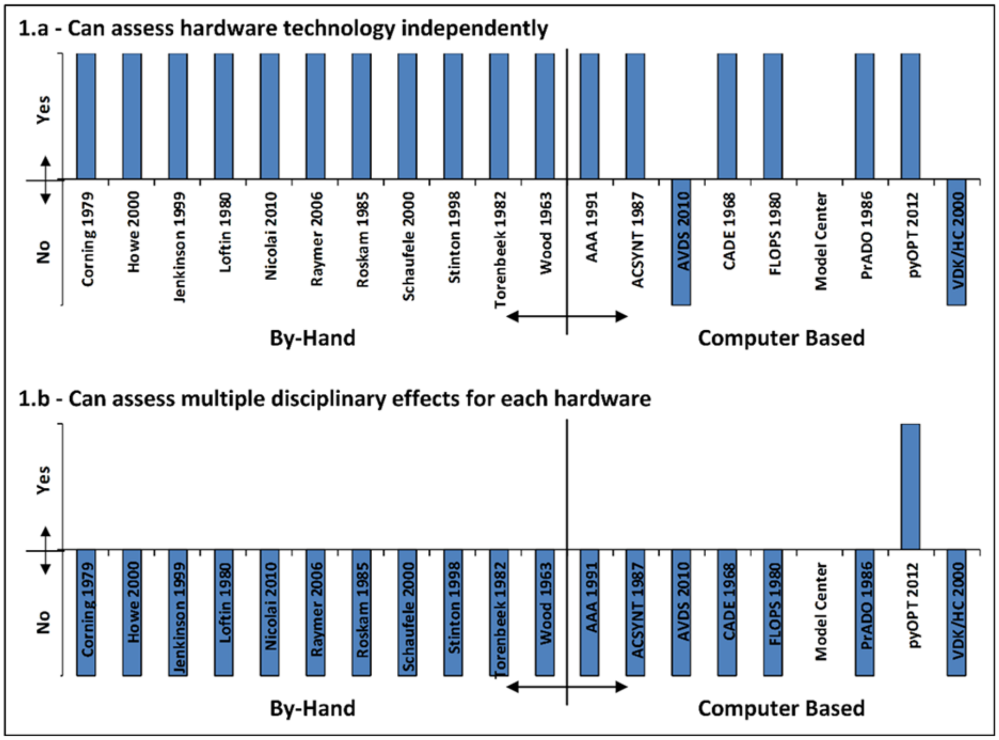


Figure 2-8 Sizing Tool System Capability Comparison – Integration and Connectivity

Criteria 1.a shows that 18 tools possess the means to allow a mode of operation where the primary disciplinary evaluations for a hardware and/or mission variation can happen outside of the synthesis framework. The number of components and heterogeneity of the data interactions constrict the degrees of multidisciplinary freedom built into synthesis loop of the system. Note that, unlike the digital tools, the analog systems require the multidisciplinary data relationships to be manually established by the researcher. Two systems, AVDS and VDK/HC do not permit independent disciplinary analysis as the data topology is the most integrated and have the most multidisciplinary data connections. Criteria 1.b notes 18 tools without the level of abstraction for disciplinary analysis beyond the disciplinary module’s data intent for a hardware. These require the complete synthesis block to be executed as a mode of operation. For instance, the propulsion blocks only create propulsion data and not the associated aerodynamic contributions of the engine hardware. Only pyOPT allows the researcher to control which disciplinary modules to connect to construct multidisciplinary effects data for a known hardware.

B. Interface Maturity

Decomposition of the sizing tool inputs reveals that aircraft technology and hardware are assembled in a heterogeneity of data structure and component compositions. Two criteria are used to explore this relationship:

- Criteria 2.a – combine hardware technologies to form a vehicle. Once combined into a product, the level of abstraction in the hardware product model reveals the preference of tools. What is priority towards flexibility and fidelity of the analysis data blocks?
- Criteria 2.b – combine individual hardware technology disciplinary effects. As the level of abstraction for the hardware data model changes according to the data requirements of disciplinary module, can the multidisciplinary effects for a hardware be synthesized to determine delta technology contributions in performance?

Figure 2-9 illustrates these trends.

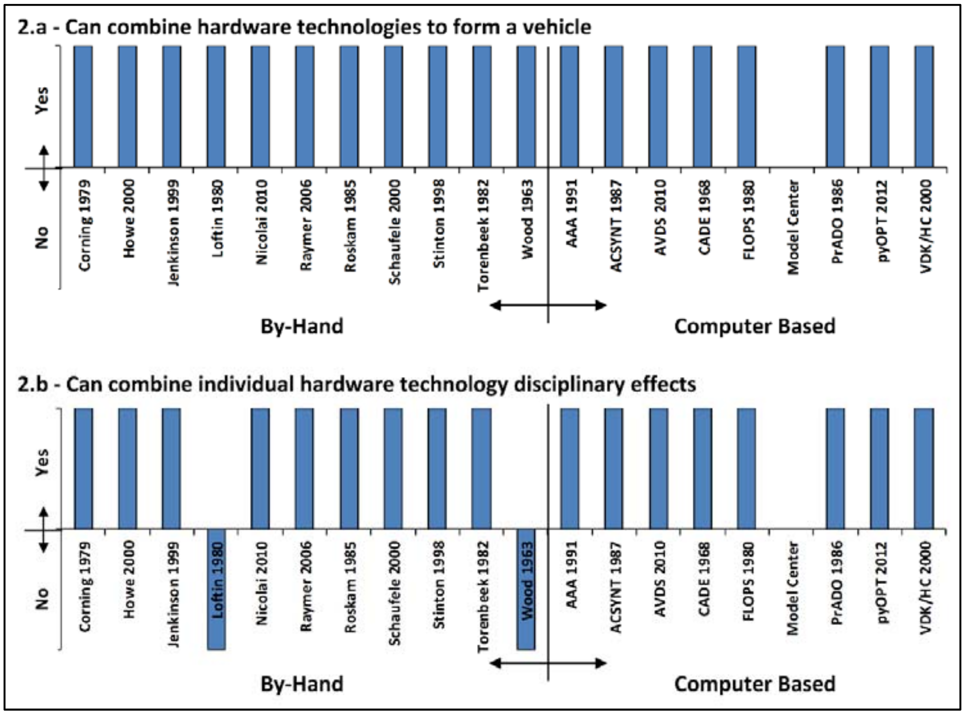


Figure 2-9 Sizing Tool System Capability Comparison – Interface Maturity

Criteria 2.a confirms that all 19 synthesis tools have the number of disciplinary blocks to solve for individual hardware effects that build a profile of total aircraft feasibility. There is no surprise here as each tool requires a somewhat unique composition of hardware model topology to know what disciplinary effects to include. Similar to Criteria 2.a, Criteria 2.b is a basic data capability for aircraft synthesis. As such, 17 systems capture the data required to build disciplinary contributions of individual hardware into the total aircraft aerodynamic characteristics (ex. AAA, AVDS, FLOPS, PrADO, and pyOPT) and propulsion system (i.e. PrADO and pyOPT). Observe that Loftin and Wood are empirical methods where the individual hardware is composed and the number of components assessed for the whole product hardware.

C. Scope of Applicability

As mentioned previously, system capability for product development synthesis tools are constructed to solve a specific CD R&D engineering problem. While the structure of the tools can be similar and include the same data analysis method blocks, it is the applicability of the system that decide in what function and mode of operation the data inputs for the hardware product model exist. Two criteria illustrate these interactions:

- Criteria 3.a – conceptual design phase applicability. Since CD is divided into three processes (PS, CL, CE), to what analysis level does a hardware model inputs contribute allow new product development data to be created?
- Criteria 3.b – aerospace product applicability – What type of hardware product model data interactions are formulated for the sizing tool?

Table 2-6 and Table 2-7 summarize these results.

Table 2-6 Sizing Tool System Capability Comparison – Scope of Applicability, CD Phase

	By-Hand											Computer								
	Corning 1979	Howe 2000	Jenkinson 1999	Loftin 1980	Nicolai 2010	Raymer 2006	Roskam 1985	Schaufele 2000	Stinton 1998	Torenbeek 1982	Wood 1963	AAA 1991	ACSYNT 1987	AVDS 2010	CADE 1968	FLOPS 1980	Model Center	PrADO 1986	pyOPT 2012	VDK/HC 2000
Parametric Sizing	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Configuration Layout	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No
Configuration Evaluation	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	No
N/A	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No

Table 2-7 Sizing Tool System Capability Comparison – Scope of Applicability, Aerospace Product

	By-Hand											Computer								
	Corning 1979	Howe 2000	Jenkinson 1999	Loftin 1980	Nicolai 2010	Raymer 2006	Roskam 1985	Schaufele 2000	Stinton 1998	Torenbeek 1982	Wood 1963	AAA 1991	ACSYNT 1987	AVDS 2010	CADE 1968	FLOPS 1980	Model Center	PrADO 1986	pyOPT 2012	VDK/HC 2000
Homebuilt	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Single Engine	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Twin Engine	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Agricultural	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Business Jet	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No
Regional TBP's	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No
Transport Aircraft	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No
Mil. Trainers	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Fighters	No	No	No	No	Yes	Yes	Yes	No	No	No	No	Yes	Yes	No	Yes	Yes	No	No	Yes	No
Mil. Patrol, bombers, transport	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Flying boats, Amphibious	No	No	No	No	No	Yes	Yes	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No
Supersonic Cruise	Yes	No	No	No	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No
Hypersonic P2P	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	Yes	No	Yes
Launcher (Rocket)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
Launcher (A/B)	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
Reentry	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No
In-Space	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No
N/A	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No

Criteria 3.a, see Table 2-6, show that 18 sizing methodologies can be applied to PS minus the PrADO system, 12 systems have the capability facilitate configuration layout (CL), and 15 tools feature analysis at configuration evaluation (CE). Consequently, the hardware input data requirements increase the more completely the tool contributes to CD. The analog systems also show a system structure that favors solving a range of CD applicability problems due to the ability to re-derive data interactions as needed which are user defined unlike the majority of the digital tools. Criteria 3.b, Table 2-7, is self-explanatory. It presents the applicability of a system relative to product types it will develop, though the technology and hardware are not shown since they are too diverse to list. The products tend toward non-innovative hardware configurations.

D. Influence of New Components or Environment

System capability is rooted within robustness, flexibility, and fidelity constraints of a sizing tool. The homogeneity of a system topology to capture hardware, operational environment, and maintain disciplinary analysis data connections dictates the CD PS problems that can be solved and the ability of the framework to adjust its’ structure to new or “off-design” data requirements and disciplinary modules. Three criteria are examined:

- Criteria 4.a – modular hardware technology. To what extent can the sizing tool include data interactions for new hardware technology and/or a new level of abstraction in the product model?
- Criteria 4.b – modular mission types. Does the mission model possess the adaptability to integrate new flight profile or trajectory components and/or data requirements into the system topology?
- Criteria 4.c – modular disciplinary analysis methods. Can new disciplinary and/or multidisciplinary data analysis blocks, and/or level of abstraction in existing analysis blocks be introduced and integrated into the synthesis structure?

Figure 2-10 discusses these trends.

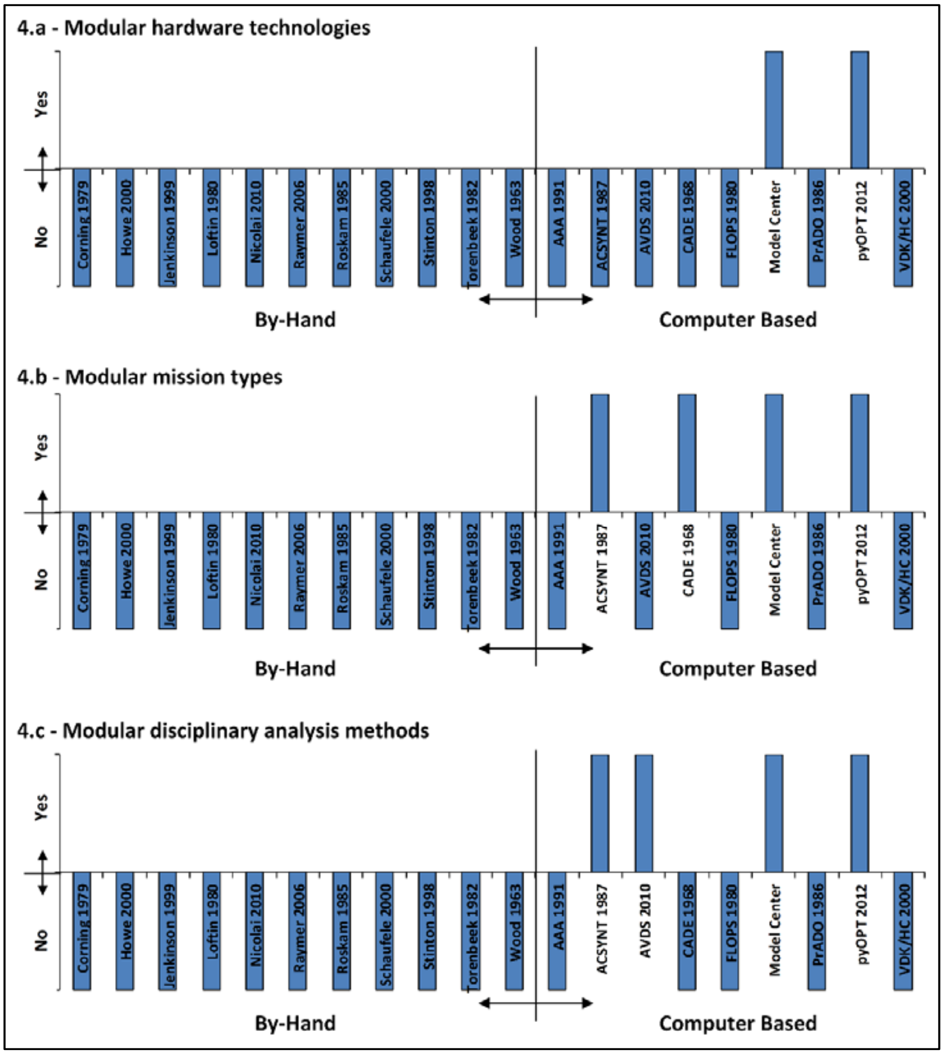


Figure 2-10 Sizing Tool System Capability Comparison – Influence of New Components or Environment

Criteria 4.a shows that 18 tools are unable to consider new hardware without adapting the data relationships the synthesis framework structure. Two systems, Model Center, though only providing a basic shell for platform integration, and pyOPT have a system structure and the object-oriented data classes to manage the changes in data relationships in an automated fashion. Criteria 4.b illustrates that 16 methodologies retain a static system topology that requires manual rework of data connections. ACSYNT, CADE, Model Center, and pyOPT provide the researcher with a means to automate the data relationships such that changes to the system structure can be tracked. Criteria 4.c presents that 16 tools have a static structure when it comes to disciplinary analysis method modularity and are limited for the same reasons as above. Four tools, ACSYNT, AVDS, Model Center, and pyOPT, allow for automation and tracking of the data relationships. However, AVDS is constrained to disciplinary method switching along the VDK/HC synthesis process.

E. Prioritization of Technology Development Efforts

The goal of a synthesis tool is to determine the feasibility of technology and hardware once integrated into an aircraft product. However, the priority for the researcher might be that the feasibility of the vehicle does not necessarily meet the level of abstraction or fidelity of a disciplinary method that is required for the researcher to make R&D decisions. This alignment of system capability structure is investigated by two criteria:

- Criteria 5.a – ability to match hardware technology disciplinary models to problem requirements. How does the flexibility and fidelity of the disciplinary analysis modules influence the inputs product hardware model?
- Criteria 5.b – data management capability. How does the structure of the synthesis and topology of data interactions determine the capability of the sizing tool?

Figure 2-11, and Table 2-8 and Table 2-9 evaluate these results, respectively.

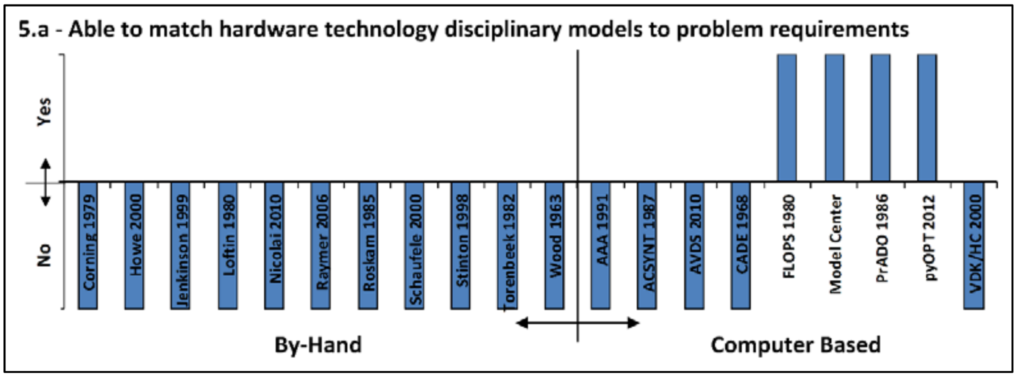


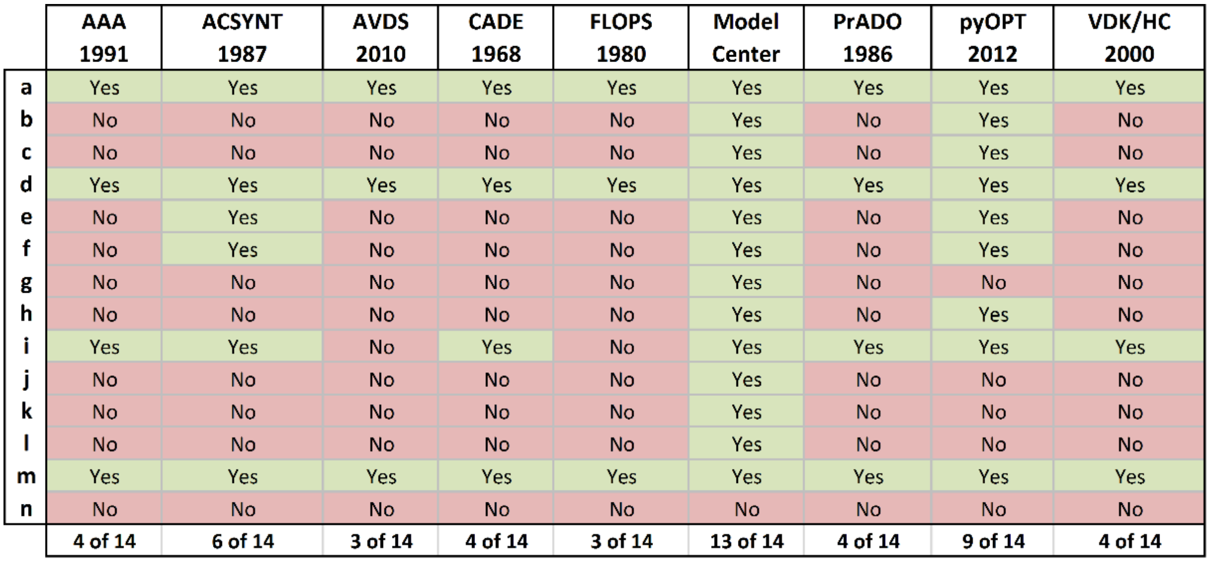
Figure 2-11 Sizing Tool System Capability Comparison – Prioritization of Technology Development Efforts

Criteria 5.a notes that 16 synthesis methodologies are static in data relationship structure and in the fidelity of the method in the disciplinary analysis block. Whereby the robustness and flexibility is fixed in terms of data inputs towards problem formulation. Four systems, FLOPS, Model Center, PrADO, and pyOPT support fidelity options for the disciplinary analysis modules. The difference in level of abstraction is treated in two ways. For FLOPS and PrADO, all the methods and data interactions exist and researcher selects the switches for outcome matching the problem. Since Model Center and pyOPT are more platform oriented, the methods are stored in a DBMS library and are introduced to the sizing topology for a static disciplinary analysis model framework.

Table 2-8 Sizing Tool System Capability Comparison Criteria – Data Management Capability

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

Table 2-9 Sizing Tool System Capability Comparison – Data Management Capability



	AAA 1991	ACSYNT 1987	AVDS 2010	CADE 1968	FLOPS 1980	Model Center	PrADO 1986	pyOPT 2012	VDK/HC 2000
a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
b	No	No	No	No	No	Yes	No	Yes	No
c	No	No	No	No	No	Yes	No	Yes	No
d	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
e	No	Yes	No	No	No	Yes	No	Yes	No
f	No	Yes	No	No	No	Yes	No	Yes	No
g	No	No	No	No	No	Yes	No	No	No
h	No	No	No	No	No	Yes	No	Yes	No
i	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
j	No	No	No	No	No	Yes	No	No	No
k	No	No	No	No	No	Yes	No	No	No
l	No	No	No	No	No	Yes	No	No	No
m	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
n	No	No	No	No	No	No	No	No	No
	4 of 14	**6 of 14**	**3 of 14**	**4 of 14**	**3 of 14**	**13 of 14**	**4 of 14**	**9 of 14**	**4 of 14**

Criteria 5.b describes the influence of a DBMS on the digital sizing tool framework options. The key takeaway here is the dichotomy in earlier- and current-generation (Model Center and pyOPT) DBMS implementations. Current generation systems feature an increased degree in data management capability. This in turn influences how the data blocks decomposed, reintegrated, and executed. Hence, the earlier-generation tools (1968-2000) reflect vertically integrated product development sizing systems and the more current-generation (2010-present) are horizontally integrated towards a hybrid silo DBMS.

F. Problem Input Characterization

In the context of the current research investigation, problem formulation plays a central role. It decides what problem the researcher can solve, if the system capability appropriately meets the data requirements, and/or if the necessary data can be created in the first place. The criterion used for study:

- Criteria 6.a – methodological problem requirements. How is product model formalized into the data block that interface with the sizing tool?

Figure 2-12 displays the results.

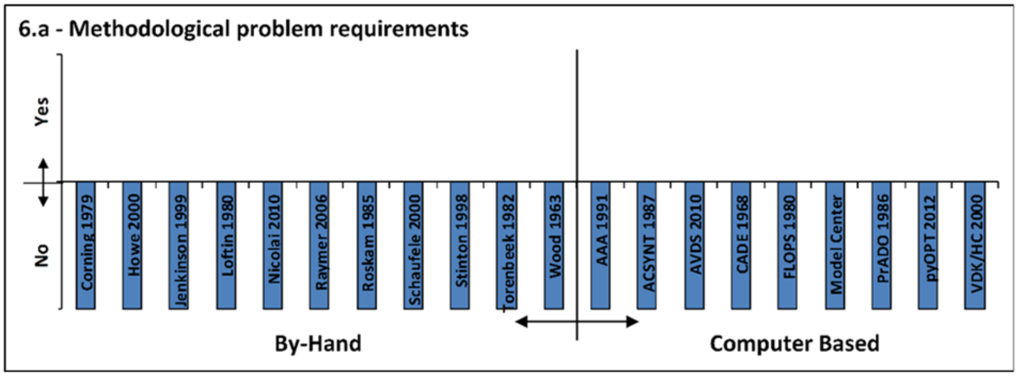


Figure 2-12 Sizing Tool System Capability Comparison – Problem Input Characterization

Criteria 6.a confirms that, for all 20 systems, the data requirements for product model inputs are static or reactive. They do not contribute to problem formulation. Furthermore, the sizing tools assume the inputs relative to the synthesis process and disciplinary analysis methods which are selected for a given problem. The problem data requirements are, therefore, communicated from the acquisition pre-design phases to CD.

2.3.1 Data Relationships Towards Automation

A review of aircraft product development synthesis tools indicates that there is a need to strengthen the data requirements towards a problem formulation model directly catering to the CD phase. The above discussion has shown that a variety of system capabilities exist and each is verified for a unique robustness, flexibility, and fidelity sizing framework structure. With regards to initializing zero silo DBMS PS processes, the problem formulation model must enable and/or complement all of criteria to allow a “plug-and-play” assembly of the data blocks. A significant step towards building a system capability to automate the data relationships would be to define a hardware product model, mission model, and operational constraint model that has a syntactically composable structure. In this manner, the engine mirrors the robustness, flexibility, and fidelity of the data requirements and allows the researcher to select the appropriate analysis method within a disciplinary (i.e. geometry, weight properties, aerodynamics, propulsion, and flight performance) module. Furthermore, this approach builds a natural “bridge” (direct data connection) to the product portfolio assessment and risk modeling data relationships required for the acquisition pre-design phase.

2.4 Specification for Problem Formulation Automation

Recall that the primary objectives of the current research is to: (1) determine what strategy should be used to initialize CD PS processes in the requirements analysis MSA stage utilizing data already constructed in the latter phase when working with a zero-silo DBMS system architecture, and (2) assess how these new data relationships can contribute for innovative decision-making when solving acquisition hardware/technology portfolio problems. As such, any specification for composable problem formulation automation has to first independently consider data interactions for the system architecture that manages the automation, acquisition pre-design portfolio management, and CD PS prior to system integration. The specification follows:

[Specification 1]	Formalize the data storage and implement the data relationships with a system architecture automated through an DBMS. The architecture is a separate process that exists outside the core CD PS synthesis tool loop to account for variation and alignment to acquisition data input requirements.
[Specification 2]	Allow for composable modeling, in terms of level of hardware abstraction, for the product model, mission model, and operational constraint model data blocks in the pre-design stages.
[Specification 3]	Allow the product model, mission model, and operational constraint model to cross reference of zero silo DBMS synthesis disciplinary analysis methods and processes.

[Specification 4]	Allow for matching, comparison, and balancing of the aircraft hardware portfolio to the associated developmental and technology risk metrics.
[Specification 5]	Allows for visualization technology portfolio decision space.

Chapter 3 – Composable Problem Formulation System Architecture Automation

There is a need for a consistent framework on which to consolidate the product development foundations supporting acquisition portfolio management decisions and the power of zero silo DBMS PS practices during requirements analysis in the materiel solution analysis (MSA) acquisition lifecycle phase. This study represents a small step in integrating these parts. The SE challenge according to Pergler and Freeman, *"… is to design a robust process to identify the key value drivers, the uncertainties around them and their impact, and then to harness all appropriate sources of information and provoke the right discussions, and so to deliver the benefits discussed. …"* [86] This system capability should ease the way towards a composable problem formulation strategy since it represents:

- Product planning – relates insertion of technology and gaps in product development;
- Strategic planning – supporting the evaluation of different opportunities or threats;
- Long-rang planning – identify opportunities of disruptive technology;
- Knowledge-asset planning – aligns knowledge-base and knowledge management with strategy objectives;
- Process planning – supports knowledge management of product development processes;
- Integration planning – integration/evolution of technology for product and architecture development. [133]

To achieve this degree of automation, the systems engineering (SE) development will effectively capture knowledge by focusing on the rules and relations the acquisition and technical data requirements as opposed to the optimizing the component parts. As such, a homogenous platform for experimentation is created. The problem is investigated in three parts: (1) the system architecture used to decompose the aircraft technology hardware data in a manner accessible for IPA and PS, (2) the PPM that synthesizes candidate vehicle (CV) options technology portfolio, and (3) characterizing the capability performance model metrics/methods for data-screening/mining of the technology portfolio. See Chapter 2.1 for more discussion on this data relationship automation concept. In this arrangement, the automation methodology exists outside the synthesis loop while still providing PS the structure and data relationships the design freedom afforded when the technology strategy is articulated in pre-design. Overall, it does benefit from the elimination of routine-like operations and directly sending risk screened aircraft technology/configuration options for reuse and update to the zero-silo DBMS sizing tool.

3.1 Impact of Composability on System Architecture

To begin this conversation, the SE characterization of system architecture is examined. Kline gives three definitions: (1) *"the object of study, what we want to discuss, define, think about, write about, and so forth,"* (2) *"a picture, equation, mental image, conceptual model, word description which represents the entity we want to discuss, analyze, think about, write about,"* and (3) *"an integrated entity of heterogeneous parts which acts in a coordinated way."* [175] It is this third definition that best captures the current research. Figure 3-1 further illustrates this system engineering approach. Ryan goes on to describe the path to build a system:

1. Input requirements – researcher problem is captured in precise, quantified requirements specifications.
2. Functional analysis – system requirements are decomposed into data blocks for subsystems, subsystem, and/or component until the appropriate level of abstraction is achieved.
3. Synthesis – data interfaces are synthesized to design the specified system, subsystems, and/or components.

4. Evaluation and decision – system verification and validation identifies the sensitivities of the on-design and off-design behavior between data interactions. Unintended interactions feedback to the functional analysis (Step 2) for rework until the system specifications are met. [133]

This generic problem solving process *“… provides the mechanisms for identifying and evolving the product [development] process definitions of* a system*. …”* [133] Essentially, the SE process enables the researcher to *“… take user requirements and iteratively create the technical and managerial processes required to realize a system” and systematically explore the solution space. …”* [17] However at present, the solution builds on this system integration dynamic by addition of system composability, to automate problem formulation.

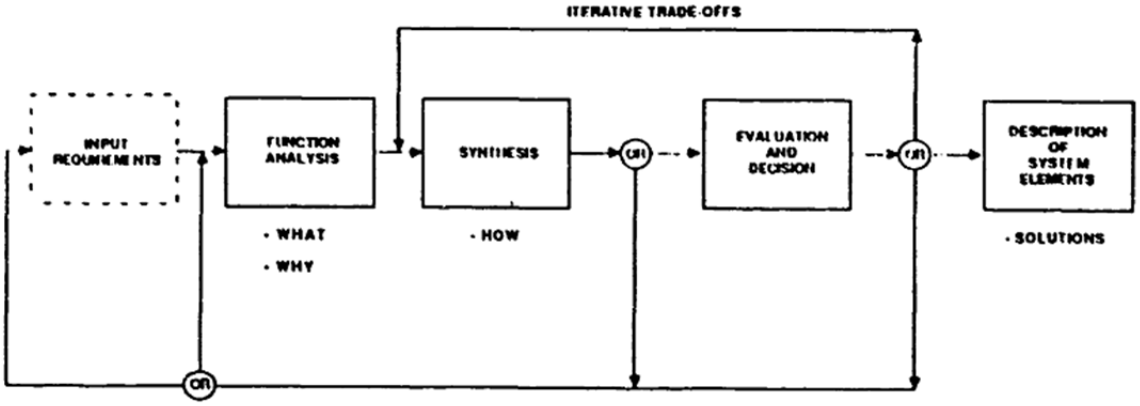


Figure 3-1 Systems Engineering Elements and Process [135]

Composability as described by Oster is a *“… systems architecture and design concept focusing on composing new systems from known components, designs, product lines, and reference architectures as opposed to focusing on ‘*blank *sheet’ designs based on requirements decomp*osition alone*. …”*. [136] The implementation lends itself to a form of platform-based engineering where the component structure or topology of data interactions do not change when interfacing other components in order to provide a *“… capability to select and assemble components to satisfy specific user requirements meaningfully. …”*. [137] A simple analogy would be having a container of building blocks and assembling the blocks through a system architecture to achieve desired analysis functionalities.

In practice, a composable platform design would include the *"… use of reference* [static] *architectures to provide design constraints and an overall problem context, integrated analytics to quickly assess solutions, and reusable component designs that can quickly integrated into new products. …"* [136] The reusable elements automate the SE problem from the system architecture-level (system-of-systems level) down through the system/product-level, subsystems, and components levels, see Figure 3-2. The benefit for researchers is the ability to focus on advancing existing and new cost, and performance functional capabilities into the system architecture without the burden of constructing custom integration and usability data interfaces (i.e. design reuse and design patterns) while developing new functional capabilities. Without this underlying architecture properly defined, it *"… will limit the usefulness of that component and often leads to component never having a clear reuse potential. …"* [136]

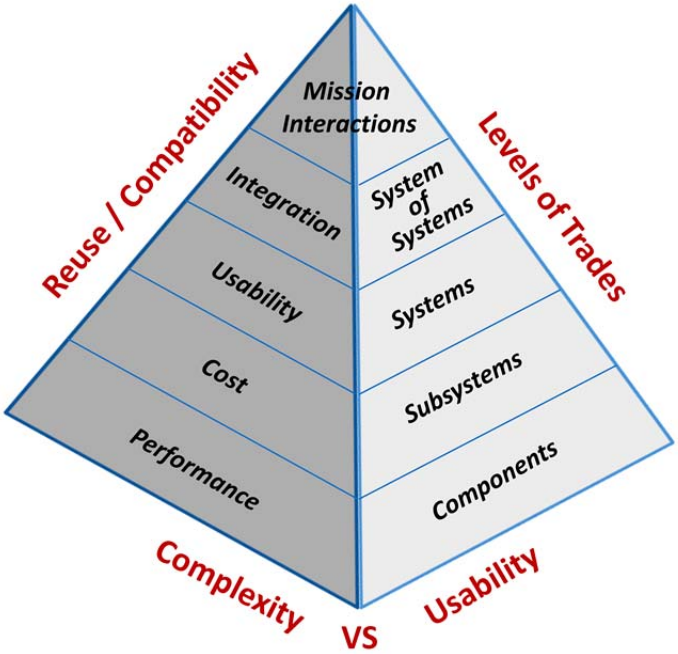


Figure 3-2 Elements of Composability [100]

Once this application to a composable system architecture is in place, the data requirements shift focus to the analysis methods adding the functional capabilities. Specifically, the data standards, data relationships, and component development interfaces that influence the matching and selecting of capabilities for reuse. Access and ease of construction for these reusable data blocks, analysis modules, and component libraries will determine how well such a methodology will be adopted and new functional capabilities developed. Therefore, it is important to minimize the roadblocks to reuse.

3.2 Composable System Architecture Design for Problem Formulation

Developing a problem formulation system architecture that can respond well to the various decision needs of the researcher is a task rooted in the design of the system structure. This complexity is in part due to types of information being interfaced. In part also, for decomposition of the data blocks that must be reconstructed for a custom decision analysis. For this reason, the architecture is determined to be syntactically composable and not the more complex semantically composable; whereby syntactically composable systems are tasked to control the data interfaces that network individual components and semantically composable systems determine how well the individual components are integrated and if the networked system make sense. [138]

Figure 3-3 describes the prototype framework developed to automate data utilized for sizing tool capability shift into pre-design. It is a heavily modified version of research being conducted at the Stevens Institute of Technology and combined with the authors experience working with technology forecasting and PS problems. [96][139-142] The framework is intended as a starting point to build more system capability with future work. The proposed three-class composable structure will help to: analyze the problem, define technology hardware priorities, and synthesize a product development plan for sizing. They include a descriptive model, parametric model, and analysis model. The descriptive models identify, manage, and construct the primary data relationships that define the system capability of the composable architecture. The parametric models define how the functional capability data modules are combined and they support access to the analysis models. The analysis models represent the method libraries of the system. Discussion of the resulting architecture is presented in the following sections. It is developed using SQL and VBA in Microsoft Access programming languages with data post-processing managed through Microsoft Excel.

Verification and validation of this innovative framework is confirmed through discussions and project with synthesis specialists with the Air Force Research Laboratory (AFRL), Aerospace Systems Directorate during USAF SFFP 2015. [143] A discussion of system capability models as it exists presently follows. Implementation of the composable problem formulation system architecture will be discussed through a hypersonic demonstrator hardware acquisition study in Chapter 4.

