DATA ENGINEERING IN AEROSPACE SYSTEMS DESIGN & FORECASTING

ERIC HANEY

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

DOCTOR OF PHILOSPHY IN AEROSPACE ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON
May 2016

ACKNOWLEDGEMENTS

I have not reached this point alone. Although I can never truly repay those that have supported me through this journey, it is my honor to pay tribute to their contributions.

First, to my parents, Janice and Rusty Haney, who have given me every opportunity to pursue my passions, both academically and personally. You have understood my potential from an early age and always expected excellence. I owe my work ethic and drive to you both – I would not have achieved this degree without you.

Next, to my colleagues at the Aerospace Vehicle Design Laboratory, who have exposed to me to a new world of ideas and concepts it takes most engineers a lifetime to experience. It has been a privilege to work with Lex Gonzalez, Amit Oza, Amen Omoragbon, Dr. Gary Coleman and the other great minds at the AVD Lab – the intersection of challenging, meaningful problems and passionate, talented engineers has been a fantastic environment to grow as a professional.

To my colleagues at Lone Star Aerospace, who have patiently supported the final leg of this degree. Your constant encouragement has invigorated me through the finish line.

To my friends and family who have, at times, wondered why I am so often absent or so slow to return phone calls, I hope you know you always been in my thoughts. I look forward to seeing more of you all in the coming years.

Finally, to my wife, Kate. You didn't know what you were signing up for when we moved to Arlington together – and you probably wouldn't have if you had understood the realty. You have been on the front lines with me the entire time. I'm not sure I would have had the strength of character to complete this dissertation by myself, but thankfully I didn't have to. Your sacrifices to make this a reality will never be forgotten. I love you and congratulations on your PhT!

ABSTRACT

Data-Engineering in Aerospace Systems Design & Forecasting

Eric Haney
The University of Texas at Arlington, 2016
Supervising Professor: Dr. Bernd Chudoba

Although engineers spend the majority of their time finding, managing, and transforming data, the process of how to handle data remains under-educated & under-researched. The alignment of engineering education & proficiency along an analysis-dominated mindset is ill-conditioned for the growing reliance on data-driven processes and holistic decision-making requirements. Although a majority of driving decisions in the aerospace industry rely heavily on utilizing existing organizational data-stores and built-in knowledge bases to make informed decisions, formalized development & implementation of data within existing engineering processes is seldom addressed.

The current research defines a complementary discipline, *Data-Engineering,* which seeks to capitalize on the exponential growth in availability of technical and socio-technical data to better inform aerospace decision-making. In particular, those design & forecasting decisions made early in the product development life-cycle are selected as the most impactful to the aerospace industry, as well as presenting the most under-exposed opportunity for improvement. This class of decisions presents unique challenges for forecasting situations with highly coupled technical & non-technical considerations. Adequately capturing market, environmental, political, social, & political issues alongside technical considerations is essential to advance the process of forecasting the total system capability & benefit of aerospace vehicle systems. The driving problems in aerospace for current and future generations of engineers will all require significant up-front investments of time, fiscal & human capital, and are therefore beholden to quality forecasting.

The primary contribution of this research has been the specification & development of *Data-Engineering* software system, designed to support aerospace design & forecasting efforts. Specification for the *Data-Engineering System* has extracted best-practices from existing fields – data and data system standards from information sciences, data-model integration from systems engineering, and vehicle system analysis from aerospace engineering. The result has been a holistic perspective of the features and requirements for a *Data-Engineering System* capable of adapting to a wide range of aerospace design & forecasting problems. The end-product provides the engineer a single software environment to access previous analyses, catalogue research source documents, store supplementary datasets, characterize data systems, execute multi-disciplinary design analysis, and visualize information deliverables – all of which are performed, stored and catalogued in an organizationally-linked environment for future reference.

When applied under a controlled experiment case study, the *Data-Engineering System* produces accurate results while substantially reducing required engineering resources – an assessment of re-entry capsule solution space showed a reduction in effort from 2 man-weeks to 2 man-days to produce similar outputs. By automating repetitive non-cognitive data tasks, the *Data-Engineering System* reduces the overall time required to execute a forecasting effort and enables the forecasting engineer to spend more time on higher level cognitive tasks, i.e. assessing multi-disciplinary analysis approaches; communicating results towards decision-makers. Additionally, the standardization and integration of all data tasks in an organizationally-shared environment has been leveraged to produce intelligent design feedback features which automatically identify and define tangentially systems, system analyses, and information deliverables for considerations. These features provide the foundation for artificially-intelligent design systems in future development.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER 1
INTRODUCTION

The alignment of engineering education & proficiency along an analysis-dominated mindset is ill-conditioned for the growing reliance on data-driven processes and holistic decision-making concepts. Although a majority of driving decisions in the aerospace industry rely heavily on utilizing existing organizational data-stores and built-in knowledge bases to make informed decisions, formalized development & implementation of data, information & knowledge within existing engineering processes is seldom addressed.

From the standpoint of aerospace design & forecasting, the use of data is only one component of the holistic information-production process – physics-based systems analysis and knowledge-driven processes remain critical to addressing modern aerospace problems. By formalizing & standardizing data tasks that have traditionally been implemented in an ad hoc fashion (or not all), a new discipline of aerospace research & education, Data-Engineering, seeks to reduce overall uncertainty & variability in the holistic decision-making process. This requires an intimate understanding of data needs within the course of design & forecasting activities, standard implementation practices, and a firm grasp of data theory and implementation outside of the aerospace industry.

1.1 AEROSPACE DESIGN & FORECASTING

Forecasting is the ability to take indeterminate information about a present situation and extrapolate the probable outcome(s) to some point(s) in the future. Whether it is corporate investment, political policy, military strategy, or any number of high-impact modern decisions, there is a need to project the future in order to arrive at present day solutions that will adapt to the evolving conditions of the modern world. The ability to correctly forecast complex situations directly determines the decision-making capability of an individual or organization, and the capability to find optimal or near-optimal solutions under evolving conditions is what ultimately defines successful decisions.

Despite the impact these decisions have on the overall success of a program[1], there remains a lack of systematic research into how to improve the essential early design forecasting process. The integrated nature of aerospace products *"…intimately bound up with economic, military, social, personal, and environmental needs and constraints*"[2] creates a daunting task for modern engineers to holistically describe in a modelling & simulation environment. The difficulty should not, however, stifle new innovation around the decision-making process. The difference between successful and unsuccessful organizations in today & tomorrow's aerospace industry will be their ability to consistently produce well-reasoned and well-substantiated forecasting.

The forecasting process takes place early in the product development process where the latitude to change the design is the highest, see Figure 1.1. Although the initial design requirements phase is often noted as a pre-phase activity[2], the resulting top-level requirements ultimately dictate the ceiling for potential product success[3][4]. As a result, these early development phases have the highest need for effective forecasting. Conversely, the organizational data & information available to the chief engineering and program manager communities at the design requirements & conceptual design phases is also the poorest defined[5]. Improving the quality & amount of information available to decision-makers at the earliest phase of development is the key to improving successful forecasting.

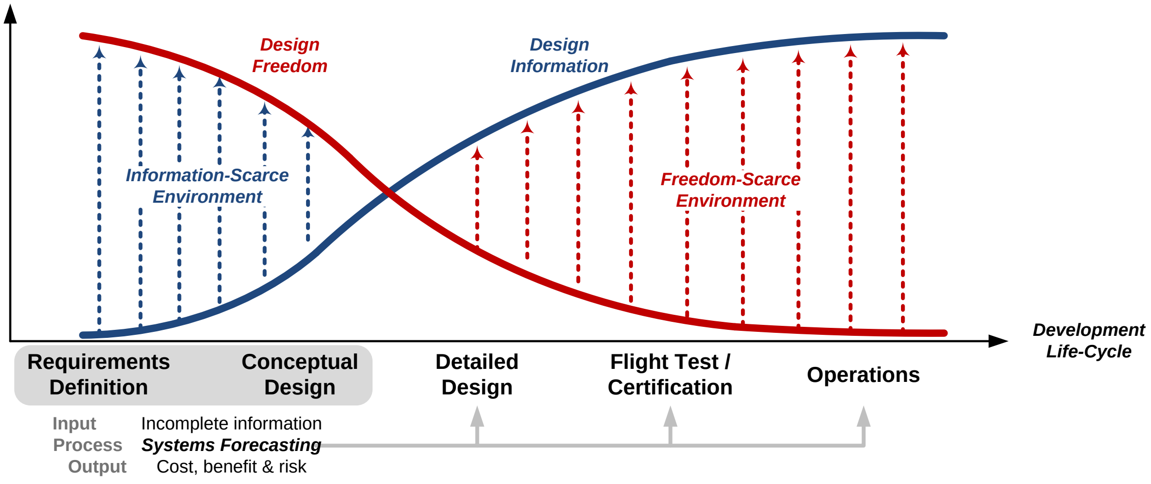


Figure 1.1 – Aerospace Development Life-Cycle

The formality of the forecasting process varies wildly based on the subject, personnel, context and timeframe allotted to decision-making. Time, in particular, is often the driving parameter of how a forecasting process is structured. Decisions made on the scale of minutes & hours, often do not have the luxury of detailed research and planning leading to a structured forecasting assessment. On the other end of the spectrum, decisions made with long (relative) time-scales of months & years have the freedom to analyze the situation in more detail and with a greater perspective. In Vincenti's words[2], "*...designers...want all the knowledge they can get.*" However, these long-term decisions also run the risk of getting lost in the details or overanalyzing the situation – "*...a good plan violently executed now is better than a perfect plan executed at some indefinite time in the future...*" (George

S. Patton Jr.). This balancing requirement to obtain both correct and quick decisions, places further demands on an already-strenuous forecasting process.

1.2 The Creation of Decision-Making Information

From this description, forecasting is solely an effort to produce more information about a situation that is indeterminate & under-conditioned. When viewed at an individual [human] level, an analogue can be drawn to a universal decision-making process – information is always produced by some combination of *memory, experience or reasoning* (referred to as the *data*, *knowledge* and *analysis* domains in an organizational setting).

Data Domain

facts, statistics and media stored for future information requirements.

Knowledge Domain

heuristics, guidelines and lessons learned from previous experiences

Analysis Domain

deconstruction of problems into constituent elements, analysis of the cause and effect of each element in a logic process, and consolidation into a coherent final solution.

While the human brain processes each of these three functions internally & concurrently, an organization (group of individuals) must create discrete, but interfacing processes so that each domain can correctly interconnect, see Figure 1.2. Where an individual-level decision would automatically produce information that incorporates all domains, the complex disseminated nature of an organization's memory, experience and reasoning capabilities often leads to decision-making processes that produce incomplete, uncertain and risk-inducing information.

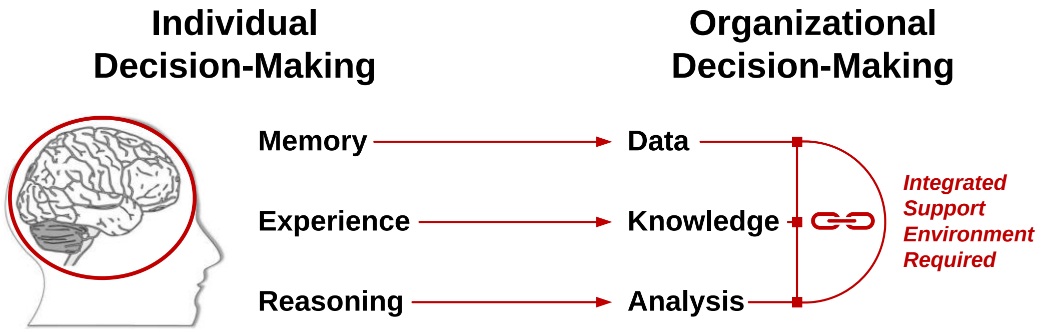


Figure 1.2 – Primary Elements to Decision-Making

In particular, the traditional decision-making environment surrounding aerospace product development lacks an adequate emphasis on the data & knowledge domains and an overemphasis on analytical capabilities. The aerospace educational structure provides the basis for this paradigm – heavy emphasis on disciplinary analysis specialization, a small amount of integrated multi-disciplinary design, and little to no formal education on the collection, organization and use of data and knowledge. Offering sparse exposure to this broader outlook means the typical engineer is ill-suited without supplementary education or is bypassed completely for decision-making roles (Figure 1.3).

Though practicing engineers spend the majority of their time identifying, organizing, and transforming data[2], there remains an opportunity to advance research into systematically developing, utilizing and thus formalizing the data & knowledge domains. The digitization of data (see Chapter 2) has improved access to a larger quantity of information through internal & external sources, but the ability to access the correct data from the correct source is still a challenging task during time-sensitive forecasting activities[6]. Furthermore, the existing ad-hoc data domain patterns practiced allow for variability in the quality of the overall forecasting process. Clearly, variability introduces risk – the primary enemy during the development process.

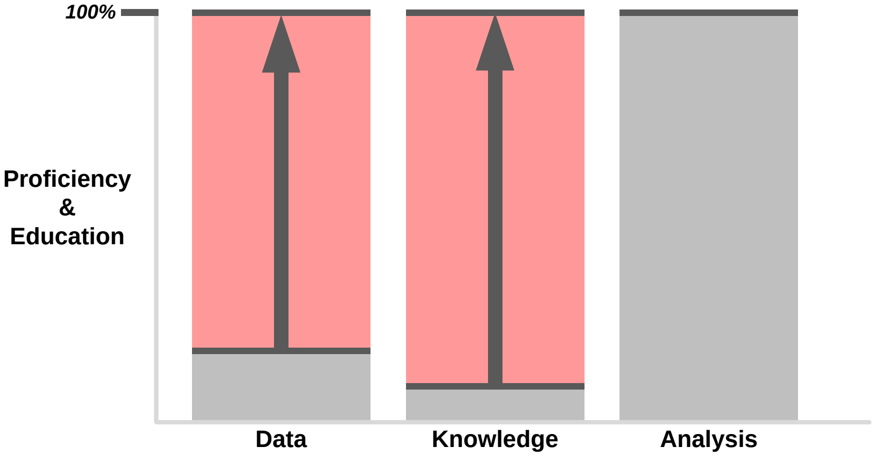


Figure 1.3 – Proficiency & Education of Aerospace Decision-Making

1.3 NEED FOR DATA & KNOWLEDGE ENGINEERING IN AEROSPACE FORECASTING

Aerospace development presents unique challenges for forecasting situations with highly coupled technical & non-technical considerations. The quality of disciplinary analysis is constantly improving, but there remains a need to advance multi-disciplinary & multi-domain capabilities towards a more complete integration concept. Adequately capturing market, environmental, social,

& political issues alongside technical considerations is essential to advance the process of forecasting the total system capability & benefit of aerospace vehicle systems. The driving problems in aerospace for the proceeding generation of engineers will all require significant investments of time, fiscal & human capital, and are therefore beholden to quality forecasting.

- The commercial use of *unmanned aerial systems* will require mission & vehicle design to incorporate complex systems in the hands of non-technical operators.
- Increased demand for higher frequency, lower cost *space launch capabilities* will necessitate novel vehicle & technology configurations, development processes, and concepts of operations.
- *Commercial subsonic transports* will require a revolutionary step-change in configuration or technology to improve operational capabilities over mature tube-wing iterations.
- *Supersonic & hypersonic point-to-point vehicles* have the potential to serve un-realized & high-demand missions, but require advanced technology development and compliance with ever-advancing operational regulations.

Leaders in the aerospace industry have realized the need to better capitalize their existing data & knowledge domain assets. Boeing[7], Lockheed Martin[8] and NASA[6], have established initiatives and designated divisions with the goal of retaining and disseminating organizational knowledge. NASA[9], the US Department of Defense[10], and professional organizations have created expansive internal repositories of legacy reports to better connect its stakeholders with their shared organizational memory. There is industry-wide support for the concept of treating data & knowledge as organizational assets – it is an initiative with immense potential benefits. However, connecting engineers & decision-makers with potential repositories data or knowledge during the development process is only a partial solution – the challenge remains to connect the correct data, information, and knowledge to the top-down decision-making process.

It is within these needs that there exists an opportunity to contribute to the current state-of-the-art capability in aerospace systems forecasting. The development of a practical prototype platform for identifying, collecting, retaining, organizing and utilizing information more effectively within an existing decision-making environment is a novel contribution to an otherwise under-represented & over-looked high-impact area within the development of aerospace systems. By detailing the needs of the modern forecasting environment whilst understanding the limitations of the current generation platforms, the development of a fundamentally innovative platform emerges as the primary goal. Creating a framework for aerospace systems forecasting organizations to improve their internal decision-making process, and therefore their organizational decisions, is the desired outcome.

1.4 FORMALIZATION OF DATA-ENGINEERING AS A REQUIRED DISCIPLINE

The integration of data into the decision-making process is already underway in several industries and organizations. The 'Big Data' movement seeks to take the exponentially growing amount of digital data produced by sensor-ified products and feed them directly into (sometimes completely automated) processes[11]. The growth of storage capacity, increase in computing power, and advancing sophistication of software to manipulate these datasets is approaching a situation where anything that can be measured *will* be measured; and stored indefinitely.

Conversely, the human interaction within this paradigm will still determine its value. The Chief Economic Officer at Google, a leading company in providing data-centric processes, speaks about the ability to interact with data as the most in demand trait of workers for the future generation of technical professionals.

> "The ability to take data—to be able to understand it, to process it, to extract value from it, to visualize it, to communicate it—that's going to be a hugely important skill in the next decades, not only at the professional level but even at the educational level for elementary school kids, for high school kids, for college kids." [12]

Unfortunately, this vision of an information-centric society with data as the primary fuel[14] does not align itself with current structure of education and proficiency for engineers. The use of data and knowledge, especially in the design forecasting fields, has not kept pace with advances in mindset & capability. It remains the norm for data to "*...get packed down and stored for normal design in textbooks, handbooks, professional journals, government publications, proprietary company reports, and the memories of individuals...*"[2] This requirement to codify, decipher and interpret data hinders the ability to adapt existing data to meet new information needs – especially when *"...much of the value of data will come from its secondary uses, its option value, not simply is primary use, as we're accustomed to think about it...*"[14]

Into this requirement to produce a more balanced data-knowledge-analytical mindset, the formalization of the discipline *Data-Engineering* is introduced as the primary focus of this dissertation research. *Data-Engineering* encompasses the holistic effort of adapting data, both originated and existing, into information for decision-making purposes. *Data-Engineering* is an applied science – the present research activity is focusing on its practical application within a professional decision-making environment. Any structured effort that improves the quality and / or effectiveness of creating, processing or re-purposing data towards insightful information is then in the realm of *Data-Engineering* (Figure 2.5). *Knowledge-Engineering*, the repurposing of existing experiential knowledge embedded in people and processes towards new decisions, is intimately connected to the study of *Data-Engineering*, but has been left as a separate research topic due to the extensive scope and different nature of both topics.