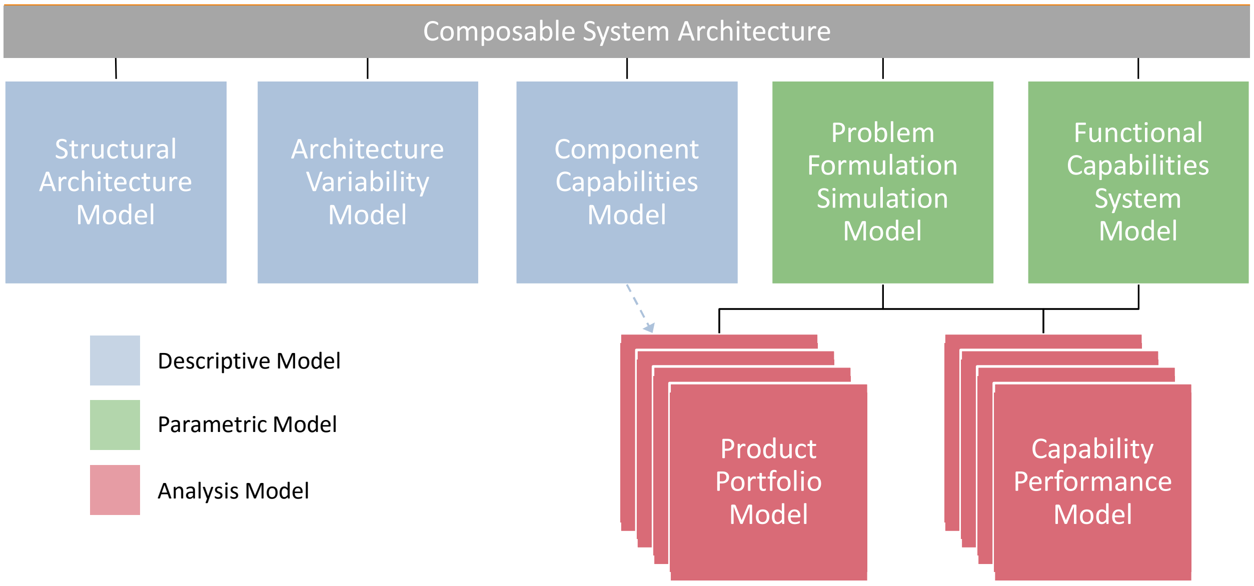


Figure 3-3 Problem Formulation Composable System Architecture (modified from [96])

3.2.1 Descriptive Model

A. Structural Architecture Model (SAM)

The structural architecture model is being developed to solve a hypersonic product development technology problem. With regards to system capability, the architecture resolves to decompose the functional requirements for the problem into a rule-based system structure, see Chapter 3.3. It establishes the network of input/output data connections, and specifies how the data blocks for the analysis components are accessed. Figure 3-4 conceptually displays the effects of functional data requirements being converted to structural data interactions for different levels of system abstraction. Basically, combinations of these data relationships will decide the degree of robustness and flexibility built into the simulation.

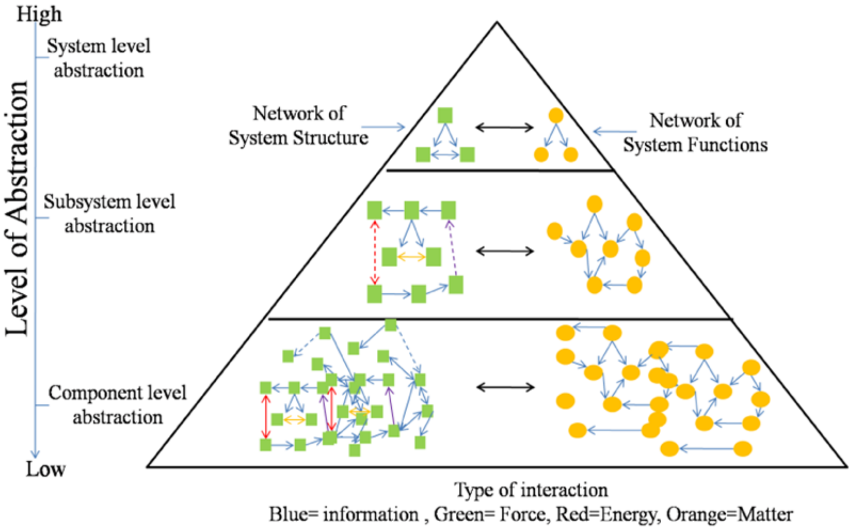


Figure 3-4 System Architecture Specification Concepts [92]

B. Architecture Variability Model (AVM)

In terms of the architecture variability model, the data relationships define how the composability rules manage component analysis block changes to the simulation. The rules represent which and in what order components are accessed for integration into the system architecture. This model structure would not be unlike the disciplinary analysis process utilized in the product development sizing tool. Development of this capability is in the experimental stages. It allows for an automated structure for product portfolio model and mostly ad-hoc for capability performance model. The necessary data relationships will be documented in the parametric model and analysis model.

C. Component Capabilities Model (CCM)

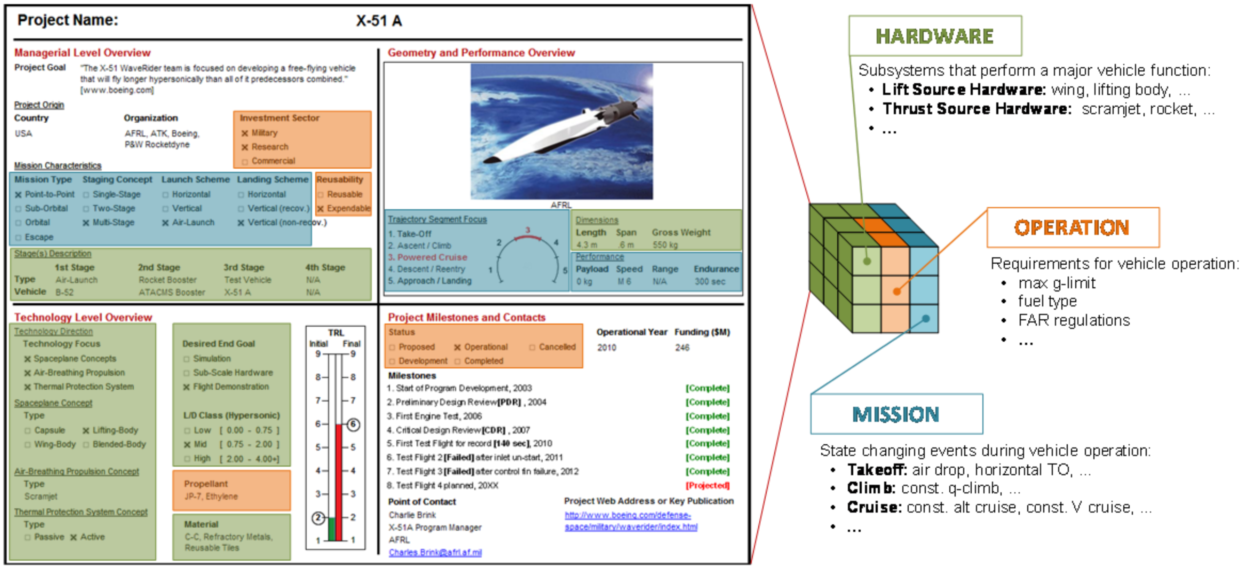
The component capabilities model provides the data rules characterizing how to build the analysis component blocks such that the data interfaces can integrate with the structural architecture model. By doing so, heterogeneity within similar function components will be reduced, and different hardware abstractions and methods fidelity options for the product portfolio model and capability performance model can be structured to maintain composable data relationships. Most of this data management capability is embedded in the implementation of the software process, Chapter 3.3, and in some part managed by the researcher. The resulting data relationships will be discussed as in the parametric model and analysis model.

3.2.2 Parametric Model

3.2.2.1 Problem Formulation Simulation Model (PFSM)

A. PFSM Data Relationships

The problem formulation simulation model is designated as the input and output framework for the researcher. It is tasked to decompose the technology and operational performance problem (i.e. hypersonic vehicle demonstrator) requirements in a manner that allows alignment with the zero silo DBMS PS tool strategy, and specify the level of abstraction requirements for the PPM as well as initialize the acquisition data metrics that measure risk exposure through the capability performance model. Consequently, the model will capture the primary technology functions (hardware options, mission constraints, and operational environment constraints) requirements, see Figure 3-5, and deliver prioritized technology options and aircraft configurations such that the project vehicle constraints for a horizontally integrated system are known. Gonzalez defines these constraints in three parts: *"… a description of the product being modelled, a definition of the analytic process being used to order and integrate the model, and a permutation of disciplinary methods performing the analysis of the model. …"* [17]



Project Name: **X-51 A**

Managerial Level Overview

Project Goal "The X-51 WaveRider team is focused on developing a free-flying vehicle that will fly longer hypersonically than all of it predecessors combined." [www.boeing.com]

Project Origin

Country	Organization	Investment Sector
USA	AFRL, ATK, Boeing, P&W Rocketdyne	☒ Military ☒ Research ☐ Commercial

Mission Characteristics

Mission Type	Staging Concept	Launch Scheme	Landing Scheme	Reusability
☒ Point-to-Point	☐ Single-Stage	☐ Horizontal	☐ Horizontal	☐ Reusable
☐ Sub-Orbital	☐ Two-Stage	☐ Vertical	☐ Vertical (recov.)	☒ Expendable
☐ Orbital	☒ Multi-Stage	☒ Air-Launch	☒ Vertical (non-recov.)	
☐ Escape				

Stage(s) Description

	1st Stage	2nd Stage	3rd Stage	4th Stage
Type	Air-Launch	Rocket Booster	Test Vehicle	N/A
Vehicle	B-52	ATACMS Booster	X-51 A	N/A

Geometry and Performance Overview

AFRL

Trajectory Segment Focus

1. Take-Off
2. Ascent / Climb
3. Powered Cruise
4. Descent / Reentry
5. Approach / Landing

Dimensions

Length	Span	Gross Weight
4.3 m	.6 m	550 kg

Performance

Payload	Speed	Range	Endurance
0 kg	M 6	N/A	300 sec

Technology Level Overview

Technology Direction

Technology Focus
- ☒ Spaceplane Concepts
- ☒ Air-Breathing Propulsion
- ☒ Thermal Protection System

Spaceplane Concept

Type
- ☐ Capsule ☒ Lifting-Body
- ☐ Wing-Body ☐ Blended-Body

Air-Breathing Propulsion Concept

Type
Scramjet

Thermal Protection System Concept

Type
☐ Passive ☒ Active

Desired End Goal
- ☐ Simulation
- ☐ Sub-Scale Hardware
- ☒ Flight Demonstration

L/D Class (Hypersonic)
- ☐ Low [0.00 - 0.75]
- ☒ Mid [0.75 - 2.00]
- ☐ High [2.00 - 4.00+]

Propellant
JP-7, Ethylene

Material
C-C, Refractory Metals, Reusable Tiles

Project Milestones and Contacts

Status
- ☐ Proposed ☒ Operational ☐ Cancelled
- ☐ Development ☐ Completed

Operational Year	Funding ($M)
2010	246

Milestones

1. Start of Program Development, 2003	[Complete]
2. Preliminary Design Review **[PDR]**, 2004	[Complete]
3. First Engine Test, 2006	[Complete]
4. Critical Design Review **[CDR]**, 2007	[Complete]
5. First Test Flight for record **[140 sec]**, 2010	[Complete]
6. Test Flight 2 **[Failed]** after inlet un-start, 2011	[Complete]
7. Test Flight 3 **[Failed]** after control fin failure, 2012	[Complete]
8. Test Flight 4 planned, 20XX	[Projected]

Point of Contact
Charlie Brink
X-51A Program Manager
AFRL
Charles.Brink@afrl.af.mil

Project Web Address or Key Publication
http://www.boeing.com/defense-space/military/waverider/index.html

HARDWARE

Subsystems that perform a major vehicle function:
- **Lift Source Hardware:** wing, lifting body, …
- **Thrust Source Hardware:** scramjet, rocket, …
- …

OPERATION

Requirements for vehicle operation:
- max g-limit
- fuel type
- FAR regulations
- …

MISSION

State changing events during vehicle operation:
- **Takeoff:** air drop, horizontal TO, …
- **Climb:** const. q-climb, …
- **Cruise:** const. alt cruise, const. V cruise, …
- …

Figure 3-5 Product Development Data Requirements for Composable System Architecture

B. PFSM Data Automation Structure

In the present architecture, the PFSM operations are user defined and output directly to the functional capabilities system model (FCSM). The processes are determined uniquely per acquisition problem.

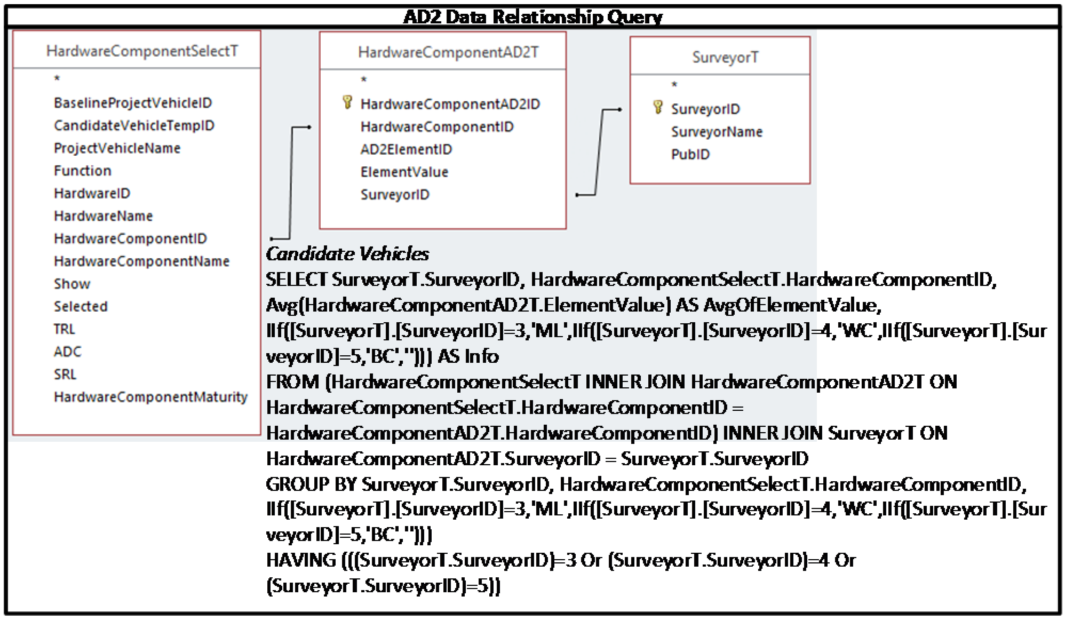
3.2.2.2 Functional Capabilities System Model (FCSM)

A. FCSM Data Relationships

Packaging the functional capabilities into a composable structure enables the researcher to control the degree of integration between the product portfolio model and capability performance model. Operation of the model produces a process that decides what data is required to assess technology hardware design and risks and couples the hardware options to methods native to product acquisition. As such, M&S guidance is provided by the problem formulation simulation model and, once the processes are executed, output is generated providing requirements for the analysis models.

B. FCSM Data Automation Structure

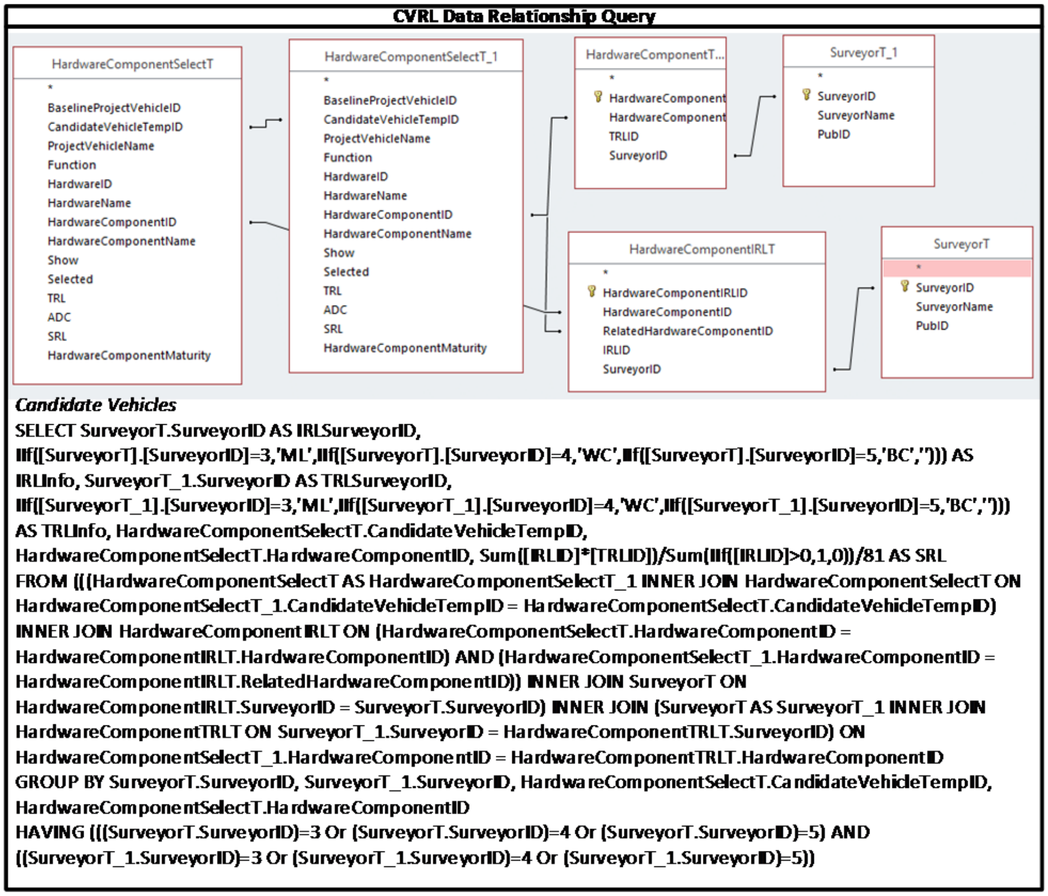
The FCSM arranges the analysis model data requirements into a logical structure. It is constructed in two parts: (1) AD2 Data Relationship Query, and (2) CVRL Data Relationship Query. Figure 3-6 and Figure 3-7 illustrate this process, respectively. Whereby the execution of the model inputs the data requirements for DBMS storage from the product portfolio model (PPM) and capability performance model (CPM). Note that the complexity of managing the multidisciplinary data interfaces has prevented this model from being fully automated. Thus, the product level of abstraction and analysis metrics are fixed in the prototype, and automation occurs in terms of data management of the preceding (PFSM) and proceeding models (PPM and CPM).



Candidate Vehicles

```
SELECT SurveyorT.SurveyorID, HardwareComponentSelectT.HardwareComponentID,
Avg(HardwareComponentAD2T.ElementValue) AS AvgOfElementValue,
IIf([SurveyorT].[SurveyorID]=3,'ML',IIf([SurveyorT].[SurveyorID]=4,'WC',IIf([SurveyorT].[Sur
veyorID]=5,'BC',''))) AS Info
FROM (HardwareComponentSelectT INNER JOIN HardwareComponentAD2T ON
HardwareComponentSelectT.HardwareComponentID =
HardwareComponentAD2T.HardwareComponentID) INNER JOIN SurveyorT ON
HardwareComponentAD2T.SurveyorID = SurveyorT.SurveyorID
GROUP BY SurveyorT.SurveyorID, HardwareComponentSelectT.HardwareComponentID,
IIf([SurveyorT].[SurveyorID]=3,'ML',IIf([SurveyorT].[SurveyorID]=4,'WC',IIf([SurveyorT].[Sur
veyorID]=5,'BC','')))
HAVING (((SurveyorT.SurveyorID)=3 Or (SurveyorT.SurveyorID)=4 Or
(SurveyorT.SurveyorID)=5))
```

Figure 3-6 Functional Capabilities System Model – AD2 Data Requirements Relationship Query



Candidate Vehicles

```
SELECT SurveyorT.SurveyorID AS IRLSurveyorID,
IIf([SurveyorT].[SurveyorID]=3,'ML',IIf([SurveyorT].[SurveyorID]=4,'WC',IIf([SurveyorT].[SurveyorID]=5,'BC','')))) AS
IRLInfo, SurveyorT_1.SurveyorID AS TRLSurveyorID,
IIf([SurveyorT_1].[SurveyorID]=3,'ML',IIf([SurveyorT_1].[SurveyorID]=4,'WC',IIf([SurveyorT_1].[SurveyorID]=5,'BC','')))
AS TRLInfo, HardwareComponentSelectT.CandidateVehicleTempID,
HardwareComponentSelectT.HardwareComponentID, Sum([IRLID]*[TRLID])/Sum(IIf([IRLID]>0,1,0))/81 AS SRL
FROM (((HardwareComponentSelectT AS HardwareComponentSelectT_1 INNER JOIN HardwareComponentSelectT ON
HardwareComponentSelectT_1.CandidateVehicleTempID = HardwareComponentSelectT.CandidateVehicleTempID)
INNER JOIN HardwareComponentIRLT ON (HardwareComponentSelectT.HardwareComponentID =
HardwareComponentIRLT.HardwareComponentID) AND (HardwareComponentSelectT_1.HardwareComponentID =
HardwareComponentIRLT.RelatedHardwareComponentID)) INNER JOIN SurveyorT ON
HardwareComponentIRLT.SurveyorID = SurveyorT.SurveyorID) INNER JOIN (SurveyorT AS SurveyorT_1 INNER JOIN
HardwareComponentTRLT ON SurveyorT_1.SurveyorID = HardwareComponentTRLT.SurveyorID) ON
HardwareComponentSelectT_1.HardwareComponentID = HardwareComponentTRLT.HardwareComponentID
GROUP BY SurveyorT.SurveyorID, SurveyorT_1.SurveyorID, HardwareComponentSelectT.CandidateVehicleTempID,
HardwareComponentSelectT.HardwareComponentID
HAVING (((SurveyorT.SurveyorID)=3 Or (SurveyorT.SurveyorID)=4 Or (SurveyorT.SurveyorID)=5) AND
((SurveyorT_1.SurveyorID)=3 Or (SurveyorT_1.SurveyorID)=4 Or (SurveyorT_1.SurveyorID)=5))
```

Figure 3-7 Functional Capabilities System Model – CVRL Data Requirements Relationship Query

3.2.3 Analysis Model

3.2.3.1 Product Portfolio Model (PPM)

A. PPM Data Relationships

The PPM refers to the physical characteristics of an aircraft being described as a function of the PS multidisciplinary effects captured. The objective is to take unstructured data and simplify the data requirements to consistently store in a structured DBMS, see Figure 3-5. The first step requires the identification of a reference operational system. Operational systems are constructed to convert specific researcher decision concerns and technology priorities into actionable items. For instance, each operational system would have a unique combination of lift source, thrust source, landing system, thermal protection, and booster to associate the mission, operation, and hardware choices. Figure 3-6 deconstructs the operational system into a multi-attribute hierarchy where:

- Functional subsystem – identifies hardware components as technology functions;
- Operational event – represents the time dependent components during flight;
- Operational requirement – defines regulation, subsystem, and non-hardware constraints.

This breakdown has been developed to aggregate sizing tool inputs in a manner that is complementary to disciplinary method selection. The current data relationship standard is comparable in capability to vertically integrated tools though not limited to a specific design problem formulation. To accomplish this, earlier sizing tool development work by Coleman has been decomposed and qualitatively assessed. [21] Next, to map the relevant topology of the synthesis systems and to arrive at the attributes for constructing the data relationships for Figure 3-8, the combined effort and conversations with Gonzalez, Omoragbon, and the author are applied in the following sections.[17][144][145-154].

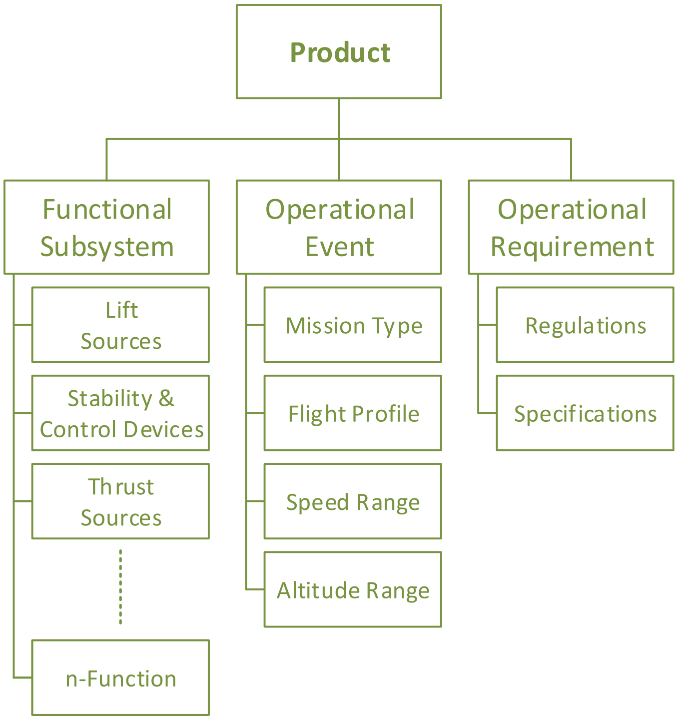


Figure 3-8 Product Portfolio Model Operational System – Primary Attributes

Once the operational system level of attributes is decided, the product portfolio model provides guidance (discussed in Chapter 4) to the researcher to continue the process of building a CV based on the operational system shell. Observe that to this point, specific hardware implementations have not been identified. This is done in order to separate the hardware from the disciplinary and/or multidisciplinary effect it will create. Later this effect will be evaluated as a method in a disciplinary sizing module(s).

Now, the hardware components of interest are modeled to the necessary level of abstraction as a functional subsystem, see Figure 3-9. Table 3-1 describes the purpose and disciplinary function for each technology category considered. In the current configuration, the abstraction level does not decompose beyond a hardware component for sizing method matching. This means that a scramjet is simulated as a single hardware and is not composable in terms of the associated subcomponents (i.e. inlet, isolator, burner, and nozzle hardware options) which might be required as part of capability performance (acquisition) model risk analysis. Next, the operational events are determined for the operational system to correlate how the hardware components will be used during vehicle operation. With this organization, the design mission, flight profile, speed range, and altitude range options, see Figure 3-10, are grouped in sets or combinations of sets. Table 3-2 and Figure 3-11 to Figure 3-13 standardize the operational events attribute definitions used concepts. Finally, the operational requirements are identifying regulatory, subsystem, and/or non-hardware constraints. Figure 3-14 illustrates the attributes in this structure. Regulations refer to design and operational conditions enforced by the Federal Aviation Administration-type governing bodies. Any regulation (airport noise limits, no supersonic flight over land, etc.) or guidance (3 *g* limit for manned high speed flight) of interest is translated into a parameter that can addressed by the sizing tool as needed. Specification refers to secondary design parameters in the sense that an aircraft can still be sized without that constraint. These can include anything from vehicle man rating and propellant selection to future limits for pollution.

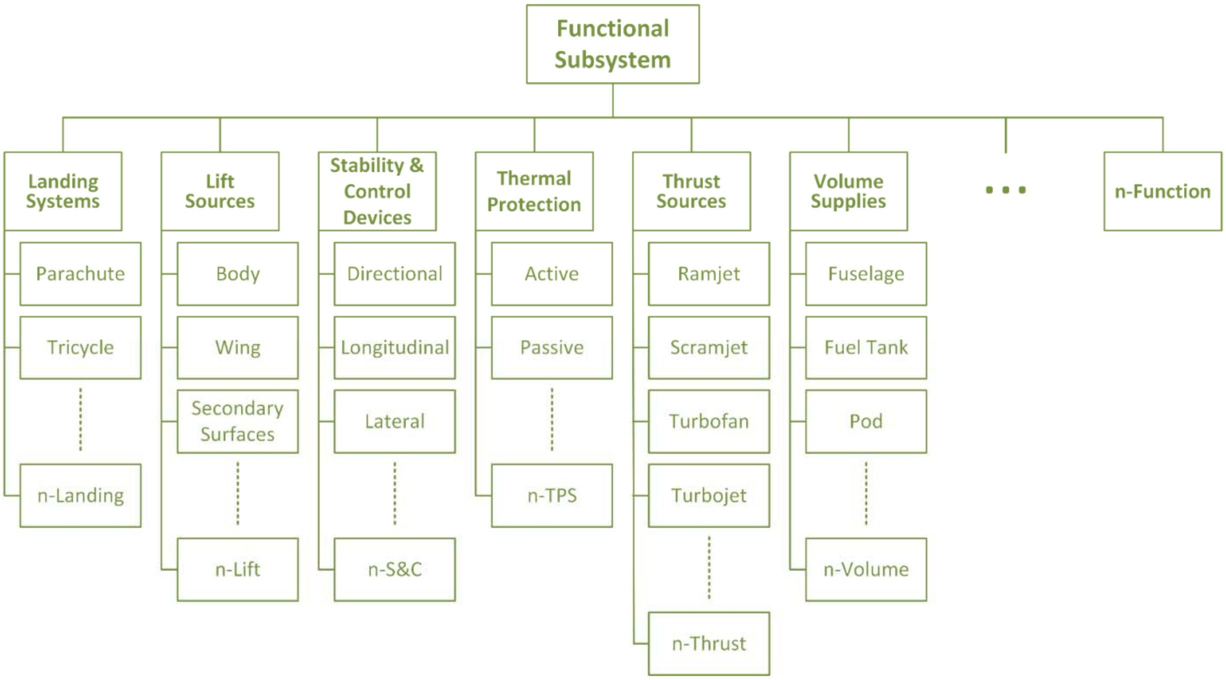


Figure 3-9 Product Portfolio Model Operational System – Functional Subsystem Attributes

Table 3-1 Product Portfolio Model Operational System – Functional Subsystem Hardware Source Definitions

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

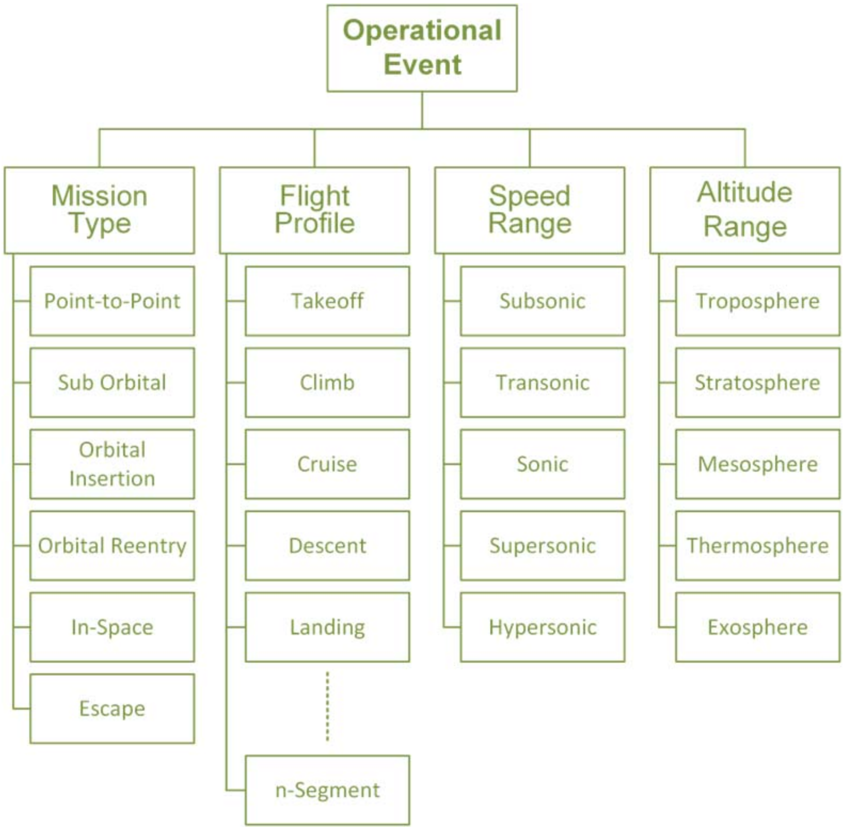


Figure 3-10 Product Portfolio Model Operational System – Operational Event Attributes

Table 3-2 Product Portfolio Model Operational System – Operational Event Mission Type Definitions

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

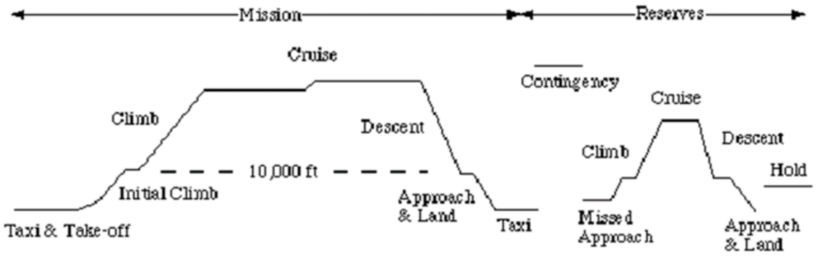


Figure 3-11 Product Portfolio Model Operational System – Operational Event Flight Profile Definitions [155]

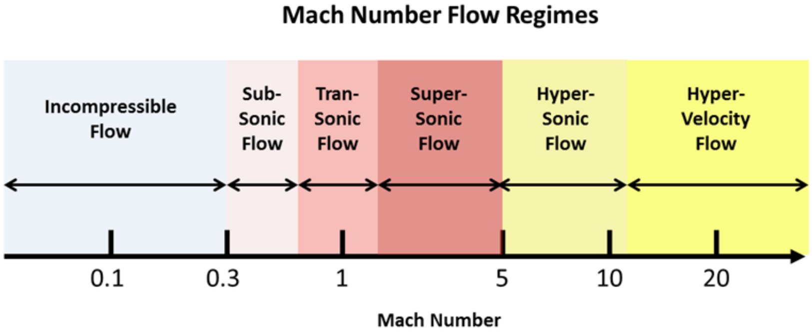


Figure 3-12 Product Portfolio Model Operational System – Operational Event Flight Profile Definitions [132]

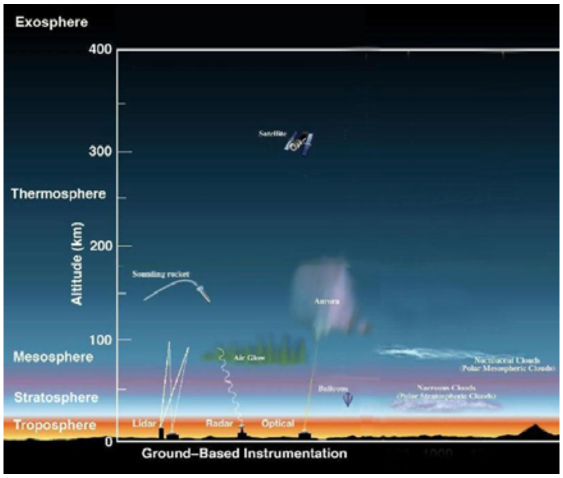


Figure 3-13 Product Portfolio Model Operational System – Operational Event Altitude Range Definitions [156]

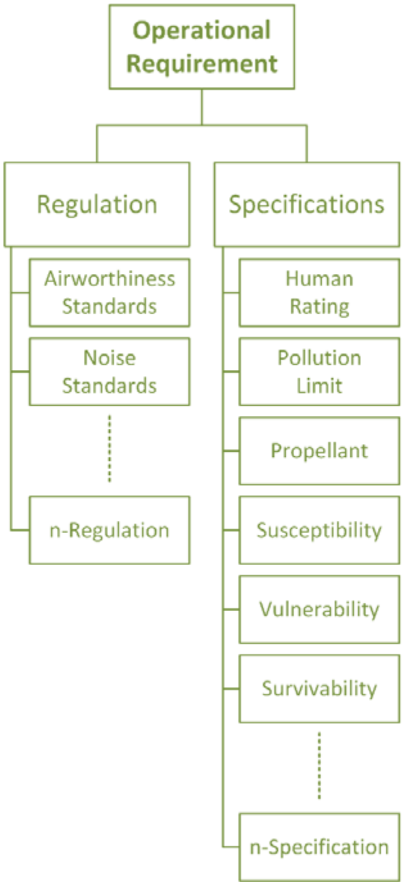


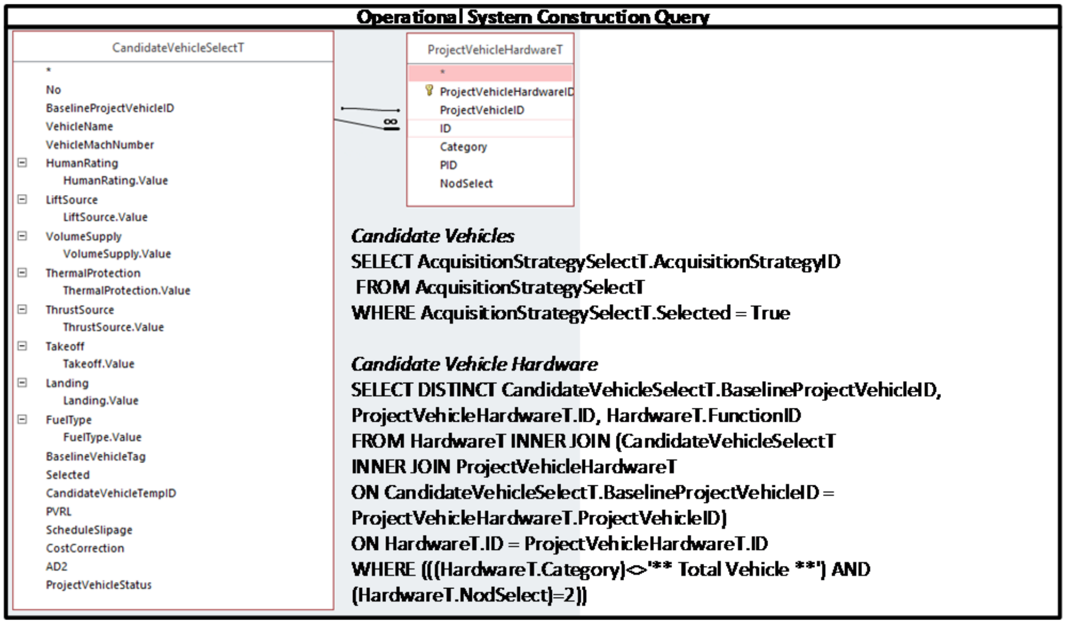
Figure 3-14 Product Portfolio Model Operational System – Operational Requirement Attributes

The product portfolio model serves two purposes towards problem formulation: (1) to establish the product-level sizing tool data input relationships and level of abstraction for disciplinary method and multidisciplinary effects mapping, and (2) it designates the MSA phase hardware level of abstraction for acquisition through the capability performance model.