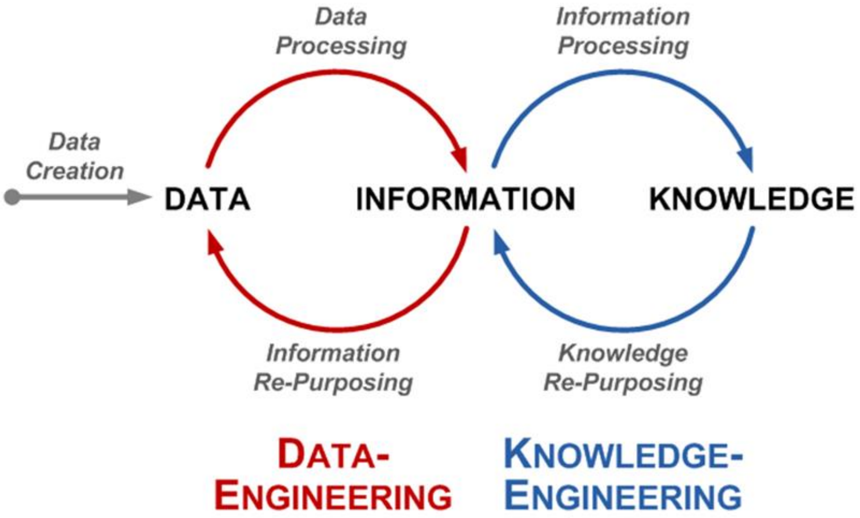


Figure 1.4 – Data-Information-Knowledge Cycle

An important aspect of *Data-Engineering* in the modern information society is that of repurposing information created for tangential uses. The cost, development time, and bureaucracy of aerospace research & development led to a situation where the cost of creating data often exceeds the cost of not knowing (e.g. the high cost and relatively low benefit of creating prototypes early in the development process of tactical military aircraft[13]), see Figure 1.5. This paradigm has also extended to more costly forms of data creation in favor of cheaper alternatives where the delta in data & information quality is negligible (i.e. wind tunnel closures in favor of widespread CFD simulations).

In order to adapt to changing decision-making requirements, meaningfully repurposing existing information and / or knowledge into new data is often the solution to produce informed decisions within limited budget and time constraints[6]. Creating data, even thru cheaper simulation alternatives, requires a time & human resource investment that is at odds with the realities of early design decision-making. Air & space vehicle systems have a significant history of research & development, most of which has been extensively documented in detailed technical reports, memorandums, drawings, professional articles and presentations. Leveraging this previously invested fiscal, human and time capital to gain insight into current and future problems is a key resource to the *Data Engineer*.

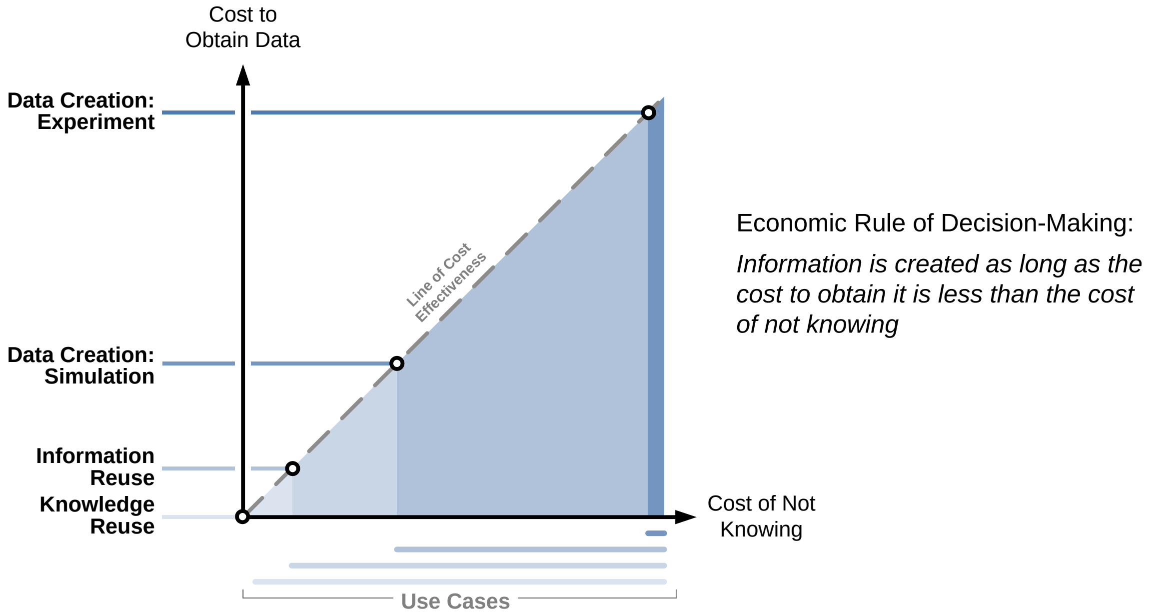
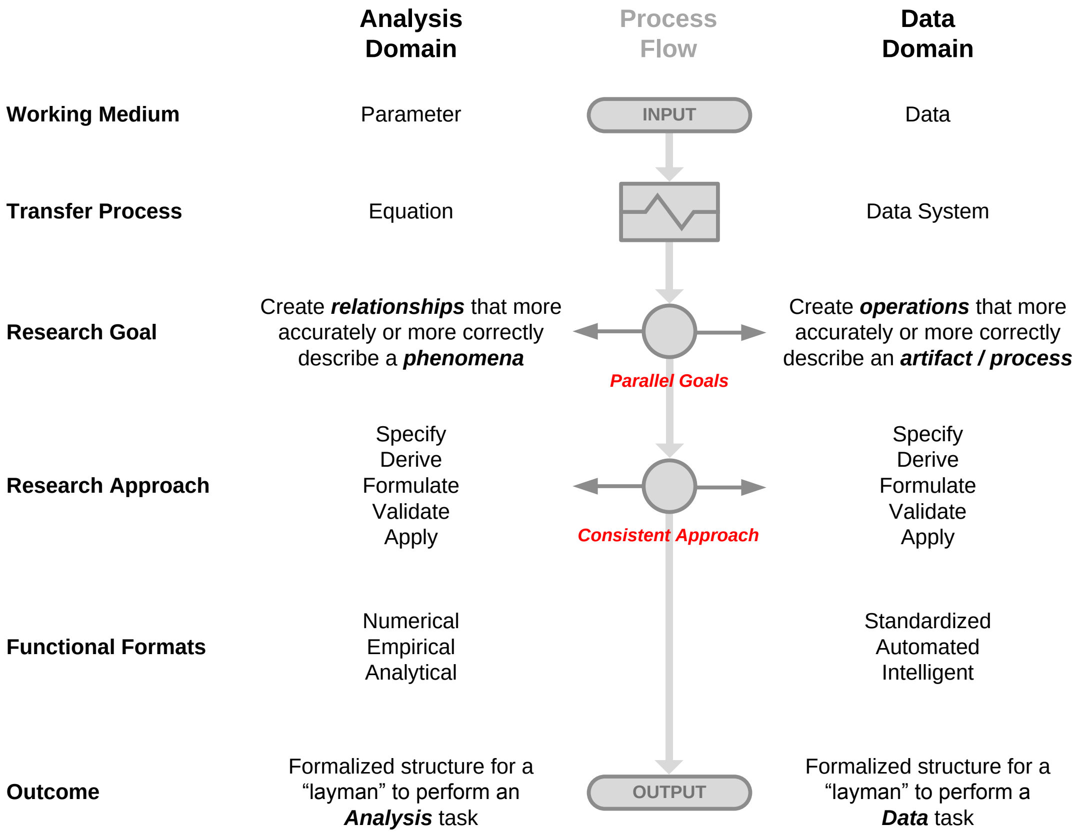


Figure 1.5 – Economic Rule of Decision-Making

Although off-the-shelf products and processes have been created for data processing (e.g. databases for data storage, search engines for data recall & graphing software for data visualization), the unique challenges of aerospace design forecasting requires processes (and therefore research) that incorporate the available datasets, existing analytical capabilities, and inherent decision-making practices. Cues and best practices can, and should, be taken from the fields of information technology, information storage, statistics and data visualization among others, but the final product must ultimately be adapted for use in a scientific engineering environment, integrated with analytical engineering toolsets and attached to the broader implications of aerospace product development. A firm foundation in both the engineering sciences and the higher-level decision-making process is required to arrive at a truly impactful research effort.

The *Data-Engineering* (DE) discipline can only be accepted as a stand-alone, but equal, aerospace discipline, in comparison to mature engineering sub-branches like multi-disciplinary optimization (MDO) or computer aided design (CAD), if research advances for DE are performed under the same scrutiny as traditional analytical research. *Data-Engineering* demands the same rigorous scientific process to develop and formalize foundational *DE* processes & tools, see Figure 1.6. Where the common goal of research in the analysis domain is to create an analysis technique (i.e. equation, empirical technique, experimental setup) that produces a repeatable, verifiable output, the data domain research analogue must also promote repeatable, verifiable results through a structured process. The final output should be backed by supporting literature, structured by hypothesis, and vetted by testing in a relevant environment.



	Analysis Domain	Process Flow	**Data Domain**
Working Medium	Parameter	INPUT	Data
Transfer Process	Equation		Data System
Research Goal	Create ***relationships*** that more accurately or more correctly describe a ***phenomena***	***Parallel Goals***	Create ***operations*** that more accurately or more correctly describe an ***artifact / process***
Research Approach	Specify Derive Formulate Validate Apply	***Consistent Approach***	Specify Derive Formulate Validate Apply
Functional Formats	Numerical Empirical Analytical		Standardized Automated Intelligent
Outcome	Formalized structure for a "layman" to perform an ***Analysis*** task	OUTPUT	Formalized structure for a "layman" to perform a ***Data*** task

Figure 1.6 – Analysis Domain vs Data Domain Research Analogue

The formalization of forecasting data practices also provides a significant opportunity for organizational memory. Within a decentralized system, when engineers and decision-makers retire, transfer divisions or leave an organization, the understanding of project data and its applicability to future design problems leaves with them. If, however, forecasting data is stored centrally and in a format that is transferable to future forecasting tasks, the draw-down in experience when personnel leaves is reduced or even eliminated. The capability of new engineers to produce quality forecasting deliverables is also greatly increased – the ability to directly tap into compounded organizational experience is tangible. Sufficient time to perform exhaustive cover-to-cover literature research is not allotted to the majority of design & forecasting tasks. Organizations can either continue to perform long-term, high-impact forecasting with incomplete and inconsistent information, or they can invest in their data processes to ensure yesterday's forecasting efforts are capitalized on and today's forecasting efforts are treated as the valuable organizational assets they truly are.

1.5 SUMMARY & OUTLINE

CHAPTER 1 Introduction
Discussion of the realities of aerospace design & forecasting, specifically the need for standardized processes and tools to support data-engineering.

CHAPTER 2 Introduction to Information & Information Systems
Review of decision-making standards and data standards, including historical evolution of the technologization of data ending with modern data platforms.

CHAPTER 3 Aerospace Data & Data Systems
Examination of existing best practices and research in aerospace data-engineering. Also addresses the common formats and mediums of aerospace data.

CHAPTER 4 Specification of an Aerospace Forecasting Data-Engineering System
Review of current approaches in aerospace design & forecasting. Definition of the feature and interface requirements of a functional aerospace data-engineering system.

CHAPTER 5 Development of an Aerospace Forecasting Data-Engineering System
Layout of data-engineering software system from a development perspective. Standardization and interface with parametric analysis processes emphasized.

CHAPTER 6 Validation & Calibration Case Study
Application of data-engineering system to a historical re-entry capsule design study where desired results are known a priori, including examination of system and engineer performance.

CHAPTER 7 Aerospace Design & Forecasting Case Studies
Three case with applications across a range of aerospace forecasting problems, utilizing different aspects of the developed data-engineering system, and intended for diverse decision-making goals.

CHAPTER 8 Summary & Conclusions
Parting thoughts on the state of aerospace design & forecasting, aerospace data & information science, and future potential of data-engineering systems.

Figure 1.7 – Research Outline

Aerospace design & forecasting is at a crossroads. Data-centric thought processes at the science, engineering, and strategic decision-making level are becoming widespread, and will only continue to grow as the availability of data expands and the tools with which to manipulate data mature. Professionals who cannot adapt to this reality are ill-equipped to contribute or are prime to be removed completely from the early design cycle decisions that truly shape the success or failure of air & space products.

The present dissertation research initiates the new scientific discipline by formalizing *Data-Engineering* with a focus on its implications in the design & forecasting of aerospace vehicle systems. The goal is to ultimately reduce uncertainty and risk during the aerospace product development process by first, improving the efficiency & effectiveness of the data domain as a stand-alone system and second, by systematically incorporating the data domain into the systems forecasting process. Expanding the desired scientific approach laid out above, the dissertation research is structured into the chapters presented in Figure 1.7.

REFERENCES

[1] Haggerty, A., McManus, H., and Murman, E., "Lean Engineering: Doing the Right Thing Right," 1st International Conference on Innovation and Integration in Aerospace Sciences, 2005.

[2] Vincenti, Walter, “What Engineers Know and How They Know It: Analytical Studies from Aeronautical History,” Johns Hopkins University Press, 1990.

[3] Bergsma, B., “Lean Beyond Manufacturing, Leveraging the Principles into Innovation and Design,” Raytheon, 2010.

[4] Ferguson, E., "Engineering and the Mind's Eye," The MIT Press, ISBN 0-262-06147-3, 1992.

[5] Bernstein, J., "Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices," Massachusetts Institute of Technology, 1998.

[6] Pinelli, T., Barclay, R., Kennedy, J., and Bishop, A., "Knowledge Diffusion in the U.S. Aerospace Industry: Part A," Ablex Publishing Corporation, ISBN 1-56750-225-3, 1997.

[7] Coogan, J., "Boeing Knowledge Management," Boeing Management Company, 2008.

[8] Anon., "Intelligent Information Factory: Knowledge Management," Lockheed Martin, 2003.

[9] NASA Scientific and Technical Information (STI) Program: About. 2/28/2014
URL: http://www.sti.nasa.gov/about-us/#.UxIwQPldW-M

[10] Pitts, S., and Rike, J., "Defense Technical Information Center Overview," U.S. Department of Defense, 2008.

[11] Manyika, J., Chui, M., Brown, B., Bughin, J., Dobbs, R., Roxburgh, C., and Hung Byers, A., “Big data: The next frontier for innovation, competition, and productivity,” McKinsey & Company, 2011.

[12] Varian, H., "Hal Varian on how the Web challenges managers," McKinsey, 2009.

[13] Anon., “Report of the Defense Science Board Task Force on Aircraft Assessment,” U.S. Office of the Undersecretary of Defense for Acquisition, 1993.

[14] Mayer-Schoenberger, V., and Cukier, K., “Big Data: A Revolution That Will Transform How We Live, Work and Think,” Houghton Mifflin Harcourt, ISBN 978-0-544-00269-2, 2013.

CHAPTER 2

INTRODUCTION TO INFORMATION & INFORMATION SYSTEMS

CHAPTER 1 Introduction
Discussion of the realities of aerospace design & forecasting, specifically the need for standardized processes and tools to support data-engineering.

CHAPTER 2 Introduction to Information & Information Systems
Review of decision-making standards and data standards, including historical evolution of the technologization of data ending with modern data platforms.

CHAPTER 3 Aerospace Data & Data Systems
Examination of existing best practices and research in aerospace data-engineering. Also addresses the common formats and mediums of aerospace data.

CHAPTER 4 Specification of an Aerospace Forecasting Data-Engineering System
Review of current approaches in aerospace design & forecasting. Definition of the feature and interface requirements of a functional aerospace data-engineering system.

CHAPTER 5 Development of an Aerospace Forecasting Data-Engineering System
Layout of data-engineering software system from a development perspective. Standardization and interface with parametric analysis processes emphasized.

CHAPTER 6 Validation & Calibration Case Study
Application of data-engineering system to a historical re-entry capsule design study where desired results are known a priori, including examination of system and engineer performance.

CHAPTER 7 Aerospace Design & Forecasting Case Studies
Three case with applications across a range of aerospace forecasting problems, utilizing different aspects of the developed data-engineering system, and intended for diverse decision-making goals.

CHAPTER 8 Summary & Conclusions
Parting thoughts on the state of aerospace design & forecasting, aerospace data & information science, and future potential of data-engineering systems.

2.1 INTRODUCTION TO THE DECISION-MAKING PROCESS

Decision-making is the process of choosing options. A rational agent (whether a single person, a structured organization, or artificial intelligent entity) must, by definition of being rational[15], assess the outcomes of possible options and then choose the option that provides the greatest utility[16]. The components of this flow – i.e. defining the situation and possible options, determining utility, selection of superior option – are largely dependent of the inherent process by which the decision is made. At the individual level this process is most often internalized, though research has shown that externalizing major decision has benefits on the outcome[17]. However, as decisions scale towards larger impacts on time, human & fiscal capital, the decision-making process is often more formalized, requiring a structured external interchange between hierarchies of individuals, see Table 2.1. As humanity advances towards artificially intelligent agents, the decision-making process becomes only an initial framework for judging and choosing options – the judgment and execution of decisions then becomes an embedded feature of the agent[18].

Table 2.1 – Decision-Making Approach Variation across Agents

	Individual	*Organization*	*Artificial Intelligence*
Number of Agents	One	Many	Infinite
Process Transparency	Internal	External	Embedded

Dissecting the decision-making process from the organizational perspective, especially those organizations with direct influence on aerospace design & forecasting decisions, facilitates a better understanding of the importance information plays in decision-making – an understanding that serves as a foundational perspective for the proceeding research.

2.1.1 Military Decision-Making Process

Tactical & strategic decisions made by militaries have historically been performed using a rigorous process. As far back as Sun Tzu[19] in the 5th century BC and Genghis Khan[20] in the 12th century AD, a structure has been put in place to gather information, assess situations and act on the most beneficial option. In these military decision-making processes, hierarchies of advisors are the gatekeepers of their organizational information. Data flows from the field through the gatekeeper up to the decision-maker who then passes back down orders through the gatekeeper for dissemination to subordinates.

This concept was materialized further in the 18th century during the French Revolution[21], when Napoleon employed a *Chief of Staff* and direct supporting staff members to be directly responsible for the flow of information governing aspects of the state. The standardization of a centralized agent for information receipt and retrieval provided Napoleon with efficient access to information required and the avenues with which to execute his orders in intelligence, logistics and strategic planning[22].