B. PPM Data Automation Structure

The product model is designed such that hardware technology options are bundled in a portfolio of operational system implementations. Before any work can happen, the DBMS must be populated, as defined by the SAM, with the functional data blocks introduced in the previous section. Following the rules in the AVM, the first composable process addresses construction of the operational system shells for an acquisition problem, see Figure 3-15. Figure 3-16 further outlines the corresponding form the researcher employs to select and prioritize components of the functional capability (lift source, thrust source, stability and control, thermal protection system, and landing system) that assemble the operational system. Data constructed is stored in the DBMS.

Next, the AVM logic in Figure 3-17 is used to assign hardware implementations to the operational systems. The input interface requires researcher specification of relevant hardware implementations (i.e. X-51A HYTECH scramjet concept, GHV twin tail and elevon concept, D-21 wing body concept, etc.), see Figure 3-18. Finally, the technology implementations are assigned to operational systems to at a baseline technology and CV portfolio, see Figure 3-19. To this end, the design of the operational system and the resulting CV is both composable and automated, and the technology portfolio is scalable in scope to the acquisition decision needs of the researcher.


Operational System Construction Query

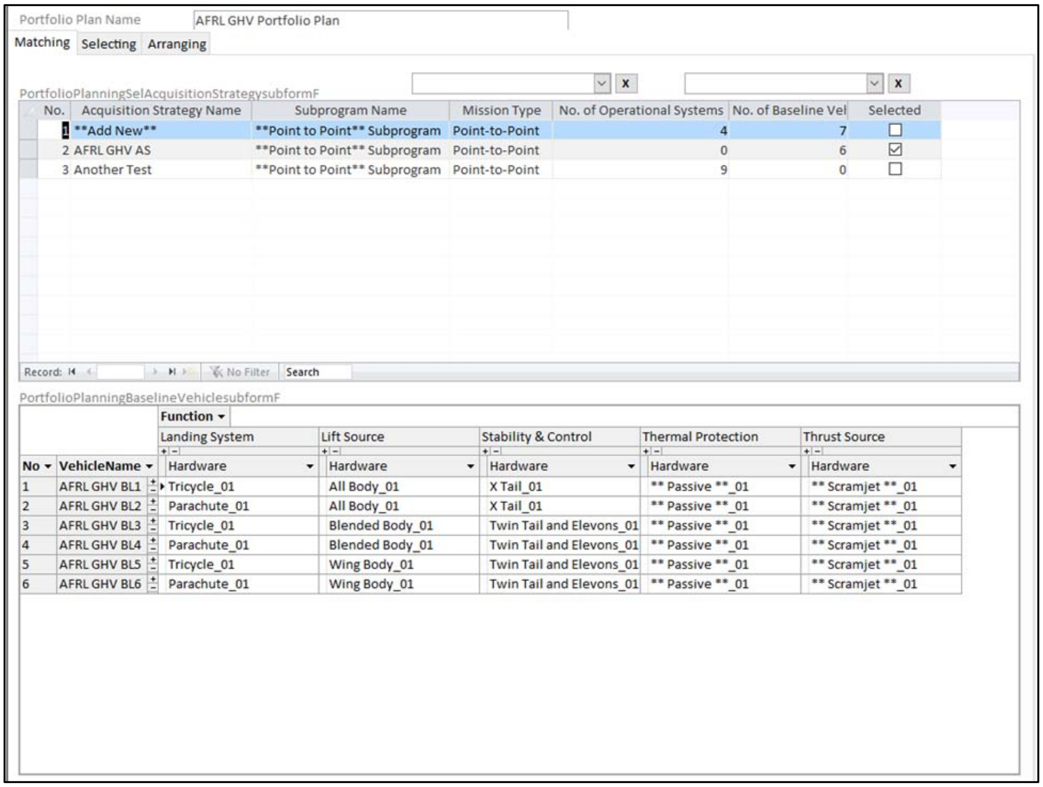
Candidate Vehicles

```
SELECT AcquisitionStrategySelectT.AcquisitionStrategyID
 FROM AcquisitionStrategySelectT
WHERE AcquisitionStrategySelectT.Selected = True
```

Candidate Vehicle Hardware

```
SELECT DISTINCT CandidateVehicleSelectT.BaselineProjectVehicleID,
ProjectVehicleHardwareT.ID, HardwareT.FunctionID
FROM HardwareT INNER JOIN (CandidateVehicleSelectT
INNER JOIN ProjectVehicleHardwareT
ON CandidateVehicleSelectT.BaselineProjectVehicleID =
ProjectVehicleHardwareT.ProjectVehicleID)
ON HardwareT.ID = ProjectVehicleHardwareT.ID
WHERE (((HardwareT.Category)<>'** Total Vehicle **') AND
(HardwareT.NodSelect)=2))
```

Figure 3-15 Product Portfolio Model – Operational System Construction Query



Portfolio Plan Name: AFRL GHV Portfolio Plan

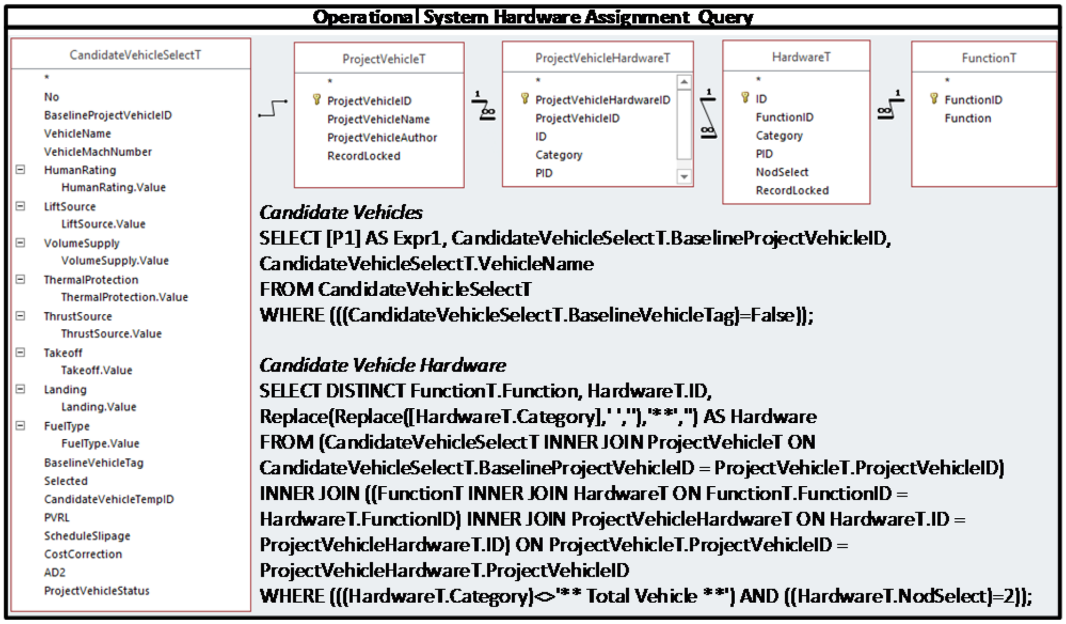
PortfolioPlanningSelAcquisitionStrategysubformF

No.	Acquisition Strategy Name	Subprogram Name	Mission Type	No. of Operational Systems	No. of Baseline Vel	Selected
1	**Add New**	**Point to Point** Subprogram	Point-to-Point	4	7	☐
2	AFRL GHV AS	**Point to Point** Subprogram	Point-to-Point	0	6	☑
3	Another Test	**Point to Point** Subprogram	Point-to-Point	9	0	☐

PortfolioPlanningBaselineVehiclesubformF

		Function				
		Landing System	Lift Source	Stability & Control	Thermal Protection	Thrust Source
No	VehicleName	Hardware	Hardware	Hardware	Hardware	Hardware
1	AFRL GHV BL1	Tricycle_01	All Body_01	X Tail_01	** Passive **_01	** Scramjet **_01
2	AFRL GHV BL2	Parachute_01	All Body_01	X Tail_01	** Passive **_01	** Scramjet **_01
3	AFRL GHV BL3	Tricycle_01	Blended Body_01	Twin Tail and Elevons_01	** Passive **_01	** Scramjet **_01
4	AFRL GHV BL4	Parachute_01	Blended Body_01	Twin Tail and Elevons_01	** Passive **_01	** Scramjet **_01
5	AFRL GHV BL5	Tricycle_01	Wing Body_01	Twin Tail and Elevons_01	** Passive **_01	** Scramjet **_01
6	AFRL GHV BL6	Parachute_01	Wing Body_01	Twin Tail and Elevons_01	** Passive **_01	** Scramjet **_01

Figure 3-16 Product Portfolio Model – Operational System Assembly Form



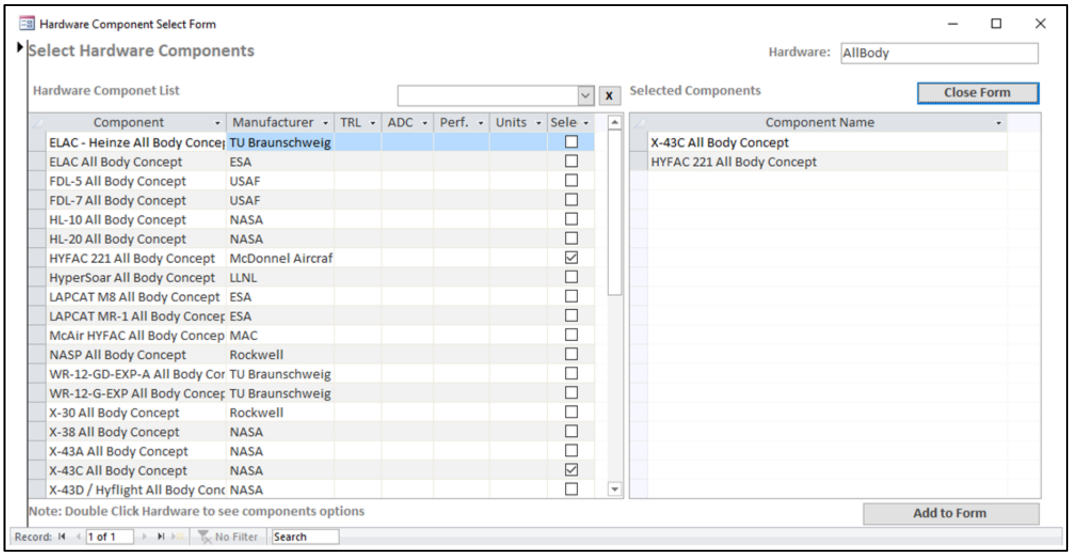
Candidate Vehicles

```
SELECT [P1] AS Expr1, CandidateVehicleSelectT.BaselineProjectVehicleID,
CandidateVehicleSelectT.VehicleName
FROM CandidateVehicleSelectT
WHERE (((CandidateVehicleSelectT.BaselineVehicleTag)=False));
```

Candidate Vehicle Hardware

```
SELECT DISTINCT FunctionT.Function, HardwareT.ID,
Replace(Replace([HardwareT.Category],' ',''),'**','') AS Hardware
FROM (CandidateVehicleSelectT INNER JOIN ProjectVehicleT ON
CandidateVehicleSelectT.BaselineProjectVehicleID = ProjectVehicleT.ProjectVehicleID)
INNER JOIN ((FunctionT INNER JOIN HardwareT ON FunctionT.FunctionID =
HardwareT.FunctionID) INNER JOIN ProjectVehicleHardwareT ON HardwareT.ID =
ProjectVehicleHardwareT.ID) ON ProjectVehicleT.ProjectVehicleID =
ProjectVehicleHardwareT.ProjectVehicleID
WHERE (((HardwareT.Category)<>'** Total Vehicle **') AND ((HardwareT.NodSelect)=2));
```

Figure 3-17 Product Portfolio Model – Operational System Hardware Assignment Query



Select Hardware Components

Hardware: AllBody

Hardware Componet List

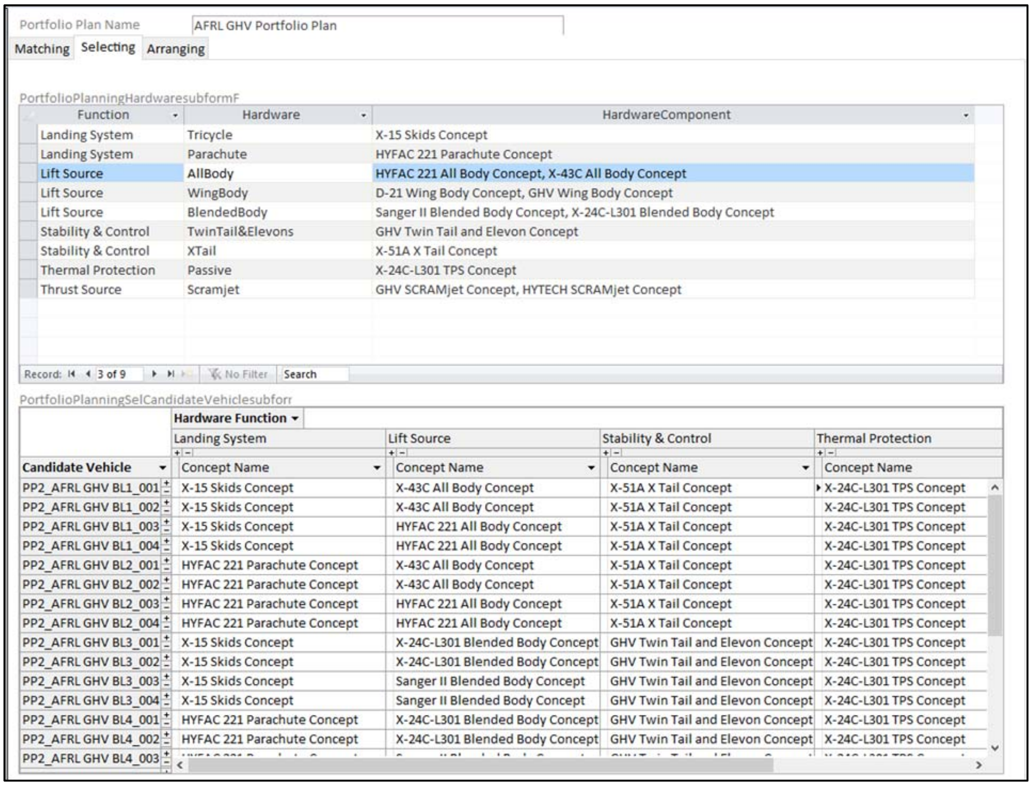
Selected Components

Component	Manufacturer	TRL	ADC	Perf.	Units	Sele
ELAC - Heinze All Body Concej	TU Braunschweig					☐
ELAC All Body Concept	ESA					☐
FDL-5 All Body Concept	USAF					☐
FDL-7 All Body Concept	USAF					☐
HL-10 All Body Concept	NASA					☐
HL-20 All Body Concept	NASA					☐
HYFAC 221 All Body Concept	McDonnel Aircraf					☑
HyperSoar All Body Concept	LLNL					☐
LAPCAT M8 All Body Concept	ESA					☐
LAPCAT MR-1 All Body Concej	ESA					☐
McAir HYFAC All Body Concep	MAC					☐
NASP All Body Concept	Rockwell					☐
WR-12-GD-EXP-A All Body Cor	TU Braunschweig					☐
WR-12-G-EXP All Body Concej	TU Braunschweig					☐
X-30 All Body Concept	Rockwell					☐
X-38 All Body Concept	NASA					☐
X-43A All Body Concept	NASA					☐
X-43C All Body Concept	NASA					☑
X-43D / Hyflight All Body Conc	NASA					☐

Component Name
X-43C All Body Concept
HYFAC 221 All Body Concept

Note: Double Click Hardware to see components options

Figure 3-18 Product Portfolio Model – Operational System Hardware Assignment Form


Portfolio Plan Name: AFRL GHV Portfolio Plan

PortfolioPlanningHardwaresubformF

Function	Hardware	HardwareComponent
Landing System	Tricycle	X-15 Skids Concept
Landing System	Parachute	HYFAC 221 Parachute Concept
Lift Source	AllBody	HYFAC 221 All Body Concept, X-43C All Body Concept
Lift Source	WingBody	D-21 Wing Body Concept, GHV Wing Body Concept
Lift Source	BlendedBody	Sanger II Blended Body Concept, X-24C-L301 Blended Body Concept
Stability & Control	TwinTail&Elevons	GHV Twin Tail and Elevon Concept
Stability & Control	XTail	X-51A X Tail Concept
Thermal Protection	Passive	X-24C-L301 TPS Concept
Thrust Source	Scramjet	GHV SCRAMjet Concept, HYTECH SCRAMjet Concept

PortfolioPlanningSelCandidateVehiclesubforr

	Hardware Function			
	Landing System	Lift Source	Stability & Control	Thermal Protection
Candidate Vehicle	Concept Name	Concept Name	Concept Name	Concept Name
PP2_AFRL GHV BL1_001	X-15 Skids Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL1_002	X-15 Skids Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL1_003	X-15 Skids Concept	HYFAC 221 All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL1_004	X-15 Skids Concept	HYFAC 221 All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL2_001	HYFAC 221 Parachute Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL2_002	HYFAC 221 Parachute Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL2_003	HYFAC 221 Parachute Concept	HYFAC 221 All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL2_004	HYFAC 221 Parachute Concept	HYFAC 221 All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL3_001	X-15 Skids Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL3_002	X-15 Skids Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL3_003	X-15 Skids Concept	Sanger II Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL3_004	X-15 Skids Concept	Sanger II Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL4_001	HYFAC 221 Parachute Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL4_002	HYFAC 221 Parachute Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept
PP2_AFRL GHV BL4_003				

Figure 3-19 Product Portfolio Model – Operational System, Hardware, and Candidate Vehicle Portfolio Form

3.2.3.2 Capability Performance Model (CPM)

A. CPM Data Relationships

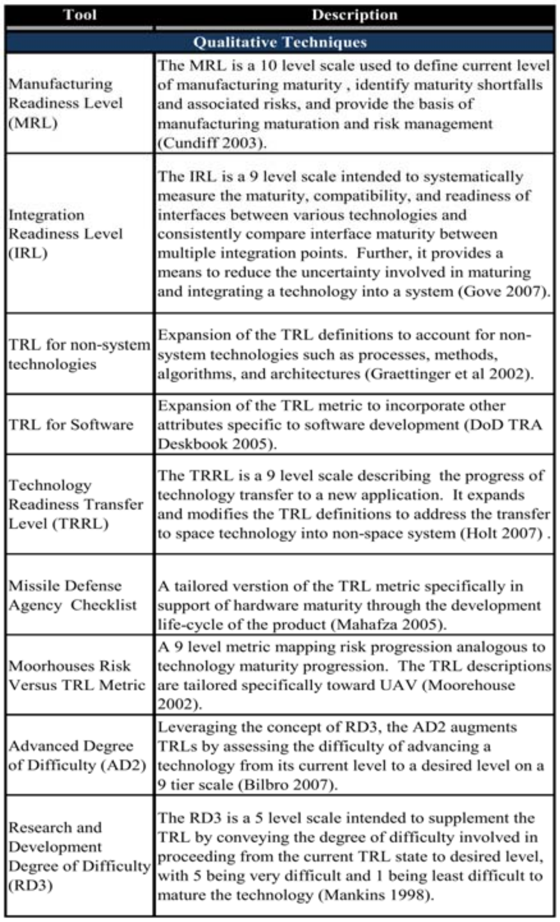
Portfolios of hardware technology and CVs are assessed within the developmental and technology risk (DTR) parameterization determined in Phase 1/2, see Table 2-1, of the IPA presented in Chapter 2.2. These objective functions have been examined to determine how best to automate integration of the data relationships into the composable architecture. As such, the acquisition uncertainty methods presented are considered standard, though are developed to interface with the PPM data structure when networked in the FCSM. As such, the associated methods library is able to assess *"… technology readiness and track technology maturity through the progression of system development lifecycle in order to provide continuous risk management and enhanced decision support …"* for the CV options. [157] Even though the current CPM represents a simplification of the complex acquisition landscape, adoption of this approach within a portfolio management framework delivers a systematic and data-driven capacity to study cost, schedule, and performance considerations. The suggested analysis benefits from a library of qualitative and quantitative data modules and DTRts that expand on TRL or integrate TRL with additional metrics to enable technology hardware prioritization and R&D strategy planning. Data constructed is stored in the DBMS.

An investigation of DTR initiatives and methodologies for the CPM methods library shows a number of successful strategies, see Table 3-3. Table 3-3(a) refers to some of the qualitative methods. Wherein, *"…their descriptive natures make these metrics subjective techniques that oversimplify many of the facets of maturity and readiness into one value. …"*.[157] Table 3-3(b) illustrates popular quantitative methods that derive from *"… mathematical operations between two or more metrics, and therefore the output value is not always indicative of technology or system maturity, but rather of the risk involved in developing the product. …"* [157] Correspondingly, the multidisciplinary data modules can be parameterized for FCSM integration to provide the researcher with a variety product risk profiles through the PFSM. Five metrics (four qualitative and one quantitative) are examined in more detail: technology readiness level (TRL), integration readiness level (IRL), manufacturing readiness level (MRL), advancement degree of difficulty (AD2), and system readiness level (SRL).

Having established the CPM metrics, hardware technology dependencies from the PPM are assessed by questions for best-case, worst-case, and most-likely product development scenarios.

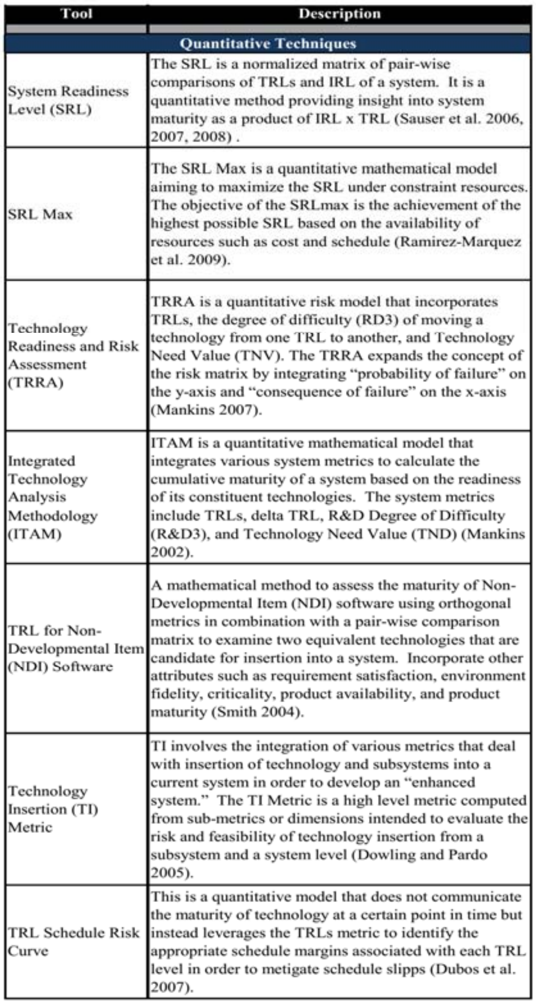
Table 3-3 Capability Performance Model – Developmental and Technology Risk Methods [157]

(a) Qualitative Methods



Tool	Description
Qualitative Techniques	
Manufacturing Readiness Level (MRL)	The MRL is a 10 level scale used to define current level of manufacturing maturity , identify maturity shortfalls and associated risks, and provide the basis of manufacturing maturation and risk management (Cundiff 2003).
Integration Readiness Level (IRL)	The IRL is a 9 level scale intended to systematically measure the maturity, compatibility, and readiness of interfaces between various technologies and consistently compare interface maturity between multiple integration points. Further, it provides a means to reduce the uncertainty involved in maturing and integrating a technology into a system (Gove 2007).
TRL for non-system technologies	Expansion of the TRL definitions to account for non-system technologies such as processes, methods, algorithms, and architectures (Graettinger et al 2002).
TRL for Software	Expansion of the TRL metric to incorporate other attributes specific to software development (DoD TRA Deskbook 2005).
Technology Readiness Transfer Level (TRRL)	The TRRL is a 9 level scale describing the progress of technology transfer to a new application. It expands and modifies the TRL definitions to address the transfer to space technology into non-space system (Holt 2007) .
Missile Defense Agency Checklist	A tailored verstion of the TRL metric specifically in support of hardware maturity through the development life-cycle of the product (Mahafza 2005).
Moorhouses Risk Versus TRL Metric	A 9 level metric mapping risk progression analogous to technology maturity progression. The TRL descriptions are tailored specifically toward UAV (Moorehouse 2002).
Advanced Degree of Difficulty (AD2)	Leveraging the concept of RD3, the AD2 augments TRLs by assessing the difficulty of advancing a technology from its current level to a desired level on a 9 tier scale (Bilbro 2007).
Research and Development Degree of Difficulty (RD3)	The RD3 is a 5 level scale intended to supplement the TRL by conveying the degree of difficulty involved in proceeding from the current TRL state to desired level, with 5 being very difficult and 1 being least difficult to mature the technology (Mankins 1998).

(b) Quantitative Methods



Tool	Description
Quantitative Techniques	
System Readiness Level (SRL)	The SRL is a normalized matrix of pair-wise comparisons of TRLs and IRL of a system. It is a quantitative method providing insight into system maturity as a product of IRL x TRL (Sauser et al. 2006, 2007, 2008) .
SRL Max	The SRL Max is a quantitative mathematical model aiming to maximize the SRL under constraint resources. The objective of the SRLmax is the achievement of the highest possible SRL based on the availability of resources such as cost and schedule (Ramirez-Marquez et al. 2009).
Technology Readiness and Risk Assessment (TRRA)	TRRA is a quantitative risk model that incorporates TRLs, the degree of difficulty (RD3) of moving a technology from one TRL to another, and Technology Need Value (TNV). The TRRA expands the concept of the risk matrix by integrating "probability of failure" on the y-axis and "consequence of failure" on the x-axis (Mankins 2007).
Integrated Technology Analysis Methodology (ITAM)	ITAM is a quantitative mathematical model that integrates various system metrics to calculate the cumulative maturity of a system based on the readiness of its constituent technologies. The system metrics include TRLs, delta TRL, R&D Degree of Difficulty (R&D3), and Technology Need Value (TND) (Mankins 2002).
TRL for Non-Developmental Item (NDI) Software	A mathematical method to assess the maturity of Non-Developmental Item (NDI) software using orthogonal metrics in combination with a pair-wise comparison matrix to examine two equivalent technologies that are candidate for insertion into a system. Incorporate other attributes such as requirement satisfaction, environment fidelity, criticality, product availability, and product maturity (Smith 2004).
Technology Insertion (TI) Metric	TI involves the integration of various metrics that deal with insertion of technology and subsystems into a current system in order to develop an "enhanced system." The TI Metric is a high level metric computed from sub-metrics or dimensions intended to evaluate the risk and feasibility of technology insertion from a subsystem and a system level (Dowling and Pardo 2005).
TRL Schedule Risk Curve	This is a quantitative model that does not communicate the maturity of technology at a certain point in time but instead leverages the TRLs metric to identify the appropriate schedule margins associated with each TRL level in order to metigate schedule slipps (Dubos et al. 2007).

Technology Readiness Level (TRL)

At first, the TRL metric is examined. Bilbo explains that it is *"… impossible to understand the magnitude and scope of a development program without having a clear understanding of the baseline technological maturity of all elements of the system. …"* [90] According to Mankins, TRLs are *"… one discipline-independent, programmatic figure of merit that allows more effective assessment of, and communication regarding the maturity of new technologies. …"* [158] Table 3-4 and Figure 3-20 describe this metric. Additionally, Figure 2-1 explains the TRL for MSA stage product development typically fall in the 4 to 5 range.

Table 3-4 Capability Performance Model – TRL Metric Definitions [159]

TRL	Definition	Description [DoD, 2005]
9	Actual System Proven Through Successful Mission Operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.
8	Actual System Completed and Qualified Through Test and Demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
7	System Prototype Demonstration in Operational Environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft
6	System/Subsystem Model or Prototype Demonstration in Relevant Environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
5	Component and/or Breadboard Validation in Relevant Environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components.
4	Component and/or Breadboard Validation in Laboratory Environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory.
3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
2	Technology Concept and/or Application Formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
1	Basic Principles Observed and Reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Example might include paper studies of a technology's basic properties.

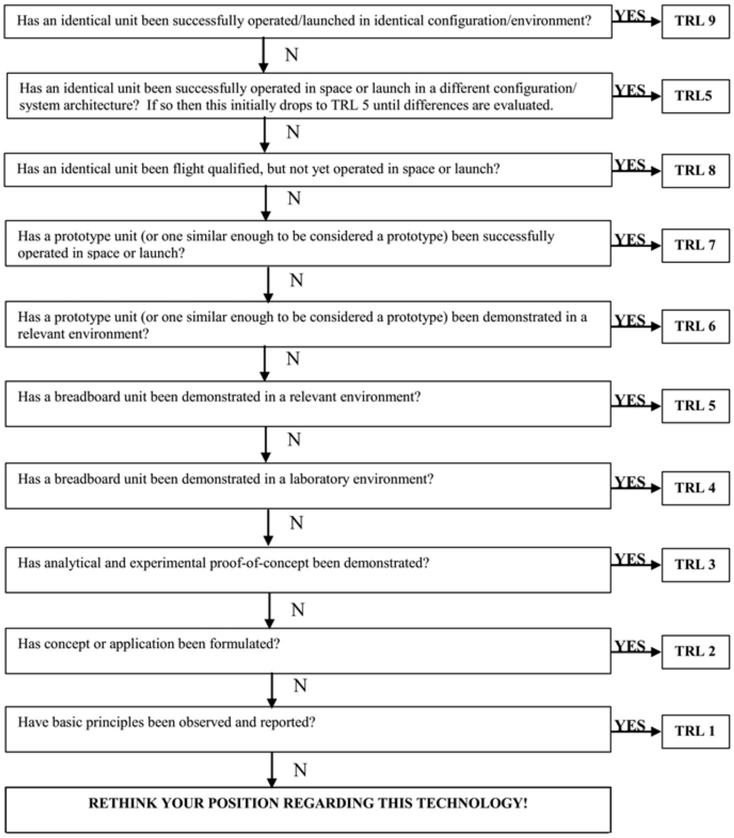
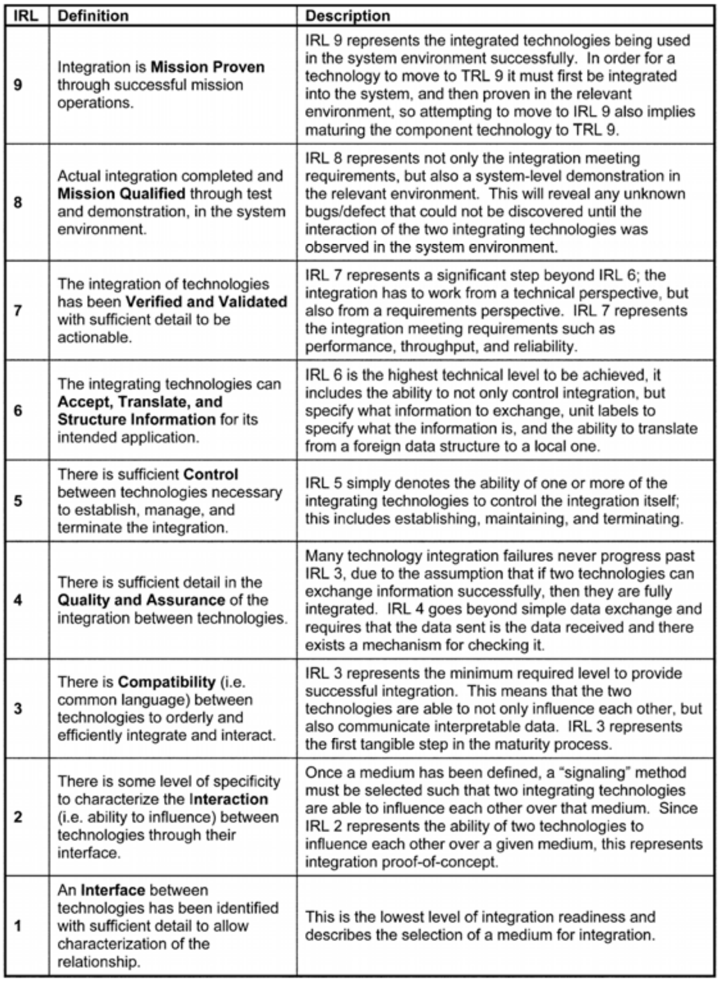


Figure 3-20 Capability Performance Model – TRL Metric Assessment [90]

Integration Readiness Level (IRL)

Next, IRL is represented. It is *"… intended to systematically measure the maturity, compatibility, and readiness of the interfaces between various technologies* [and levels of abstraction] *to consistently compare interface maturity between multiple hardware integration points. Further, it provides a means to reduce the uncertainty involved in maturing and integrating a technology …"* (i.e. lifting body plus scramjet engine), typically, for product R&D with TRL < 6. [160] Evaluating the product relationships identifies *"… inadequate levels of integration maturity as well as specific areas of development which … could prevent* [or reduce] *fa*ilure of these systems. *…"* [159] Table 3-5 discusses the strength of the multidisciplinary effects being modeled.

Table 3-5 Capability Performance Model – IRL Metric Definitions [159]



IRL	Definition	Description
9	Integration is **Mission Proven** through successful mission operations.	IRL 9 represents the integrated technologies being used in the system environment successfully. In order for a technology to move to TRL 9 it must first be integrated into the system, and then proven in the relevant environment, so attempting to move to IRL 9 also implies maturing the component technology to TRL 9.
8	Actual integration completed and **Mission Qualified** through test and demonstration, in the system environment.	IRL 8 represents not only the integration meeting requirements, but also a system-level demonstration in the relevant environment. This will reveal any unknown bugs/defect that could not be discovered until the interaction of the two integrating technologies was observed in the system environment.
7	The integration of technologies has been **Verified and Validated** with sufficient detail to be actionable.	IRL 7 represents a significant step beyond IRL 6; the integration has to work from a technical perspective, but also from a requirements perspective. IRL 7 represents the integration meeting requirements such as performance, throughput, and reliability.
6	The integrating technologies can **Accept, Translate, and Structure Information** for its intended application.	IRL 6 is the highest technical level to be achieved, it includes the ability to not only control integration, but specify what information to exchange, unit labels to specify what the information is, and the ability to translate from a foreign data structure to a local one.
5	There is sufficient **Control** between technologies necessary to establish, manage, and terminate the integration.	IRL 5 simply denotes the ability of one or more of the integrating technologies to control the integration itself; this includes establishing, maintaining, and terminating.
4	There is sufficient detail in the **Quality and Assurance** of the integration between technologies.	Many technology integration failures never progress past IRL 3, due to the assumption that if two technologies can exchange information successfully, then they are fully integrated. IRL 4 goes beyond simple data exchange and requires that the data sent is the data received and there exists a mechanism for checking it.
3	There is **Compatibility** (i.e. common language) between technologies to orderly and efficiently integrate and interact.	IRL 3 represents the minimum required level to provide successful integration. This means that the two technologies are able to not only influence each other, but also communicate interpretable data. IRL 3 represents the first tangible step in the maturity process.
2	There is some level of specificity to characterize the **Interaction** (i.e. ability to influence) between technologies through their interface.	Once a medium has been defined, a "signaling" method must be selected such that two integrating technologies are able to influence each other over that medium. Since IRL 2 represents the ability of two technologies to influence each other over a given medium, this represents integration proof-of-concept.
1	An **Interface** between technologies has been identified with sufficient detail to allow characterization of the relationship.	This is the lowest level of integration readiness and describes the selection of a medium for integration.

Advancement Degree of Difficulty (AD2)

AD2 is an automated technology assessment methodology that *"… augments TRLs by assessing the difficulty of advancing a technology from its current level to a desired level. …"* [157] Table 3-6 describes the effects. It consists of a two-part process, see Figure 3-21, that translates component and subcomponent technology maturity to calibrate (1) design and analysis, (2) manufacturing, (3) operations, and (4) test and evaluation R&D potential and project end-state (i.e. breadboard, brassboard, scale model, engineering unit, and prototype) attributes. [90] Equation 3-1 calculates AD2:

$$Composite\ AD2 = \frac{\Sigma(Attribute \cdot Developmental\ Risk)}{Attributes_{Total}} \qquad (3\text{-}1)$$

As a result, the TRL and AD2 metrics are correlated with the required DoD research and development test and evaluation budget activities to formalize the technology development risk. [161-163]

Table 3-6 Capability Performance Model – AD2 Metric Definitions [90]

Degree of Difficulty	Description
9	0% Development Risk - Exists with no or only minor modifications being required. A single development approach is adequate.
8	10% Development Risk - Exists but requires major modifications. A single development approach is adequate.
7	20% Development Risk - Requires new development well within the experience base. A single development approach is adequate.
6	30% Development Risk - Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.
5	40% Development Risk - Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.
4	50% Development Risk - Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (Desired performance can be achieved in subsequent block upgrades with high degree of confidence.)
3	60% Development Risk - Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.
2	80% Development Risk - Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.
1	100% Development Risk - Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.

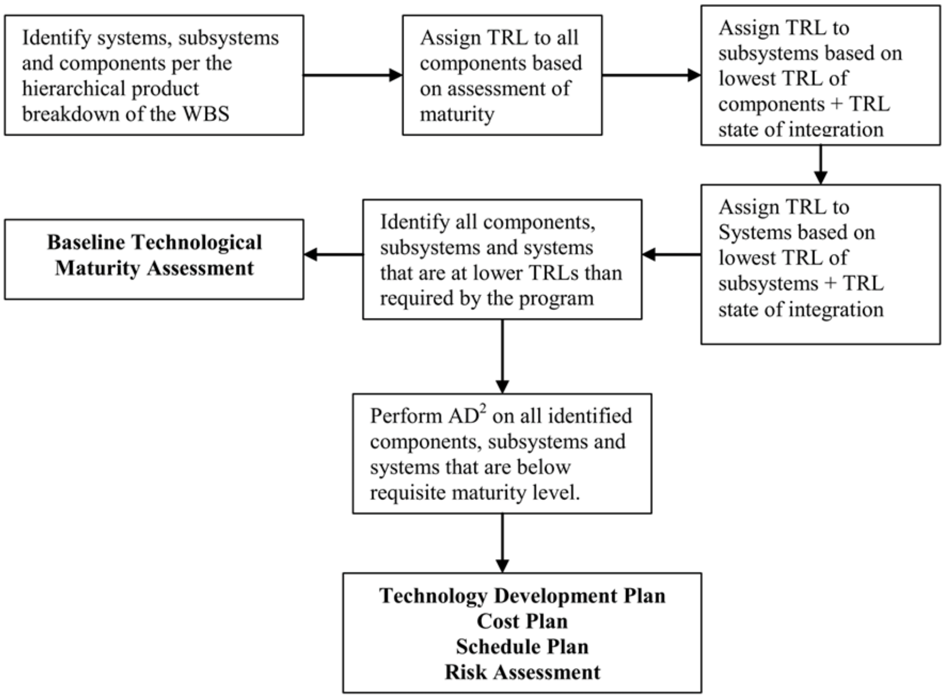


Figure 3-21 Capability Performance Model – AD2 Methodology [90]

System Readiness Level (SRL)

SRL utilizes a "… normalized matrix of pair-wise comparisons of TRLs and IRL of a system. …" [157] The data interface provides a quantitative measure of technology system maturity along the defense acquisition lifecycle, see Table 3-7, and is derived from the MRL scale. *"… The assumption here is that the subjectivity of TRL and IRL have been mitigated through the use of guidelines,* [and] *standardized* assessment procedures*. …"* [159] Consequently, the SRL methodology more realistically reflects the actual value of the product. Additionally, within the CPM, SRL is employed to integrate a 'family' of TRLs into a total value or CV readiness level (CVRL), where the composite SRL = CVRL.

The analysis is decomposed into three parts: [164]

1. Normalize intrinsic component and subcomponent TRL and IRL values from a [1 to 9] range into [0, 1], Equation 3-2 and Equation 3-3.

$$[TRL]_{nx1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \cdots \\ TRL_n \end{bmatrix} \xrightarrow{normalize} \begin{bmatrix} TRL_1 \\ TRL_2 \\ \cdots \\ TRL_n \end{bmatrix} \tag{3-2}$$

$$[IRL]_{nxn} = \begin{bmatrix} IRL_{11} & IRL_{12} & \cdots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \cdots & IRL_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ IRL_{n1} & IRL_{n2} & \cdots & IRL_{nn} \end{bmatrix} \xrightarrow{normalize} \begin{bmatrix} IRL_{11} & IRL_{12} & \cdots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \cdots & IRL_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ IRL_{n1} & IRL_{n2} & \cdots & IRL_{nn} \end{bmatrix} \tag{3-3}$$

where IRL_{ij} = IRL_{ji} = 0 for no integration between technology and IRL_{ii} = 9 when a technology is integrated with itself.

2. Component SRL is determined as a product of TRL and IRL.

$Component\ [SRL]_{nx1} = [Norm]_{nxn} \times [IRL]_{nxn} \times [TRL]_{nx1},$

where [Norm] = diag[$1/m_1$, $1/m_2$, …, $1/m_n$]

$$\begin{bmatrix} SRL_1 \\ SRL_2 \\ \cdots \\ SRL_n \end{bmatrix} = \begin{bmatrix} 1/m_1 & 0 & \cdots & 0 \\ 0 & 1/m_2 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & 1/m_n \end{bmatrix} \times \begin{bmatrix} IRL_{11} & IRL_{12} & \cdots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \cdots & IRL_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ IRL_{n1} & IRL_{n2} & \cdots & IRL_{nn} \end{bmatrix} \times \begin{bmatrix} TRL_1 \\ TRL_2 \\ \cdots \\ TRL_n \end{bmatrix}$$

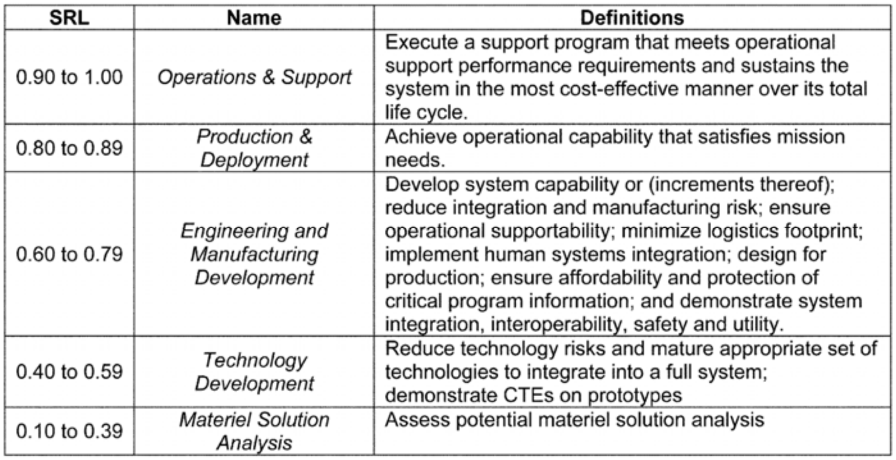
$$= \begin{bmatrix} (IRL_{11}TRL_1 + IRL_{12}TRL_2 + \cdots + IRL_{1n}TRL_n)/m_1 \\ (IRL_{21}TRL_1 + IRL_{22}TRL_2 + \cdots + IRL_{2n}TRL_n)/m_2 \\ \cdots \\ (IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \cdots + IRL_{nn}TRL_n)/m_n \end{bmatrix} \tag{3-4}$$

where each technology (i) is characterized by the number (m) of unique technology interactions plus itself. Then SRL_i normalized from [0, m_i] to [0, 1].

3. The composite SRL is the mean of the component SRLs to calibrate the technology risk status with the defense lifecycle.

$$Composite\ SRL = \frac{SRL_1 + SRL_2 + \cdots + SRL_n}{n} = \frac{\sum_{i=1}^{n} SRL_i}{n} \qquad (3\text{-}5)$$

Table 3-7 Capability Performance Model – SRL Metric Definitions [157][164]



SRL	Name	Definitions
0.90 to 1.00	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle.
0.80 to 0.89	*Production & Deployment*	Achieve operational capability that satisfies mission needs.
0.60 to 0.79	*Engineering and Manufacturing Development*	Develop system capability or (increments thereof); reduce integration and manufacturing risk; ensure operational supportability; minimize logistics footprint; implement human systems integration; design for production; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety and utility.
0.40 to 0.59	*Technology Development*	Reduce technology risks and mature appropriate set of technologies to integrate into a full system; demonstrate CTEs on prototypes
0.10 to 0.39	*Materiel Solution Analysis*	Assess potential materiel solution analysis

B. CPM Data Automation Structure

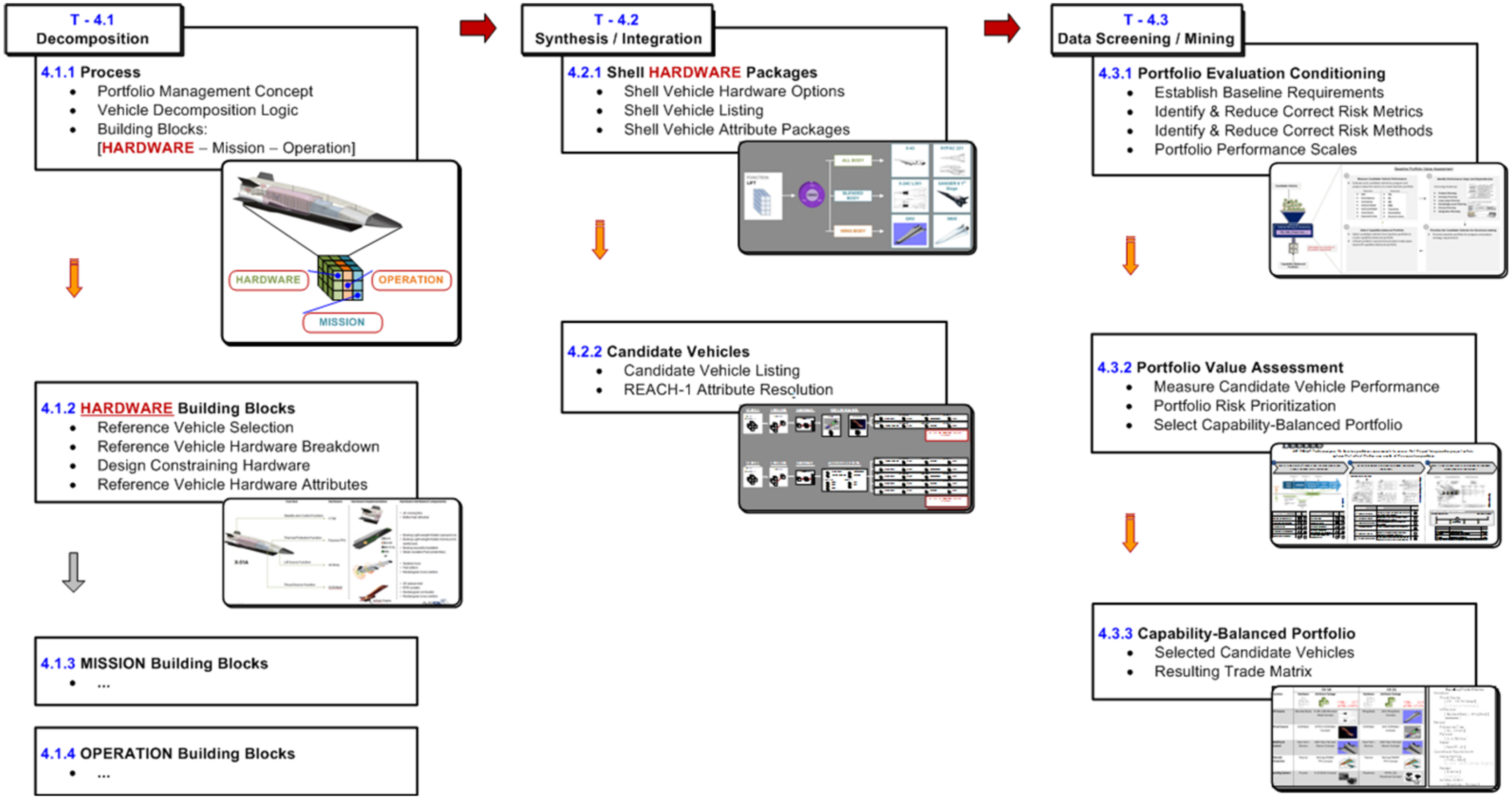
In terms of data generation, the CPM is automated based on the DTRts data blocks stored directly to the composable architecture’s DBMS. The tables are employed to capture user defined knowledge such that the risk values forecast the preferences of the researcher and/or be compared by the team. This metrics data is discussed more comprehensively in Chapter 4. Unlike the PPM which is composable, the AVM data interfaces representing the acquisition disciplinary methods and multidisciplinary effects are not and must be created anew, according to the CCM until the data standards for the library can be established. As a practical matter, it is believed that this system structure allows for scalability of the system capability in order to facilitate future FCSM method switching.

Chapter 4 – Portfolio-based Implementation of Problem Formulation Architecture

The problem formulation composable architecture benefits from a consistent methodological foundation that allows the researcher to automate data relationships to better study technology investments at various levels of abstraction and provides the data inputs for matching aircraft synthesis disciplinary analysis blocks. The implementation of the architecture follows, in part, a combination of four strategies: (1) Strategic Assessment of Risk and Technology (START) approach by the Jet Propulsion Laboratory [165], (2) Innovation Portfolio Management process from the management consulting firm Frost and Sullivan [166-168], (3) Mission Engineering SE decomposition concept formulated by the management consulting firm SmartOrg [169], and (4) the authors experience working with technology forecasting and PS problems [139-143]. Technology portfolio M&S with this strategy, is adopted from more sophisticated techniques to support innovation of the technology trade space and extract key insights to control DTR drivers during product development. Whereby, the goal is to examine the underlying cause for the difference in portfolio outcomes.

Please note that the problem formulation simulation capability is explained by way of a technology portfolio assessment for the Generic Hypersonic Vehicle case study. It is specified by the AFRL High Speed Systems Division. The design specification requires investigation for product-, knowledge asset-, and integration-planning to:

- *"… studies of operability, controllability, and aero-propulsion integration …"*
- *"… blended wing-body configuration, 3D inlet and nozzle, axisymmetric scramjet combustor, and a metallic structure with a thermal protection coating …"*
- *"… cruise at Mach 6 at 1000 < q < 2000 psf, and maneuver at a maximum loading factor of approximately 2 g …".* [GHV for CD Analyses2g". [170]



T - 4.1
Decomposition

4.1.1 Process
- Portfolio Management Concept
- Vehicle Decomposition Logic
- Building Blocks:
  [**HARDWARE** – Mission – Operation]

4.1.2 HARDWARE Building Blocks
- Reference Vehicle Selection
- Reference Vehicle Hardware Breakdown
- Design Constraining Hardware
- Reference Vehicle Hardware Attributes

4.1.3 MISSION Building Blocks
- ...

4.1.4 OPERATION Building Blocks
- ...

T - 4.2
Synthesis / Integration

4.2.1 Shell HARDWARE Packages
- Shell Vehicle Hardware Options
- Shell Vehicle Listing
- Shell Vehicle Attribute Packages

4.2.2 Candidate Vehicles
- Candidate Vehicle Listing
- REACH-1 Attribute Resolution

T - 4.3
Data Screening / Mining

4.3.1 Portfolio Evaluation Conditioning
- Establish Baseline Requirements
- Identify & Reduce Correct Risk Metrics
- Identify & Reduce Correct Risk Methods
- Portfolio Performance Scales

4.3.2 Portfolio Value Assessment
- Measure Candidate Vehicle Performance
- Portfolio Risk Prioritization
- Select Capability-Balanced Portfolio

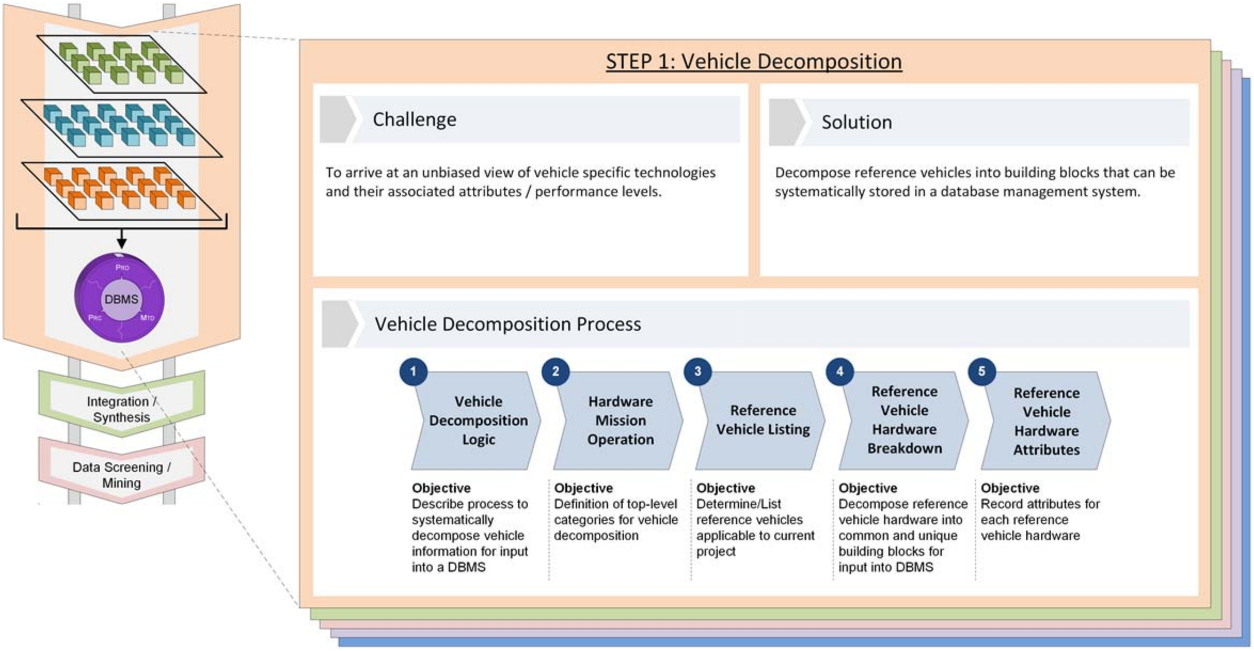
4.3.3 Capability-Balanced Portfolio
- Selected Candidate Vehicles
- Resulting Trade Matrix

Figure 4-1 Roadmap for Composable Problem Formulation System Architecture Implementation

Figure 4-1 presents a roadmap of the technology portfolio management process with a functional emphasis on vehicle decomposition, CV synthesis/integration, and CV data screening/mining. As with the automation of the composable architecture (Chapter 3), verification and validation of this innovative implementation is confirmed by discussions with synthesis specialists with the Air Force Research Laboratory Aerospace Systems Directorate during USAF SFFP 2015. [143]

4.1 Vehicle Decomposition

With the ground rules for problem formulation now set, the portfolio analysis starts with vehicle decomposition. In terms of technology portfolio management, the challenge for the researcher to arrive at unbiased quantitative capability requirements for vehicle specific technology investments. To a greater extent, the unbiased analysis is a direct reference to arrive at a more objective decision path. The data requirements can be prioritized for DBMS storage. Figure 4-2 illustrates the five step process.



Challenge

To arrive at an unbiased view of vehicle specific technologies and their associated attributes / performance levels.

Solution

Decompose reference vehicles into building blocks that can be systematically stored in a database management system.

Objective
Describe process to systematically decompose vehicle information for input into a DBMS

Objective
Definition of top-level categories for vehicle decomposition

Objective
Determine/List reference vehicles applicable to current project

Objective
Decompose reference vehicle hardware into common and unique building blocks for input into DBMS

Objective
Record attributes for each reference vehicle hardware

Figure 4-2 Overview of Vehicle Decomposition Process

1. Vehicle Decomposition Logic

The level of abstraction for the FCSM data interactions is described as a process to systematically decompose vehicle information for input into the product (PRD) portion of the DBMS, see Figure 4-3. The objective is to manage the common and unique problem specific vehicle capabilities in order to populate and avoid data redundancies in the PPM DBMS requirements. Additionally, the logic is prescribed to track the need technology capabilities.

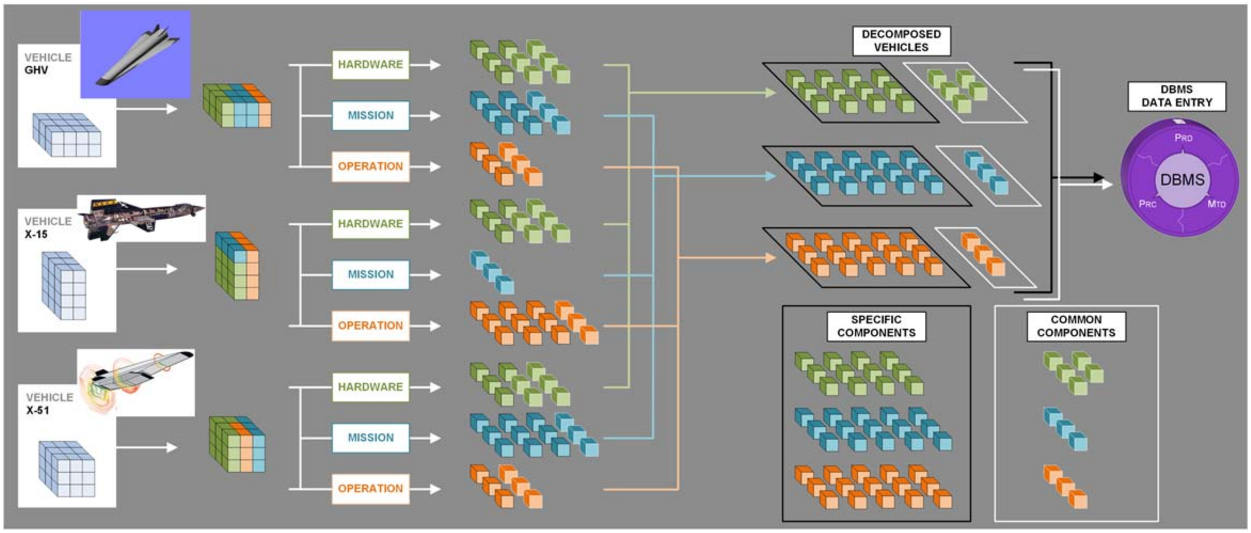


Figure 4-3 Vehicle Decomposition Logic Concept

2. Hardware, Mission, Operation Data Requirements

For the current study the categories for vehicle decomposition are found in the PPM. Consider for instance the X-51 hardware, see Figure 4-4. The current decomposition logic necessitates that the vehicle only describes hardware component sources that create effects or multidisciplinary effects as thrust, lift, stability and control, and stability and control functions. Accordingly, the hardware implementation and associated hardware components cannot be extended beyond these constraints for problem formulation M&S. Mission and operation data requirements are treated similarly. See Figure 3-8 to Figure 3-10, and Figure 3-14 for more information. Results of the portfolio analysis uses these data standards to initiate sizing tool method matching (research by Gonzalez), once connected manually with research being conducted by Omoragbon.[17][144]

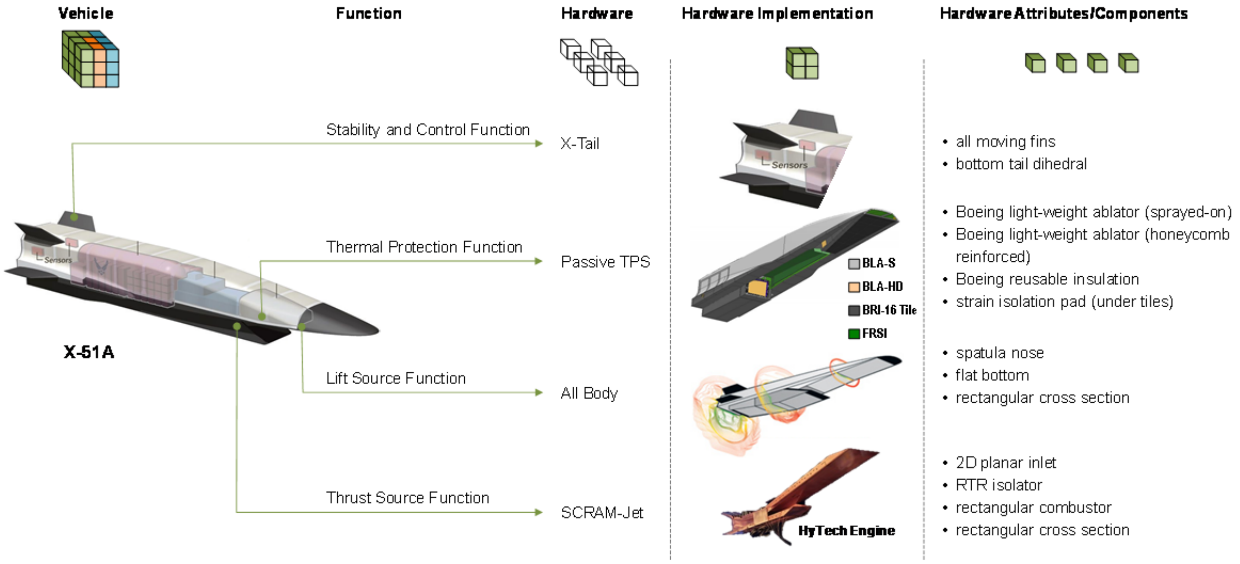


Figure 4-4 Vehicle Decomposition – Hardware Data Requirements

3. Reference Vehicle Listing

Development of the GHV vehicle is oriented towards building a state-of-the art technology demonstrator and to advance the overall technical capabilities of the A&D community. As such, to facilitate objective decision-making, it is necessary to arrive at a baseline set of relevant technology to enable the researcher to measure what risks are being built into the vehicle. In terms of M&S, Figure 4-5 provides a list of reference vehicles with primary hardware technology implementations applicable to the current project. Two groups of aircraft are presented. Those in the feasibility era contain technology implementations that exist or existed as a scaled model or flight demonstrator, and those in the maturation era that represent current generation product development efforts being proposed for flight test and/or ground test. The former includes the X-15, X-24C L301, HYFAC 221, X-43C, and X-51A; the latter, GHV, HiFiRE 6, and Falcon HTV-3x. The corresponding hardware functions, mission requirements, and operational requirements are described in Table 4-1, Table 4-2, and Table 4-3 respectively.

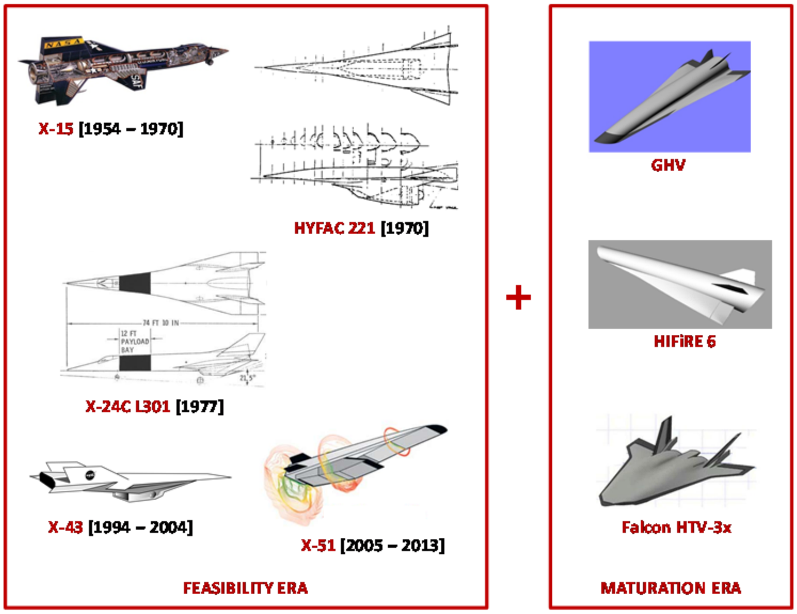


Figure 4-5 Vehicle Decomposition – Reference Vehicle Listing

Table 4-1 Vehicle Decomposition – Reference Vehicle Hardware Functions [143]

Hardware Function	Type	GHV	X-24C-L301	HYFAC 221	X-43 C	X-51A Cruiser	HIFiRE 6	Falcon HTV-3x
Lift Source	*All-Body*			x	x	x		
	Blended Body		x					x
	Wing Body	x					x	
Stability & Control	*Twin Vertical Tail*	x	x				x	x
	Twin Tail			x	x			
	X-tail					x		
	Elevons	x	x				x	x
Thrust Source	*Rocket*		x					
	SCRAMjet	x	x		x	x	x	
	Ramjet			x				
	Turbo-Ramjet							x
Landing System	*Tricycle Gear*		x					
	Chute			x				
Thermal Protection System	*Active*							
	Passive	x	x	x	x	x	x	x
Actuator System	Hydraulic		x	x				
	Electromechanical				x	x		
Power System	Battery		x		x	x		x
	Gas Generator			x				x
GN&C Avionics	Digital		x	x	x	x		
	Analog		x	x	x			

Table 4-2 Vehicle Decomposition – Reference Vehicle Mission Requirements [143]

Mission Requirements			**GHV**	**X-24C-L301**	**HYFAC 221**	**X-43 C**	**X-51A Cruiser**	**HIFiRE 6**	**Falcon HTV-3x**
Altitude	Troposhpere		x	x	x	x	x	x	x
	Stratosphere		x	x	x	x	x	x	x
	Mesophere								
	Thermosphere								
	Exosphere								
Design Objective	Escape								
	In-Space								
	Orbital Insertion								
	Orbital Reentry								
	Point-to-Point		x	x	x	x	x	x	x
	Sub Orbital								
Speed	Subsonic		x	x	x	x	x	x	x
	Transonic		x	x	x	x	x	x	x
	Supersonic		x	x	x	x	x	x	x
	Hypersonic		x	x	x	x	x	x	x
Trajectory Segment	*Takeoff*	Air-drop	1	1		1	1	1	
		Booster Seperation	2		2	2	2	2	
		HT							1
		VT			1				
	Acceleration	Constant Altitude	3					3	
	Climb	Constant Q	4	3				4	3
		Constant V							
		Steady Climb							2
	Cruise	Constant Mach	5, 7	4	3	3	3	5	4
	Turn	Steady Level	6						
	Descent	Ballistic							
		Parachute							
		Powered							5
		Gliding Decent	8	5	4	4	4	6	
	Landing	Air Snatch							
		Ballistic				5	5		
		Parachute			5				
		Powered							6
		Unpowered		7					
	Manueveer	Pull-Up		2					
		Push-Over							
		Coast							

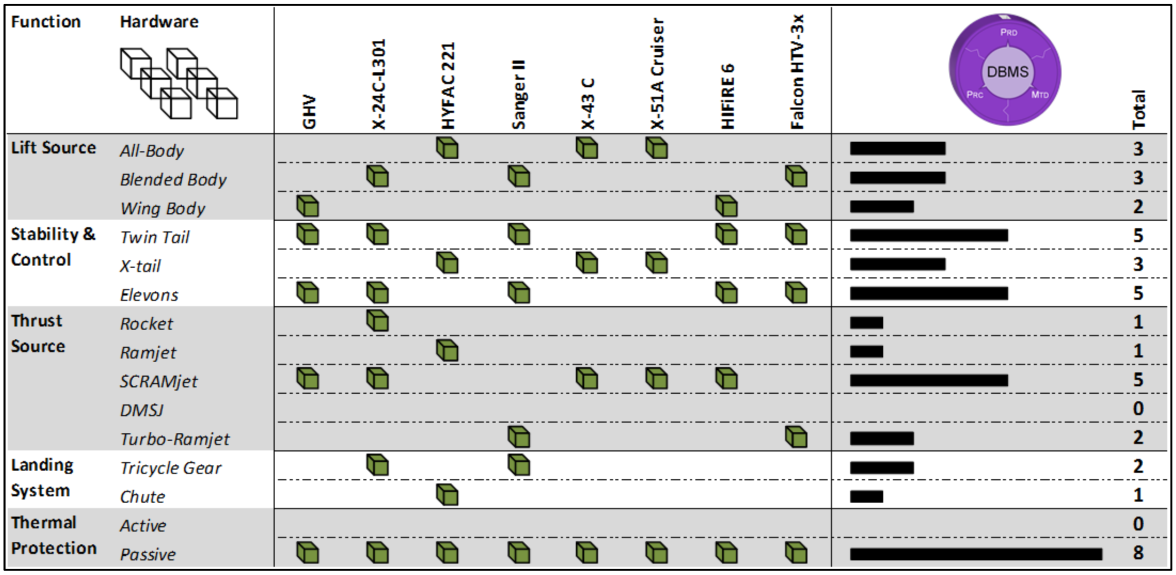
Table 4-3 Vehicle Decomposition – Reference Vehicle Operational Requirements [143]

Operational Reqs			**GHV**	**X-24C-L301**	**HYFAC 221**	**X-43 C**	**X-51A Cruiser**	**HIFiRE 6**	**Falcon HTV-3x**
Human Rating	Manned			x					
	Unmanned		x		x	x	x	x	x
Propellant	*Oxidizer*	Oxygen		x					
		Air	x	x	x	x	x	x	x
	Fuel	Hydrocarbon	x	x		x	x	x	x
		Hydrogen			x				
Reusability	Expendable					x	x	x	
	Reusable		x	x	x				x

Note that the mission and operational requirements data tables will be utilized at a later stage, outside of the baseline technology portfolio assessment. Additionally, the numerical values in Table 4-2 denote the order that the mission trajectory is executed.