German militaries followed suit starting in this same time period[23], culminating in World War I further standardized this command structure by introducing set guidelines for the protocol of military staff members when making strategic & tactical decisions[24]. This process includes distinct windows to interchange with both superior and subordinate personnel, description of alternatives and forecasted analysis of outcomes. Along with the increased complexity, the demands on the staff personnel also increased – the German *General Staff* became a group of professional military strategists[24].

This concept of formal decision-making steps implemented by a professional officer corps has been evolved to its current state, most notably exhibited by the US military, see Table 2.2. The process of analyzing Courses of Action (COAs) has been further distilled to reflect the expansion of war-gaming and conflict simulation techniques. The governing US Army document, FM-105[25], prescribes what tasks (and subtasks) are required of the military decision-maker from *receipt* through *execution* – a complete formalization of the decision-making process, including a discrete section solely dedicated to *Information Management*.

Table 2.2 – Military Decision-Making Process Steps[25]

Decision-Making Step	*Description*
Receipt of Mission	Passing of mission requirements from superior to subordinate
Mission Analysis	Determine assets & constraints and provide an initial assessment
COA Development	Identify possible options and their requirements
COA Comparison	Simulation of identified COAs and their likely outcomes with associated risk and future utility
COA Approval	Communication of chosen COA to superior
Orders Production	Dispersion of command to subordinates
Rehearsal	Procedural walk-through of planned COA
Execution	Carrying out planned COA
Assessment	Comparison of projected and actual outcomes, lessons learned

2.1.2 Engineering Decision-Making Process

Engineering design has also evolved its own decision-making procedures although, expectedly, with a more distinct focus on the analysis of the proposed product / process. Top-level decisions made with regards to integrated disciplines (i.e. those most in line with the above strategic & tactical military decisions) fall under the concentration of systems engineering, which seeks to understand the interactions design decisions have from both a technical & non-technical perspective[27]. This often requires a determination of a multi-disciplinary definition of what value the product should offer the decision stakeholders – characterized as the product's utility[26]. The system engineer's function then is to design a product (modelled as a system of components) that provides the greatest utility. It is important to note that this approach is intended to provide a framework for engineering of a product in response to a firm set of assumptions & requirements – the initial derivation of requirements and framing of potential solution concepts is not addressed, and therefore fails to provide complete support for forecasting-focused tasks at the beginning of the product life-cycle.

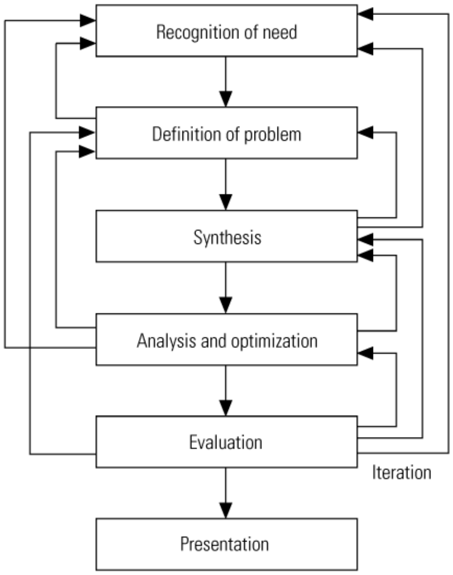


Figure 2.1 – Engineering Design / Decision-Making Process[28]

Top-level engineering design decisions are performed with an inherent level of uncertainty both from the input assumptions as well as the model itself (i.e. "*…essentially, all models are wrong, but some are useful…*"[29]). At the beginning of a product's life cycle, the ability to accurately model the utility of a product at its end-state is difficult, if not impossible, especially when designing products with long lead times and / or products with utility heavily tied to outside influences (e.g. competition, commodities, regulations, politics, technology evolution, etc.). Under these circumstances, the concept of set-based design has taken hold – definitive design choices are not made until late in the design cycle, instead keeping multiple parallel competing designs under development until the requirements and constraints are more know-able[30]. At discrete points in the decision cycle, designs choices are narrowed to reflect the most current information and definition of utility. This concept has been applied theoretically to the military decision-making process (at the tactical level) in the form of decision-point tactics[31], but it is yet to be established in the formal doctrine.

2.1.3 Representative Decision-Making Process

Although both the engineering and military approaches to decision-making share fundamental tenets, the nuances of each lack the holistic approach required to take an integrated socio-technical problem from start to finish: the military approach lacks substance in the aspects of systems modelling & analysis while the engineering framework lacks the broad prospective of how decision-makers are influenced by information and the protocols in place for acting on that information in the face of risk & uncertainty. The flow of information from executive decision-makers to program managers to chief engineers to disciplinary specialists must be captured & addressed.

The flow-chart presented below with Figure 2.2 represents the philosophical high points of the military decision-making process, while stripping some of the procedural aspects required of a war-fighting process. The result is a general process flow, starting with clear identification of the decision-making problem statement and ending with the selection of options based on created or recalled information. By connecting the driving parameters within a holistic view, the flow of information from the decision-maker (e.g. executive) to the information creator (e.g. design forecasting engineer) and back to the decision-maker can take place within a communally-held framework.

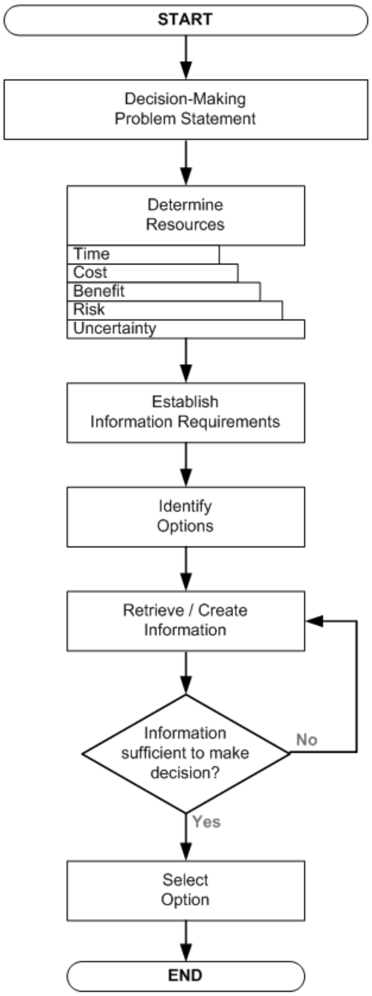


Figure 2.2 – Decision-Making Process Flow Diagram

2.1.4 *Data-Information-Knowledge Distinction*

Within the decision-making process, the retrieval and / or creation of information is identified as the key segment where the engineering discipline contribute, see Figure 2.3, and therefore warrants further exploration. The concept of information must be made separate from the linked terms of data & knowledge for this discussion. Each entity has its own unique attributes that warrants a different treatment for the current research purposes.

As introduced previously, there are only three possible sources of information for decision-making[32]: *Memory*, *Experience* and *Reasoning* each correlating to their organizational counterparts: *Data*, *Knowledge* and *Analysis* domains (respectively). Even with societal advances, the integrated nature of organizational decision-making is still trailing behind the efficiency with which the human is able to process all three domains together to produce actionable decision-making.

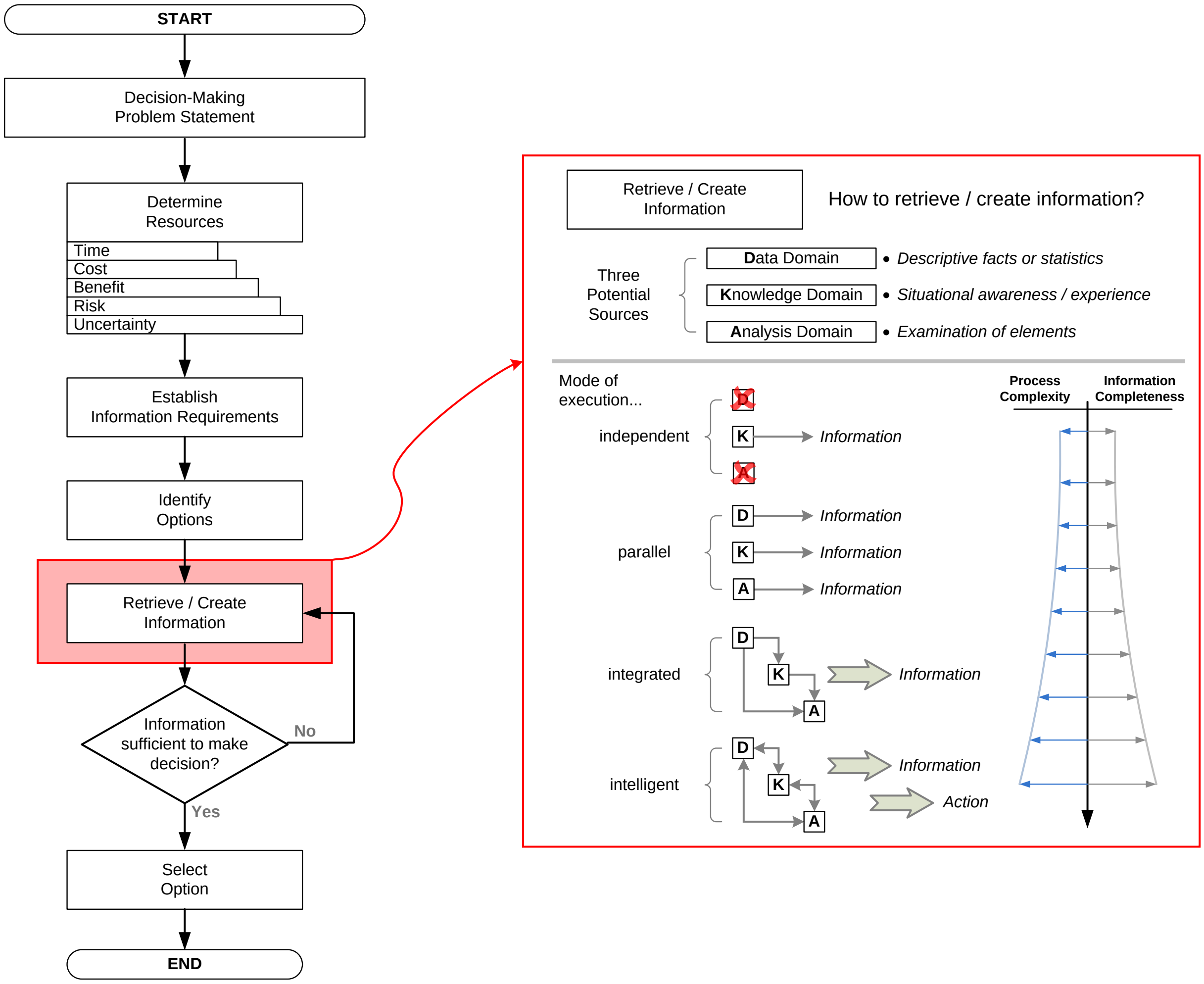


Figure 2.3 – Information Retrieval / Creation Process within Decision-Making

The organizational decision-making process is often clunky, ad-hoc, subject to non-rational constraints and non-transparent. Advancing organizational processes towards an integrated *brain-analogue* or *artificial intelligence* (AI), complete with functioning central nervous systems that is able to tap any and all capabilities of the (organizational) body is the ultimate goal. Integrating the *Data*, *Knowledge* and *Analysis* domains together requires an increased complexity and highly integrated processes, but with the positive outcome of more complete information (i.e. information that provides more actionable insight and, ultimately, more efficient & correct decision-making).

The working distinction between data, information and knowledge here centers around the point at which at a decision is made and how that entity is related to the decision; that is, a single entity can be data, information, and knowledge at the same time when taken from different decision-making perspectives or can transition from data to information to knowledge if taken from a static decision perspective (Figure 2.4).

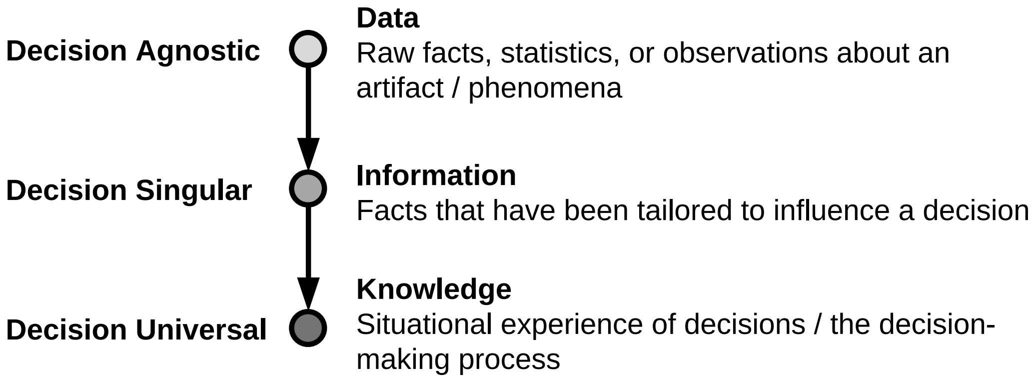


Figure 2.4 – Data-Information-Knowledge Decision Scope

Referring to Figure 2.4, at the beginning of the spectrum, *data* is an entity that is not aware of the existence of any – a solution in search of a problem. The source of data or the process by which it is collected does not inherently affect its status as data – though this will indeed affect the data quality (see Section 2.3 – data remains data as long as it is a fact / observation and it is not being currently applied to a decision.

Information is the central figure to the decision-making process. Information has been selected as information only because it is relevant to the decision to be made. This decision-specific nature makes information singular in nature – the facts that make up that portion of information has a relationship with the current decision that will most likely never be exactly replicated (ignoring redundant situations). For this reason, the power and weight of information will vary between decisions, even as it relates to the same base entity.

Knowledge is the embodiment of the decision-making process, answering the question, ‘what *data* comprised what *information* influencing the decision in what way?’ This includes the ability to apply a retrospective lens to the actual outcome of the decision compared to the forecasted outcome of the decision-making process. Knowledge is not a static end-of-the-line however – it is applied in a Bayesian (i.e. updating of prior approach) format that directly influences the way future decisions are made.

It should be clear from the above descriptions that although *data*, *information* and *knowledge* have distinct roles, they are also part of a transitive continuum. For this reason, any treatment of the subject must be able to handle fluidity in entities while at the same time providing a structure to the specific role in the decision-making process. Two disciplines unique to this paradigm have been adopted:

Data-Engineering is the discipline focusing on the holistic interchange between data & information including the creation of new data, processing of data into information for a decision-specific purpose, and the repurposing of the same information back into generalized datasets that can be used for future decisions. *Data-Engineering*, and all the requisite skills required, are the prime focus of this dissertation research.

Similarly, the *Knowledge-Engineering* discipline is the study of the processing of information applied towards a decision into broad knowledge guidelines and heuristics that can be repurposed towards influencing future decisions. Concurrent research within the author’s organization (AVD Laboratory) is taking place in the *Knowledge-Engineering* field. References to knowledge-driven processes are discussed at points in this research, but a more complete treatment is certainly required and presented elsewhere.

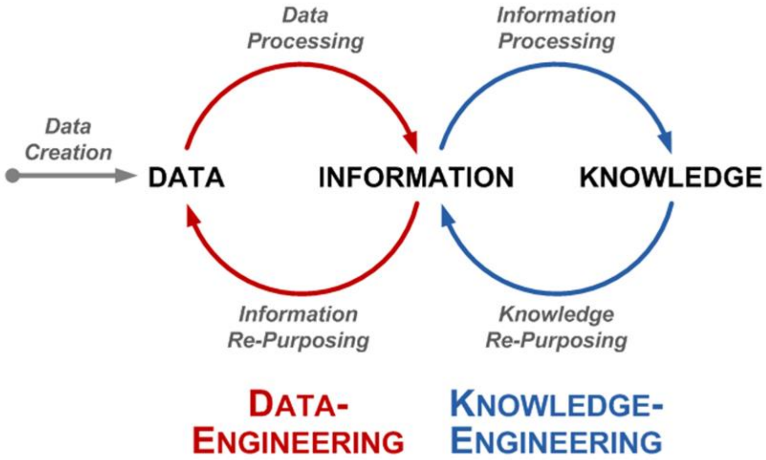


Figure 2.5 – Data-Information-Knowledge Cycle

2.2 CLASSIFICATION OF DATA SYSTEMS

In order to better understand the next-generation uses & requirements for *Data-Engineering Systems* (DES), it is beneficial to formally decompose data and its associated terminology. A framework of formalized data qualities and data processing procedures are drawn here and will serve as the template for further research.

2.2.1 Components of Data

Data, especially in today's digitally-driven world, has developed distinct components that make up the more abstract whole[33]. Semantically, it is difficult to remove the definition of the components in a theoretical sense from the explicit deconstruction used in data processing systems. Data was data before it came into contact with formal data systems, implying further deconstruction is only a matter of convenience & clarity for ease-of-use within prescribed systems and not an inherent property.

Although different data systems take different approaches to handling & processing tasks that decompose data into slightly different components, data is generally made up of *fields*, *values*, and *attributes*, all describing an *object*, see Table 2.3. Within modern data terminology, *meta-data* has also been introduced to identify any other data that describes more about the artifact / process / idea or about the source of the data[34].

Table 2.3 – Components of Data (adapted from references [33] & [34])

Component	*Description*
Object	artifact, process, or idea of interest
Field	a defined characteristic of the Object
Value	observation (fact) describing the Field characteristic
Attributes	tangential Field-Value pairs that clarify other characteristics of the Object
Meta-Data	attributes that specify the source, format, or state of the data

As a verbal example, consider the factual statement (datum):

"*The wingspan of the Boeing 747-400 is 211.4 ft.*" [35]

Deconstructing the data, the data *value* is '211.4' – everything else is further required to understand the context and meaning of the value data. The *field*, the property of the artifact or process that the value data is describing, is "wingspan". *Attributes*, pieces of data with their own field and value, further detail the data (e.g. the attribute field 'units' has an attribute value of 'ft' and the attribute field 'object' has an attribute value of 'Boeing 747-400'). Further attributes provide a more detailed breakdown of the object by its manufacturer (Boeing), the aircraft series (747), and the aircraft model (-400). Then, *meta-data* includes the data type (number) and the source of the data (Boeing 747 website, reference [35]). The final decomposition is show in Table 2.4 below.

Table 2.4 – Components of Data, Example Breakdown

Component	*Property*
Value	211.4
Field	Wingspan
Units	ft
Object	Boeing 747-400

2.2.2 Steps of Data Processing

It has so far been defined that *data* and *information* exist along a shared continuum, and that there exists some process to convert the former into the latter in order to make a decision. It is a requirement that the process by which *data* transforms into *information* should be a generic, universal framework – these concepts have been applied, although inherently, long before the current research effort. The process steps should, however, align themselves with current landscape of data & information sciences and the software platforms that support modern data tasks.