4. Reference Vehicle Hardware Breakdown

Compartmentalization of the common (redundant) or similar, and unique (reference vehicle specific) hardware implementations allows for the researcher to focus on the hardware attributes that define the performance of the technology application. Figure 4-6 decomposes the vehicle building blocks for input into the PRD DBMS. Relative to the hardware functions being captured, the hardware breakdown shows 13 implementations (three types for lift source, three for stability and control, five for thrust source, two for landing systems, and two for thermal protection system).



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

Figure 4-6 Vehicle Decomposition – Reference Vehicle Hardware Breakdown

5. Reference Vehicle Hardware Attributes

Definition of attribute sets represent the hardware subcomponents that build a vehicle specific hardware implementation (component), see Figure 4-7. This capability is of particular interest when manipulating the technology level of abstraction. The objective of the attribute that will decide the performance for multidisciplinary effect being measured. For instance, a scramjet is characterized by four components: (1) inlet, (2) isolator, (3) combustor, and (4) nozzle. The combination of attribute data blocks decides whether the implementation has performance comparable to the GHV inward-turning design, X-51A HYTECH engine or some variation dependent on hardware compatibility. Put simply, an arrangement of attributes coupled with hardware implementation are treated as data blocks for assembling an aircraft. Table 4-4 shows the attributes building the thrust and lift functions for the reference vehicles. However, at this time the DBMS is limited to the attributes modeled as fixed configurations of hardware implementation; hardware attributes equal hardware implementations.

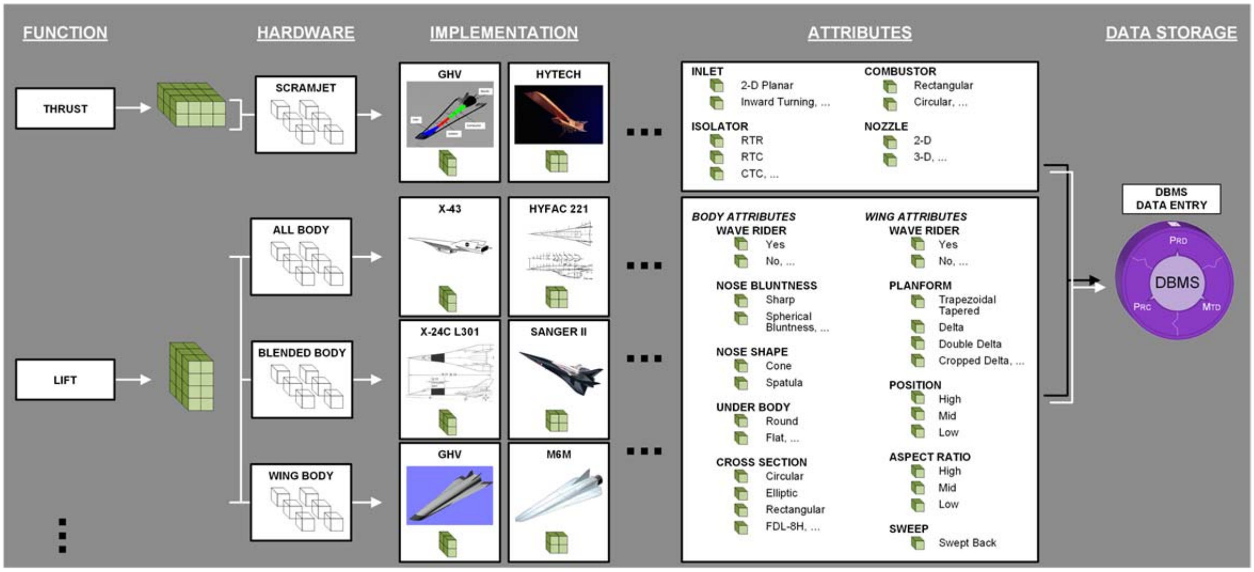


Figure 4-7 Vehicle Decomposition – Reference Vehicle Hardware Attribute Concept

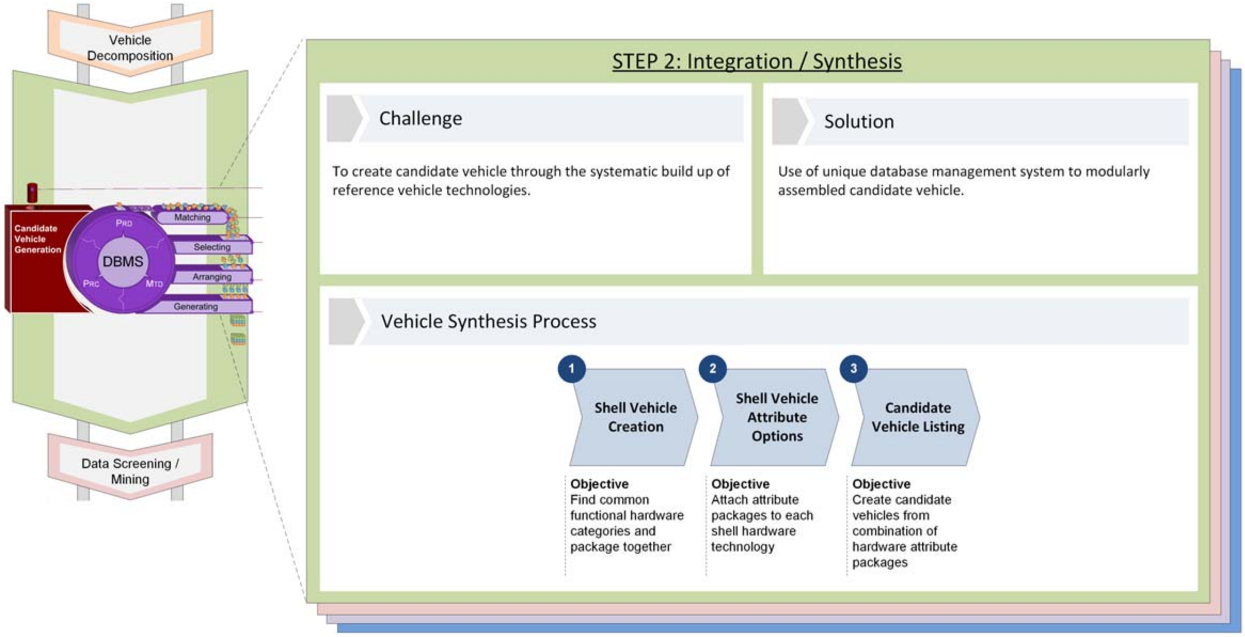
4.2 Candidate Vehicle Synthesis

Design of CVs ensures that portfolio technology components are evaluated as objectively as possible by the researcher. With the individual hardware attribute data blocks

Table 4-4 Vehicle Decomposition – Reference Vehicle Hardware Attribute [143]

Function	**HW**	**Attribute**	**Reference Options**	**GHV**	**X-24C-L301**	**HYFAC 221**	**X-43 C**	**X-51A Cruiser**	**HIFiRE 6**	**Falcon HTV-3x**
Lift Source	*Body*	*Waverider*	Yes, No	No	No	No	No	No	No	No
		Nose Bluntness	Sharp, Spherical Bluntness		Spherical Bluntness	Spherical Bluntness	Sharp	Sharp		
		Nose Shape	Cone, Spatula		Cone	Cone	Spatula	Spatula		
		Under Body	Round Bottom, Flat Bottom	Flat	Round and flat	Flat	Flat	Flat	Flat	
		Cross Section	Circular, Elliptic, Rectangular, FDL-8H	Circular	FDL-8H	Elliptic	Rectanglar	Rectanglar	Circular	
		TPS Material				T.D. NiCr, Radiation Shingle (Superalloy)	Carbon-Carbon, TUFI/AETB, Haynes	BLA-S, BLA-HD, BRI-16, FRSI, SIP		
		Structure Material			LockAlloy	Aluminum	Tungsten, Steel, Aluminum	Tungsten, Inconel, Ttanium, Aluminum, Steel, Composite hot		
	Wing	*Waverider*	Yes, No	Yes	No				Yes	No
		Planform	Trapezoidal Tapered, Delta, Double Delta, Cropped Delta	Cropped	Cropped				Cropped	Double
		Dihedral	Dihedral, Anhedral, gull, Inverted gull, Channel, Cranked							
		Position	High, Mid, Low	Low	Low				Low	Low
		Aspect Ratio	High, Mid, Low	Low	Low				Low	Low
		Sweep	Swept Back	Swept Back	Swept Back				Swept Back	Swept Back
		TPS Material								
		Structure Material			LockAlloy					
Thrust Source	*SCRAMJET*	Engine Name					HyTech	HyTech		
		Inlet	2-D Planar, 3-D Inward Turning	3-D Inward Turning	2-D		2-D Planar	2-D Planar	3-D Inward Turning	
		Isolator	2-D, 3-D	3-D			2-D	2-D	3-D	
		Combustor	2-D, 3-D	3-D			2-D	2-D	3-D	
		Nozzle	SERN, 3-D, 2-D	3-D	2-D		2-D	2-D	3-D	
	RamJet	Engine Name				MA145				
		Inlet				2-D				
		Combustor				3-D				
		Nozzle				3-D				
	Rocket	Engine Name			LR-105, LR-101					

now accessible in the PRD DBMS, hypersonic demonstrator options can be composably assembled for study. The data block integration, or vehicle synthesis process, is accomplished in three steps, see Figure 4-8.



To create candidate vehicle through the systematic build up of reference vehicle technologies.

Use of unique database management system to modularly assembled candidate vehicle.

Objective
Find common functional hardware categories and package together

Objective
Attach attribute packages to each shell hardware technology

Objective
Create candidate vehicles from combination of hardware attribute packages

Figure 4-8 Overview of Vehicle Integration / Synthesis Process

1. Operational System Hardware to Shell Vehicle Package Creation

The operational system, as described within the PPM, are constructed to convert specific researcher decision concerns and technology priorities into actionable items. Recall that 13 hardware implementations and 41 hardware component configurations (green shaded blocks) are identified for the GHV technology portfolio problem, see Step 1 in Figure 4-9. Thus, the operational system puts a priority on nine technology implementations with the not relevant thrust source and active thermal protection hardware options being removed, see Step 2 in Figure 4-9. In terms of shell vehicle creation, the operational system hardware data blocks are packaged minus the hardware component configurations (unshaded or hollow data blocks), to arrive at six distinct data requirement packages. Table 4-5 summarizes the shell integrations.

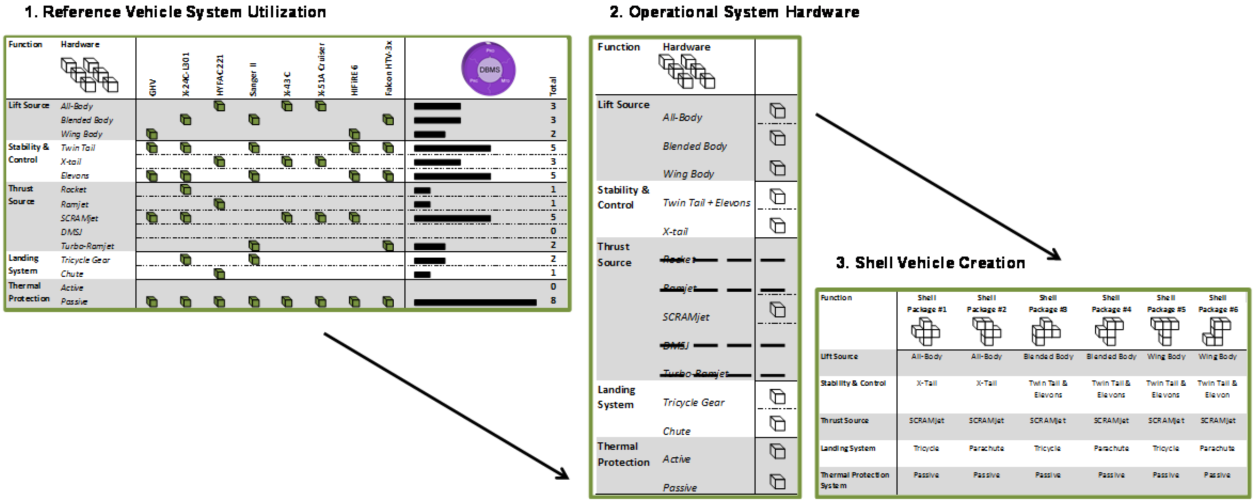


Figure 4-9 Candidate Vehicle Synthesis – Operation System to Shell Vehicle Creation Process

Table 4-5 Candidate Vehicle Synthesis – Summary of Shell Vehicle Packages

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

2. Assignment of Shell Vehicle Attribute Packages

With the shell vehicle packages now established, the operational system hardware data blocks are assigned impartially to the different function modes. Note that for the GHV study, the attribute packages are at the same level of abstraction as that for hardware implementation. Therefore, the attachment of 13 attributes/implementations to the applicable shell hardware technology results in Figure 4-10. The PRD DBMS associations for lift source show two relevant technologies for all-body configurations, two for blended-body, and two for wing-body; thrust source has two for scramjet; stability and control with one for the ‘X-tail’ and one for twin tail and elevons; thermal protection system presents one for a passive structure; landing system displays one for tricycle and one for parachute.

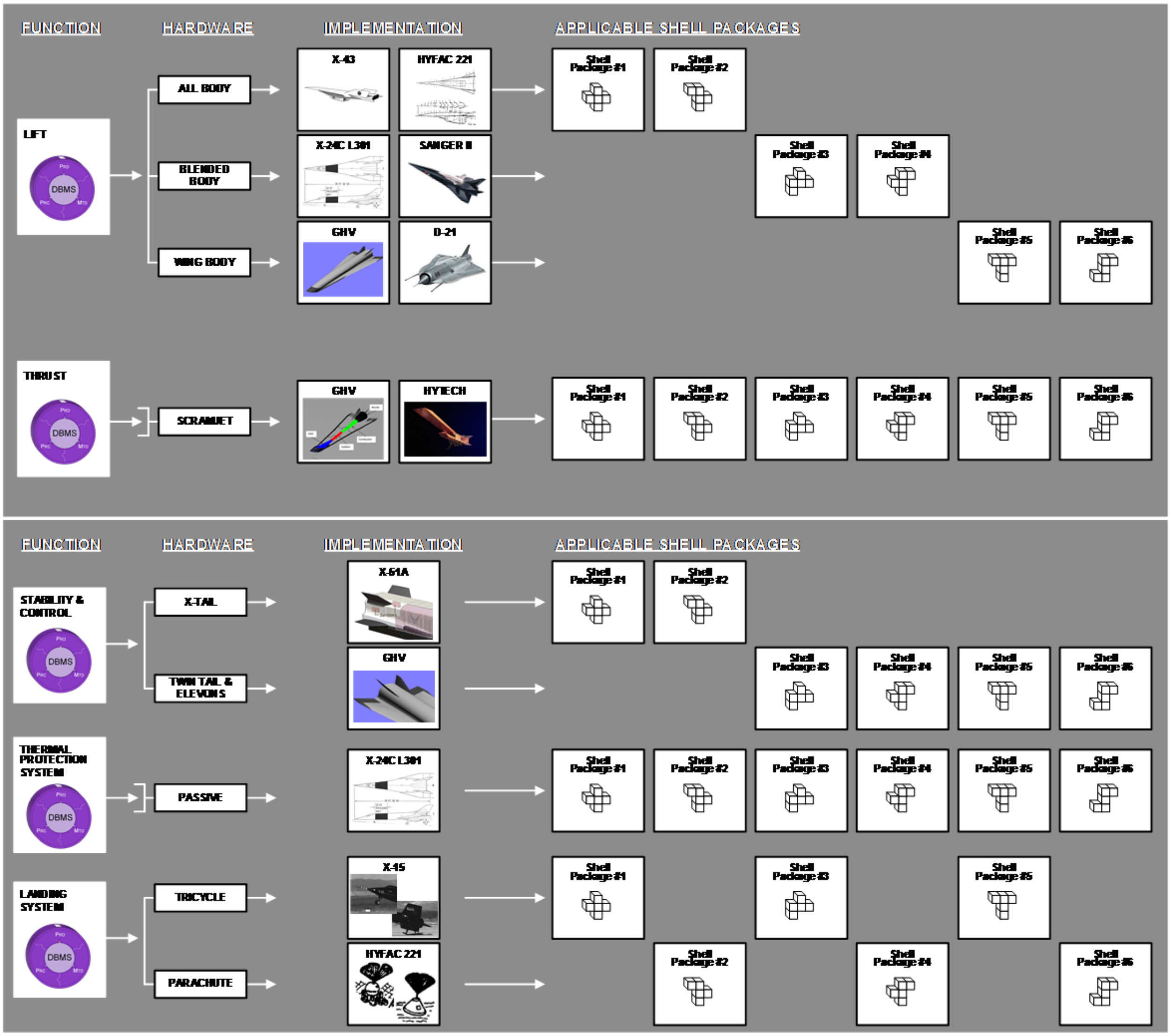


Figure 4-10 Candidate Vehicle Synthesis – Assignment of Shell Vehicle Attribute Packages

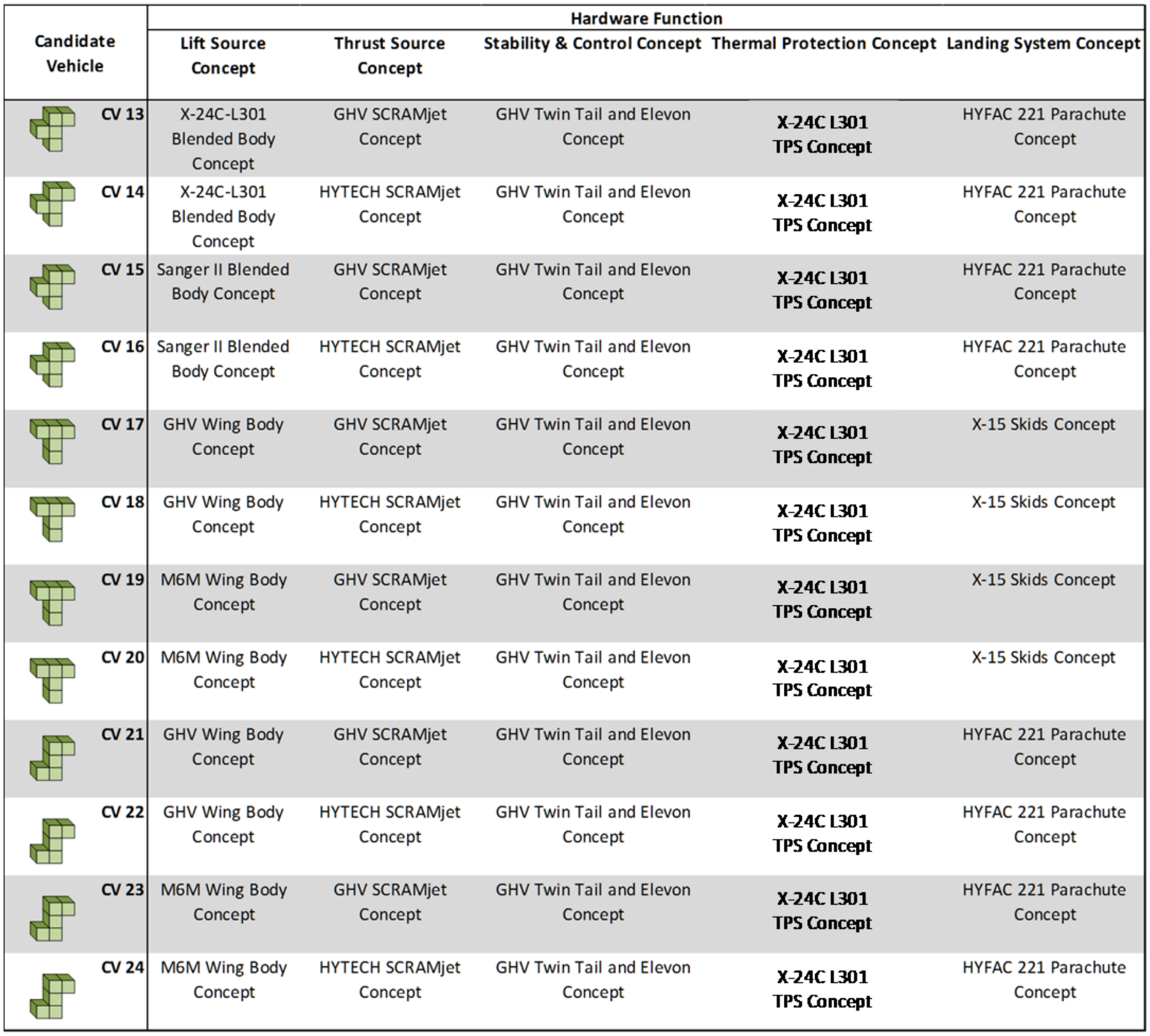
3. Candidate Vehicle Listing

Simulation of the hardware attribute packages with the shell packages is done by the PPM and creates the CV options. The previously hollow vehicle shells are filled according to the data requirements. Figure 4-6 illustrates the capabilities of the not yet prioritized CVs identified for the GHV technology portfolio assessment. The original set of 7 reference vehicles is expanded to 24 baseline vehicles, which are analyzed in the FCSM by CPM techniques.

Table 4-6 Candidate Vehicle Synthesis – Product Portfolio Model Results

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

Table 4-6 Candidate Vehicle Synthesis – Product Portfolio Model Results Continued

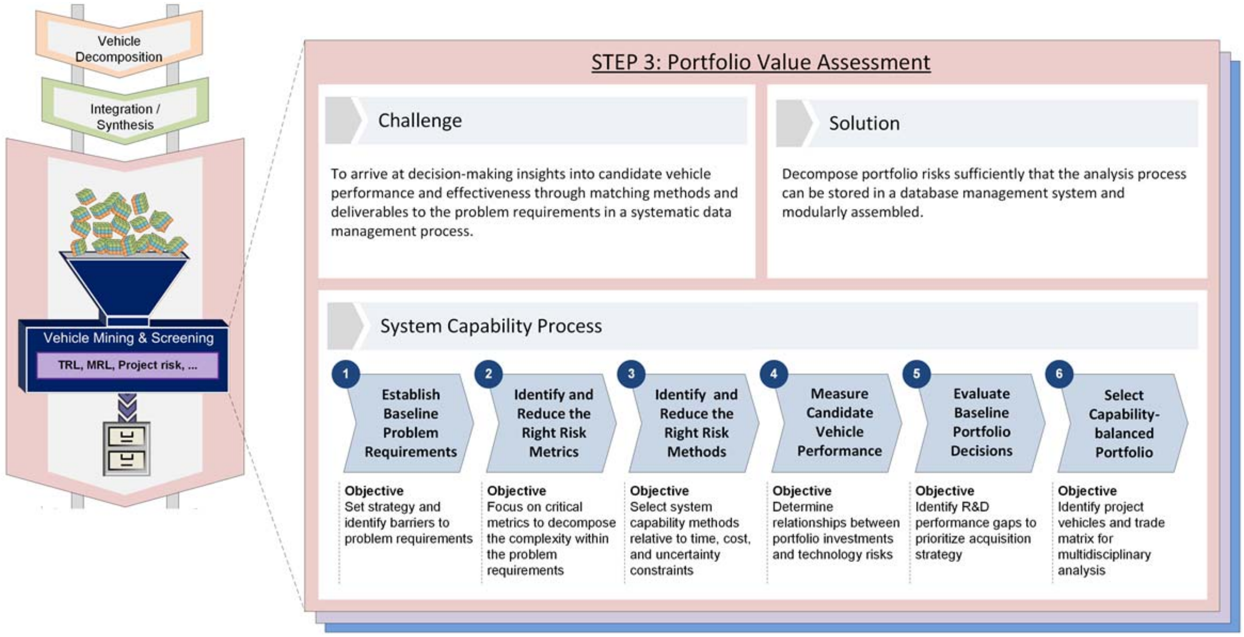


Candidate Vehicle	Hardware Function				
	Lift Source Concept	Thrust Source Concept	Stability & Control Concept	Thermal Protection Concept	Landing System Concept
CV 13	X-24C-L301 Blended Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept	**X-24C L301 TPS Concept**	HYFAC 221 Parachute Concept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

4.3 Technology Portfolio Value Assessment

The FCSM is structured to assess CV performance by way of the CPM. In terms of the portfolio analysis, the objective strives to arrive at decision-making insights by matching acquisition risk methods and deliverables to the PPM data requirements through a composable data management process, see Figure 4-11. As a standalone process, there are six steps but the PRD DBMS already has interfaces to store the DTRts data relationships identified in the CPM (Chapter 3.4). Thus, the need to:

1. **Establish baseline problem requirements** – set strategy and identify barriers to problem requirements.
2. **Identify and reduce the right risk metrics** – focus on critical metrics to decompose the complexity within the problem requirements.
3. **Identify and reduce the right risk methods** – select system capability methods relative to time, cost, and uncertainty constraints.
4. is bypassed and the current discussion starts at step four.



To arrive at decision-making insights into candidate vehicle performance and effectiveness through matching methods and deliverables to the problem requirements in a systematic data management process.

Decompose portfolio risks sufficiently that the analysis process can be stored in a database management system and modularly assembled.

Objective
Set strategy and identify barriers to problem requirements

Objective
Focus on critical metrics to decompose the complexity within the problem requirements

Objective
Select system capability methods relative to time, cost, and uncertainty constraints

Objective
Determine relationships between portfolio investments and technology risks

Objective
Identify R&D performance gaps to prioritize acquisition strategy

Objective
Identify project vehicles and trade matrix for multidisciplinary analysis

Figure 4-11 Overview of Technology Portfolio Value Assessment Process

4. **Measure Candidate Vehicle Performance**

Relative to the portfolio assessment, CV performance determines the risk trends and sensitivities to measure technology value and potential for developmental growth. The application of the DTR methods in the CPM adapted sufficiently to meet this goal, though are shown to be sensitive to researcher perspective during data generation. To diminish this effect, a scenario approach using variations best-case, worst-case, and most likely across the DTR metrics is utilized, see Figure 4-12. Generation of this multidisciplinary data aids in the construction of solution spaces that integrate data relationships between portfolio investments and technology risks. Table 4-7 to Table 4-9 present the DTR metrics for the most likely scenario. Appendix A contains the complete DTRts used by the FCSM. The values, while more cautious, are suitable for verifying the data relationship in the prototype system.

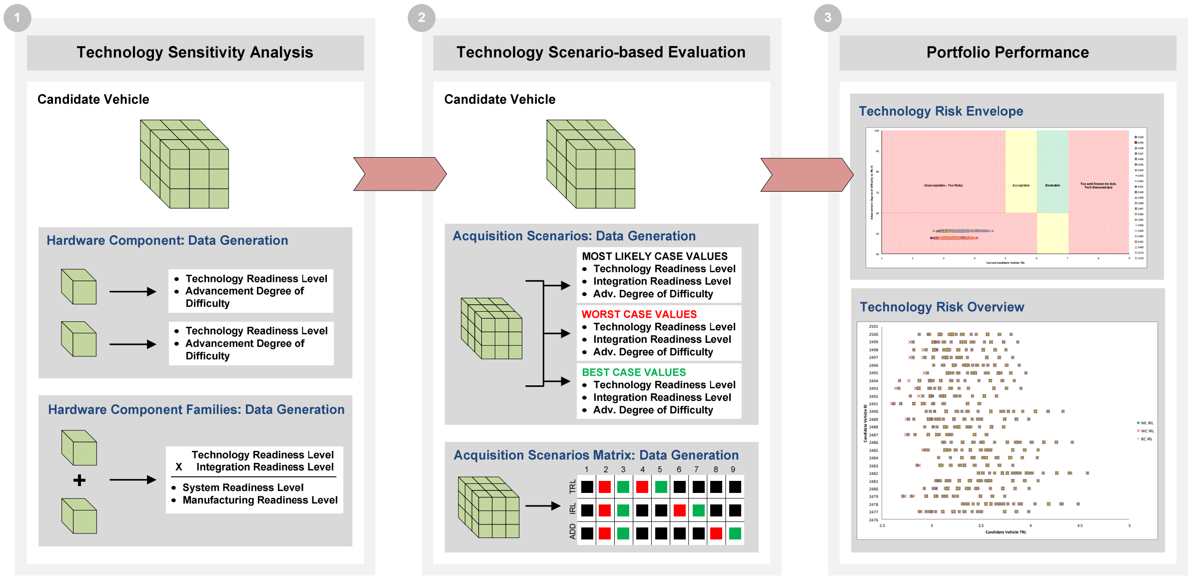


Figure 4-12 Portfolio Value Assessment – Technology Scenario-based Evaluation

Table 4-7 Portfolio Value Assessment – TRL Metric (Most Likely Scenario)

Lift Source	**Concept**	**Organization Name**	**TRL**
All Body	X-43C	NASA	4
	HYFAC 221	McDonnel Aircraft	3
Wing Body	GHV	AFRL	3
	D-21	Lockheed	3
Blended Body	X-24C	NASA / Lockheed	4
	Sanger	MBB	3
Thrust Source	**Concept**	**Organization Name**	**TRL**
SCRAMJET	GHV	AFRL	4
	HYTECH	Pratt & Whitney	5
Stability & Control	**Concept**	**Organization Name**	**TRL**
Twin Vertical Tail & Elevons	GHV	AFRL	5
Twin Tail	X-43C	NASA	5
X-Tail	X-51A	AFRL	5
Landing System	**Concept**	**Organization Name**	**TRL**
Nose Gear + Skids	X-15	NASA	9
Thermal Protection	**Concept**	**Organization Name**	**TRL**
Passive	X-24C	AFRL	3

Table 4-8 Portfolio Value Assessment – AD2 Metric (Most Likely Scenario)

			Design and Analysis							Manufacturing													Operability							Test and Evaluation					Demonstration Units					
			Databases	Design Methods and Tools	Analytical Methods and Tools	Appropriate Models	Manufacturability	Testability	Personnel Skills	Components	Materials	Personnel Skills	Facilities	Machines	Tooling	Metrology	Mfg. Software	Mfg. Processes	Min. Process Variability	Reproducibility	Assembly and Alignment	Integration	Min. Life Cycle Costs	Min. Operating Costs	Max. Maintainability	Max. Reliability	Max. Availability	GSE Required	Personnel Skills	Personnel Skills	Facilities	Environmental Facilities	Analytical Tools	Test Equipment	Breadboard	Brassboard	Scale Model	Prototype	Flight Qualified Unit	**AD2 Total**
Lift Source	**Concept**	**TRL**																																						
All Body	X-43C	4	6	5	9	7	6	9	7	9	9	9	5	5	5	5	5	5	5	5	5	5	N/A	N/A	N/A	9	9	5	9	9	5	7	7	7	0	0	7	0	0	**6.67**
	HYFAC 221	3	6	5	9	7	6	9	5	5	5	6	4	4	4	4	4	4	4	4	4	4	N/A	N/A	N/A	9	9	5	9	9	5	7	7	7	0	0	9	0	0	**5.97**
Wing Body	GHV	3	6	5	9	7	6	9	7	7	5	6	4	4	4	4	4	4	4	4	4	4	N/A	N/A	N/A	5	5	5	9	9	5	7	7	7	0	0	9	0	0	**5.83**
	D-21	3	6	5	7	5	6	9	7	7	5	6	4	4	4	4	4	4	4	4	4	4	N/A	N/A	N/A	9	9	5	9	9	5	7	7	7	0	0	6	0	0	**5.87**
Blended Body	X-24C	4	9	5	7	7	6	9	7	7	9	6	5	5	5	5	5	5	5	5	5	5	N/A	N/A	N/A	9	9	5	9	9	5	7	7	7	0	0	8	0	0	**6.57**
	Sanger	3	6	5	7	7	6	9	5	5	5	4	4	4	4	4	4	4	4	4	4	4	N/A	N/A	N/A	9	9	5	9	9	5	7	7	7	0	0	5	0	0	**5.70**
Thrust Source	**Concept**																						N/A	N/A	N/A															
SCRAMJET	GHV	4	5	5	7	7	7	9	7	7	7	7	5	5	5	5	5	5	5	5	5	5	N/A	N/A	N/A	3	3	3	3	7	3	3	5	5	0	0	7	0	0	**5.33**
	HYTECH	5	7	7	7	9	9	9	7	7	5	7	5	5	5	5	5	5	5	5	5	5	N/A	N/A	N/A	3	3	3	3	7	3	3	7	7	0	0	9	0	0	**5.73**
Stability & Control	**Concept**	**TRL**																					N/A	N/A	N/A															
Twin Vertical Tail & Elevons	GHV	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	N/A	N/A	N/A	6	6	6	6	6	6	6	6	6	0	0	0	0	6	**6.00**
Twin Tail	X-43C	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	N/A	N/A	N/A	6	6	6	6	6	6	6	6	6	0	0	0	0	6	**6.00**
X-Tail	X-51A	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	N/A	N/A	N/A	6	6	6	6	6	6	6	6	6	0	0	0	0	6	**6.00**
Landing System	**Concept**	**TRL**																					N/A	N/A	N/A															
Nose Gear + Skids	X-15	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	N/A	N/A	N/A	9	9	9	9	9	9	9	9	9	0	0	0	0	9	**9.00**
Thermal Protection	**Concept**	**TRL**																					N/A	N/A	N/A															
Passive	X-24C	3	9	7	9	9	5	7	7	6	5	6	6	6	6	6	5	5	7	7	7	6	N/A	N/A	N/A	7	7	7	7	7	7	7	7	7	0	0	0	0	5	**6.63**

Table 4-9 Portfolio Value Assessment – IRL Metric (Most Likely Scenario)

			Lift Hardware						**Thrust Hardware**		**Stability & Control**			**Landing System**	**Thermal Protection**
			All Body		*Wing Body*		*Blended Body*		*SCRAMJET*		*Twin Vertical Tail & Elevons*	*Twin Tail*	*X-Tail*	*Skids*	*Passive*
			X-43C	HYFAC 221	GHV	D-21	X-24C	Sanger	GHV	HYTECH	GHV	X-43C	X-51A	X-15	X-24C
Lift Source	*All Body*	X-43C	9						3	7	0	7	3	3	3
		HYFAC 221		9					3	3	0	7	3	7	3
	Wing Body	GHV			9				7	3	7	0	0	7	3
		D-21				9			7	3	7	0	0	7	3
	Blended Body	X-24C					9		3	7	7	0	0	7	7
		Sanger						9	3	7	7	0	0	7	3
Thrust Hardware	*SCRAMJET*	GHV	3	3	7	7	3	3	9		3	3	3	3	3
		HYTECH	7	3	3	3	7	7		9	3	3	3	3	3
Stability & Control	*Twin Vertical Tail & Elevons*	GHV	0	0	7	9	7	7	3	3	9			3	3
	Twin Tail	X-43C	7	7	0	0	0	0	3	3		9		3	3
	X-Tail	X-51A	3	3	0	0	0	0	3	3			9	3	3
Landing System	*Nose Gear + Skids*	X-15	3	7	7	7	7	7	3	3	3	3	3	9	3
Thermal Protection	*Passive*	X-24C	3	3	3	3	7	3	3	3	3	3	3	3	9

Consequently, the initial CV measurements provide a ‘birds-eye’ view of DTR performance, see Figure 4-13. This simulation results in 648 vehicles being modeled with 3,240 hardware implementation and 15,552 acquisition metric data points. No automated data-mining techniques are built into the PFSM at this time, thus the data interpretation is done manually. For the sake of simplicity, only data for the most likely scenario is examined for the GHV study.

Next, DTR risk constraints are integrated into the portfolio simulation. These values are extracted from research completed by Bilbro where they are organized into research, development, and test and evaluation budget activities (RDT&E) that can assist researchers during acquisition life-cycle decision-making [90][162-163] Here, three classes are explored to investigate technology status as: (2) applied research, (3) advanced technology development (ATD), or (4) advanced component development and prototype (ACD&P). Note that (1) basic research and (5) system development and demonstration are beyond the scope of the GHV project. Figure 4-14 to Figure 4-16 illustrate these results and a few comments are provided.

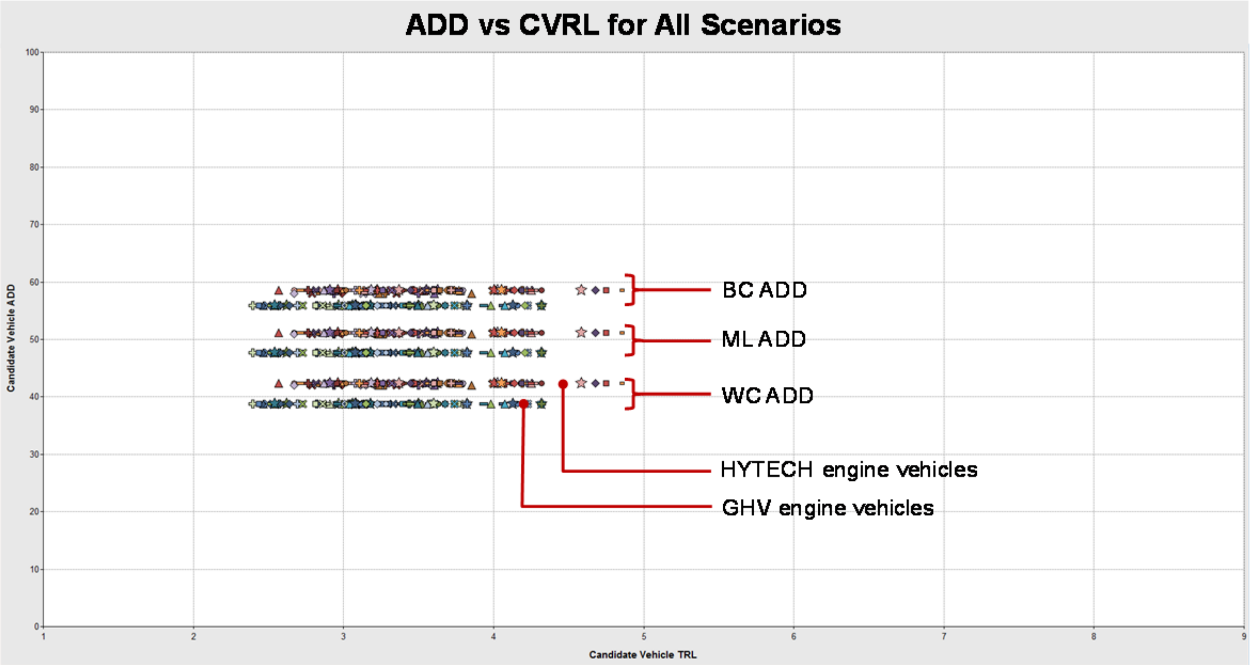


Figure 4-13 Portfolio Value Assessment – CVRL Results (All Scenarios)

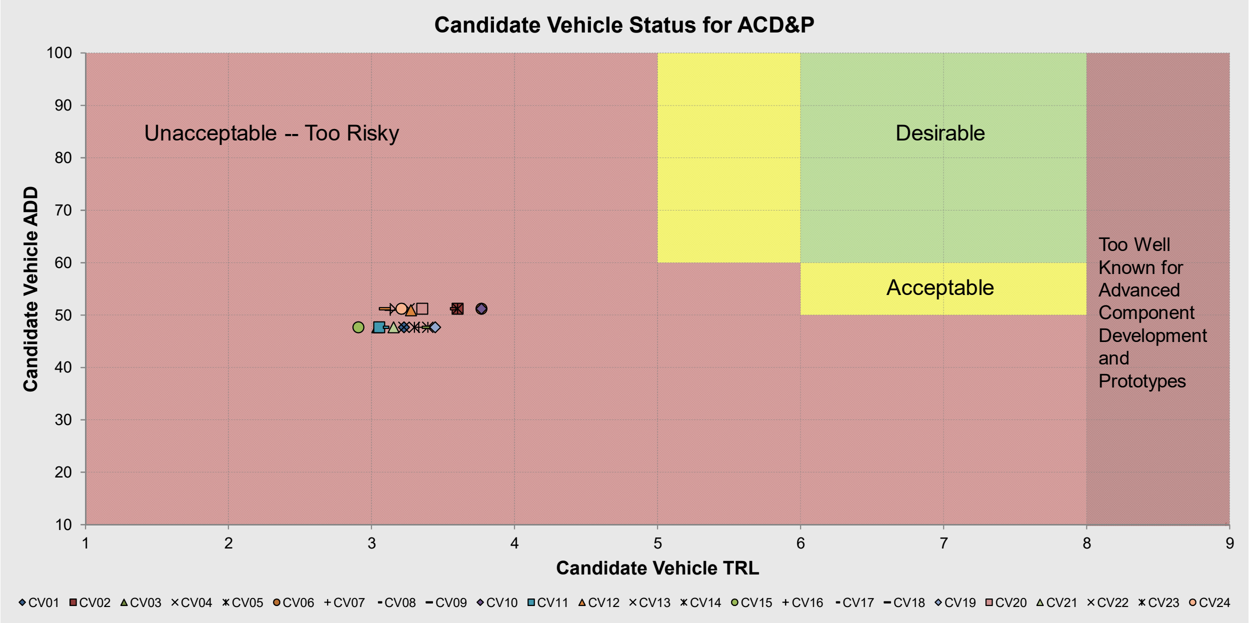


Figure 4-14 Portfolio Value Assessment – CVRL Results (Most Likely – ACD&P)

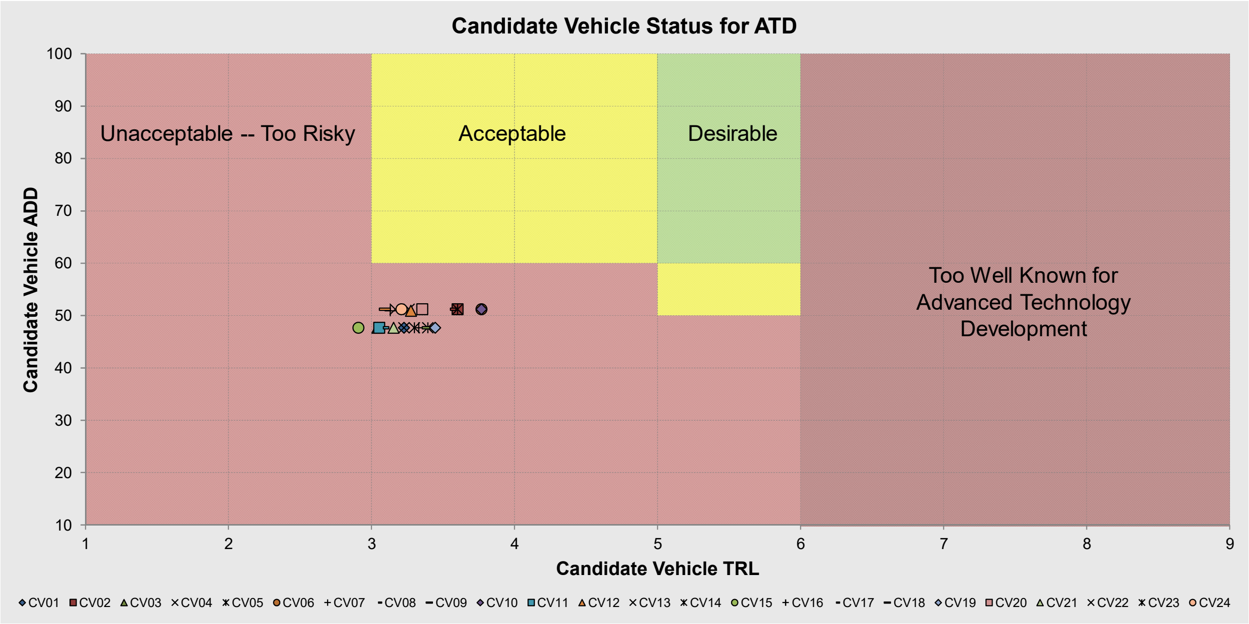


Figure 4-15 Portfolio Value Assessment – CVRL Results (Most Likely – ATD)

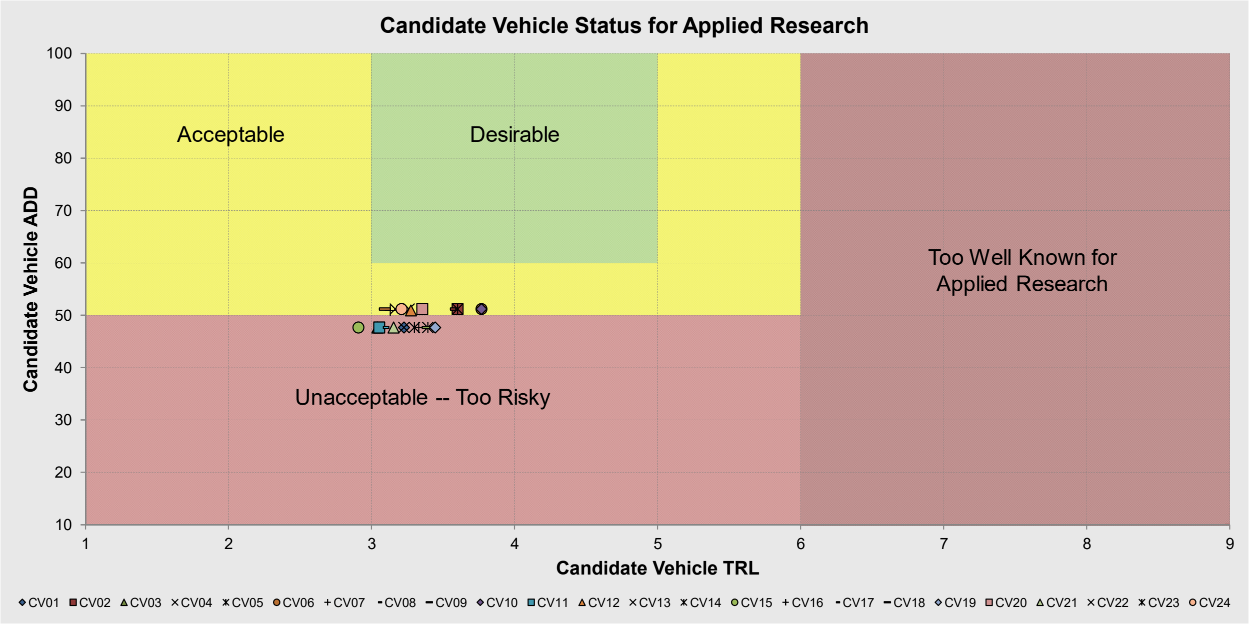
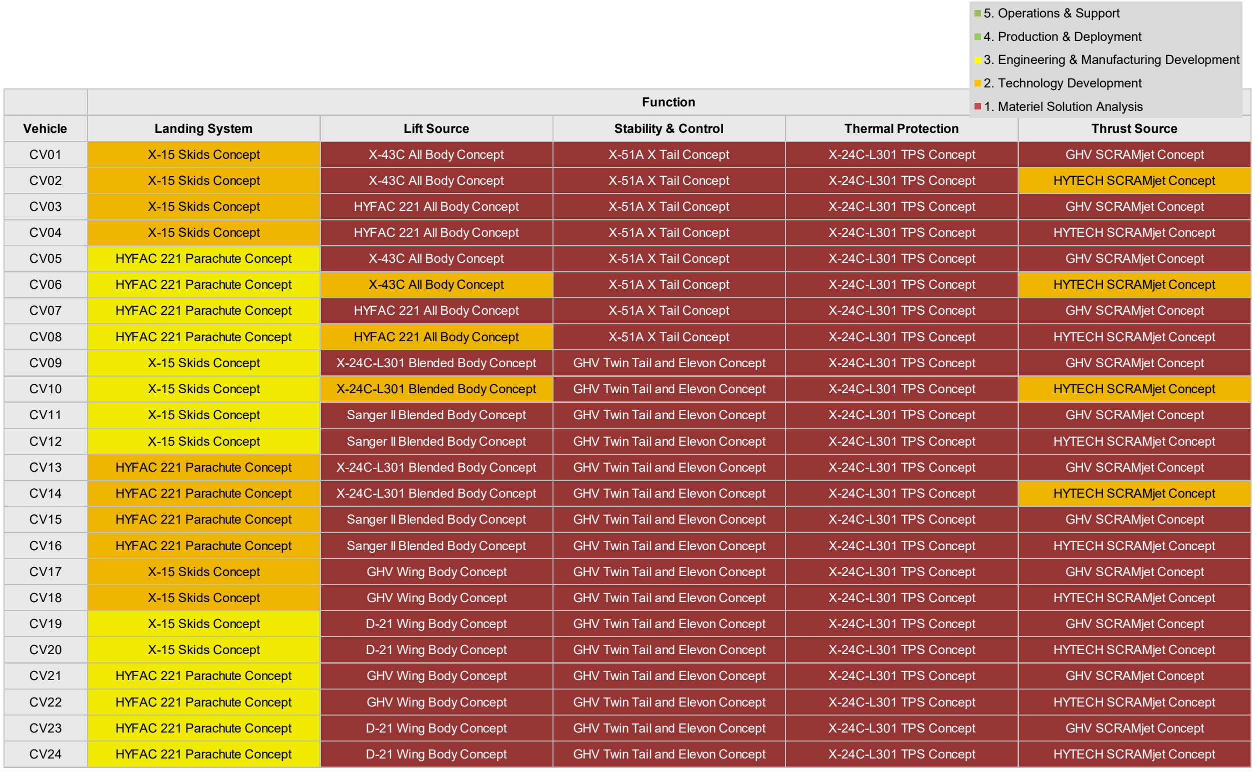


Figure 4-16 Portfolio Value Assessment – CVRL Results (Most Likely – Applied Research)

It is shown that all CV options are considered “unacceptable – too risky” for the ACD&P and ATD risk status. Most of the vehicles fall in the CVRL, though low, in the 3-4 range and AD2 to mature to applied research program of 45-55%. Matching of the acquisition life-cycle with the RDT&E activities is confirmed for an applied research type project, though it includes only vehicles with the HYTECH scramjet hardware implementation. As such, this is not sufficient information to understand the DTR risks built into the CVs and require further study. The vehicles are, next, investigated by MRL performance metrics, see Figure 4-17. Again, no CV options are easily discernable. Though it is worth noting that thermal protection, and stability and control implementations are only in the MSA and could require significant investment before being compatible with the landing system, lift source, and thrust source MRL risks. Still, a more detailed portfolio assessment is required prior to any technology investment decisions being made.

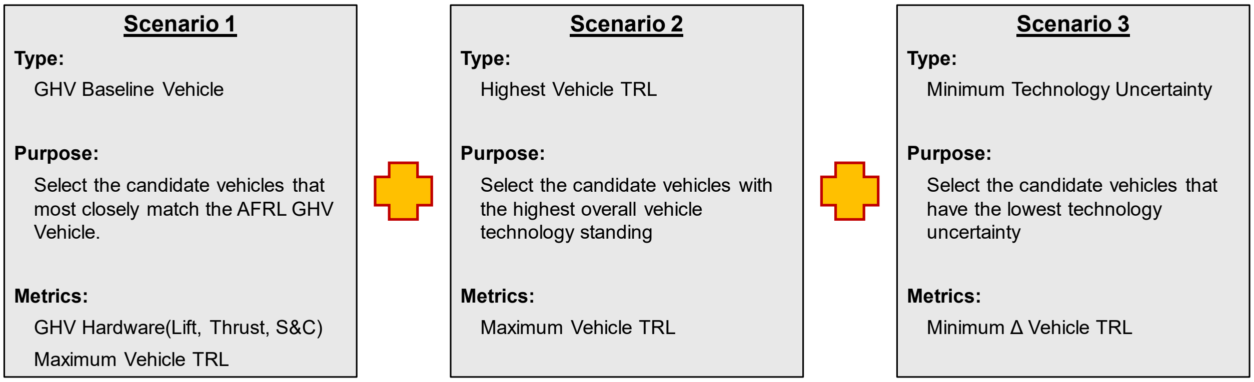


🟩 5. Operations & Support
🟩 4. Production & Deployment
🟨 3. Engineering & Manufacturing Development
🟧 2. Technology Development
🟥 1. Materiel Solution Analysis

	Function				
Vehicle	Landing System	Lift Source	Stability & Control	Thermal Protection	Thrust Source
CV01	X-15 Skids Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV02	X-15 Skids Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV03	X-15 Skids Concept	HYFAC 221 All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV04	X-15 Skids Concept	HYFAC 221 All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV05	HYFAC 221 Parachute Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV06	HYFAC 221 Parachute Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV07	HYFAC 221 Parachute Concept	HYFAC 221 All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV08	HYFAC 221 Parachute Concept	HYFAC 221 All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV09	X-15 Skids Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV10	X-15 Skids Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV11	X-15 Skids Concept	Sanger II Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV12	X-15 Skids Concept	Sanger II Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV13	HYFAC 221 Parachute Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV14	HYFAC 221 Parachute Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV15	HYFAC 221 Parachute Concept	Sanger II Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV16	HYFAC 221 Parachute Concept	Sanger II Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV17	X-15 Skids Concept	GHV Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV18	X-15 Skids Concept	GHV Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV19	X-15 Skids Concept	D-21 Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV20	X-15 Skids Concept	D-21 Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV21	HYFAC 221 Parachute Concept	GHV Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV22	HYFAC 221 Parachute Concept	GHV Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV23	HYFAC 221 Parachute Concept	D-21 Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV24	HYFAC 221 Parachute Concept	D-21 Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept

Figure 4-17 Portfolio Value Assessment – Candidate Vehicle MRL Results (Most Likely)

The data analysis, now, shifts perspective to assessing the candidate vehicle DTR values to measure technology performance relative to the potential for uncertainty growth scenarios, see Figure 4-18. Objective is to observe the effects of data prioritization on the resulting vehicle selection.



Scenario 1

Type:
GHV Baseline Vehicle

Purpose:
Select the candidate vehicles that most closely match the AFRL GHV Vehicle.

Metrics:
GHV Hardware(Lift, Thrust, S&C)
Maximum Vehicle TRL

Scenario 2

Type:
Highest Vehicle TRL

Purpose:
Select the candidate vehicles with the highest overall vehicle technology standing

Metrics:
Maximum Vehicle TRL

Scenario 3

Type:
Minimum Technology Uncertainty

Purpose:
Select the candidate vehicles that have the lowest technology uncertainty

Metrics:
Minimum Δ Vehicle TRL

Figure 4-18 Portfolio Value Assessment – Candidate Vehicle Data Screening Scenarios

Scenario 1 is designed to compare the technology component risks of the GHV against the portfolio as shown in Figure 4-19. It intends to make the researcher aware of the maximum CVRL GHV configuration and it does observe how it compares to other CVs. As the green box indicates, CV17 and CV21 are GHVs with differences in landing system skids and parachute, respectively. The error variation is consistent with the other vehicles; however, the vehicles rank toward the bottom of the portfolio. Scenario 2 shows CV06 and CV10 have the maximum CVRL (red box), see Figure 4-19. Both vehicles are configured for the HYTECH scramjet implementation with changes in the lift source (X-43C vs. X-24C L301). Again, the errors are consistent with the other vehicles at 46% and 49.5%, correspondingly.

Unlike, the first two scenarios that evaluate the data directly, Scenario 3 aims to identify the CV with the minimum hardware technology uncertainty. Figure 4-20 illustrates the CV technology as a function of hardware function. It presents that the thermal protection system has the lowest integrated hardware TRL across all vehicles, whereby the landing system has the highest TRL with lowest variation from best case to worst case values, and CV with the GHV scramjet (odd numbered CVs) have lower TRLs and higher error variation compared to the CVs with the HYTECH scramjet implementation (even numbered CVs). To reduce the portfolio by uncertainty, a margin of CV data variation greater than 60% is set and screened for: (1) thrust source since it is the primary technology, (2) lift source since it significantly impacts the vehicle outer mold shape, and (3) thermal protection system since it possesses the lowest hardware TRL.

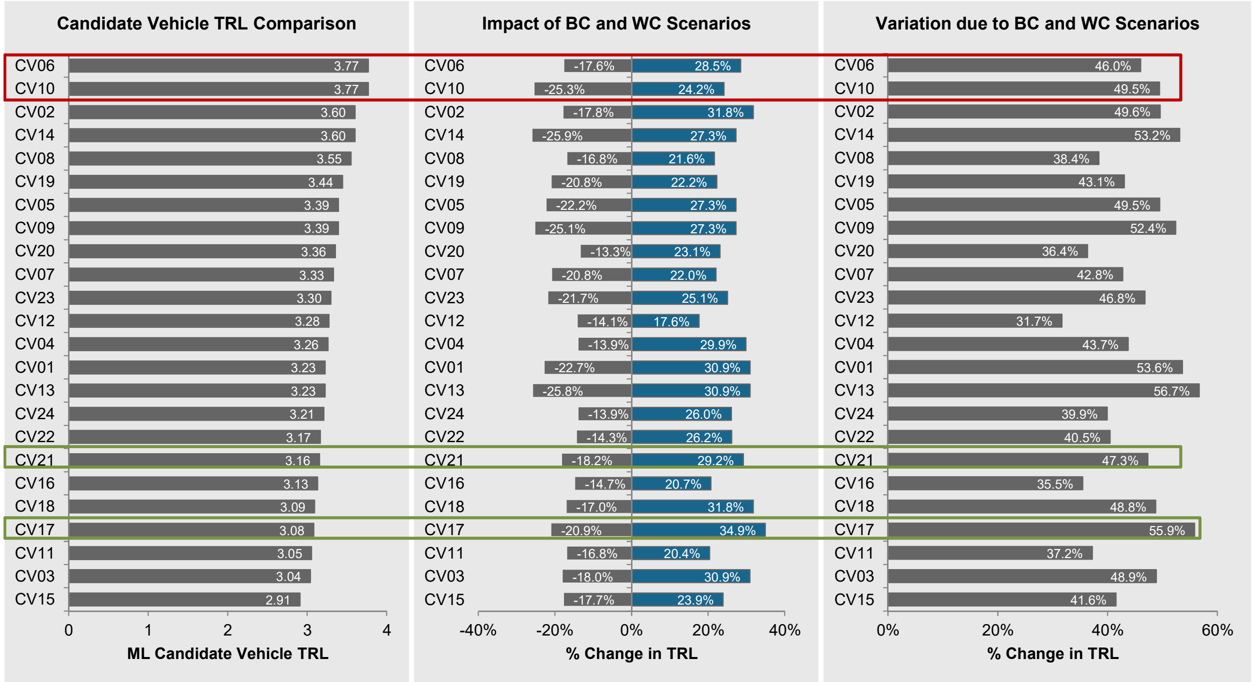


Figure 4-19 Portfolio Value Assessment – Results Data Screening Scenarios 1 and 2

Based on the above analysis considerations, the six vehicles remain the technology portfolio: CV17 and CV22 (Scenario 1), CV6 and CV10 (Scenario 2), and CV12 and CV16 (Scenario 3). Figure 4-21 further describes the vehicle options. Note that the differences in MRL for common hardware components is due to different vehicle integration potential (IRL). With the technology risks examined, half of the DTR study is completed. Next, the developmental risks are next explored for the baseline portfolio.

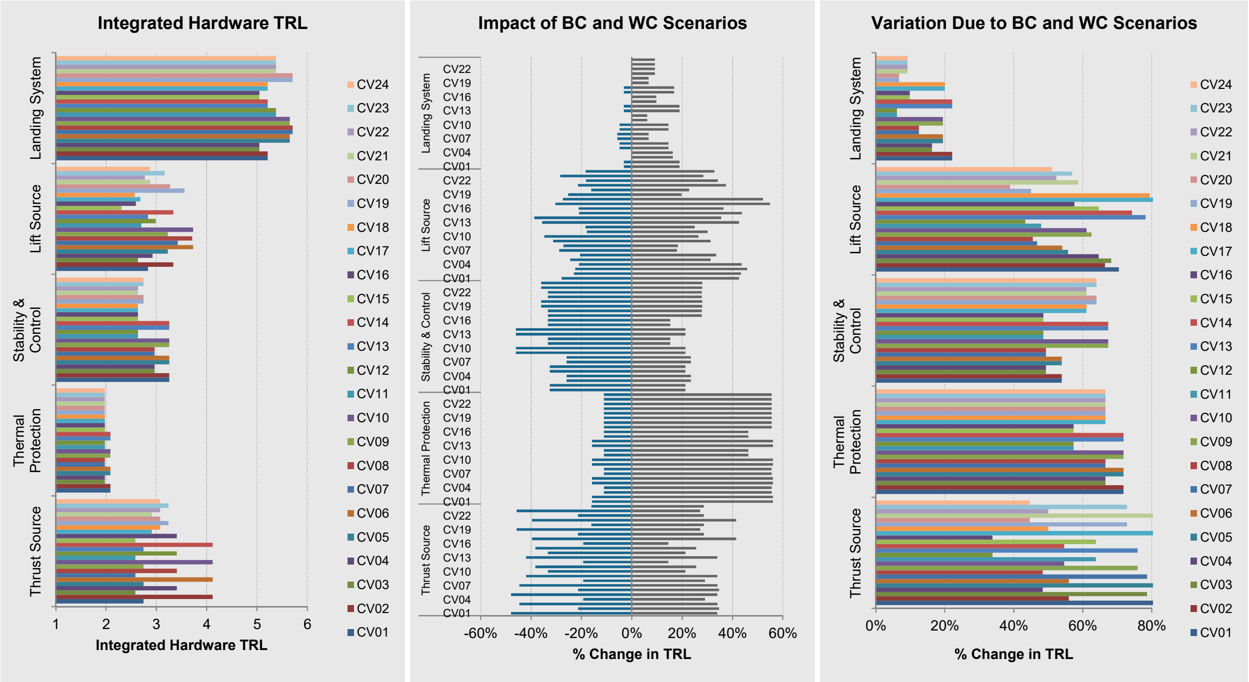
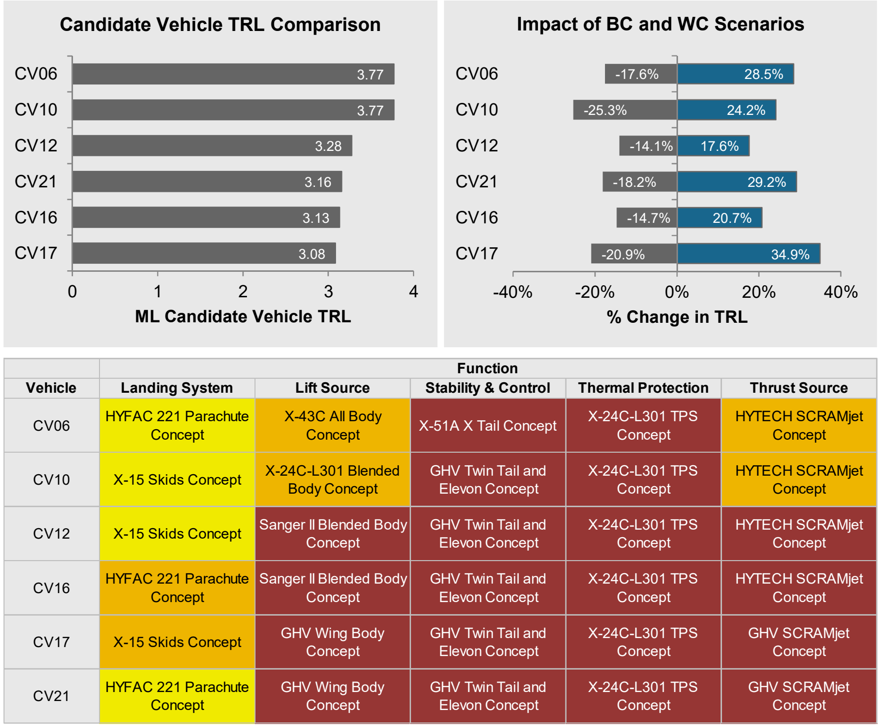


Figure 4-20 Portfolio Value Assessment – Results Data Screening Scenario 3



	Function				
Vehicle	**Landing System**	**Lift Source**	**Stability & Control**	**Thermal Protection**	**Thrust Source**
CV06	HYFAC 221 Parachute Concept	X-43C All Body Concept	X-51A X Tail Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV10	X-15 Skids Concept	X-24C-L301 Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV12	X-15 Skids Concept	Sanger II Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV16	HYFAC 221 Parachute Concept	Sanger II Blended Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	HYTECH SCRAMjet Concept
CV17	X-15 Skids Concept	GHV Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept
CV21	HYFAC 221 Parachute Concept	GHV Wing Body Concept	GHV Twin Tail and Elevon Concept	X-24C-L301 TPS Concept	GHV SCRAMjet Concept

Figure 4-21 Portfolio Value Assessment – Portfolio Data Screening Results

5. Evaluate Baseline Portfolio Decisions

Study of R&D developmental risks leads to identification of CV performance gaps. This data along with the previous section is applied to prioritize the baseline portfolio and the acquisition strategy adjusted based on considerations of risk versus return. Figure 4-22 to Figure 4-27 track this measurement for the remaining CVs on the basis that the GHV is designed to achieve the ACD&P status. Furthermore, Table 4-10 summarizes the analysis.