Academia offers one potential source of guidance towards the steps of data processing. Graduate programs in data science, information science, informatics, and analytics have representative courses that distinguish unique tasks within the data-information realm, see Table 2.5: database design & maintenance courses to deal with data storage & organization, data retrieval topics to discuss adaptive search techniques, statistics, analytics & machine learning courses focus on transforming data into insights or actionable criteria, and visualization courses teach the representation of data to convey a specific piece of information or set of information.

The functionality of ubiquitous modern data software platforms also provides a common point to derive generic data processing steps. These platforms have emerged as independent entities in response to siloed professional specialties and data tasks. Databases provide capability to store & organize data, see Section 2.5.1.2. Search engines provide operations to recall data, see Section 2.5.1.3. Statistics software platforms offer data analysis and graphing capabilities, see Section 2.5.1.4.

Table 2.5 – Representative Data & Information Science Degree Programs

Institution	*Berkley*	*USC*	*ASU*	*Columbia*	*DePaul*	*Indiana Bloomington*	*North Carolina State*	*Northwestern*	*Cincinnati*	*Univ. of San Francisco*
Program	*Data Science M.S.*	*Informatics M.S.*	*Business Analytics M.S.*	*Data Science Certificate*	*Predictive Analytics*	*Data Science M.S.*	*Analytics M.S.*	*Analytics M.S.*	*Business Analytics M.S.*	*Analytics M.S.*
Department	*Information*	*Engineering*	*Business*	*Data Science*	*Computing & Digital Media*	*Informatics & Computing*	*Advanced Analytics*	*Engineering & Applied Sciences*	*Business*	*Management*
Source	*datascience.berkley.edu*	*informatics.usc.edu*	*wpcarey.asu.edu*	*datascience.columbia.edu*	*cdm.depaul.edu*	*soic.indiana.edu*	*analytics.ncsu.edu*	*analytics.northwestern.edu*	*business.uc.edu*	*usfca.edu/analytics*
Courses	**Storing & Retrieving Data**	**Information Retrieval**	**Data Mining**	**Probability & Statistics**	**Intelligent Information Retrieval**	**Information Retrieval**	**Data Access & Management**	**Databases & Information Retrieval**	**Data Management**	**Data Acquisition**
	Exploring & Analyzing Data	**Data Management**	**Applied Regression Models**	**Machine Learning**	**Data Analysis & Regression**	**Data Curation**	**Relational Databases & Data Warehouses**	**Data Mining**	**Data Mining**	**Relational Databases**
	Applied Machine Learning	**Data Mining**	**Decision Modeling**	**Data Analysis & Visualization**	**Mining Big Data**	**Data Mining**	**Data Querying & Reporting**	**Analytics for Big Data**	**Forecasting & Time Series Methods**	**Machine Learning**
	Visualizing & Communicating Data	**Machine Learning**			**Data Visualization**	**Information Visualization**	**Data Mining**	**Data Visualization**	**Multivariate Statistical Methods**	**Multivariate Statistical Analysis**
		User Interface Design			**Information Visualization & Infographics**		**Data Visualization**		**Data Visualization**	**Data Visualization**

By cross-comparing the two approaches, several unique steps in data processing emerge. These steps represent the required tasks to take data from a raw material & transform it into actionable information, see Figure 2.6. Therefore, further discussion of *Data-Engineering* and *Data-Engineering Systems* should be framed around this same communal tasking process. A description of each task and its representative function is outlined below.

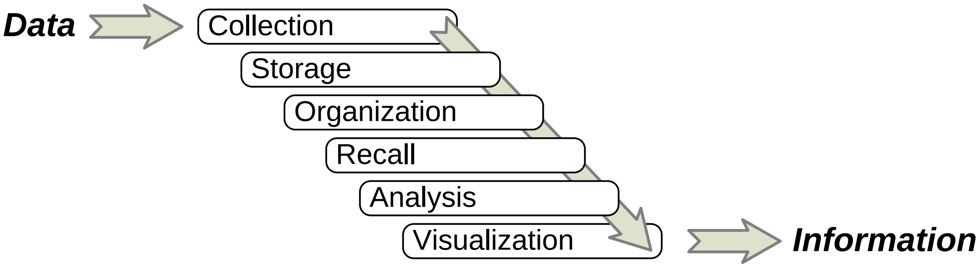


Figure 2.6 – Data Processing Steps for Transforming into Information

2.2.2.1 Collection

Collection is the first step of processing data and is the act of transferring data from its native source. In some instances, *collection* may be as simple as referring to a single source that houses data in well-formatted fashion or it may require compiling data from several sources to piece together a cohesive data-set[36]. Extracting implicit or embedded data in graphs, figures and drawings plays an important role in the functional use of data for aerospace forecasting purposes and will be discussed in great detail in Chapter 5.

2.2.2.2 Storage

Once data is collected, it must be *stored* for further use. The medium in which data is stored often drives its cost, longevity, transferability & accessibility (i.e. the evolution from cave paintings to papyrus scrolls to books to digital files, see Section 2.4). Although the capacity of storage formats drove physical constraints in the past (i.e. libraries to house books), the growth of networked digital storage offers an amorphous, near-limitless capacity, which brings its own unique challenges[37].

2.2.2.3 Organization

Organization is the step of filtering, sorting, & indexing data to better define the contents of data for further use. This can include creating taxonomies of data so they are categorized along topic or functionality (i.e. materials data separated from geometry data separated from aerodynamics data), as well as utilizing meta-data to define tangential & tertiary data connections[38]. In a database-driven paradigm, this involves creating an entity-relationship model[39] – a top-level design specification that shows, within a unified database, where data fields are stored, what objects they describe, and how they are related to other data.

2.2.2.4 Recall

Recall is the process of pulling the correct piece of data for the correct situation. In an ad-hoc data handling system, the steps from *collection* to *recall* are often comingled – data does not exist before it is specifically needed and is therefore used as soon as it is found. Conversely, *recall* in a structured system consists of finding data that has already been stored through a structured querying process[40]. This process often entails connecting the current data needs with the existing stored data through meta-data association and adaptive search algorithms, see Section 2.5.1.3.

2.2.2.5 Analysis

Data analysis involves using statistics and mathematical operations to better understand a dataset. This involves parsing, aggregating and transforming existing datasets (i.e. creating regression trends, correlating datasets, or predictive analysis) to gain more insight than the original dataset could provide[41]. As the capacity for data storage & computational power has grown, analytics software platforms (e.g. R, SAS, SPSS – see Section 2.5.1.4) have allowed the mathematical foundations rooted in statistics to be applied to massive datasets. This availability of data, the platforms with which to perform data analysis, and the computational power to combine the two in an actionable timeframe are the basis of the *Big Data* movement, discussed below in Section 2.4.4.4.

2.2.2.6 Visualization

Visualization is the process of taking data and communicating it in a visual format to convey information more easily & more efficiently[42]. This can include representations in figures, graphs, tables, and any combination of the above – each *visualization* contains its own specialty for communicating different types of data-sets and is often tailored towards the exact needs & expectations of the intended audience. *Infographics* have evolved one step further towards combining the data visualization task along with elements of graphic design and journalism to communicate information.

2.3 UNDERSTANDING DATA-ENGINEERING PERFORMANCE

The goal, then, of *Data*-Engineering is to perform the preceding data tasks in a standardized & efficient manner so that the resultant information produced is more consistently productive to decision-making, see Figure 2.7. However, in order to realize these concepts of *standardization*, *efficiency* & *productivity*, quantifiable metrics with which to measure these *Data-Engineering* processes are required.

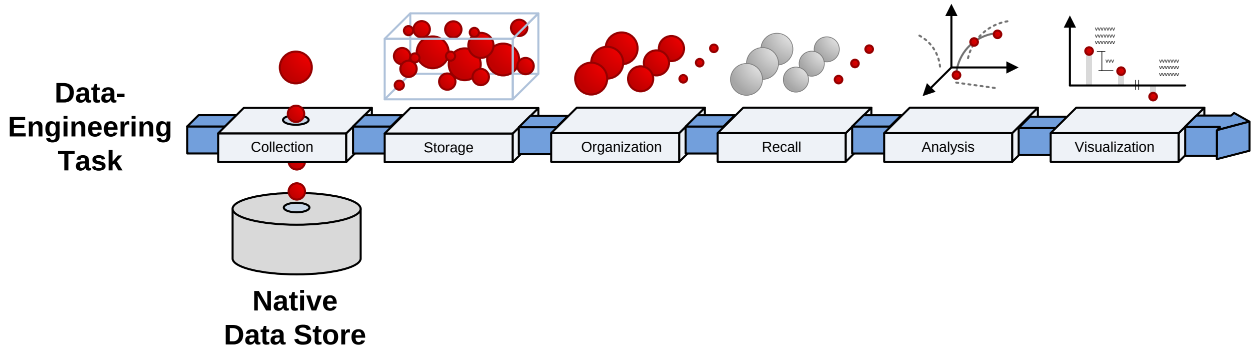


Figure 2.7 – Data-Engineering Process Flow

While metrics for data tasks have been developed in previous research (discussed in the proceeding sections) the disintegrated execution of data tasks (i.e. library sciences collect & organize meta data, information technology stores & recalls data, statisticians analyze data) has led to metrics applicable only with their defined scope & specialty. A consolidated effort is required to view metrics across the entire *Data-Engineering* spectrum and, in some instances, must be newly introduced to account of inter-task communication (e.g. the result of data collection quality on the ability to analyze & visualize data is not addressed in traditional data metrics, but is a required condition of *Data-Engineering* process metrics).

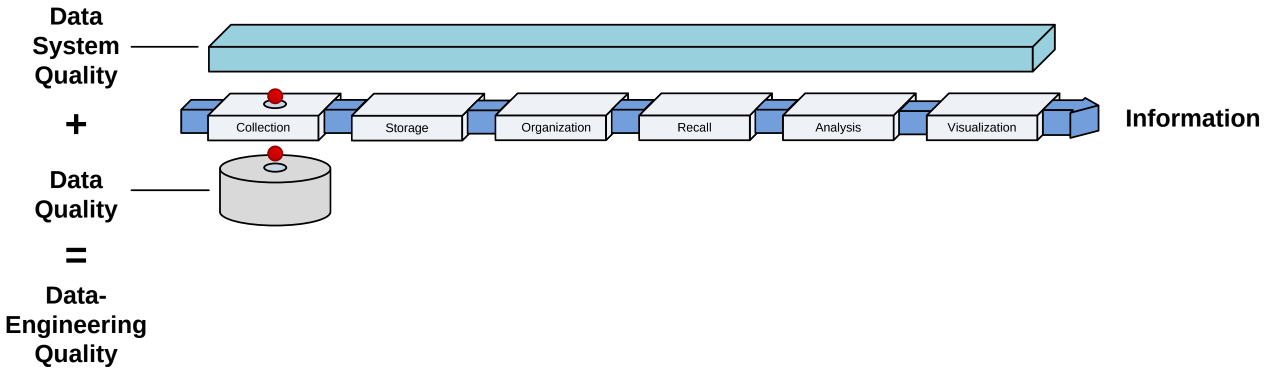


Figure 2.8 – Data-Engineering Quality

2.3.1 Dimensionality of Performance Metrics

Just as physics-based performance metrics start with fundamental building block dimensions to derive more advanced dimensions, the same concept has been applied to data-based performance metrics. A digitally-centric viewpoint has been take with these dimensions, see Table 2.6, to reflect the realities of modern data (i.e. in other eras of data, a more appropriate dimension of data storage capacity may have been word count, page count or physical weight, but the byte has become the de facto digital data storage dimension). Where possible, conversions between physical and digital media have been addressed and documented in further *Data-Engineering* analysis.

Table 2.6 – Primary Data-Engineering Dimensions

Concept	*Dimension*	*Description*	*Foundational Field*
Breadth	Record*	data elements that describe an object[43]	Database Management
Depth	Field*	descriptive attribute of an object[43]	Database Management
Storage	GB	a unit of data equal to one billion bytes	Information Technology
Speed	Second	base unit of time	-
Cost	$	fiscal investment required to perform a task	-
Constraints	Degrees of Freedom	independent elements that can be varied[44]	Statistics

*database specific, see Section 2.5 for further explanation

2.3.2 Metrics of Data Quality

The performance of the overall Data-Engineering task starts with the quality of the incoming 'raw' resource, that is, how is the quality an existing dataset assessed. Taking the working definition of data to be a collection of observations about object(s) or process(es), three fundamental metrics of data quality have been identified.

Table 2.7 – Data Quality Metrics

Metric	*Description*	*Unit*
Scope	Quantity of objects being described	Records
Density	Quantity of observations about each object	GB / Record
Meta-Data Ratio	Ratio of descriptive data to value data	-

2.3.2.1 Scope

The scope of a dataset determines the overall breadth in objects of which the dataset conveys. The more objects a dataset contains, the larger the scope of that dataset[45]. By itself, the data quality metric of scope alone provides insight into the number of way a dataset may be applied (i.e. an encyclopedia with entries for 100,000 objects has a larger scope, and thus a wider range of applicability, than a detailed weight breakdown of a Boing 747).

2.3.2.2 Density

As opposed to the breadth described by the scope, the density of a dataset determines the depth of its observations (i.e. how many observations are recorded pertaining to each object (record) in the dataset). Depth as a quality metric is used to determine the ability of a dataset to be applied for alternative approaches.

2.3.2.3 Meta-Data Ratio

Meta-Data (described above) characterizes the amount of data available to frame the core dataset – this not only pertains to a description of what the data is, but how it was created, what its intended use is, and how it has been applied[34]. The *Meta-Data Ratio* quality metric, then, quantifies the amount of context put around a dataset – the higher the meta-data ratio, the more likely it is that the dataset will be correctly applied towards new data uses[46].

2.3.2.4 Other Data Quality Metrics

In addition to the above metrics, others have been previously defined but are either difficult to quantity and / or do not match the working paradigm of *Data-Engineering*. This distinction does not mean these metrics do not play a role in whether a dataset is useful – only that they cannot be standardized to a point of objective usability.

Believability, discussed by Wang et al[47], attempts to determine how much weight should be put behind the data within a dataset based on some scale of believability. If the user knows, trusts, and believes in a data source, then that data source is given a subjective amount of weighting over a previously unknown data source (or one with a dubious background). While this construct certainly falls within the norms of actual data usage, the heuristic nature lacks the objectivity desired for measuring *DES* performance.

Consistency can refer to multiple interpretations: As discussed by Askham et al[48], consistency ensures whether the representation of an object is the same across different instances within the dataset. In a parallel vein, consistency could be defined as the commonality amongst data dimensions within a dataset[43], usage of the same field names to describe object properties[49], or standardized attribute naming conventions[33]. In a purely mechanical interpretation, consistency is taken as a check of data value formatting adhering to their specified schema.

Readability of a data source would refer to its ability to express data in a format that is easily extracted. Data found in tables, graphs & figures are more easily transferred to external platforms. Relations stated with explicit equations increase the usability in analysis procedures, as opposed to implicitly visualized relationships.

2.3.3 Metrics of Data Systems

Throughout the survey of status quo data (non-aerospace) data processing, the distinct steps to the process of transforming data into information were used as primitive guide into the strengths & weaknesses of each system. From Collection through Visualization, these steps identify broad tasks that, in practice, may even be performed by different personnel and / or different platforms. In reference to these steps, it is desired to have a more systemic breakdown so that platforms may be ranked against each other and ideal traits can be identified.

The metrics have naturally aligned themselves along the functional groupings of data systems (Figure 2.9). The holistic Data-Engineering performance will draw from these previously-defined fields where possible and where the intent of the approaches intersects.

Broad *data quality* metrics are discussed in database management[50], *Big Data*[51] & information science communities[52]. Within their discussion, data is almost exclusively an entity internal to the organization (i.e. the data is created internally, or the organization has direct input into the creation process) – the concept of gauging the quality of externally-created data is left unaddressed. Additionally, data handling often ends when the data is prepared for further business processes – the end-use requirements are incorporated into the *data quality* discussion, but functional execution is omitted.

Information retrieval metrics have been discussed by significantly by the search engine community[53]. There are standardized tests which are executed on a new search algorithm to quantify its performance. There are international competitions where teams are given a fixed dataset and a defined data-task; the results of their recall-specialized data system are then judged on (pseudo) objective metrics[54].

In contrast, the metrics for *DES* must be grounded in common attributes of non-aerospace data systems (below), current research in data systems & data processing, and the author's experience as user of data systems. All presented metrics have been outlined with a qualitative end-metric (the ability of data within the data system to serve its purpose) central to all discussion.

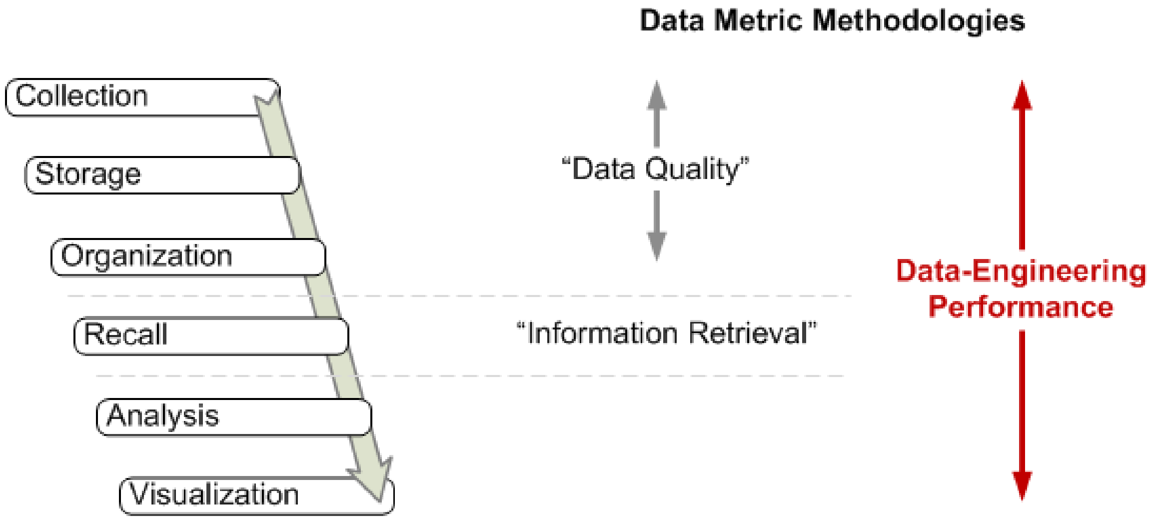


Figure 2.9 – Previous Methodologies to Quantify Data & Data Systems

2.3.4 *Collection, Storage & Organization Metrics*

Data collection entails the pulling of one or more pieces of data from one or more sources into a new information-production process. Therefore, the metrics for collection must convey the system's capability to successfully translate data from its native source into it's the new construct.

Table 2.8 – Data System Collection, Storage & Organization Quality Metrics

Metric	*Description*	*Unit*
Completeness	Percent of data-set filled (not null)	%
Capacity	Maximum size of stored data	GB
Accessibility	Ratio of write users to read users	%
Adaptability	Time required to alter dataset	sec / GB

2.3.4.1 Completeness

Completeness is identified as the lack of blank (unfilled) data element[48]. A data system with low *completeness* (i.e. sparsely filled) is either poorly suited for the data requirements of the current information task or does not effectively collect data from native sources.

2.3.4.2 Capacity

The *capacity* of a data system represents the upper limit on the amount of data that can possibly be stored – this is a strong function of the level of technologization inherent in the data system.

2.3.4.3 Accessibility

Accessibility seeks to distinguish between single-point, slowly adapting data systems to multi-user collaborative environments[55]. Those data-systems that have democratized their data collection efforts (e.g. organization-internal wiki portals) have a higher accessibility metric as opposed to those data-systems following the traditional editorialize-publish-revise cycle of textbooks & reference books – a high value of accessibility conveys a data-system that is more able to reflect the full data picture (i.e. the wisdom of crowds).

2.3.4.4 Adaptability

Adaptability represents the time required of the data practitioner to change the data collection, storage or organization schema to reflect new requirements in data. This could include addition of a new field, different formatting of the data file or incorporation of a new topic within an existing dataset. Data-systems with high adaptability are open architectures that treat data generically (do not distinguish by topic or format), while those with low adaptability are closed architectures built towards specific data types with little-to-no opportunity for changes.

2.3.4.5 Other Collection, Storage & Organization Metrics

Accuracy of a data-system measures the degree to which the data-system represents *"…the real-life objects they are intended to model…"*[50]. Although accuracy is a goal that all data-systems should aspire to, the definition of what constitutes the 'real-life' description of an artifact / phenomena is difficult to ascertain a priori except in controlled test cases.

2.3.5 Recall Metrics

Data recall is the ability to find the data / dataset within a data-system that address an information request – data is only as useful as it is available. The following metrics have identified that measure the performance of a data-system in recalling stored data.

2.3.5.1 Time Cost

The amount of time required to access & retrieve data is quantified through the Time Cost metric. As capacities of data-systems expands, so too does the time to recall required data[56]. Network-enabled recall procedures have reduced the time cost of searches towards a near-zero value, a distinct advantage over physical data recall and / or processes that require intermediate layers of bureaucracy before accessing datasets.

Table 2.9 – Data System Recall Quality Metrics

Metric	*Description*	*Unit*
Time Cost	Time to recall a standardized unit of data	sec / GB
Economic Cost	Dollar cost to obtain a standardized unit of data	$ / GB
Precision	Ratio of recalled data that is relevant	%
Sensitivity	Ratio of relevant data that is recalled	%

2.3.5.2 Economic Cost

Economic Cost conveys the actual fiscal cost to access recalled data including one-time data acquisition costs as well as additional upkeep costs. Underlying infrastructure costs required to operate the data-system (i.e. computer cost, internet subscription cost) should not be considered for clarity sake – datasets made available through public forum should be considered as an absolute zero economic cost.

2.3.5.3 Precision

Precision measures the fraction of the returned results that are relevant to the information need[53] – this requires the user to have a firm understanding of is, is not and could potentially be useful in the context of the information task. A high value of precision conveys only relevant responses by the data recall system, where a low value of precision suggests most results are erroneous.

2.3.5.4 Sensitivity

Sensitivity is measured as the ratio of the total relevant data that exists in the data system to the data returned through the recall process (an inverse of the precision metric). The higher the sensitivity, the more a data recall system is presenting the user with the “whole truth”. Sensitivity has been used as a standardized metric by which to judge search algorithms within controlled settings[53], however, its application in practical settings requires a subjective and topic-specific approach.

2.3.6 Analysis & Visualization Metrics

The following Data-Engineering metrics have been identified that characterize the ability of data to be conveyed as information, both through statistical data analysis and data visualization.

2.3.6.1 Multiplicity

As discussed previously, analysis of datasets alone can produce substantial insight for decision-making. Multiplicity, the number of data fields presented for data analysis, quantifies the ability of the data-system to directly convey information. Larger multiplicity values allow the user to perceive trends and-or identify correlation between data variables.

Table 2.10 – Data System Analysis & Visualization Quality Metrics

Metric	*Description*	*Unit*
Multiplicity	Number of variables available for comparison	Fields
Degrees of Freedom	Independent methods to visualize data	-
Interoperability	Time to export a standardized unit of data	sec / GB

2.3.6.2 Degrees of Freedom

The Degrees of Freedom metric captures the number of ways a user can visualize a dataset[44]. Providing user flexibility between tables, univariate and multivariate graphical representations along self-defined variables allows the ultimate in 'sand-box' data exploration – pre-defined visualization & variable settings, however, can be preferable in well-defined information scenarios.

2.3.6.3 Interoperability

When further structured analysis is required, Interoperability measures the time required to format data such that it may be exported and imported within external platforms. Because of this definition, Interoperability is a proxy for the ability of a data-system to operate in an integrated decision-making environment – a data-system should seek to address all data-tasks locally where possible, but allow the user access to the raw & intermediate data whenever possible. Increasing values of interoperability convey this flexibility in platform and task execution.

2.4 HISTORY OF DATA & DATA MANAGEMENT SYSTEMS

Although the modern conceptualization of data is skewed towards numerical values tabulated and ready for computational use, data has historically been a dynamic entity adapted to meet the societal needs and expectations of the time. As human culture has become more structured and systematic, so has the treatment of factual statistics describing man's surroundings. The fields of language, mathematics, statistics, cartography, library science, journalism, engineering, and information technology, among others, have shaped the modern definition of data & data systems. By studying the history of data up to its current status, a logical pattern for how and why society has collected & disseminated data will begin to form.

A contextual conversation about aerospace data and data systems cannot start with the advent of the aerospace industry itself. The era of designing air vehicles, and especially space, vehicles has only come at the tail end of a long lineage of technical & informational progress. Throughout history, the de facto decision-making process has evolved from one driven by the ‘old wise man’ leading through personal experience towards the modern paradigm of automated data processing feeding complex algorithms that make decisions with humans comparatively out-of-the-loop. Distinct eras of human-data interaction, shown in Figure 2.10, have been segmented by well-defined advances in overall data capabilities with each era having its representative techniques, processes or tools that fundamentally shaped them, see Table 2.11. The proceeding sections discuss each era in more detail.

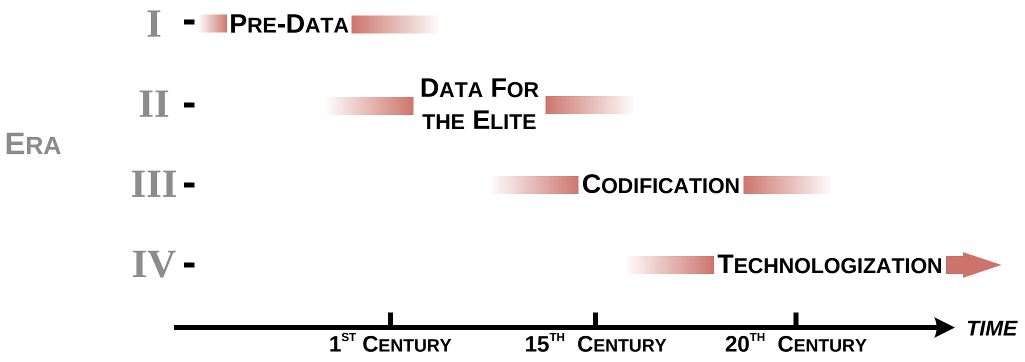


Figure 2.10 – Historical Eras of Data
(adapted from references [62][63][74])

Table 2.11 – Representative Data Mediums throughout History

	Data-Engineering Task(s)		
Era	Collection, Storage & Organization	Recall	Analysis & Visualization
Pre-Data	Human brain	Human speech	Pictograph
Data for the Elite	Scroll	Library	Tables
Codification	Book	Encyclopedia	Map
Technologization	Database	Search Engine	Infographic

2.4.1 First Era: Pre-Data [Before 1st Century A.D.]

One cannot divorce the history of data, without discussing the construct of the written word. Without words or numbers, there is no data. Without data, societal information is largely conceptual. Before the invention of written communication, oral communication dominated the flow of information between individuals and communities[57]. In order to become information, an individual had to observe some phenomena personally, identify that event as something that required action or further discussion, and then be able to communicate that observation to another individual through a verbal medium. This model of transferring information required face-to-face communication between individuals who were often limited by the available modes of transportation[58]. Even amongst neighboring communities, any lack of standardization in languages would immediately cause a barrier in the passage of information[59]. The prospects of relaying data to more than an individual's close community would have been a challenge.

If an individual was successful in communicating information within a group, the process of keeping the information structured and relevant was equally as limiting in verbally-based system (e.g. non-written languages in Native American cultures before European contact leading to a lack of Native-driven historical texts[60]). With only oral communication, the spread of ideas and information could only occur person-to-person-to-person, daisy-chaining internally throughout groups of individuals that were able to communicate with each other[63]. When the first-hand (primary) source of the data ceases to exist, it is left to the remaining individuals to retain and pass the information on to the next generation.

However, human memory is not a perfect data storage system. The process of internalizing information and then passing that information along verbally always opens up the possibility of skewing the original data. Whether through forgetfulness of the complete information or by additional self-interpretation, that piece of information is no longer singular – there is not a single factual basis for the original phenomena, but multiple versions based on the individual[61]. The details are now a dynamic entity, a function of both time & space.

Table 2.12 – Approximate Date of Oldest Known Evidence of Logographic Languages[64]

Language	*Date*
Egyptian	2700 BC
Sumerian	2600 BC
Greek	1500 BC
Chinese	1200 BC
Phoenician	1000 BC
Latin	700 BC
Persian	500 BC
Tamil	200 BC
Arabic	300 AD
English	600 AD

For these reasons, a systematic historical understanding of knowledge and data can only really begin with the societies that utilized the written word. Independently, several cultures have created, standardized and disseminated their own embodiments of writing[62] , see Table 2.12, and there is a clear progression to these attempts to describe the world from pictographic to ideographic to logographic representation – "…'*writing the pictures*' to '*writing the idea*' to '*writing the word*'…"

[63]. This evolution would be necessary to transition data from a personal internal state into an externalized element that could be used, and exploited, by others.

The invention and refinement of standardized number systems also emerged alongside the evolution of the invention word. The Sumerian civilization is credited with inventing arithmetic in response to needs to count livestock & crop harvests for future recordkeeping[65]. For the first time, independent counts of objects (which had previously been taken by counting fingers or making tally marks) could be added, subtracted, multiplied & divided by each other to perform a series of calculations[66]. Although invented to facilitate trade & commerce, numerals and arithmetic were soon applied to a broad range of applications including geometry & astronomy.

2.4.2 Second Era: Data for the Elite [1st Century AD – 15th Century AD]

With the advances in written language, technical & cultural advances progressed in lock-step. As civilizations grew to incorporate commerce, navigation, engineering, law & medicine, so did the needs to formally address data. Efforts were soon underway to begin systematically collecting data. Individuals realized that those who had data had information, and those who had information had power.

Within this era, the rise of the library is one of the key movements [62]. It represents not only the symbolic need to collect data in a centralized location, but also to organize data to be accessed at a later time. Unlike the modern incarnations, the first libraries were often privately owned & operated by powerful individuals or organizations; they were not yet a socially-shared asset[67]. Despite this exclusivity, the library soon began to grow into a central place for scholarly research & academic pursuits.

Table 2.13 – Early Ancient Libraries (consolidated from references [62][67][68][70])

Library	*Empire*	*Dates*	*Size (No. of Texts)*
Library of Alexandria	Greek	300 BC-50 BC	400,000
Royal Library of Antioch	Greek	200 BC	-
Library of Pergamon	Greek	200-100 BC	200,000
Han Dynasty Imperial Library	Chinese	200 BC-200 AD	11,000
Library of Celsus	Roman	100-250 AD	12,000
Imperial Library of Constantinople	Roman	300-1200 AD	100,000
House of Wisdom	Arabic	800-1250 AD	400,000

The Library of Alexandria is perhaps the best archetype of early libraries, see Table 2.13. Located in Egypt, it was a center for scholarship and study for over three centuries from approximately 300 BC to 48 BC[68]. Under the direct supervision of the rulers of Egypt, scholars at the Library were given the task of collecting the (perceived) entirety of the world's knowledge by transcribing any texts that could be found into copies for the Library's use. At this point in history, texts were still hand-written (usually on scrolls), thus requiring significant time & human resources to stock a library the size of the one in Alexandria. The library employed chief librarians to organize texts into categories of history, reference texts, and foreign languages, each stored alphabetically by author[69]. It is no coincidence that Egypt was the main political power during this period – the Library of Alexandria was a display of geopolitical power as much as it was a pursuit of data[70].

Throughout the middle ages, religious organizations, especially Catholicism, also took a significant interest in collecting data about its constituents. In addition to collecting religious and philosophical texts, the Catholic Church under immediate direction of the Pope, began keeping detailed data records of its congregation in the thirteenth century[62]. By tasking community churches to collect data about the church members in each region, the Church was able to track the overall spiritual and financial growth of their entire organization.

Governing bodies at this time also kept a unifying catalogue of data: the census. The tracking of a ruler's people (as well as the value of its lands) has been an important data point for leaders past & present[71]. However, the physical limitations of keeping an accurate census have proven cumbersome even in modern times – manual census of individuals and their properties is a time-consuming, laborious, and costly ordeal. The benefits however, tracking population & health trends, real estate accounting, estimating tax revenue, planning city infrastructure, and forecasting military strength[71], ensured rulers and governing bodies to gather as much census data as was possible. Despite the enormous cost of obtaining the data, the price of not having the data tended to be even more costly.

2.4.3 Third Era: Codification of Data [15th Century AD – 20th Century AD]

The next great era saw the spread of data from a tightly held treasure of the elite, to structured silos with immense quantities of data available to the common man. This era is ultimately defined by the liberating invention of the printing press, and with it, the ability to mass produce documents at a much faster pace and much cheaper overhead cost than traditional methods[72]. Although religious texts demanded the majority of the printing effort during the early era of printing, several other data-dominated documents became mainstays in the public and private life.

As people began to read more books, demand grew to understand the meaning of unknown words, giving rise to the invention and widespread dissemination of dictionaries[74]. These documents organized all words known to the dictionary author (often groups of author-editors) and gave pronunciation of the verbal expression, as well as the common meaning. Along the same conceptual theme of information collection, the encyclopedia also popularly emerged within this era, seeking to condense the necessary knowledge needed to understand the world into one place (often series of books)[73]. Unlike more focused texts, an encyclopedia takes a holistic viewpoint on a theoretically infinite number of subjects – each subject with its own verbal (and / or visual) description of the artifact, process or idea.

This time period is also known as an era of exploration and trade as countries began to expand their footprint across multiple continents. This required two things: the ability to sustain long-distance travel, and the requisite knowledge of how to navigate such distances[74]. Along with advances in ships, shipbuilding, railroads and then automobiles, there was a constant necessity to increase in the quality of topographic maps, as well as to standardize maps of multiple regions into a single compendium (i.e. an atlas). The ability to navigate across long distances required both precise data of the size, shape, & location of landmasses, and a functional format for interfacing this data with the traveler. Standardizing the man-data interface by codifying geographic data into maps (like words into a dictionary & ideas into an encyclopedia) is central to data processes until today[75].

As formal collections of data grew in size and complexity, so too did the desire to analyze them to gain further insight, giving rise to the discipline of statistics (Table 2.14). Although some advances had been made in the 1st millennium in the form of accounting[77], the majority of common applied statistics were achieved during the 3rd era of data. These advancements pushed the boundaries of data analysis and allowed for the expansion of technical analyses and visualization towards more varied and abstract applications.

Table 2.14 – Contributors to Statistics (adapted from reference [78])

Statistical Theory	*Founder*	*Dates*
Frequency Analysis	Al-Kindi	801-873
Probability	Bayes	1702-1761
Graphing	Playfair	1759-1823
Correlation & Regression	Galton	1822-1911
Confidence Interval	Neyman	1894-1981
Sampling & Control	Deming	1990-1993

2.4.4 Fourth Era: Technologization of Data [20th Century – Present]

The final (current) era of data has seen the storage and analysis capabilities of data systems exponentially increase as technology has transformed the medium, capacity and transfer rate of data. Although the computer can be seen as the central cog in this evolution, the interface between man, machine & data actually predates the computer. The following trends are driving the technologization of data.

Table 2.15 – Technologization of Data Era Advances

Concept	*Description*	*References*
Physical Storage Miniaturization	Shrinking of physical size of storage size while also increasing capacity	[79][80][81][82]
Cloud Storage / Computing	Relocation of storage and computational processes into shared universal networks	[80][83][84][85]
Sensor-ification	Measurement of all an organization's transactions, processes & operations	[87][88][89]
Big Data Analytics	Analysis of transaction, process & operational datasets to gain insight that were previously answerable through data	[90][91][92][93][94]
Machine Learning	Application of iterative algorithms to improve processes based on observed & learned data	[86][95][96][97]
Infographics	Visualization of information in an integrated format incorporating data in a variety of formats	[100][42][101][102][103][106]

2.4.4.1 Physical Storage Miniaturization

Punched cards were an early form of data transmittance for mechanically controlled textile looms & organs in the late 19th century (and continue on in some forms today) [76]. Holes were punched into the paper in a systematic format that represented letters and numbers to the human input and automated instructions to the machine. As computers came into being and advanced, punched cards remained the de facto interface between man & machine. Rolls of magnetic tape drive, however, offered superior storage capacity and read-speed – these characteristics made them superior for data storage and transmittal internally. This leapfrogging of capabilities was the first in a line of technologization of storage medium during this era. Miniaturization of tape drives, floppy disks, compact discs, and USB storage are all in a lineage of one-upping each other through smaller, faster, and more efficient transmission of data[80].

As technologization of data continues, data processing & storage is more and more becoming a 'black-box' entity that is detached from most users. Data is collected by ubiquitous sensors, stored within unified cloud-based systems, and analyzed with automated predictive algorithms. The human operator is increasingly only necessarily in-the-loop at the initial design & development phase. The science-fiction prophecy of a machine-led infrastructure is already underway as reality in some instances[86], with many more to follow.