	Gap	CV06
Landing System	TRL	+1
	ADD	0
Lift Source	TRL	+3
	ADD	+0.9%
Stability & Control	TRL	+3
	ADD	+7.1%
Thermal Protection	TRL	+4
	ADD	+1.5%
Thrust Source	TRL	+2
	ADD	+8.8%

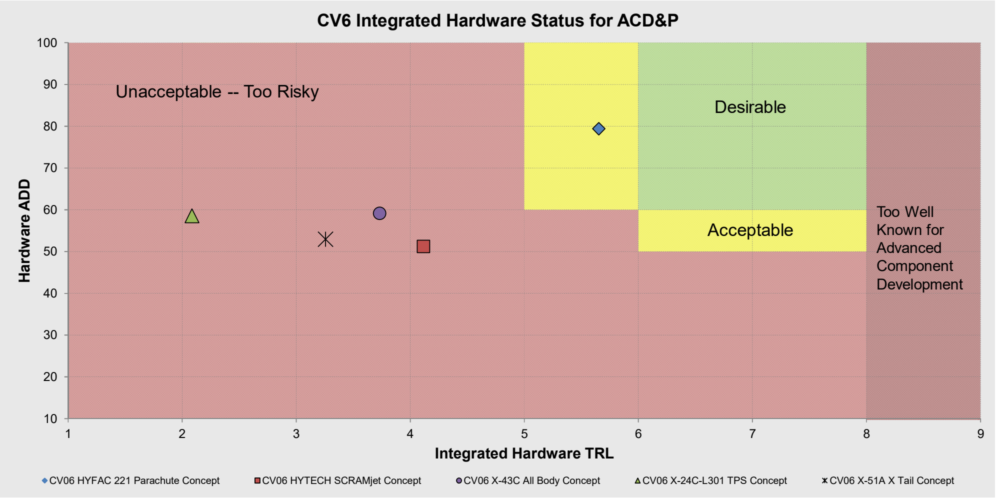


Figure 4-22 Portfolio Value Assessment – Results CV6 Risk Prioritization

	Gap	CV10
Landing System	TRL	+1
	ADD	0
Lift Source	TRL	+3
	ADD	+1.5%
Stability & Control	TRL	+3
	ADD	0
Thermal Protection	TRL	+4
	ADD	+1.5%
Thrust Source	TRL	+2
	ADD	+8.8%

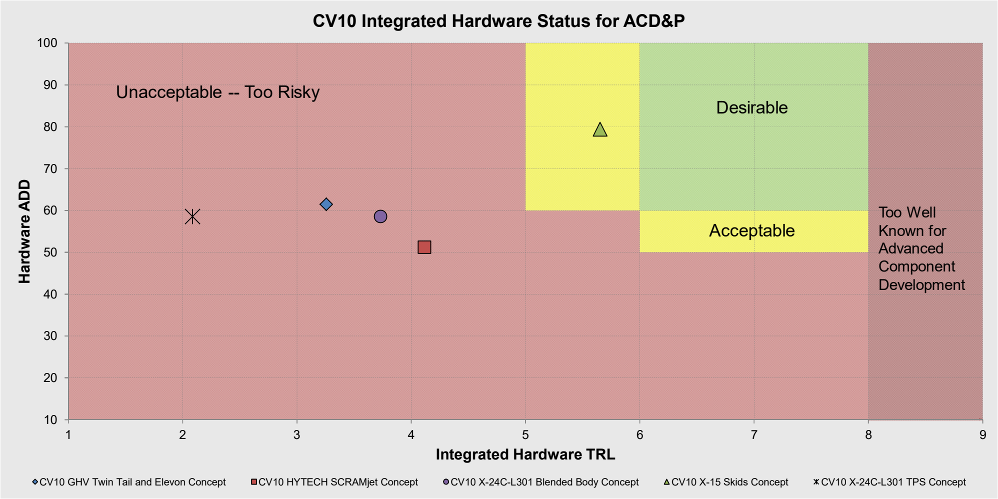


Figure 4-23 Portfolio Value Assessment – Results CV10 Risk Prioritization

	Gap	CV12
Landing System	TRL	+1
	ADD	0
Lift Source	TRL	+4
	ADD	+9.1%
Stability & Control	TRL	+4
	ADD	0
Thermal Protection	TRL	+5
	ADD	+1.5%
Thrust Source	TRL	+3
	ADD	+8.8%

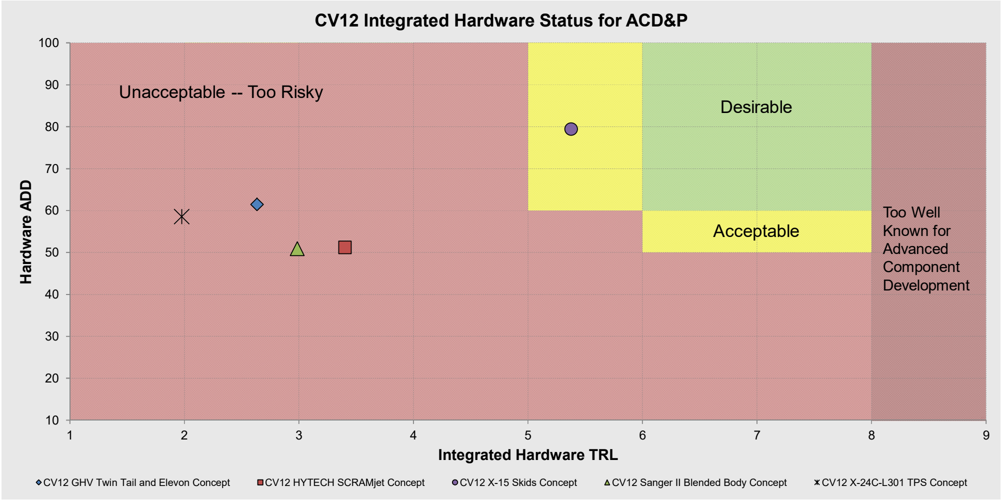


Figure 4-24 Portfolio Value Assessment – Results CV12 Risk Prioritization

	Gap	CV16
Landing System	TRL	+1
	ADD	0
Lift Source	TRL	+4
	ADD	+9.1%
Stability & Control	TRL	+4
	ADD	0
Thermal Protection	TRL	+5
	ADD	+1.5%
Thrust Source	TRL	+3
	ADD	+8.8%

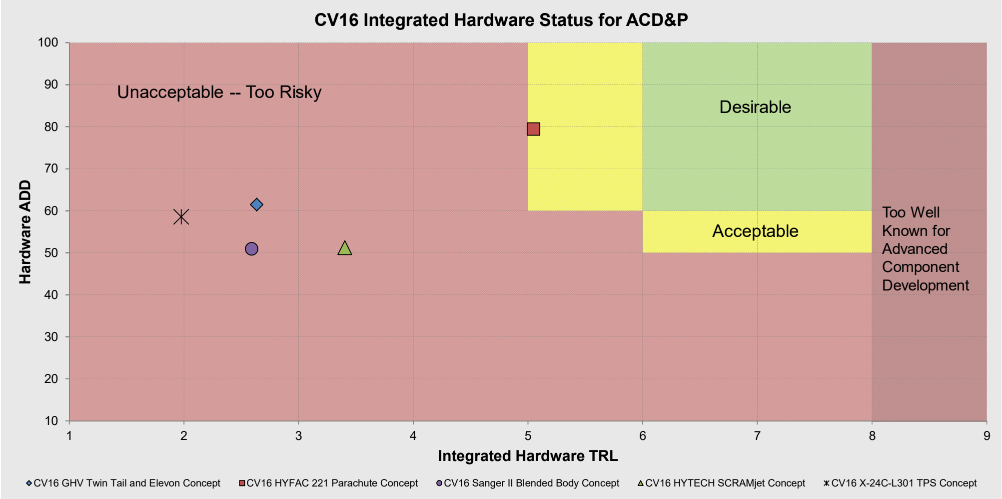


Figure 4-25 Portfolio Value Assessment – Results CV16 Risk Prioritization

The DTR risk margins are specified are the same used previously when assessing the CV. As such a technology implementation is generally considered acceptable if it meets an integrated hardware TRL of 5 and a AD2 around 60%. Unsurprisingly, for all the of the CVs, only the landing system does not require R&D to fill design knowledge gaps and is viable prototyping. Lift source, thrust source, thermal protection system, and stability and control source all require significant time and cost investment. Thrust source needs an estimated 10% improvement across all CV to be considered acceptable, followed by lift source at about 8%. However, the existing GHV lift configuration possesses knowledge and capability to advance without the technology readiness to execute. This behavior is also seen with the stability and control function and increases for the thermal protection system.

	Gap	CV17
Landing System	TRL	+1
	ADD	0
Lift Source	TRL	+4
	ADD	+7.9%
Stability & Control	TRL	+4
	ADD	0
Thermal Protection	TRL	+5
	ADD	+1.5%
Thrust Source	TRL	+4
	ADD	+12.4%

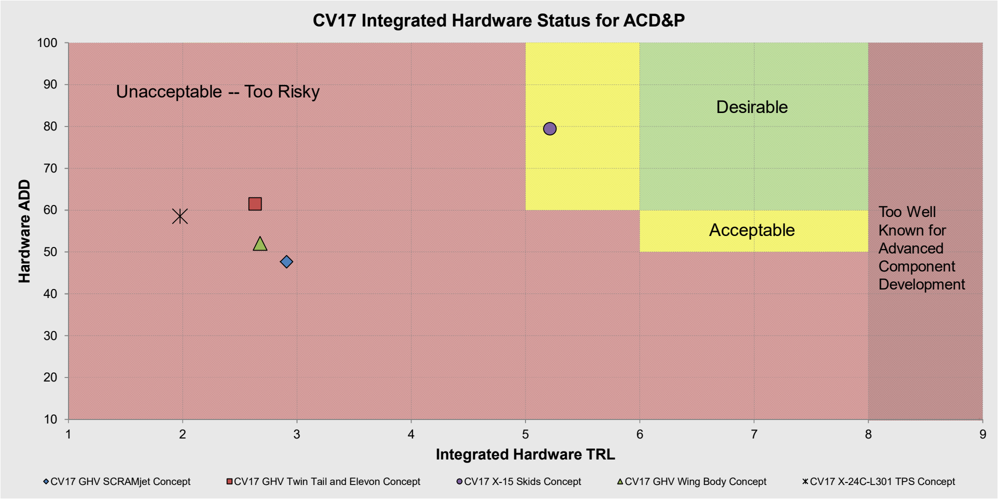


Figure 4-26 Portfolio Value Assessment – Results CV17 Risk Prioritization

	Gap	CV21
Landing System	TRL	+1
	ADD	0
Lift Source	TRL	+4
	ADD	+7.9%
Stability & Control	TRL	+4
	ADD	0
Thermal Protection	TRL	+5
	ADD	+1.5%
Thrust Source	TRL	+4
	ADD	+12.4%

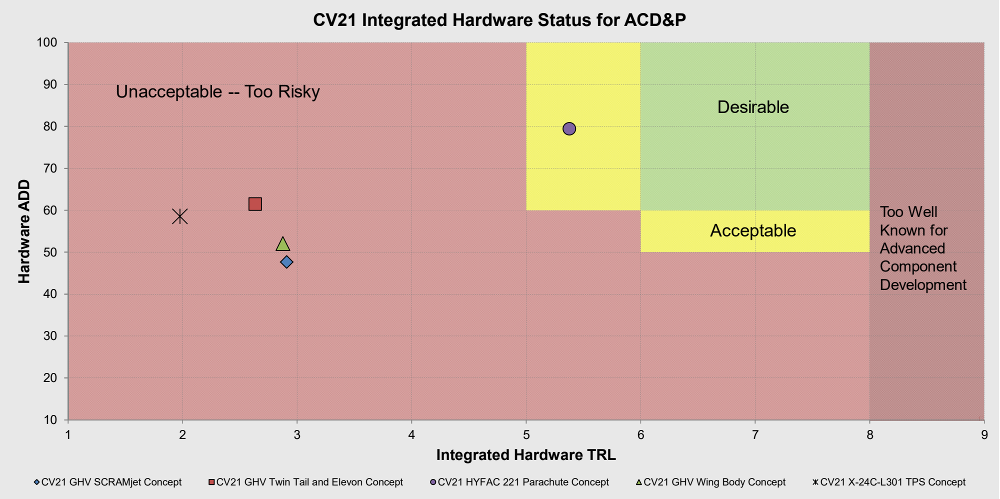


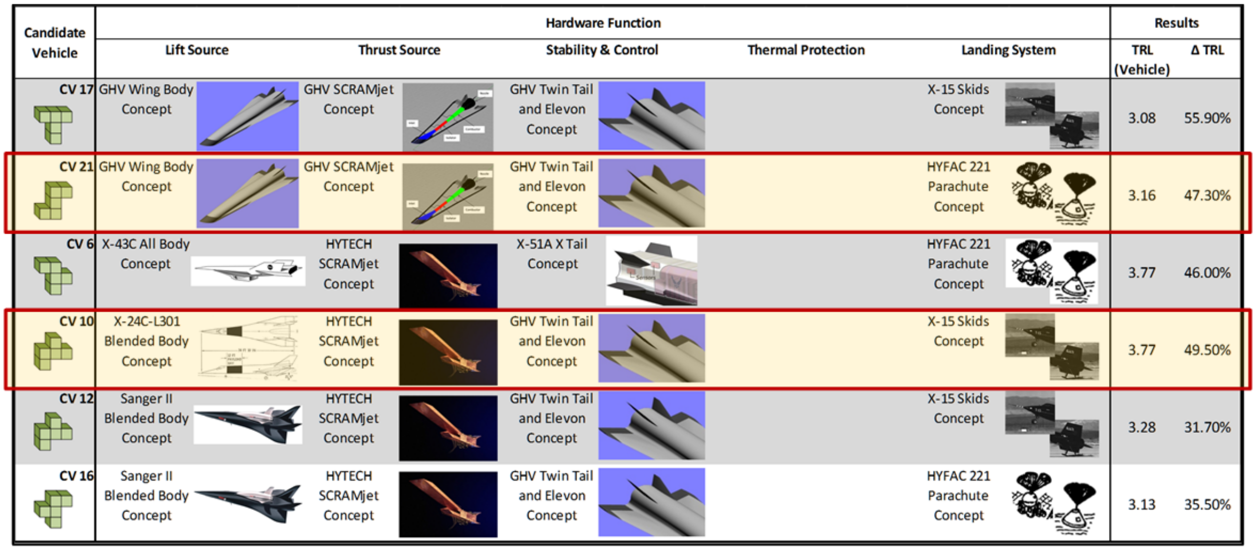
Figure 4-27 Portfolio Value Assessment – Results CV21 Risk Prioritization

Table 4-10 Portfolio Value Assessment – Summary of CV Risk Prioritization

	Landing System		Lift Source		Stability & Control		Thermal Protection		Thrust Source	
Vehicle	**TRL Gap**	**ADD Gap**	**TRL Gap**	**ADD Gap**	**TRL Gap**	**ADD Gap**	**TRL Gap**	**ADD Gap**	**TRL Gap**	**ADD Gap**
CV06	+1	0	+3	+0.9%	+3	+7.1%	+4	+1.5%	+2	+8.8%
CV10	+1	0	+3	+1.5%	+3	0	+4	+1.5%	+2	+8.8%
CV12	+1	0	+4	+9.1%	+4	0	+5	+1.5%	+3	+8.8%
CV16	+1	0	+4	+9.1%	+4	0	+5	+1.5%	+3	+8.8%
CV17	+1	0	+4	+7.9%	+4	0	+5	+1.5%	+4	+12.4%
CV21	+1	0	+4	+7.9%	+4	0	+5	+1.5%	+4	+12.4%

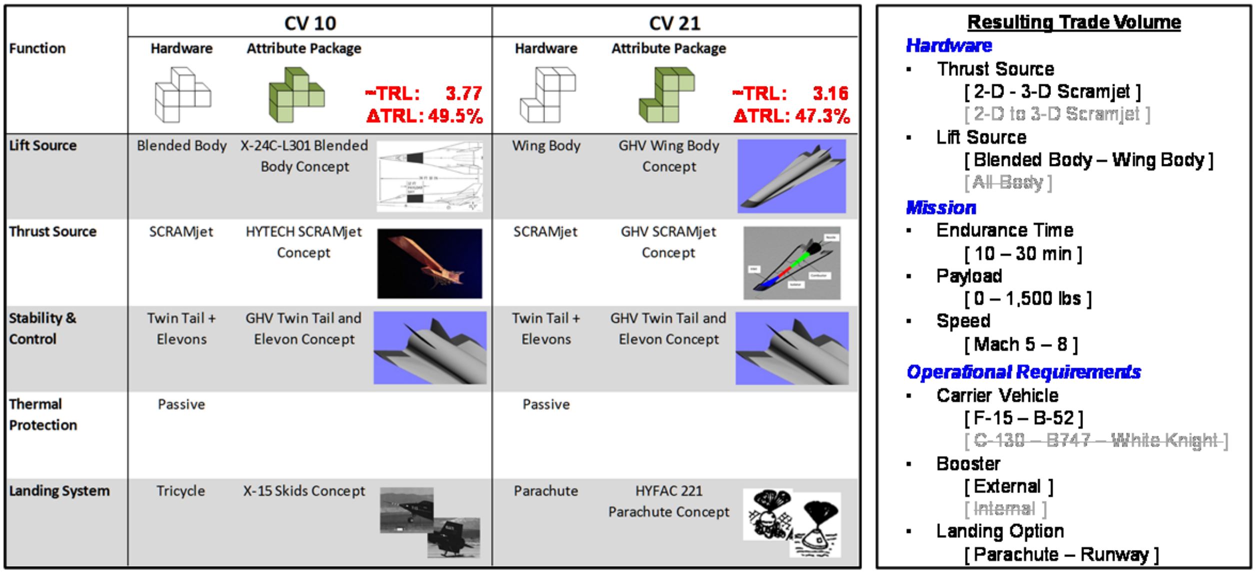
6. Select Capability-Balanced Technology Portfolio

The CV portfolio is prioritized to meet or partially meet the required technology performance. In effect, this knowledge capture activity allows the researcher to better understand the DTRs created by the vehicles in order to build a capability-balanced portfolio. Figure 4-28 highlights the project vehicle (PV) selections for further study. The balanced portfolio for the GHV study includes CV10 and CV21. Accordingly, the PV results in the trade matrix for zero silo DBMS analysis, see Figure 4-29.



Candidate Vehicle	Hardware Function					Results	
	Lift Source	Thrust Source	Stability & Control	Thermal Protection	Landing System	TRL (Vehicle)	Δ TRL
CV 17	GHV Wing Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept		X-15 Skids Concept	3.08	55.90%
CV 21	GHV Wing Body Concept	GHV SCRAMjet Concept	GHV Twin Tail and Elevon Concept		HYFAC 221 Parachute Concept	3.16	47.30%
CV 6	X-43C All Body Concept	HYTECH SCRAMjet Concept	X-51A X Tail Concept		HYFAC 221 Parachute Concept	3.77	46.00%
CV 10	X-24C-L301 Blended Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept		X-15 Skids Concept	3.77	49.50%
CV 12	Sanger II Blended Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept		X-15 Skids Concept	3.28	31.70%
CV 16	Sanger II Blended Body Concept	HYTECH SCRAMjet Concept	GHV Twin Tail and Elevon Concept		HYFAC 221 Parachute Concept	3.13	35.50%

Figure 4-28 Portfolio Value Assessment – Selection of Capability-Based Technology Portfolio



Function	CV 10		CV 21	
	Hardware	Attribute Package ~TRL: 3.77 ΔTRL: 49.5%	Hardware	Attribute Package ~TRL: 3.16 ΔTRL: 47.3%
Lift Source	Blended Body	X-24C-L301 Blended Body Concept	Wing Body	GHV Wing Body Concept
Thrust Source	SCRAMjet	HYTECH SCRAMjet Concept	SCRAMjet	GHV SCRAMjet Concept
Stability & Control	Twin Tail + Elevons	GHV Twin Tail and Elevon Concept	Twin Tail + Elevons	GHV Twin Tail and Elevon Concept
Thermal Protection	Passive		Passive	
Landing System	Tricycle	X-15 Skids Concept	Parachute	HYFAC 221 Parachute Concept

Resulting Trade Volume

Hardware

- Thrust Source
  [2-D - 3-D Scramjet]
  ~~[2-D to 3-D Scramjet]~~
- Lift Source
  [Blended Body – Wing Body]
  ~~[All Body]~~

Mission

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

Operational Requirements

- Carrier Vehicle
  [F-15 – B-52]
  ~~[C-130 – B747 – White Knight]~~
- Booster
  [External]
  ~~[Internal]~~
- Landing Option
  [Parachute – Runway]

Figure 4-29 Portfolio Value Assessment – Capability-Based Technology Portfolio Trade Matrix

4.3 Capability-Based Technology Portfolio Preparation for Zero-Silo DBMS Sizing

With the acquisition strategy now set, the researcher can now look to the preparation of data interfaces to execute zero-silo DBMS PS. Most of this work is beyond the scope the of the current research, however research efforts being undertaken by Omoragbon and Gonzalez support the capability-based technology portfolio with its' associated hardware, mission, and operational constraint data blocks as a strategy towards product R&D and design during the MSA phase. [17][144] According to Omoragbon, the first step is to transform the data blocks to a domain mapping matrix (DMM) topology [144] This means a product DMM, process DMM, and method DMM are used to initialize and/or decide the order of activities to build an aircraft synthesis tool. Table 4-11 and Table 4-12 present the resulting data interfaces for the GHV study. Specifically, the data conversion illustrates the PV21 (formerly CV21) configuration, see Figure 4-30. The next step utilizes the DMM structure for identifying and matching the relevant disciplinary analysis blocks during zero-silo DBMS sizing. Gonzalez describes the process in detail in his thesisbook. [17] Completion of the process results in design structure matrix (DSM) topology as shown in Figure 4-31. Whereby the characterization of the PV21 DSM establishes the computational framework for the final disciplinary analysis methods (i.e. aircraft geometry, aerodynamics, mass properties, engine performance, and flight performance requirements), data interactions (Table 4-13) that are built into the PS tool and the sequence of events necessary is defined to generate the data modules. With the execution of the product R&D tool now possible, the researcher decides the system inputs and creates the PV21 synthesis data.

Figure 4-32 to Figure 4-34 describe the disciplinary and multidisciplinary effects data for the PV21. The discussion of the results is purposefully kept brief, since the intent is to show that PS can directly contribute during the MSA pre-design acquisition stage. Three types of data screening filters are applied to the data: (1) product design versus technology performance, (2) structural capability versus product design versus technology performance, and (3) launch constraints versus product design versus technology performance. A more detailed conversation can be found in Reference 143.

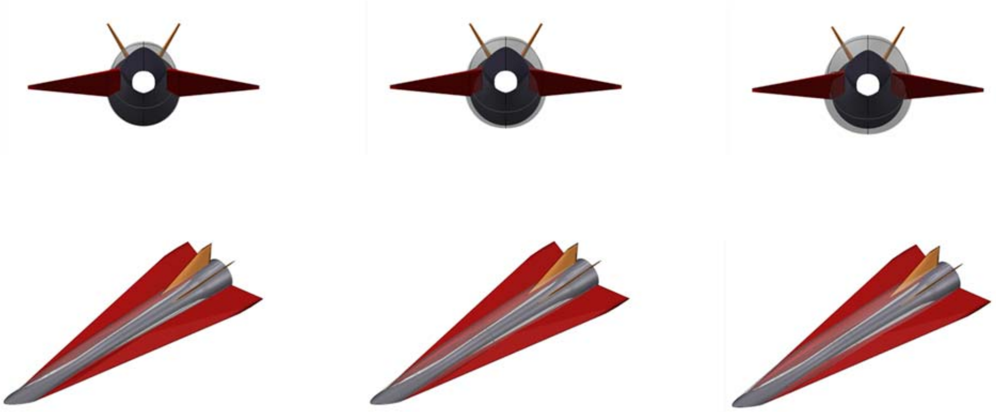


Figure 4-30 Parametric Geometry for PV21 (GHV)

Table 4-11 Product DMM Attributes and Data Interfaces

Product DMM 			Product																																							
			Add New	HYFAC 200	HYFAC 201	HYFAC 204	HYFAC 205	HYFAC 206	HYFAC 207	HYFAC 210	HYFAC 211	HYFAC 212	HYFAC 213	HYFAC 214	HYFAC 220	HYFAC 221	HYFAC 231	HYFAC 232	HYFAC 233	HYFAC 234	HYFAC 250	HYFAC 251	HYFAC 252	HYFAC 253	HYFAC 254	HYFAC 255	HYFAC 256	HYFAC 257	HYFAC 270	HYFAC 271	HYFAC 280	HYFAC 281	HYFAC 282	HYFAC 284	HYFAC 285	HYFAC 290	HYFAC 291	HYFAC 292	VAB Air-launched Hydrogen	VAB Air-launched Hydrogen 2Qs	VAB Air-Launched Kerosene	VAB Expendable Booster Hydrogen	VAB Expendable Booster Kerosene
Functional Subsystems	**Lift Source**	All Body	1		1			1	1		1	1	1	1	1	1	1	1	1		1		1	1	1			1	1	1	1	1	1	1	1		1	1	1	1	1	1	1
		Wing Body		1		1	1			1										1		1				1	1										1							
	Thermal Protection	Heat Shingles		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				1	1	1	1	1
	Thrust Source	** Ramjet **							1			1	1		1	1																													
		** RamScramjet **	1													1	1							1	1		1		1	1									1	1	1	1	1
		** Rocket **	1						1				1	1				1	1	1	1	1	1	1	1	1	1	1		1	1		1	1	1	1				1	1	1		
		** Turbojet **										1					1												1									1	1	1					
		** TurboRamjet **		1	1	1	1	1		1	1																																	
	Volume Supply	** Integral Tank **		1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Operation Events	**Mission Segment**	Air Launch				1	1	1	1									1	1	1	1														1						1	1	1		
		Booster Launch													1	1																	1	1	1									1	1
		Horizontal Takeoff		1	1					1	1	1	1	1							1	1	1	1	1	1	1	1										1	1					
		Vertical Takeoff																											1	1														
		Constant Q Climb	2																																					1	2	1	1	1
		Constant Altitude Acceleration	1																																					1	1	1		
		Constant Mach Endurance Cruise																																							1	1	1	1	1
		Constant Mach Range Cruise |1|																																								
		Gliding Descent	1																																					1	1	1	1	1
		Air Snatch														1																														
		Parachute Landing													1																1	1	1										
		Powered Landing		1	1	1	1	1	1	1	1	1					1										1										1	1	1					
		Unpowered Landing											1	1				1	1	1	1	1	1	1	1	1	1			1	1				1	1									
	Mission Speed	Subsonic	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	
		Supersonic	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1		1	
		Transonic	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1		1	
		Hypersonic	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				1	1		1	
	Mission Type	Point-to-Point																																					1			1	
Operational Requirements	**Human Rating**	Manned		1	1		1	1	1	1	1	1	1	1			1	1	1	1	1	1	1	1	1	1	1	1	1	1						1	1	1					
		Unmanned				1									1	1															1	1	1	1	1								
	Fuel (Storage State)	Aerozine 50 (Liquid)																					1			1						1										
		Hydrogen (Cryogenic Liquid)	1			1	1	1	1			1	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1	1	1	1		1	1				1	1		1	
		JP-5 (Liquid)		1	1					1	1																									1	1	1			1		1
	Oxidizer (Storage State)	Air (N/A)		1	1	1	1	1	1	1	1	1	1		1	1	1	1								1	1		1		1	1						1	1	1	1	1		1	
		Nitrogen Tetroxide (Liquid)																					1			1						1										
		Oxygen (Cryogenic Liquid)	1						1				1	1				1	1	1	1	1	1		1	1			1	1		1		1	1									

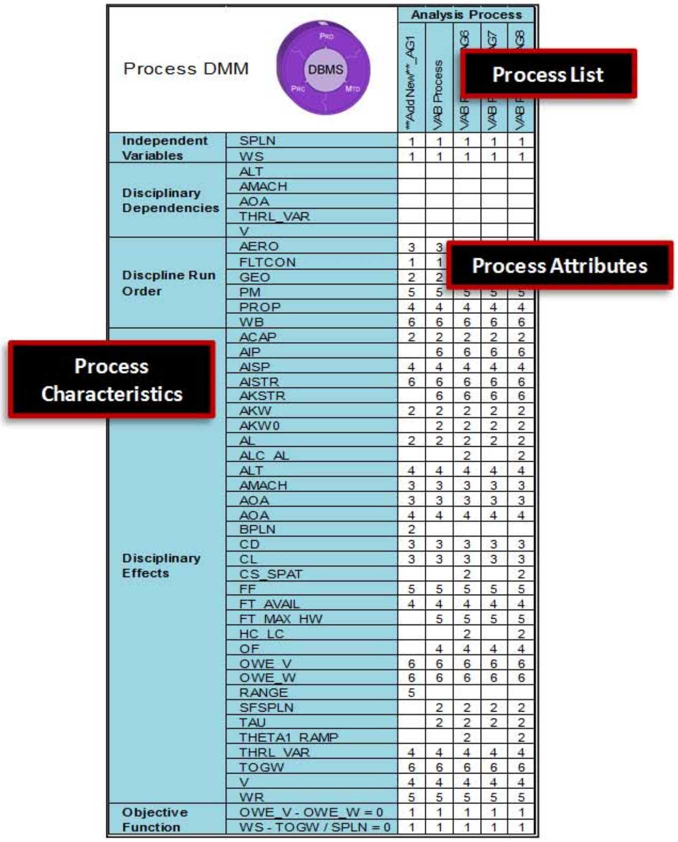
Product Characteristics

Product List

Product Attributes

Table 4-12 Process and Method DMM Attributes and Data Interfaces

Process domain mapping matrix



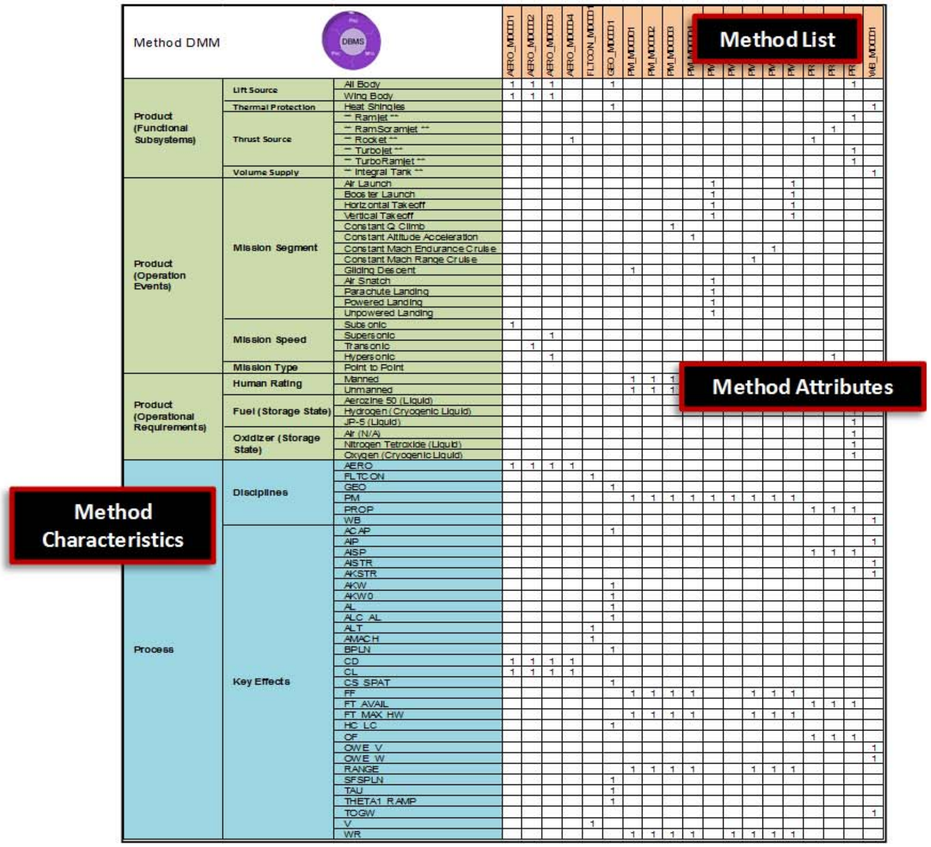
Process List

Process Attributes

Process Characteristics

Process DMM		Analysis Process				
		Add New_AG1	VAB Process	VAB F[illegible]G6	VAB F[illegible]G7	VAB F[illegible]G8
Independent Variables	SPLN	1	1	1	1	1
	WS	1	1	1	1	1
Disciplinary Dependencies	ALT					
	AMACH					
	AOA					
	THRL_VAR					
	V					
Discpline Run Order	AERO	3	3	[illegible]	[illegible]	[illegible]
	FLTCON	1	1	[illegible]	[illegible]	[illegible]
	GEO	2	2	[illegible]	[illegible]	[illegible]
	PM	5	5	5	5	5
	PROP	4	4	4	4	4
	WB	6	6	6	6	6
Disciplinary Effects	ACAP	2	2	2	2	2
	AIP		6	6	6	6
	AISP	4	4	4	4	4
	AISTR	6	6	6	6	6
	AKSTR		6	6	6	6
	AKW	2	2	2	2	2
	AKW0		2	2	2	2
	AL	2	2	2	2	2
	ALC_AL			2		2
	ALT	4	4	4	4	4
	AMACH	3	3	3	3	3
	AOA	3	3	3	3	3
	AOA	4	4	4	4	4
	BPLN	2				
	CD	3	3	3	3	3
	CL	3	3	3	3	3
	CS_SPAT			2		2
	FF	5	5	5	5	5
	FT_AVAIL	4	4	4	4	4
	FT_MAX_HW		5	5	5	5
	HC_LC			2		2
	OF		4	4	4	4
	OWE_V	6	6	6	6	6
	OWE_W	6	6	6	6	6
	RANGE	5				
	SFSPLN		2	2	2	2
	TAU		2	2	2	2
	THETA1_RAMP			2		2
	THRL_VAR	4	4	4	4	4
	TOGW	6	6	6	6	6
	V	4	4	4	4	4
	WR	5	5	5	5	5
Objective Function	OWE_V - OWE_W = 0	1	1	1	1	1
	WS - TOGW / SPLN = 0	1	1	1	1	1

Method domain mapping matrix



Method List

Method Attributes

Method Characteristics

Method DMM			AERO_MDC001	AERO_MDC002	AERO_MDC003	AERO_MDC004	FLTCON_MDC001	GEO_MDC001	PM_MDC001	PM_MDC002	PM_MDC003	PM_MDC[illegible]	PM[illegible]	PM[illegible]	PM[illegible]	PM[illegible]	PM[illegible]	PR[illegible]	PR[illegible]	PR[illegible]	WB_MDC001
Product (Functional Subsystems)	Lift Source	All Body	1	1	1			1												1	
		Wing Body	1	1	1																
	Thermal Protection	Heat Shingles						1													1
	Thrust Source	** Ramjet **																		1	
		** RamScramjet **																	1		
		** Rocket **				1												1			
		** Turbojet **																		1	
		** TurboRamjet **																		1	
	Volume Supply	** Integral Tank **																			1
Product (Operation Events)	Mission Segment	Air Launch											1				1				
		Booster Launch											1				1				
		Horizontal Takeoff											1				1				
		Vertical Takeoff											1				1				
		Constant Q Climb									1										
		Constant Altitude Acceleration										1									
		Constant Mach Endurance Cruise														1					
		Constant Mach Range Cruise													1						
		Gliding Descent							1												
		Air Snatch											1								
		Parachute Landing											1								
		Powered Landing											1								
		Unpowered Landing											1								
	Mission Speed	Subsonic	1																		
		Supersonic			1																
		Transonic		1																	
		Hypersonic			1														1		
	Mission Type	Point to Point										[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Product (Operational Requirements)	Human Rating	Manned							1	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Unmanned							1	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Fuel (Storage State)	Aerozine 50 (Liquid)										[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Hydrogen (Cryogenic Liquid)										[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		JP-5 (Liquid)																		1	
	Oxidizer (Storage State)	Air (N/A)																		1	
		Nitrogen Tetroxide (Liquid)																		1	
		Oxygen (Cryogenic Liquid)																		1	
Process	Disciplines	AERO	1	1	1	1															
		FLTCON					1														
		GEO						1													
		PM							1	1	1	1	1	1	1	1	1				
		PROP																1	1	1	
		WB																			1
	Key Effects	ACAP						1													
		AIP																			1
		AISP																1	1	1	
		AISTR																			1
		AKSTR																			1
		AKW						1													
		AKW0						1													
		AL						1													
		ALC_AL						1													
		ALT					1														
		AMACH					1														
		BPLN						1													
		CD	1	1	1	1															
		CL	1	1	1	1															
		CS_SPAT						1													
		FF							1	1	1	1			1	1	1				
		FT_AVAIL																1	1	1	
		FT_MAX_HW							1	1	1	1			1	1	1				
		HC_LC						1													
		OF																1	1	1	
		OWE_V																			1
		OWE_W																			1
		RANGE							1	1	1	1			1	1	1				
		SFSPLN						1													
		TAU						1													
		THETA1_RAMP						1													
		TOGW																			1
		V					1														
		WR							1	1	1	1		1	1	1	1				