2.4.4.2 Cloud Storage / Computing

The Cloud – current technological king-of-the-hill in data storage – removes the physical component necessary for storage, transportation, and transmission of data. In cloud-based systems, the physicality of data has been completely removed[84] – as long as the user is connected to the cloud's network, *unlimited* potential for storage and transfer of data is available. It remains to be seen if the benefits of having unlimited, but amorphous, data storage will supplant physical storage media or remain as a supplement to 'traditional' storage mediums[80].

2.4.4.3 Sensor-ification

As more & more data is stored on cloud systems and passed through communal networks (i.e. the internet), data-oriented organizations have emerged as world-class commercial entities.

Google, the company that began as a minimalistic and more efficient search portal for the internet, has the mission statement of "*…mak[ing] the world's information universally accessible…*" This trend has rapidly expanded to touch data not only from personal computers & the internet, but to smartphones, televisions, cars, wearable technology, and aircraft. Hand-in-hand with their *sensor-ification* of objects and processes, Google's competitive advantage has been their ability to integrate this multi-source data into information tailored to a user's needs, entering the realm of truly real-time predictive analytics on an individual level[87].

General Electric (and others) are taking advantage of the simultaneous miniaturization and integration of sensors alongside cloud-based data storage and computing capabilities to propose a hyper-connected business-industrial complex. In the '*Industrial Internet*' or the '*Internet of Things*'[88], all machines within an enterprise would have a shared, collective database that is refreshed in real-time over a shared network. In theory, this will allow the '*Unified Internet*' to produce macro-scale efficiency & proficiency gains by adjusting micro-scale actions of an existing infrastructure (i.e. automatically adapting component manufacturing production rates based on real-time logistics and market data).

2.4.4.4 Big Data Analytics

Big Data is a movement towards the integration of large-scale data-sets to derive insights independent from the original data[90]. Two things are driving the movement: the open availability of huge data-sets (think billions of data points) and the capability to process this data into information in a timeframe that is still useful for decision-making[91]. Although core tenets of Big Data like correlation analysis and Bayesian learning techniques are not new, the application of data-sets that are being refreshed in pseudo real-time from processes around the world allows for revolutionary insight to questions that may have been deemed ‘un-answerable’ previously[92].

Organizations that have subscribed to the *senor-ification* process like operations, logistics and manufacturing as well as those organizations with huge sampling pools like advertising and government have been the leading adopters of Big Data implementation[92] spurring the growth of data & information science as a supplementary discipline.

2.4.4.5 Infographics

Data visualization has expanded greatly in formulation, maturity and reception during the era of *Technologization*. Complex graphic figures representing information towards a specific topic, referred to as an *infographic*, have become a very powerful tool for data practitioners. Most regard this movement to have been started in the mid-19th century with Minard’s graphic of Napolean’s failed invasion of Russia earlier that century[98]. Minard’s ability to capture time, geographic position, military strength and key events within a single succinct graphic provided a density of information not previously available in a single visualization[99].

Today, modern data & information scientists have continued to push the boundaries of displaying and conveying information more efficiently & effectively. Tukey, considered to be one of the pioneers of this infographic movement, explored several innovative graphical techniques and visualization guidelines within his field of statistics & data exploration[100]. Tufte has published works solely discussing how and why engineers, scientists and other data professionals should convey information more clearly and effectively through properly design visuals[42]. He has used this approach to decompose the Space Shuttle Challenger as a case study where poor data visualization contributed to a miscommunication of crucial information that led to disastrous results [101].

The concept of executive dashboards, dynamic infographics that update based on real-time operational data, has taken this topic one step further and has been embraced by technical & non-technical communities[102]. Being able to see all driving variables of a development or operational process within a condensed view offers the decision-maker a snapshot of when and when not to investigate further[103]. Few has approached the design of dashboards as an extension of data visualization, graphic design & statistics, providing guidelines & rules of thumb towards organizations looking to implement dashboards to monitor their own processes[106].

2.4.5 Prospective Future Era of Data

The technologization of data is already underway, and in many cases, transforming analysis of business and operational processes. Advancingly, future paths forward are already being discussed, at least conceptually. One of the driving concepts in these visions requires inherently linking the data collection processes with the data analysis process with the decision process. In operational settings, this concept is referred to as edge computing – where current Internet of Things concepts will require a central hub where parametric analysis will occur, edge computing suggests as much analysis as possible happen as close as possible to the sensor[104][105]. This allows decisions to be made faster as well as reducing the requirement for network traffic to only high-level monitoring and decision criteria. While this approach offers pseudo real-time analysis, the technique for implementation may be much different than analysis techniques used in cloud-based *Internet of Things* and *Big Data* efforts. Models may only be aware of the limited local data environment – the onus for accurate forecasting, then, goes back to parametric multi-disciplinary and away from causation-less data correlation models.

2.5 CURRENT STATE OF DATA SYSTEMS

Due to the sheer size of today's aerospace & defense industry, as well as the complex technical nature of aerospace engineering in general, the field has remained insulated the environment from many changes and adaptations that have already been adopted in other fields. The ability to find and use data in a quick fashion has become commonplace in everyday life for people on and off the job – a capability the 'high-tech' aerospace industry has been slow to integrate. The recent launch of an internal search engine, built by Google, for the NASA Langley Research Center exemplifies the industry's desire to upgrade its capability with the support of data-centric enterprises[107]. For this project, Google adapted their search platform to Langley's existing stores of data in order to better help NASA engineers find the documents, pictures, and contacts – to which they already had access – in a more efficient manner. By studying of the common practices and platforms of modern data support provides insight, as NASA tapped into Google's core competencies, the lessons learned through years of research, development, and testing of data systems can be extracted and applied to an aerospace-centric platform.

2.5.1 Data Platforms

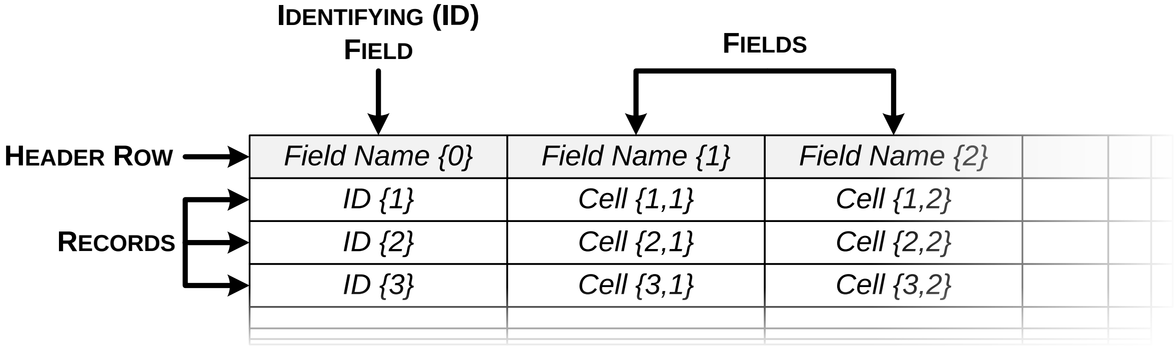
A platform in this context is defined as any distinct system that aids a user in performing one or more of the associated data processing elements, see Section 0. Within this general definition, select classes of data platforms have been identified that fundamentally shape the way individuals interact with modern data. These classes, and the primarily-used software platforms that exemplify them, are discussed in this section. The accompanying figure within each grouping of data platforms represents the highlighted areas of processing focus for the platforms. A more exhaustive format for rating data processing is established in the following chapter and applied to aerospace-specific data systems & data-centric forecasting studies, see Chapter 3.

Table 2.17 provides a broad overview of the data platforms considered to be industry leaders. They have been organized both on the user base that employs them (general non-technical population, data & information technologists, science/technology/engineering/mathematics professionals) and the previously-defined *Data-Engineering* tasks in which they are most often employed. A more detailed description of each platform follows in the proceeding sections.

2.5.1.1 Collection: Data Tables

The most fundamental element in modern data systems, the table, was established as the go-to method for comparing numerical values during the rise of statistics[15]. The simplicity and human-readability has kept it relevant & widespread, even as the majority of data is handled digitally.

A table is identified by its use of two-dimensional rows and columns to arrange and store data. Where a row & column intersect is defined as a cell, this is where individual data elements are stored. The row and column of each cell identifies what the data is describing. In the example of Figure 2.11, the data presented in *Cell {1,1}* would describe the property described by *Field Name {1}* in the header row about some artifact or process identified by *ID {1}*. There is no restriction made on the size or scope of the data held with each cell; although, a table is traditionally thought of as a numerically-based entity, it can just as easily hold any format of data (text, images, meta-data, files, etc.). However, traditional data structures require homogeneity along each column (i.e. each field specifies its own scope & formatting whether it is stated implicitly or explicitly).



Field Name {0}	*Field Name {1}*	*Field Name {2}*
ID {1}	*Cell {1,1}*	*Cell {1,2}*
ID {2}	*Cell {2,1}*	*Cell {2,2}*
ID {3}	*Cell {3,1}*	*Cell {3,2}*

Figure 2.11 – Elements of a data table

Table 2.16 – Industry-Leading Data Systems and Their Uses

Data Platform	*References*	*User Base*		*Data Processing Task*						
		General	Data Practitioners	STEM	Collection	Storage	Organization	Recall	Analysis	Visualization
CSV	[108]		X			X	X			
XML	[110][111]		X			X	X	X		
Excel	[113]	X	X	X	X	X	X	X	X	X
SQL	[43][49]		X		X	X	X	X		
Access	[43][112]	X	X		X	X	X	X	X	
Oracle	[114][115]		X		X	X	X	X	X	
NoSQL	[116][117]		X		X	X	X	X		
Google	[87][118][119]	X	X	X	X	X	X	X	X	X
Wikipedia	[120]	X	X	X	X	X	X	X		
MATLAB	[124][125]			X			X	X	X	X
R	[122]		X	X			X	X	X	X
SAS	[122][123]		X			X	X	X	X	X
SPSS	[122][126]		X			X	X	X	X	X

Due to their systematic (i.e. mathematical) nature, tables are a natural fit for technologization (Section 2.4.4); they can be read, manipulated, and written by a computer if the data table is well-formatted for interfacing with software data platforms and there is sufficient meta-data to describe the contents of the data table. Two common formats for data tables will be furthered discussed: text-based formatting & spreadsheet-based formatting.

Text-based Data Tables

Although Figure 2.11 represents what would be considered a well-formatted data table from a visualization perspective, its qualities are somewhat ambiguous in a computing environment. For instance, the distinction between cells & fields is made by lines and the header row is identified by a different color shade. Although such a format could be interpreted by today's computing capabilities, the first generations of computers were limited to simple text input & output due to inherent digital memory and calculation limitations. As a consequence, standardized text formats were adopted that remain in use today, especially where extremely large datasets are required.

Comma Separated Values Format

The comma-separated values (CSV) file format gets around this discrepancy by using the comma character as a delimiter to separate cell elements (other characters may be used, such as a semicolon, but are less commonly accepted)[108]. The general format of the data table remains the same – all elements of a row are entered on a single line before returning to enter the first cell of the next row, see Figure 2.12. Due to the intended computer interactions however, the data within the cell must be formatted to particular specification: (1) cells may only contain text, (2) spaces and commas should only be used if the entire cell data is surrounded by double quotes - spaces before and after the delimiting character will be included as data, and (3) each record should contain the same number of fields. Although the CSV file format (CSV files usually have the extension '.csv') has limitations in complexity & flexibility with non-standard data-types, the standardization made it very popular in passing data between different spreadsheet (below), databases (below) and analysis (below) platforms that require their own specialized input formatting.

Machine Readable Cataloging Format

Where the CSV file format was mainly intended to handle data for analysis purposes, the MAchine-Readable Cataloging (MARC) text file format has been created to specifically deal with bibliographic meta-data. The MARC format, created for the Library of Congress in the 1960s to help deal with the immense influx of publications[109], has a standardized list of index categories that identifies what field the data is describing. The index identification number is the first character in each row, followed by a tab and the data element. Unlike the CSV format, the MARC format does not have flexibility in field names, but must confine to the predetermined set of field indices, see Figure 2.13. However, because each data element is entered on its own line the size of each record can be variable – more or less data can be used to describe an artifact as it is needed or available. Clearly, the flexibility in description is not offered with tabular-based file formats like CSV. As such, MARC formatting thrives for bibliographic indexing where artifacts have very different identifying fields (the Library of Congress indexes books, movies, songs, serial publications & more), but must be accessible through the same format.

VISUAL TABLE

Field Name {0}	*Field Name {1}*	*Field Name {2}*		
ID {1}	*Cell {1,1}*	*Cell {1,2}*		
ID {2}	*Cell {2,1}*	*Cell {2,2}*		
ID {3}	*Cell {3,1}*	*Cell {3,2}*		

CSV TABLE

```
Field_Name{0},Field_Name{1},Field_Name{2}
ID{1},”Cell{1,1}”,”Cell{1,2}”
ID{2},”Cell{2,1}”,”Cell{2,2}”
ID{3},”Cell{3,1}”,”Cell{3,2}”
```

Figure 2.12 – CSV data table format

VISUAL META-DATA

Terrace, Vincent. *Fifty Years of Television: A Guide to Series and Pilots*, *1937-1988*. New York: Cornwall Books, 1991.

MARC META-DATA

```
Leader/00-23*****nam##22*****#a#4500
001    <control number>
003    <control number identifier>
005    19920331092212.7
008/00-39     820305s1991####nyu###########001#0#eng##
040    ##$a[organization code]$c[organization code]
100    1#$aTerrace, Vincent,$d1948-
245    10$aFifty years of television :$ba guide to series and
       pilots, 1937-1988 /$cVincent Terrace.
260    ##$aNew York :$bCornwall Books,$cc1991.
300    ##$a864 p. ;$c24 cm.
```

Figure 2.13 – MARC meta-data text file format

Extensible Markup Language (XML)

With the increasing digitization of data and the need to understand what data is describing (and how to use it), a series of "self-describing" data markup languages have emerged[110]. XML is a semi-readable language used in describing data on webpages, databases, and as an intermediary for translating data formats[111]. The basis of XML is a series of user-defined elements (i.e. field names with corresponding field values) and attributes. Each element can have sub-elements which are described by their own attributes with unlimited element nesting and attributes – an element with attributes has a value that is an element which has its own attributes and its own value, ad infinitum.

Standardized relationships between elements and attributes can be defined in a data schema to provide more structure to XML document (i.e. all names entered are required to have a first name and last name element), allowing for a pseudo database design with the XML structure. Although this provides a very logical and intuitive interface between man & data, XML's solely text-based programming language limits its usage as a primary data processing platform.

VERBAL DATA

The wingspan of the Boeing 747-400 is 211.4 ft.

XML DATA FORMAT

```
<xml>
    <object manufacturer = “Boeing” series = “747” model = “-400”>
        <wingspan units = “ft”>
                211.4
        </wingspan>
    </object>
</xml>
```

Figure 2.14 – XML data format

Spreadsheet Data Tables (Microsoft Excel)

Although spreadsheets have the same appearance as the visual data table presented in Figure 2.11, they offer additional flexibility & interactivity that the text-based formats cannot offer[113]. Where the discussion of text-based tables mentioned nothing of organization, visualization, or recall, spreadsheets have, in contrast, the capability to perform operations on cells to modify or create new data. In a spreadsheet, operations between cells are written as mathematical statements and can be referenced to concrete values and-or cell locations.

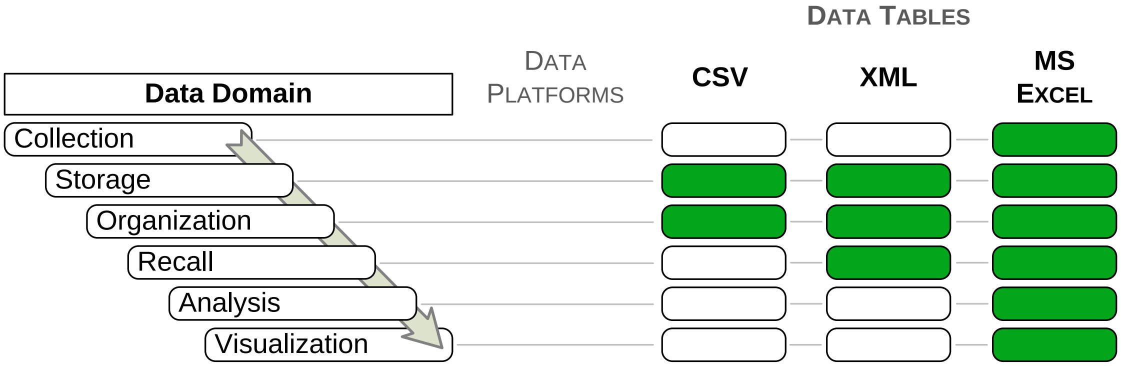
Microsoft Excel is ubiquitous as a spreadsheet platform, and is more or less representative of the classes' capabilities. Introduced in 1985, Excel has gained this position because of its ease of use and adaptability to the user’s needs. Excel spreadsheets are not just a single, static data table, but a group of linked data tables that may be used to input raw data, perform computations, visualize results, and perform numerical analysis. As such, Excel is not solely a means of data collection – it offers several additional capabilities that make it a very flexible data handling toolbox.

Excel has the built-in functionality to import data from existing spreadsheets as well as text-based data tables (such as CSV). Within the data table, cells can be entered as formulas to perform computations, or may be formatted individually as values with preset templates for numeric, text, currency or date. To modify the contents of the spreadsheet, Excel has a native library of close to 400 functions that may be applied to individual cells or recursively to a group of cells (ranges). Users may also define their own functions through cell-by-cell formulas.

Excel also allows data to be visualized through a number of graphical output presets where the user is given the flexibility of changing plotting and graphical details. Because cells may be modified and visualized as reference to a cell’s location, the output of a spreadsheet is able to change dynamically if the independent cells are updated. This flexibility can allow for spreadsheets to be structured as a logic process independent of the cell values, therefore representing a pseudo-programming language that can be used in lieu of more advanced languages for some tasks.

Data Tables Summary

The data table platforms presented (Figure 2.15) play a significant role in modern data processing. Although the CSV & XML platforms are limited in their complexity, their universal format and ability to handle large datasets using text-only formatting make them a popular intermediary for passing datasets. Excel’s capabilities across the spectrum of data processing make it a go-to toolbox for a number of data tasks.



	DATA TABLES		
Data Domain / DATA PLATFORMS	**CSV**	**XML**	**MS EXCEL**
Collection			🟩
Storage	🟩	🟩	🟩
Organization	🟩	🟩	🟩
Recall		🟩	🟩
Analysis			🟩
Visualization			🟩

Figure 2.15 – Data Platform Area of Focus: Data Tables

2.5.1.2 Storage & Organization: Database Management Systems

Unlike data tables which lack the necessary functionality to manipulate or recall multi-leveled data easily, database management systems (DBMS) have evolved to more efficiently handle large datasets[43]. The overarching downside is that DBMS require users to understand some level of platform-specific language and commands, translating into a tradeoff between functionality and complexity.

Within the DBMS paradigm, meta-data and the data treated as unique and separate entities. Data fields are first defined based on their description and the type of data that the field contains and then a second level of user interface is required to enter, edit and manipulated data – the layers of functionality between data manipulation and the user vary between each software platform. Unlike data tables where calculations can easily be made within a dataset, DBMS are generally weak in integrating analytical functions and are more focused on filtering & sorting operations on existing datasets.

Structured Query Language (SQL)

SQL is a standardized programming language that handles the creation, query, and update of large datasets[49]. Commands in SQL are human-readable text that describes a process to be performed on a dataset with specific action phrases. Because of its simplicity, SQL has widespread adoption when dealing with large datasets, and is common across the majority of enterprise-level DBS[49] (e.g. Access, MySQL, Microsoft SQL Server, Oracle). SQL by itself, however, has little data analysis or visualization capabilities and is therefore linked manually (ad hoc) to other platforms that perform other data handling functions or imbedded within more complex platforms.

Manipulating text within SQL requires the use of keyword commands in a specified sequence and context according to a standardized protocol. To view data from an existing table a ‘SELECT’ statement is used; a ‘CREATE’ statement is needed to create a new table; the ‘UPDATE’ command can change the properties of an already-established data table[43]. When creating a new data table, variables must be specified by a field name, the data type, and the ability to handle null values. Additional properties such as specifying a primary key value and placing bounded constraints on field values are also user options. An additional strength of SQL lies in its ability to adapt multiple datasets and quickly pull queries from a combined data set through the ‘JOIN’ command – combining tangential datasets and creating integrated insights is a key strength of SQL. The example in Figure 2.16 shows one possible definition of the verbal data statement shown.

VERBAL DATA

The wingspan of the Boeing 747-400 is 211.4 ft.

SQL DATA FORMAT

```
CREATE TABLE objects
(
    manufacturer varchar(50) NOT NULL,
    series varchar(50) NOT NULL,
    model varchar(50) NOT NULL,
    wingspan float NULL
    units varchar(10)
)

INSERT INTO object
VALUES
(‘Boeing’,’747',’-400',211.4,’ft’)
```

Figure 2.16 – SQL data format

Microsoft Access

Microsoft offers a DBMS software platform, *Access*, which has functionalities in common with Excel and other MS Office products, but with a heavier reliance on Visual Basic for Applications (VBA) event-driven programming language and query-based search & filtering capabilities through SQL[112]. Instantiating data tables is similar to other DBMS, with field names and data types specified individually and data entry handled graphically in a separate table-based view (similar to Excel) where the data field of each record can be adjusted.

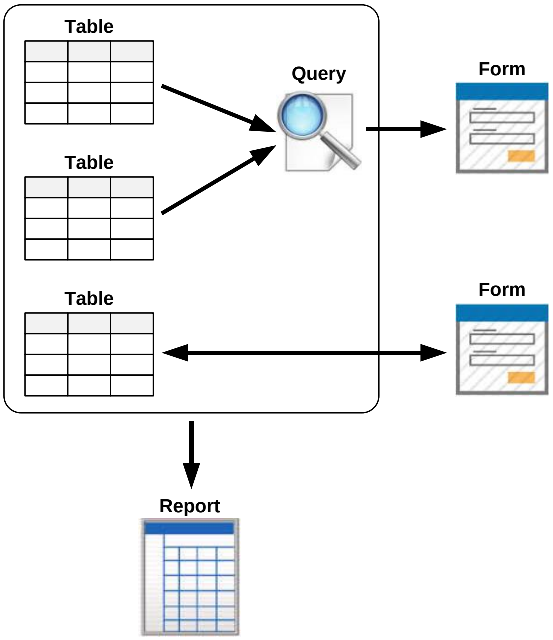


Figure 2.17 – Microsoft Access Data Functionality

The unique functionality of Microsoft Access is its ability to create graphical ‘forms’ that represent data from one or more data tables. In addition to a standard tabular view, an Access developer can create input interfaces, formatted output deliverables, and automated summary reports. Having these added capabilities allows a well-developed Access data system to implement additional data handling functions beyond storage and organization, overall a great benefit to a unified platform approach. This functionality comes at the price of decreased enterprise scalability however – the native file limit of an Access database is 2 GB and platform performance can decline substantially with simultaneous users.

Oracle Database

The software company *Oracle* has created and maintains a relational database management system (RDBMS) built on the SQL data structure. Data is presented in a series of two-dimensional data tables with the rows representing records describing the same artifact and process and the columns containing values for fields previously defined. Field definition is handled in a separate GUI with the field name, data type, value constraints, and default value specified individually[114]. A major strength of the Oracle RDMBS is its ability to scale to enterprise levels covering vast amounts of data across multiple sites with simultaneous and overlapping user interactions. These features have made Oracle a dominant platform in large-scale enterprise applications.

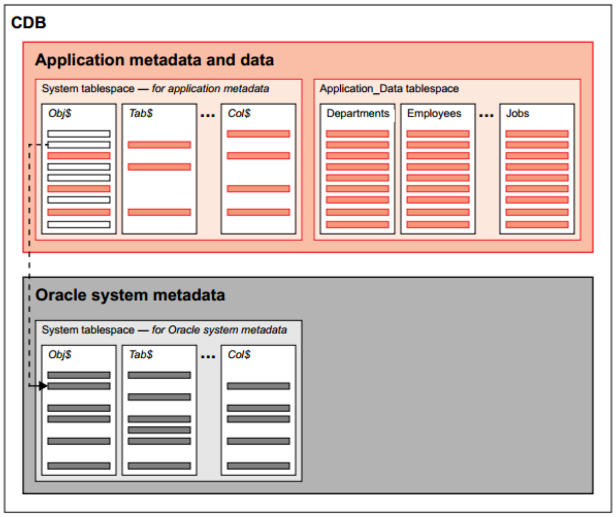


Figure 2.18 – Oracle Database Architecture[115]

NoSQL

In contrast to the previously discussed relational DBMS, recent developments in database systems have sought to separate the data from the structure of the data system. In the NoSQL construct, the data is defined independently from a structured DBMS. For example, a NoSQL database would store an entire PDF document alongside a table of values alongside a graph, each representing the equivalent of a record in a RDBMS[116]. The user is then allowed to dynamically change the definition of elements within each entity so that like-fields can be cross-correlated and queried, regardless of structure in their native source [117]. This dynamic adaptability to varying structures will be a key trait in unifying data systems.

Table 2.18 – Relational to NoSQL Database Term Translation

Relational Database Item	*NoSQL Database*
Table	Collection
Row	Document
Column	field

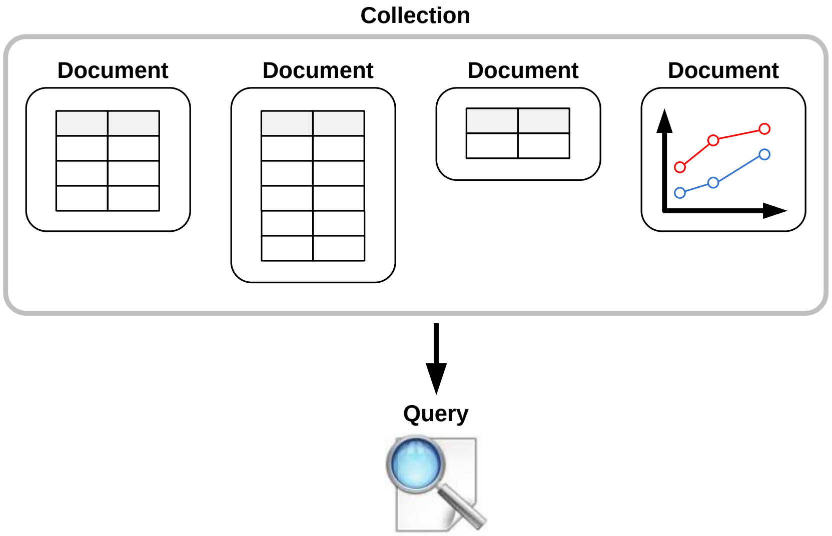


Figure 2.19 – NoSQL Data Architecture

Database Management Systems Summary

Relational database management systems all share some core functionality and capabilities especially efficient sorting, organizing & querying of existing data records. Access's additive ability to create GUI's for simple user input & output makes it powerful tool for data tasks beyond the complexity of data tables, but not requiring advanced visualization or the scaling demands of enterprise-level employment, see Figure 2.20. NoSQL and other document-based database systems offer a new paradigm for data collection and offer some exciting new capabilities, especially for organizations with data tasks requiring the integration of variable and or unstructured datasets. DBMS do, however, lack the ability to perform detailed analyses, as is required in aerospace conceptual design and forecasting, and therefore require manual integration with separate analysis platforms.

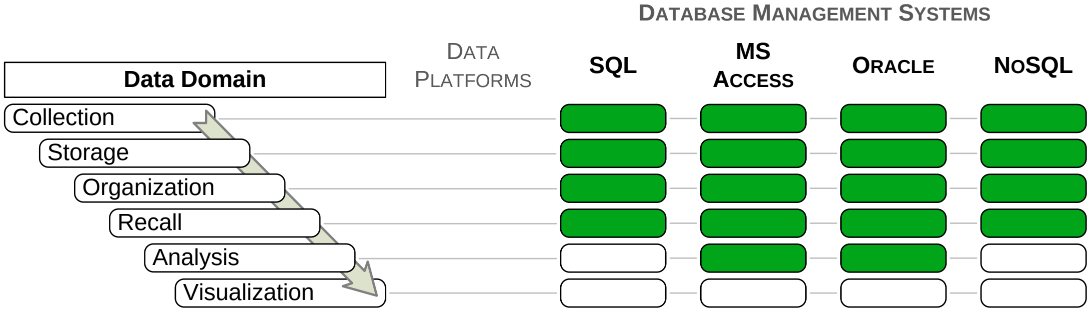


Figure 2.20 - Data Platform Area of Focus: Database Management Systems

2.5.1.3 Recall: Search Portals

As the availability of data and information has increased exponentially, the need for advanced search capabilities has expanded in lock-step. The abilities to focus searches on topics and sub-topics, sort and filter results for relevancy, and gain access to data sources in real-time has become an expected trait of a data system in a relatively short-period of time.

Google

Search, especially Internet search, has become synonymous with *Google*, whose mission to '*…organize the world's information and make it universally accessible and useful…*' is a driving cornerstone to their development strategy[118]. Starting as a keyword-matching search engine for internet websites[119], Google has evolved its platform to a self-adjusting entity that attempts to guide the search-user directly to the solution when possible. Previous related searches are used as a basis for users to ask the 'right' questions, and recent development of the *Google Now* platform aims to predict the information that is relevant to the user based on time, location, and past data-seeking patterns without waiting for an explicit search command.

Wikipedia

In the default information reference role once filled by physical encyclopedias, Wikipedia has become a go-to source for internet information retrieval[120]. Information is updated in real-time of with user additions having minimal editorial oversight. The editing is handled through a collaborative and democratic process amongst users. In addition to evolving topic-specific information, Wikipedia's other dominant feature is the digital linking of concepts & concepts within concepts. The ability to drill down, zoom out, and explore tangential information allows the user to self-define what the information retrieval process entails.

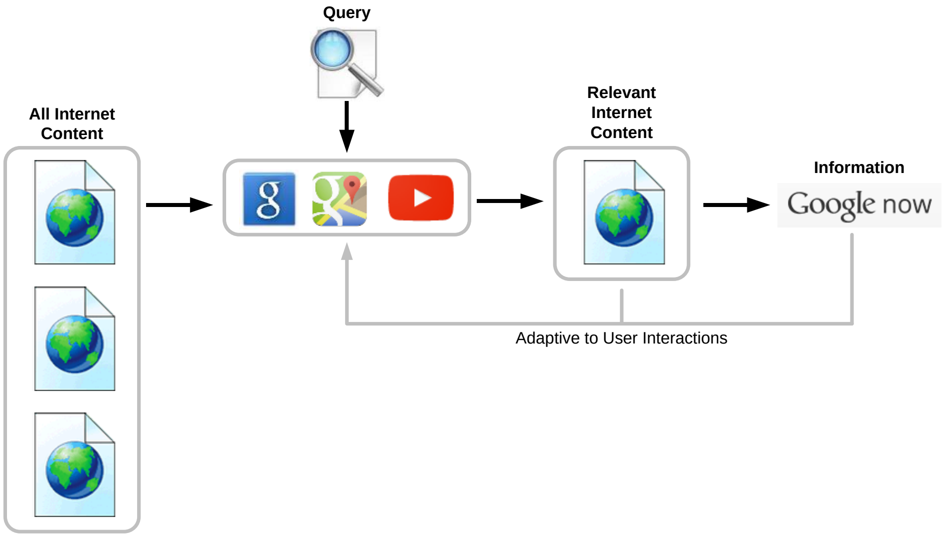


Figure 2.21 – Google Data & Information Recall

Search Portals Summary

The Internet has fundamentally changed the way humans search for and interact with data. Through Google, Wikipedia (Figure 2.22), and other parallel efforts, a user can instantly recall data from a theoretically unlimited pool of data – not only is the data made available, but the platforms have been developed so that the most relevant data to your topic the easiest to find and tangent searches have already been pre-processed for further consideration. Although search portal platforms themselves are directly applicable in *DES*, the features that they have developed, established and refined for generic information consumption will provide similar value in an aerospace-specific data system.

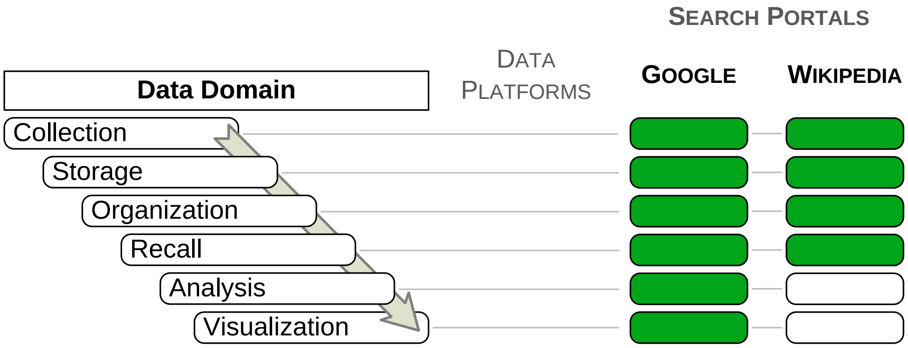


Figure 2.22 – Data Platform Area of Focus: Search Portals

2.5.1.4 Visualization & Analysis: Data Analytics

Platforms have emerged beyond standard data spreadsheets that solely focus on the analysis & visualizations of data. These platforms often have significant grounding in technical, scientific & statistical communities as tools for creating analytical data through simulated experiment and / or preparation of data for presentation to others.

MATLAB

MATLAB is a high-level programming language, created by *MathWorks*, that specializes in matrix-based analytic functions and native graphic visualization[124]. Large libraries of statistical & engineering-centric functions have been built into the programming environment, with user-defined functions also available through a standardized declaration structure[125]. *MATLAB*'s open-ended programming environment allows a user's experience to scale use from graphing calculator functionality all the way to modelling & simulation of complex systems of systems.

The key differentiator of *MATLAB* is its ability to store n-dimensional matrices within a single variable definition and then allow the user to perform matrix operations between variables. In older, more rudimentary programming languages, such as a *C* and *FORTRAN*, performing arithmetic function on matrices requires cumbersome instantiation and interim calculations – *MATLAB* performs these steps internally and requires the user to only define the intended top-level operation. *MATLAB* also supports object oriented variable definitions where variables may have several properties, each of which is its own variable with its own variable type. This feature, along with advanced 2-D and 3-D visualization capabilities, make *MATLAB* a popular tool in the engineering & scientific communities for data analysis tasks.

R

R is a high-level open-source programming language intended to focus on statistical analysis & graphic visualization[121]. Native functions of *R* have been built with regression analysis, correlation and analysis of variance tasks in mind – these functions calls are often much simpler & intuitive than other data analysis platforms. The open-source development of *R* also allows for constant capability updates and adaptations to emerging data analysis techniques. The ability to output graphic visualizations of datasets, especially probabilistic datasets and multivariate plots, is one of the main strengths of the *R* programming platform[122].

SAS

SAS is a commercially-offered data management & statistical analysis package offered by *SAS Institute Inc.*[122]. It contains elements of relational databases systems, with datasets defined in a structured format within data tables – variable are defined within set attributes (name, data type, length, format, informat and labels)[123]. After data sets are created within the text-based prompt or loaded from an external file, *SAS* offers a graphic output of the data table for viewing & editing data values. Statistical analysis packages focus on predictive analysis, business intelligence and data mining tasks, all available through native function calls.

SPSS

SPSS is a commercial statistical analysis and graphic visualization platform offered by *IBM* (formerly by *SPSS Inc.*). In *SPSS*, existing data sets are uploaded or linked through multiple file formats and viewed through in graphic data table view – data values and number formats can be changed dynamically from this view[122]. Full-scale data manipulation and statistical analysis is handled through a high-level text-based (and GUI-aided) command prompt. Datasets, as well as any statistical analysis results, can be viewed through a built-in graphic visualization suite.

Data Analytics Summary

Data analytics platforms, see Figure 2.23, almost exclusively focus on the end-portion of the data-to-information flow down. Their structure is designed to take existing datasets and add layers of understanding through statistics and visualization. The open-ended nature of *MATLAB* and *R* allows for more flexibility in use – their analysis capabilities are extensive enough that a dataset can fundamentally be changed within the platform (no longer data analysis, but technical analysis). This capability to perform functions of both the data domain & and the analysis domain (of the larger information-production process) make *R*, but especially *MATLAB* ideal candidates for holistic forecasting platform development.