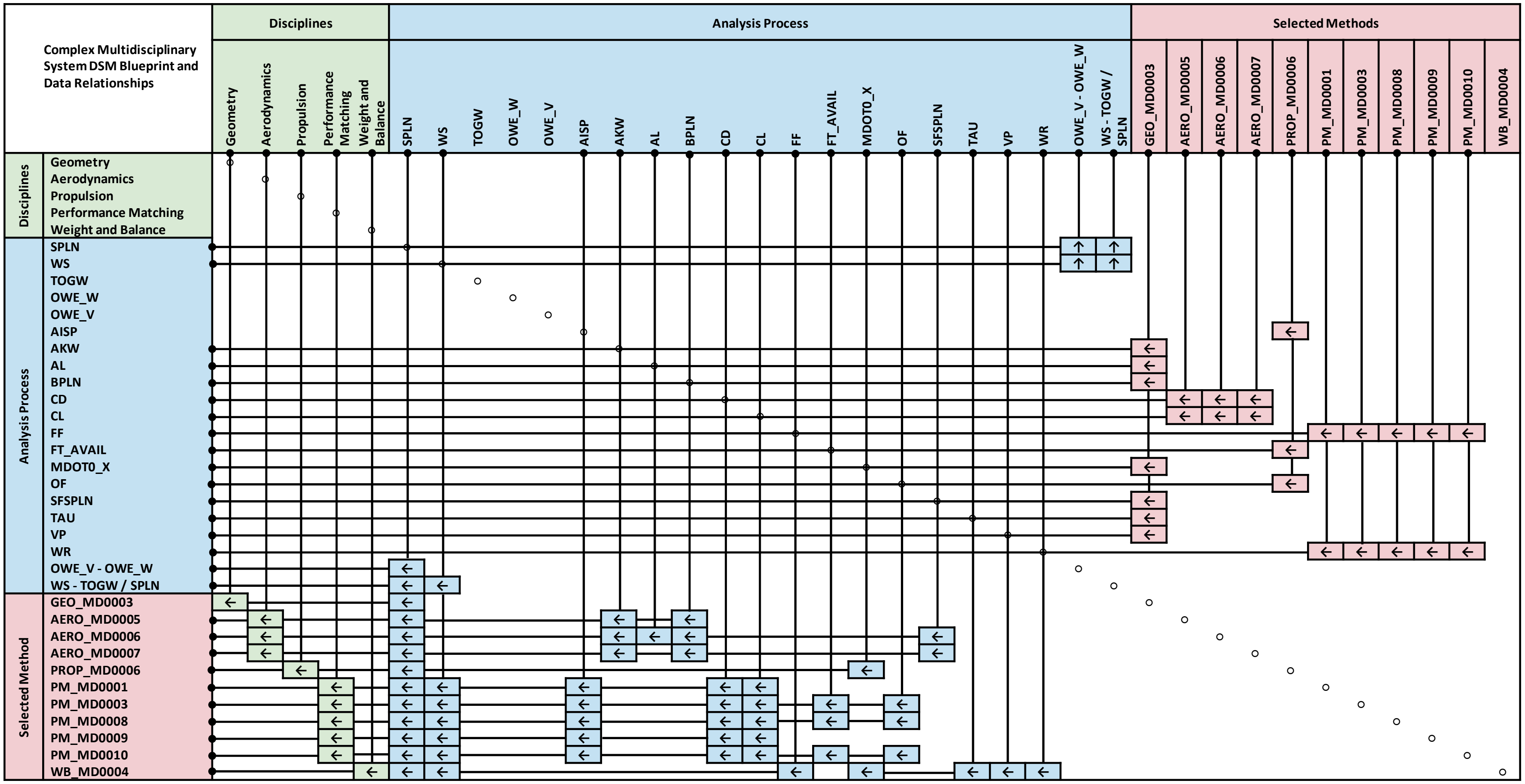


Figure 4-31 Parametric Sizing Tool DSM – PV21

Table 4-13 Parametric Sizing Tool GHV Study Methods Library

SizingName	MethodTitle	Title	Page No.	LastName	FirstName
FLTCON_MD0001	Atmospheric Model	The ARDC Model Atmosphere, 1959	All	Minzner	R. A.
				Champion	K. S. W.
				Pond	H. L.
GEO_MD0003	Hypersonic Airbreather Geometery (AFRL SFFP CV21)	Generic Hypersonic Vehicle for Conceptual Design Analyses	All	Liston	Glenn
				Ruttle	Brent
				Stork	Jacob
AERO_MD0005	MCAir Wing Body / Blended Body Subsonic Aerodynamics	Hypersonic Research Facilities Study Volume II Part 2 - Phase 1 Flight Vehicle Synthesis	4-21	Mcdonell Aircraft Company	
AERO_MD0006	MCAir Wing Body / Blended Body Transonic/Supersonic Aerodynamics	Hypersonic Research Facilities Study Volume II Part 2 - Phase 1 Flight Vehicle Synthesis	4-21	Mcdonell Aircraft Company	
AERO_MD0007	MCAir Wing Body / Blended Body Supersonic/Hypersonic Aerodynamics	Hypersonic Research Facilities Study Volume II Part 2 - Phase 1 Flight Vehicle Synthesis	4-21	Mcdonell Aircraft Company	
PROP_MD0006	GHV Engine	Generic Hypersonic Vehicle for Conceptual Design Analyses	All	Liston	Glenn
				Ruttle	Brent
				Stork	Jacob
PM_MD0003	Constant Q-Climb to an Altitude and Velocity at Small Flight Path Angles	Flight Mechanics, Vol. 1: Theory of Flight Paths		Miele	Angelo
PM_MD0001	Gliding Decent at Max L/D	Flight Mechanics, Vol. 1: Theory of Flight Paths	200	Miele	Angelo
PM_MD0009	Launch Methods using WR	Flight Mechanics, Vol. 1: Theory of Flight Paths		Miele	Angelo
PM_MD0008	Constant Mach Range Cruise at Small Flight Path Angles	Flight Mechanics, Vol. 1: Theory of Flight Paths		Miele	Angelo
PM_MD0010	Steady Level Turning Flight to Origin	Optimal Trajectory Atmospheric Flight	59-60	Vinh	Nguyen X.
WB_MD0004	Convergence OWE Esitmation for Scramjet w/ Parachute	Hypersonic Convergence	164	Czysz	Paul
		Hypersonic Research Facilities Study Volume II Part 2 - Phase 1 Flight Vehicle Synthesis	134	Mcdonell Aircraft Company	
		Parachute Recovery Systems Design Manual	6-93, 6-94	Knacke	Theo
		Recovery System Design Guide	435	Ewing	E. G.
				Bixby	H. W.
				Knacke	T. W.

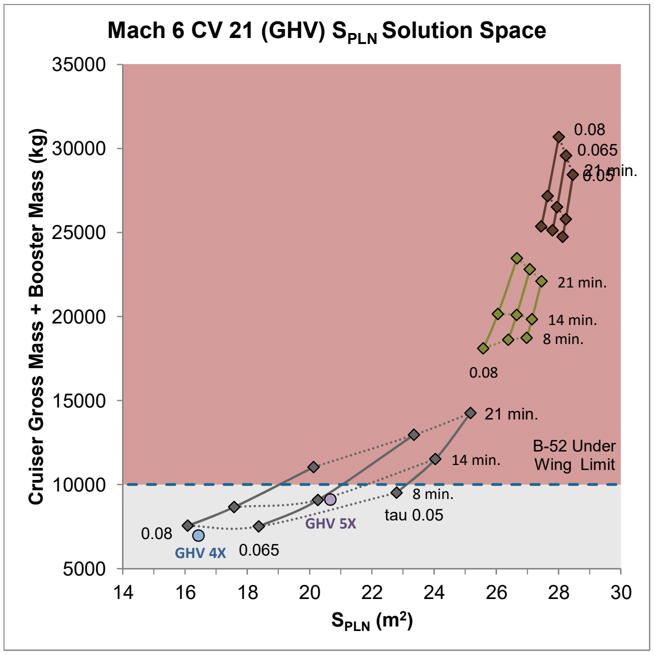


Figure 4-32 Data Screening and Results PV21 – Product Design vs. Technology Performance

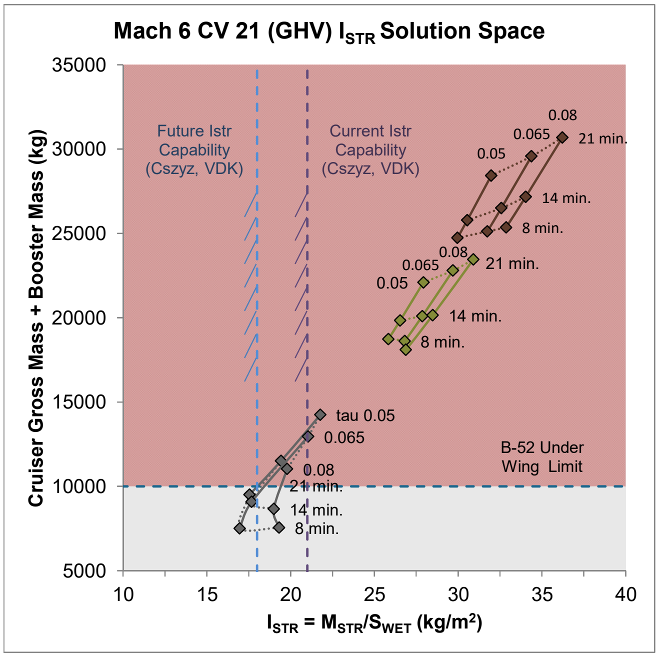


Figure 4-33 Data Screening and Results PV21 – Structural Capability vs. Product Design vs. Technology Performance

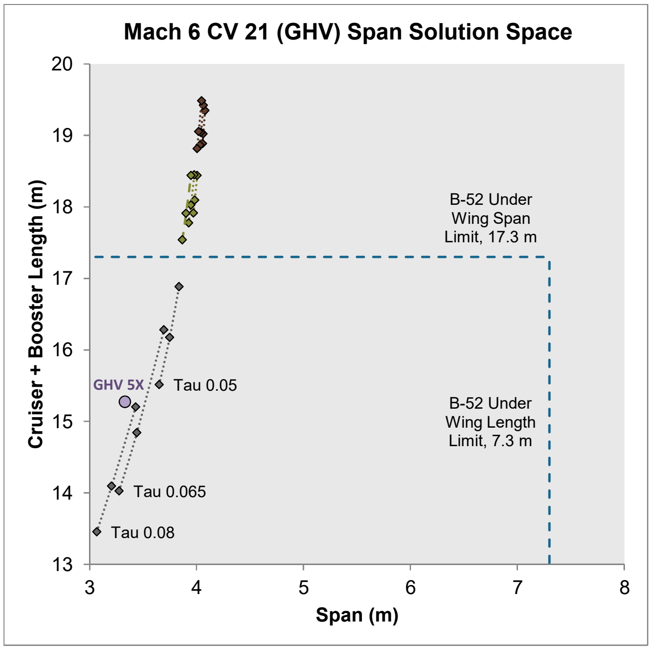


Figure 4-34 Data Screening and Results PV21 – Launch Constraints vs. Product Design vs. Technology Performance

Chapter 5 – Discussion, Conclusions, and Future Work

In this final chapter, discussion and conclusions related to the contributions of this study are presented. Collectively, this effort challenges how and what work can be accomplished when knowledge is less likely to reside within separate teams of researchers and is integrated by a common focus on data management and data relationships. Value added from this innovative system capability provides a foundation for a next generation technology forecasting decision support tool with a focus on reimagining the behavior and ideas for how innovation studies can be executed. Specifically, the design of a data integration platform allows for a reduction in the level of effort required for acquisition analysis tool development and, subsequently, by aligning technology problem requirements deterministically to a generic aircraft synthesis capability.

The current prototype of the composable problem formulation architecture focuses on data automation, in order to increase the impact of technology innovation portfolio assessment (IPA) and parametric sizing (PS) in the materiel solution analysis (MSA) pre-design acquisition stage. Whereby, the goal is to improve research and development (R&D) effectiveness towards aerospace and defense (A&D) planning in the early stages of the product development lifecycle. Though all the features discussed are not fully integrated computationally, all concepts are adequately developed such that the benefits of the framework to support with analysis of decisions under uncertainty are readily observable. The emphasis is on: (1) correct formulation of a decision problem, with special attention to account for data relationships between the individual design problem and the system capability required to PS the aircraft, (2) understanding of the meaning of the acquisition strategy objective and subjective data requirements that are required to arrive at an objective analysis and/or "correct" mix of projects, (3) understanding the meaning of the outputs that can be created from the technology analysis, and (4) methods the researcher can use at effectively support decisions at the acquisition and PS levels through utilization of a R&D portfolio strategy.

5.1 Discussion

A. Influence of Composable Architecture on Data Automation

As such, composable architecture and data automation methodology are recognized as new options to reduce design schedule and costs, and innovate more freely. While the adoption of these techniques is growing in the A&D industry, it will take some time before the full potential is realized. On the acquisition side implementation is limited by the freeform levels of abstraction used in IPA processes and making the establishment data redundancies difficult; on the other side, conceptual design (CD) PS is impeded by the layers of vertically integrated product development tools built from different levels of abstraction, thus making the identification repetitive data activities challenging. However, in terms of the current strategy of shifting synthesis directly into the acquisition sequence little to no research exists.

Through the adoption of a composable problem formulation architecture, tasks that are not routinely automated are characterized and define a product such that the PS disciplinary analysis modules can be initialized for sizing tool building. According to Amadori and Stokes, *"… in a given design project, as many as 80% of all design activities can be routine tasks, but at the same time, the 'creation of a good project depends largely on creativity of the designer himself'…*[172]". [107] Figure 5-1 describes the potential influence of this relationship. Through the benefits of data automation, coupled with the composable architecture researchers are afforded an opportunity to reduce the time spent on repetitive activities. This redistribution of resources, in turn, enables the researcher to solve more complex and innovative issues.

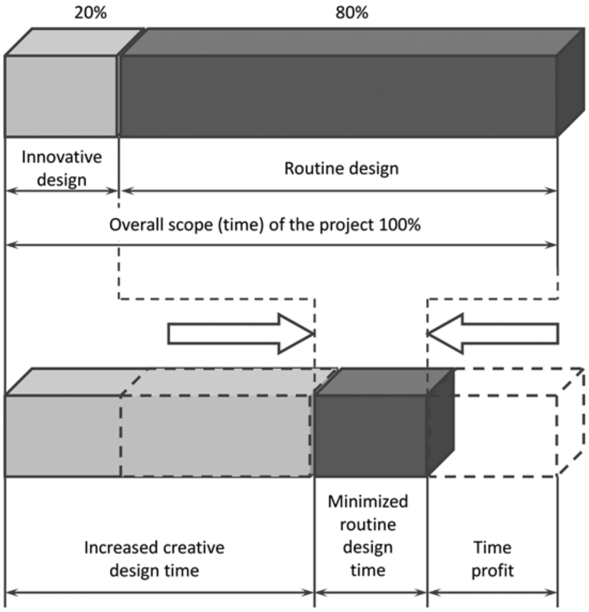


Figure 5-1 Influence of data automation on product development [107]

B. Automation of Data Relationships for Composable Architecture

Parameterization of problem formulation for the composable architecture benefits from a consistent methodological structure to decompose and integrate data requirements according to the level of abstraction specified. Much of the architecture's design and implementation is dedicated to controlling data structures in the product portfolio model (PPM) and capability performance model (CPM) to facilitate construction of the R&D product model. Moreover, since there is no universally accepted strategy for problem formulation decomposition, the objective is to manage the simulation sufficiently that the researcher can: (1) spend more time parameterizing the problem formulation simulation model (PFSM) to appropriately match the decision data requirements, and/or (2) create new data relationships and levels of abstraction with a reduced focus on integrating PPM, CPM, and functional capabilities system model (FCSM) system capability. Whereby, the syntactically composable architecture is a representative of a data management platform that generates data standards and rules for automation to ensure a systematic and transparent MSA process.

It can be argued that neither specification of system composability or data automation is required if the problem formulation complexity of the IPA and PS is not high and/or the required SE capability can be iterated quickly. While it is true that the overhead of building the platform is of concern, it is of greater interest to address how to keep evolving the problem formulation processes such that stagnation in terms of tool development is avoided. This is necessary for two reasons: (1) problem formulation processes can be continuously upgraded and modified, and (2) system capability is open to development and compatibility towards artificial intelligence or deep learning. Consequently, if the problem formulation M&S is adequately represented, the opportunity exists is to consistently scale the architecture without automatically requiring a major investment in systems engineering (SE) resources.

C. Robustness, Flexibility, and Fidelity Data Relationships for Problem Formulation and PS

As discussed previously, data relationships dictate the impact of the system capability presently developed. The success of the effort is dependent on understanding the connection of the individual robustness, flexibility, and fidelity of the problem formulation and PS capability, and how the strategy for the data integration impacts the multidisciplinary effects captured for the product. Thus, the degrees of freedom of the PS decision space corresponds directly to the simulation created by PFSM; where the PFSM was verified by decomposing the sizing processes and the data requirements mapped backwards in the product lifecycle to fill gaps in data continuity. Interestingly, the certainty in this data relationship “bridge” is limited going forward into the aircraft synthesis process as the high variability in modeling (i.e. FCSM, PPM, and CPM) the problem formulation data relationships is only in early stages of development. Yet the foundation laid addresses the data interface disconnects to continue development as the consistency, transparency, and automation of the architecture grows. Furthermore, the value added goes on to change the dynamics of acquisition researcher and CD engineer relationships.

5.2 Conclusions

Product development requires a complex understanding of decision risk landscapes to ensure that a technology problem is being objectively characterized. The current priority is on providing a better starting point for the CD technical processes. More specifically, how can the data requirements for PS be initialized in the MSA stages.

The research was initiated with the intent of exploring PS specific product development tools to understand where the methodology can better contribute to the pre-design acquisition stages. Three types of sizing tool data topology are identified: single-silo (vertically integrated) tool, hybrid-silo DBMS (horizontally integrated) tool, zero-silo DBMS (horizontally integrated) tool. Each system is found to have a unique capability for robustness, flexibility, and fidelity integration resulting in models that simulate a variety multidisciplinary effect solution spaces. Decomposing these frameworks, it is revealed that the multidisciplinary effects correspond to disciplinary method modules which in turn represent functional hardware, mission environment, and operational environment constraint data from the acquisition researcher. Thus, two things are revealed: (1) data relationships required to “bridge” the CD to pre-design are found with the latter data requirements, and (2) a zero-silo DBMS sizing infrastructure is required to maximize the opportunity for R&D M&S (Chapter 1). From here, referring back to the research questions, the investigation is formulated to determine:

[RQ1] How should a problem formulation model be built to be suitable for acquisition strategic alignment and sizing tool design to automate data relationships?

[RQ2] Is it possible to design a data integration or composable system architecture with reference to pre-design problem formulation and multidisciplinary effects modeling?

[RQ3] Which composable problem decomposition methodology could enable data reuse and scalability?

[RQ4] How could the concurrent use of technology and developmental risk methods support R&D innovation strategy portfolio maturation?

In response to the research questions, the following contributions are made. The problem formulation data implementations are mapped to arrive at strategies for data automation to interface with: (1) product acquisition processes outside the synthesis loop and (2) CD processes building input models for aircraft sizing. Whereby, establishing heterogeneity in the data relationships enables a natural "bridge" or data standard the researcher can utilize to seamlessly to consistently operate within both environments. The data relationships adopted are discussed in Chapter 2. In terms of automation, routine operations are isolated to decompose the functional product hardware and the associated developmental and technology risk (DTR) metrics to arrive at consistent data hierarchies for DBMS storage. The preferred implementation of the DBMS is governed through a portfolio management setup. In this way, a relative and objective measure for technology acquisition risk exposure can be had prior to the data being presented for PS. To address the portfolio management and technology acquisition data requirements a composable architecture is developed (Chapter 3). This framework custom assembles the data analysis blocks to build a problem formulation simulation through execution of a descriptive model, parametric model, and analysis model. Furthermore, it decides the level of abstraction for the PPM, DTR metrics and methods through the CPM, and degree of decision freedom and system integration by the FCSM. The resulting M&S capability is validated by successful assessment of GHV design study (Chapter 4). Moreover, (1) operational systems are identified, (2) a technology hardware portfolio is assembled, (3) candidate vehicles are constructed, (4) a capability-balanced portfolio of candidate vehicles is prioritized, and (5) project vehicles for PS selected. The project vehicles form the basis of the hardware, operational events, and operational requirements used to design the domain mapping matrix (DMM) and initialize the multidisciplinary effects and design structure matrix (DSM) analysis (i.e. aircraft geometry, aerodynamics, mass properties, engine performance, and flight performance requirements) processes for zero-silo DBMS synthesis tool construction.

With the research questions answered, it should be mentioned that verification and validation of this innovative framework is confirmed through discussions with synthesis specialists with the Air Force Research Laboratory (AFRL), Aerospace Systems Directorate during USAF SFFP 2015. [143]

5.2 Recommendations and Future Work

During the course of research has inevitably resulted in lessons learned and insights worth further investigation. Several directions are presented below.

- Create new levels of hardware abstraction and the associated data relationships for the PPM. The data blocks are decomposed to the component level currently. With the data hierarchies composable to higher levels of abstraction, the researcher has the freedom to assemble hardware subcomponents be better calibrate the problem formulation requirements.
- Expand the methods library and create new data relationships for the CPM. Proper technology portfolio analysis requires additional risk, time, cost, and return on investment metrics to capture decision uncertainty exposure.
- Evolve the composable architecture and PFSM into an executable, standalone decision support tool. The current implementation requires a researcher with a data analysis, aerospace engineering, and information technology (IT) backgrounds. Unfortunately, this can limit access of the capability from acquisition and business researchers without these technical skills.
- Study how uncertainty in acquisition decision-making and problem formulation impacts development of the PS tool that simulates the aircraft. Initial experimentation utilizing

this capability are largely positive, however further testing is necessary to the determine system effectiveness and, if any, data management controls for problem formulation to PS is required.

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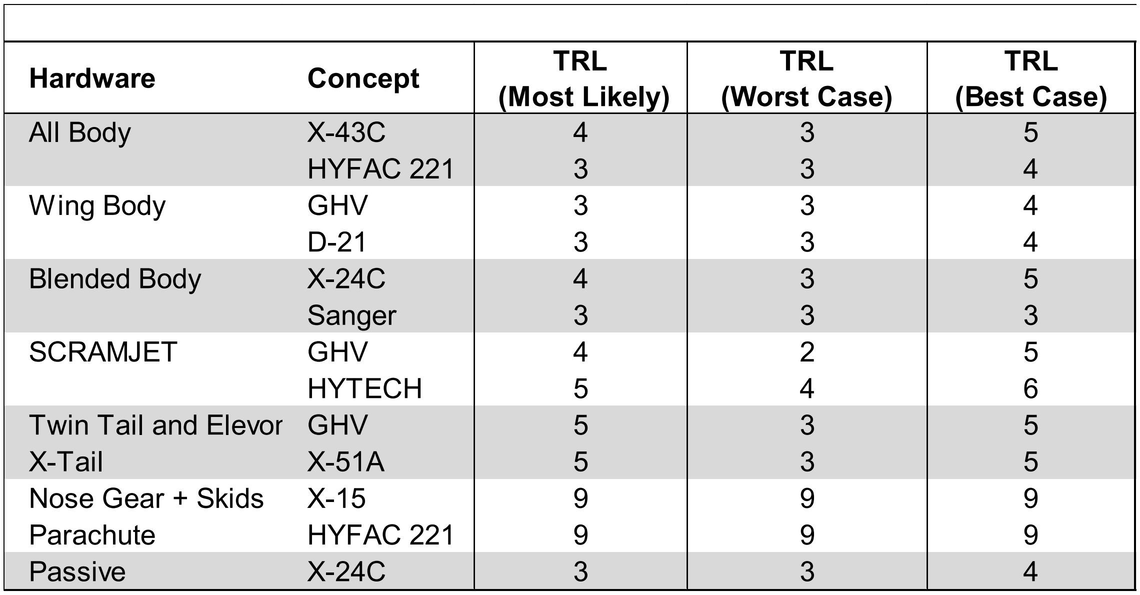
Appendix A

Developmental and Technology Risk Metric Data Tables

Hardware Component Technology Readiness Levels (TRL):



Hardware	Concept	TRL (Most Likely)	TRL (Worst Case)	TRL (Best Case)
All Body	X-43C	4	3	5
	HYFAC 221	3	3	4
Wing Body	GHV	3	3	4
	D-21	3	3	4
Blended Body	X-24C	4	3	5
	Sanger	3	3	3
SCRAMJET	GHV	4	2	5
	HYTECH	5	4	6
Twin Tail and Elevor	GHV	5	3	5
X-Tail	X-51A	5	3	5
Nose Gear + Skids	X-15	9	9	9
Parachute	HYFAC 221	9	9	9
Passive	X-24C	3	3	4

Figure A-1 GHV Case Study TRL Data

Hardware Component Integration Readiness Levels (IRL):

			All Body		*Wing Body*		*Blended Body*		*SCRAMJET*		*Twin Vertical T*	*X-Tail*	*Skids*	*Parachute*	*Passive*
Most Likely			X-43C	HYFAC 22	GHV	D-21	X-24C	Sanger	GHV	HYTECH	GHV	X-51A	X-15	HYFAC 22	X-24C
Lift Hardware	*All Body*	X-43C	9	0	0	0	0	0	3	7	0	8	3	5	3
		HYFAC 221	0	9	0	0	0	0	3	5	0	8	3	7	3
	Wing Body	GHV	0	0	9	0	0	0	5	3	5	0	4	5	3
		D-21	0	0	0	9	0	0	7	3	6	0	7	5	3
	Blended Body	X-24C	0	0	0	0	9	0	3	7	8	0	5	3	3
		Sanger	0	0	0	0	0	9	3	5	5	0	5	3	3
Thrust Hardware	*SCRAMJET*	GHV	3	3	5	7	3	3	9	0	0	0	0	0	0
		HYTECH	7	5	3	3	7	5	0	9	0	0	0	0	0
Stability & Control	*Twin Vertical Tail & Elevons*	GHV	0	0	5	6	8	5	0	0	9	0	0	0	3
	X-Tail	X-51A	8	8	0	0	0	0	0	0	0	9	0	0	3
Landing System	*Nose Gear + Skids*	X-15	3	3	4	7	5	5	0	0	0	0	9	0	0
	Parachute	HYFAC 221	5	7	5	5	3	3	0	0	0	0	0	9	0
Thermal Pro+B4+B3:L1	*Passive*	X-24C	3	3	3	3	3	3	0	0	3	3	0	0	9
Best															
Lift Hardware	*All Body*	X-43C	9	0	0	0	0	0	4	9	0	8	6	7	5
		HYFAC 221	0	9	0	0	0	0	4	6	9	8	6	7	5
	Wing Body	GHV	0	0	9	0	0	0	7	4	6	0	7	6	5
		D-21	0	0	0	9	0	0	7	4	7	0	7	6	5
	Blended Body	X-24C	0	0	0	0	9	0	4	7	8	0	7	6	5
		Sanger	0	0	0	0	0	9	4	5	5	0	7	6	5
Thrust Hardware	*SCRAMJET*	GHV	4	4	7	7	4	4	9	0	0	0	0	0	0
		HYTECH	9	6	4	4	7	5	0	9	0	0	0	0	0
Stability & Control	*Twin Vertical Tail & Elevons*	GHV	0	9	6	7	8	5	0	0	9	0	0	0	5
	X-Tail	X-51A	8	8	0	0	0	0	0	0	0	9	0	0	5
Landing System	*Nose Gear + Skids*	X-15	6	6	7	7	7	7	0	0	0	0	9	0	0
	Parachute	HYFAC 221	7	7	6	6	6	6	0	0	0	0	0	9	0
Thermal Protection	*Passive*	X-24C	5	5	5	5	5	5	0	0	5	5	0	0	9
Worst															
Lift Hardware	*All Body*	X-43C	9	0	0	0	0	0	2	7	0	7	3	5	3
		HYFAC 221	0	9	0	0	0	0	2	4	0	7	3	5	3
	Wing Body	GHV	0	0	9	0	0	0	4	2	3	0	3	5	3
		D-21	0	0	0	9	0	0	4	3	3	0	7	5	3
	Blended Body	X-24C	0	0	0	0	9	0	3	4	3	0	5	3	3
		Sanger	0	0	0	0	0	9	3	4	3	0	5	3	3
Thrust Hardware	*SCRAMJET*	GHV	2	2	4	4	3	3	9	0	0	0	0	0	0
		HYTECH	7	4	2	3	4	4	0	9	0	0	0	0	0
Stability & Control	*Twin Vertical Tail & Elevons*	GHV	0	0	3	3	3	3	0	0	9	0	0	0	3
	X-Tail	X-51A	7	7	0	0	0	0	0	0	0	9	0	0	3
Landing System	*Nose Gear + Skids*	X-15	3	3	3	7	5	5	0	0	0	0	9	0	0
	Parachute	HYFAC 221	5	5	5	5	3	3	0	0	0	0	0	9	0
Thermal Protection	*Passive*	X-24C	3	3	3	3	3	3	0	0	3	3	0	0	9

Figure A-2 GHV Case Study IRL Data

Advance Degree of Difficulty (AD2) Values:

ADC			Design and Analysis							Manufacturing																	Test and Evaluation					Demonstration Units					
		TRL	Databases	Design Process and Tools	Analytical Methods and Tools	Appropriate Models	Manufacturability	Testability	Personnel Skills	Components	Materials	Personnel Skills	Facilities	Machines	Tooling	Metrology	Mfg. Software	Mfg. Processes	Min. Process Variability	Reproducibility	Assembly and Alignment	Integration	Max. Reliability	Max. Availability	GSE Required	Personnel Skills	Personnel Skills	Facilities	Environmental Facilities	Analytical Tools	Test Equipment	Breadboard	Brassboard	Scale Model	Prototype	Flight Qualified Unit	
All Body	X-43C	4	7	5	9	7	6	9	7	9	9	9	5	5	5	5	5	5	5	5	5	5	9	9	5	9	9	5	7	7	7	0	0	7	0	0	6.70
	HYFAC 221	3	4	5	9	7	6	9	5	5	5	6	4	4	4	4	4	4	4	4	4	4	9	9	5	9	9	5	7	7	7	0	0	9	0	0	5.90
Wing Body	GHV	3	6	7	9	7	6	9	7	7	5	6	4	4	4	4	4	4	4	4	4	4	5	5	5	9	9	5	7	7	7	0	0	9	0	0	5.90
	D-21	3	6	7	9	5	6	9	7	7	5	6	4	4	4	4	4	4	4	4	4	4	9	9	5	9	9	5	7	7	7	0	0	6	0	0	6.00
Blended Body	X-24C	4	9	5	9	7	6	9	7	7	9	6	5	5	5	5	5	5	5	5	5	5	9	9	5	9	9	5	7	7	7	0	0	8	0	0	6.63
	Sanger	3	6	5	9	7	6	9	5	5	5	4	4	4	4	4	4	4	4	4	4	4	9	9	5	9	9	5	7	7	7	0	0	5	0	0	5.77
SCRAMJET	GHV	4	5	5	9	7	7	9	7	7	7	7	5	5	5	5	5	5	5	5	5	5	3	3	3	3	7	3	3	5	5	0	0	7	0	0	5.40
	HYTECH	5	7	7	9	9	9	9	7	7	5	7	5	5	5	5	5	5	5	5	5	5	3	3	3	3	7	3	3	7	7	0	0	9	0	0	5.80
Twin Vertical Tail & Elevons	GHV	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	0	0	0	0	6	6.00
X-Tail	X-51A	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	0	0	0	0	6	6.00
Nose Gear + Skids	X-15	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	9	9.00
Parachute	HYFAC 221	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	9	9.00
Passive	X-24C	3	9	7	9	9	5	7	7	6	5	6	6	6	6	6	5	5	7	7	7	6	7	7	7	7	7	7	7	7	7	0	0	0	0	5	6.63
All Body	X-43C	4	6	4	8	6	5	8	6	8	8	8	4	4	4	4	4	4	4	4	4	4	8	8	4	8	8	4	6	6	6	0	0	6	0	0	5.70
	HYFAC 221	3	3	4	8	6	5	8	4	4	4	5	3	3	3	3	3	3	3	3	3	3	8	8	4	8	8	4	6	6	6	0	0	8	0	0	4.90
Wing Body	GHV	3	5	6	8	6	5	8	6	6	4	5	3	3	3	3	3	3	3	3	3	3	4	4	4	8	8	4	6	6	6	0	0	8	0	0	4.90
	D-21	3	5	6	8	4	5	8	6	6	4	5	3	3	3	3	3	3	3	3	3	3	8	8	4	8	8	4	6	6	6	0	0	5	0	0	5.00
Blended Body	X-24C	4	8	4	8	6	5	8	6	6	8	5	4	4	4	4	4	4	4	4	4	4	8	8	4	8	8	4	6	6	6	0	0	7	0	0	5.63
	Sanger	3	5	4	8	6	5	8	4	4	4	3	3	3	3	3	3	3	3	3	3	3	8	8	4	8	8	4	6	6	6	0	0	4	0	0	4.77
SCRAMJET	GHV	4	4	4	8	6	6	8	6	6	6	6	4	4	4	4	4	4	4	4	4	4	2	2	2	2	6	2	2	4	4	0	0	6	0	0	4.40
	HYTECH	5	6	6	8	8	8	8	6	6	4	6	4	4	4	4	4	4	4	4	4	4	2	2	2	2	6	2	2	6	6	0	0	8	0	0	4.80
Twin Vertical Tail & Elevons	GHV	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	5	5.00
X-Tail	X-51A	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	5	5.00
Nose Gear + Skids	X-15	9	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	0	0	0	0	8	8.00
Parachute	HYFAC 221	9	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	0	0	0	0	8	8.00
Passive	X-24C	3	8	6	8	8	4	6	6	5	4	5	5	5	5	5	4	4	6	6	6	5	6	6	6	6	6	6	6	6	6	0	0	0	0	4	5.63
All Body	X-43C	4	8	6	9	8	7	9	8	9	9	9	6	6	6	6	6	6	6	6	6	6	9	9	6	9	9	6	8	8	8	0	0	8	0	0	7.40
	HYFAC 221	3	5	6	9	8	7	9	6	6	6	7	5	5	5	5	5	5	5	5	5	5	9	9	6	9	9	6	8	8	8	0	0	9	0	0	6.67
Wing Body	GHV	3	7	8	9	8	7	9	8	8	6	7	5	5	5	5	5	5	5	5	5	5	6	6	6	9	9	6	8	8	8	0	0	9	0	0	6.73
	D-21	3	7	8	9	6	7	9	8	8	6	7	5	5	5	5	5	5	5	5	5	5	9	9	6	9	9	6	8	8	8	0	0	7	0	0	6.80
Blended Body	X-24C	4	9	6	9	8	7	9	8	8	9	7	6	6	6	6	6	6	6	6	6	6	9	9	6	9	9	6	8	8	8	0	0	9	0	0	7.37
	Sanger	3	7	6	9	8	7	9	6	6	6	5	5	5	5	5	5	5	5	5	5	5	9	9	6	9	9	6	8	8	8	0	0	6	0	0	6.57
SCRAMJET	GHV	4	6	6	9	8	8	9	8	8	8	8	6	6	6	6	6	6	6	6	6	6	4	4	4	4	8	4	4	6	6	0	0	8	0	0	6.33
	HYTECH	5	8	8	9	9	9	9	8	8	6	8	6	6	6	6	6	6	6	6	6	6	4	4	4	4	8	4	4	8	8	0	0	9	0	0	6.63
Twin Vertical Tail & Elevons	GHV	5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	0	0	0	0	7	7.00
X-Tail	X-51A	5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	0	0	0	0	7	7.00
Nose Gear + Skids	X-15	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	9	9.00
Parachute	HYFAC 221	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	9	9.00
Passive	X-24C	3	9	8	9	9	6	8	8	7	6	7	7	7	7	7	6	6	8	8	8	7	8	8	8	8	8	8	8	8	8	0	0	0	0	6	7.53

Figure A-3 GHV Case Study AD2 Data