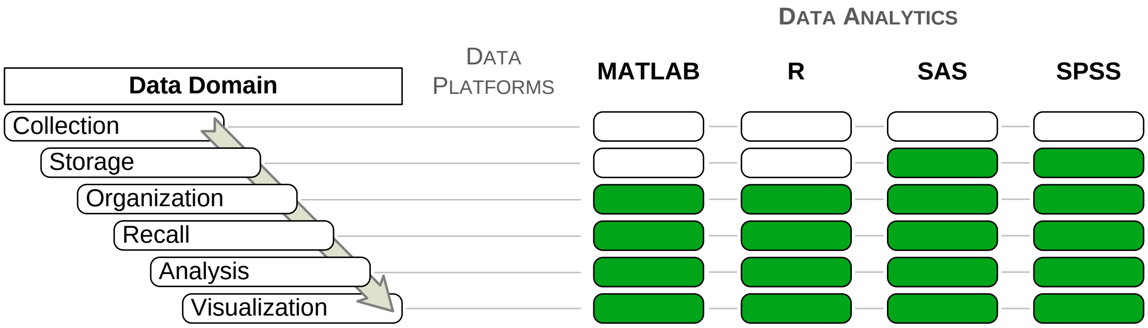


Figure 2.23 – Data Platform Area of Focus: Data Analytics

2.6 CONTRIBUTION SUMMARY

As a basis for the research specification of an aerospace forecasting data system, this chapter has covered the following topics:

- definition of the generic decision-making process as it pertains to complex, high-value decisions
- definition of the Data-Engineering discipline
- key tasks of Data-Engineering processes outlined with perspective from historical treatment of data and usage within modern platforms
- identification of quantifiable data & data system quality metrics
- history of data & data systems with an eye towards human-data interfaces, as well as public perception of data as an information source
- baseline capabilities of a modern data system established by surveying the status quo of leading non-aerospace data processing platforms

REFERENCES

[15] Robbins, S., and Judge, T., “Organizational Behavior,” Pearson Prentice Hall, 2007.

[16] Fishburn, P., “Utility Theory for Decision Making,” Research Analysis Corporation, 1970.

[17] Pettigrew, A., “The Politics of Organizational Decision-Making,” The International Behavioural and Social Sciences Library, 1973.

[18] Phillips-Wren, G., and Jain, L., “Artificial Intelligence for Decision Making,” Knowledge-Based Intelligent Information and Engineering Systems, Vol. 4252, pp 531-536, 2006.

[19] Neilson, R., “Sun Tzu and Information Warfare,” National Defense University Press, 1997.

[20] Man, J., “The Leadership Secrets of Genghis Khan,” Transworld Publishers, 2009.

[21] Bowden, S., “Napoleon’s Grande Arme’e of 1813,” Armies of the Napoleonic War Research Series, Emperor’s Press, 1990.

[22] Elting, J., “Swords Around a Throne,” Da Capo Press, 1997.

[23] Lupfer, T., “The Dynamics of Doctrine: The Changes in German Tactical Doctrine During the First World War,” U.S. Army Command and General Staff College, 1981.

[24] Bruns, L., “The German General Staff in World War I,” U.S. Army Command and General Staff Colege, 1983.

[25] Anon., “Staff Organization and Operations,” Headquarters, U.S. Department of the Army, FM 101-5, 1997.

[26] Price, M., Raghunathan, S., and Curran, R., "An integrated systems engineering approach to aircraft design," Progress in Aerospace Sciences, Vol. 42, Pgs. 331-376, 2006.

[27] Hazelrigg, G., "Systems Engineering: An Approach to Information-Based Design," Prentice Hall, ISBN 0-13-461344-9, 1996.

[28] Shigley, J., and Mitschke, C., "Shigley's Mechanical Engineering Design," McGraw-Hill Publishing Company, 2002.

[29] Box, G., and Draper, N., "Empirical Model-Building and Response Surfaces," Wiley Series in Probability and Mathematical Statistics, 1987.

[30] Bernstein, J., "Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices," Massachusetts Institute of Technology, 1998.

[31] Alex, C., "Process and Procedure: The Tactical Decision-Making Process and Decision Point Tactics," US Army Command and General Staff College, 2000.

[32] Kolodner, J., and Riesbeck, C., “Experience, Memory, and Reasoning,” Artificial intelligence Series, 1986.

[33] Anon., “Information Technology – Metadata Registries (MDR),” International Organization for Standardization, ISO/IEC 11179, 2005.

[34] Anon., “Understanding Metadata,” National Information Standards Organization, 2004.

[35] Anon., “747 Family: Technical Characteristics – Boeing 747-400,” Boeing, 2014.
URL: http://www.boeing.com/boeing/commercial/747family/pf/pf_400_prod.page

[36] Sapsford, R., and Jupp, V., “Data Collection and Analysis,” SAGE Publications, 2006.

[37] Gantz, J, and Reinsel, D, “The Digital Universe in 2020: Big Data, Bigger Digital Shadows, and Biggest Growth in Far East,” IDC, 2012.

[38] Dunkel, B., and Soparkar, N., “Data Organization and Access for Efficiency Data Mining,” Data Engineering, 1999.

[39] Chen, P., “The Entity-Relationship Model – toward a unified view of data,” Association for Computing Machinery Transactions on Database Systems, 1976.

[40] Aho, A., and Ullman, J., “Universality of Data Retrieval Languages,” Association for Computing Machinery Symposium on Principles of Programming Languages, 1979.

[41] Tukey, J., “Exploratory Data Analysis,” Pearson, 1977.

[42] Tufte, E., "The Visual Display of Quantitative Information," Graphics Press, ISBN 096132142, 1983.

[43] Connolly, T., and Begg, C., "Database Systems: A Practical Approach to Design," Pearson Education Limited, ISBN 0201708574, 2002.

[44] Ye, J., “On Measuring and Correcting the Effects of Data Mining and Model Selection,” Journal of the American Statistical Association, 1998.

[45] Turbit, N., “Defining the Scope of a Project,” The Project Perfect White Paper Collection, 2005.

[46] Margaritopoulos, M., Margaritopoulos, T., Mavridis, I., and Manitsaris, A., "Quantifying and Measuring Metadata Completeness," Journal of the American Society for Information Science and Technology, Vol. 63, Issue 4, 2011.

[47] Chen, H., Hailey, D., Wang, N., and Yu, P., "A Review of Data Quality Assessment Methods for Public Health Information Systems," International Journal of Enviornmental Research and Public Health, doi: 10.3390/ijerph110505170, 2014.

[48] Askham, N., Cook, D., Doyle, M., Fereday, H., Gibson, M., Landbeck, U., Lee, R., Maynard, C., Palmer, G., and Schwarzenbach, J., "The Six Primary Dimensions for Data Quality Assessment: Defining Data Quality Dimensions," Data Management Association UK, 2013.

[49] Anon., “Database Languages – SQL.” International Organization for Standardization (ISO), ISO/IEC 9075, 2015.

[50] Loshin, D., "Monitoring Data Quality Performance Using Data Quality Metrics," Informatica, 2006.

[51] Sebastian-Coleman, L., "Dissecting Data Measurement: Key Metrics for Assessing Data Quality," The Morgan Kaufmann Series on Business Intelligence, ISBN 0123970334, 2013.

[52] Wang, R., and Strong, D., "Beyond Accuracy: What Data Quality Means to Consumers," Journal of Management Information Systems, Vol. 12, No. 4, pp. 5-33, 1996.

[53] Manning, C., Raghavan, P., and Schutze, H., "An Introduction to Information Retrieval," Cambridge University Press, 2009.

[54] Anon., “Text Retrieval Conference Proceedings,” National Institute of Standards and Technology (NIST), 2014.
URL: http://trec.nist.gov/presentations/presentations.html

[55] Harvey, D., and Holdsworth, R., "Knowledge Management in the Aerospace Industry," Proceedings International Professional Communication Conference, ISBN 0780390288, 2005.

[56] Ramscar, M., Hendrix, P., Shaoul, C., Milin, P., and Baayen, H., “The Myth of Cognitive Decline: Non-Linear Dynamics of Lifelong Learning,” Topics in Cognitive Science (2014) 1-38, 2014.

[57] Daniels, P., and Bright, W., “The World’s Writing Systems,” Oxford University Press, 1996.

[58] Norman, J., “History of Information,” 2015.
URL: www.historyofinformation.com

[59] Bickerton, D., “Roots of Language,” Karoma, 1981.

[60] Fixico, D., “The American Indian Mind in a Linear World: American Indian Studies & Traditional Knowledge,” Routledge, 2003.

[61] Dainty, A., Moore, D., and Murray, M., “Communication in Construction: Theory and Practice,” Taylor & Francis, 2006.

[62] Burke, P., "A Social History of Knowledge: From Gutenberg to Diderot," Polity Press, ISBN 978-0-7456-2484-6, 2000.

[63] Gleick, J., "The Information: a Theory, a History, a Flood," Pantheon Books, ISBN 978-0-375-42372-7, 2010.

[64] Coulmas, F., “The Blackwell Encyclopedia of Writing Systems,” Wiley-Blackwell, 1999.

[65] Ifrah, G., “The University History of Numbers: From Prehistory to the Invention of the Computer,” 2000.

[66] Kramer, S., “The Sumerians: Their history, Culture, and Character,” University of Chicago Press, 1971.

[67] Murray, S., “The Library: An Illustrated History,” Skyhorse Publishing, 2007.

[68] Casson, L., “Libraries in the Ancient World,” Yale University Press, 2002.

[69] Blum, R. “The Alexandrian Library and the Origins of Bibliography.” Madison, Wisconsin: University of Wisconsin Press, 1991.

[70] Erskine, A., “Culture and Power in Ptolemaic Egypt: The Museum and Library of Alexandria,” Greece and Rome, Vol. 42, No. 1, pp. 38-48, 1995.

[71] Alterman, H., “Counting People: The Census in History,” Harcourt, Brace & Company, 1969.

[72] Man, J., “Gutenbury: How One Man Remade the World with Words,” Wiley, 2002.

[73] Lindberg, D., “The Beginnings of Western Science,” The University of Chicago Press, 2007.

[74] Burke, P., "A Social History of Knowledge: From Encyclopedia to Wikipedia," Polity Press, ISBN 978-0-7456-5042-5, 2012.

[75] Pickles, J., “Representations in an Electronic Age: Geography, GIS, and Democracy,” Ground Truth, The Social Implications of Geographic Information Systems, 1995.

[76] Lubar, S., “’Do Not Fold, Spindle or Mutilate’: A Cultural History of the Punched Card,” Journal of American Culture, 1992.

[77] Heefer, A., “On the Curious Historical Coincidence of Algebra and Double-Entry Bookkeeping,” Foundations of the Formal Sciences, 2009.

[78] Stigler, S., “The History of Statistics: The Measurement of Uncertainty before 1900,” Belknap Press, 1990.

[79] Moore, G., “Cramming More Components onto Integrated Circuits,” Proceedings of the IEEE, 1998.

[80] Freeman, L., Hope, M., and Simpson, D., “Evolution of the Storage Brain,” Amazon Digital Services, 2010.

[81] Zarros, A., and Kumar, A., “Digitization of DNA: Miniaturization of Information Storage Moving Toward Data in DNA,” Journal of Natural Science, Biology, and Meddicine, 2013.

[82] Borghoff, U., and Rodig, P., “Long-Term Preservation of Digital Documents: Principles and Practices,” Springer, 2006.

[83] Amherst, M., Fox, A., Griffith, R., Joseph, A., Katz, R., Konwinski, A., Lee, G., Patterson, D., Rabkin, A, Stoica, I., and Zaharia, M., “A View on Cloud Computing,” Communications of the ACM, 2010.

[84] Badger, L, Grance, T., Patt-Corner, R., and Voas, J., “Cloud Computing Synopsis and Recommendations,” National Institute of Standards and Technology (NIST), 2012.

[85] Mell, P, and Grance, T., “The NIST Definition of Cloud Computing,” National Institute of Standards and Technology, 2011.

[86] Armstrong, S., “Smarter Than Use: The Rise of Machine Intelligence,” Machine Intelligence Research Institute, 2014.

[87] “Google Prediction API,” Google Cloud Platform, 2014.
URL: https://cloud.google.com/prediction/#features

[88] Evans, P., and Annunziata, M., "Industrial Internet: Pushing the Boundaries of Minds and Machines," General Electric, 2012.

[89] Jacobs, A., “The Pathologies of Big Data,” Communications of the ACM, 2009.

[90] Mayer-Schoenberger, V., and Cukier, K., "Big Data: A Revolution That Will Transform How We Live, Work and Think," Houghton Mifflin Harcourt, ISBN 978-0-544-00269-2, 2013.

[91] Anon., “Big Data Meets Big Data Analytics,” SAS White Paper, 2012.

[92] Manyika, J., Chui, M., Brown, B., Bughin, J., Dobbs, R., Roxburgh, C., and Hung Byers, A., "Big data: The next frontier for innovation, competition, and productivity," McKinsey & Company, 2011.

[93] Russom, P., “Big Data Analytics,” TDWI Research & IBM, 2011.

[94] LaValle, S., Hopkins, M., Lesser, E., Shockley, R., and Kruschwitz, N., “Analytics: The New Path to Value,” MIT Sloan Management Review, 2010.

[95] Bishop, C., “Pattern Recognition and Machine Learning,” Springer, 2007.

[96] Goldberg, D., and Holland, J., “Genetic Algorithms and Machine Learning,” Machine Learning, 1988.

[97] Andrieu, C., De Freitas, N., Doucet, A, and Jordan, M., “An Introduction to MCMC for Machine Learning,” Machine Learning, 2003.

[98] Friendly, M., “Visions and Re-Visisions of Charles Joseph Minard,” Journal of Educational and Behavioral Sciences, Vol. 27, No. 1, pp. 31-51, 2002.

[99] Rosenberg, D., and Grafton, A., "Cartographies of Time: A History of the Timeline," Princeton Architectural Press, 2010.

[100] Tukey, J., "The Future of Data Analysis," The Future of Data Analysis, DA36-034-ORD-2297, 1961.

[101] Tufte, E., "Data Analysis for Politics and Policy," Prentice Hall, ISBN 0-13-197541-2, 1974.

[102] Few, S., “Information Dashboard Design: Displaying Data for At-a-Glance Monitoring,” Analytics Press, 2013.

[103] Eckerson, W., "Performance Dashboards: Measuring, Monitoring, and Managing Your Business," John Wiley & Sons, HD31.E2942011, 2011.

[104] Anon., “Processing Data From the Edge: A Platform for the Internet of Your Things,” Microsoft Blogs, 2014.

[105] Anon., “The Path to Profitable Growth through the Internet of Things,” Accenture, 2015.

[106] Few, S., "Information Dashboard Design: The Effective Visual Communication of Data," O'Reilly Media, 2006.v

[107] Hodges, J., “Langley Google Offers another Tool to Center’s Researchers,” NASA, 2009. URL: http://www.nasa.gov/centers/langley/news/researchernews/rn_google.html

[108] Shafranovich, Y., "Common Format and MIME Type for Comma-Separated Values (CSV) Files," Internet Engineering Task Force, 2005.

[109] Avram, H., “Machine-Readable Cataloging (MARC) Program,” The Library of Congress, 2003.

[110] Tidwell, D., "Introduction to XML," IBM developerWorks, 2002.

[111] Bray, T., Paoli, J., Sperberg-McQueen, C., Maler, E., and Yergeau, F., “Extensible Markup Language (XML) 1.0 (Fifth Edition),” W3C, 2008.

[112] Alexander, M., and Kusleika, D., “Microsoft Access 2013 Bible,” Wiley, 2013.

[113] Walkenbach, W., “Excel 2013 Bible,” Wiley, 2013.

[114] Anon., "Oracle Database: 2 Day DBA," Oracle, B14196-03, 2012.

[115] Anon., “Oracle Multitenant: An Oracle White Paper,” Oracle, 2013.

[116] Anon., “NoSQL Databases Explained,” MongoDB, 2014.
URL: www.mongodb.com/nosql-explained

[117] Anon., "Top 5 Considerations When Evaluating NoSQL Databases," MongoDB, 2015.

[118] Spector, A., Norvig, P., and Petrov, S., “Google’s Hybrid Approach to Research,” Google, 2011.

[119] Ghemawat, S., Gobioff, H., and Leung, S. “Google file system,” In Proc. of ACM SIGOPS, 2003.

[120] Anon., “Wikimedia Foundation 2014-2015 Annual Plan,” Wikimedia Foundation, 2014.

[121] Torfs, P., and Brauer, C., "A (very) short introduction to R," Wageningen University, The Netherlands, 2014.

[122] Muenchen, R., "R for SAS and SPSS Users," Springer Science+Business Media, ISBN 978-0-387-09417-5, 2009.

[123] “SAS Programmer’s Bookshelf,” SAS, 2015.
URL: http://support.sas.com/documentation/onlinedoc/bookshelf/

[124] Attaway, S., “Matlab, Third Edition: A Practical Introduction to Programming and Problem Solving,” Butterworth-Heinemann, 2013.

[125] Hahn, B., and Valentine, D., “ Essential MATLAB for Engineers and Scientists,” Academic Press, 2013.

[126] Field, A., “Discovering Statistics using IBM SPSS Statistics,” SAGE Publications, 2013.

CHAPTER 3

AEROSPACE DATA & DATA SYSTEMS

CHAPTER 1 Introduction
Discussion of the realities of aerospace design & forecasting, specifically the need for standardized processes and tools to support data-engineering.

CHAPTER 2 Introduction to Information & Information Systems
Review of decision-making standards and data standards, including historical evolution of the technologization of data ending with modern data platforms.

CHAPTER 3 Aerospace Data & Data Systems
Examination of existing best practices and research in aerospace data-engineering. Also addresses the common formats and mediums of aerospace data.

CHAPTER 4 Specification of an Aerospace Forecasting Data-Engineering System
Review of current approaches in aerospace design & forecasting. Definition of the feature and interface requirements of a functional aerospace data-engineering system.

CHAPTER 5 Development of an Aerospace Forecasting Data-Engineering System
Layout of data-engineering software system from a development perspective. Standardization and interface with parametric analysis processes emphasized.

CHAPTER 6 Validation & Calibration Case Study
Application of data-engineering system to a historical re-entry capsule design study where desired results are known a priori, including examination of system and engineer performance.

CHAPTER 7 Aerospace Design & Forecasting Case Studies
Three case with applications across a range of aerospace forecasting problems, utilizing different aspects of the developed data-engineering system, and intended for diverse decision-making goals.

CHAPTER 8 Summary & Conclusions
Parting thoughts on the state of aerospace design & forecasting, aerospace data & information science, and future potential of data-engineering systems.

Where the previous chapter discussed the broad topic of data & data systems, this chapter covers an aerospace-centric view of data processing, data platforms, data use in forecasting & design, and research in all of the above. A more detailed inspection within the focused field is required so that previous & current development can be incorporated into the specification for future development. Due to the scope of aerospace vehicle research and development, especially when considering its rich history spanning more than 100 years, a complete survey is unattainable. This chapter does, however, attempt to gather those examples of data use in aerospace design, forecasting and engineering that are representative of past and present capabilities.

3.1 HISTORICAL DATA USE IN AEROSPACE DESIGN & FORECASTING

The history of research and development of aircraft and space vehicles is littered with examples of high-performing individuals and organizations that took special attention of data. Through innovative usage of data and data systems, they positioned themselves as pioneers in the field. These examples range from solving disciplinary issues all the way to complete vehicle system synthesis.

3.1.1 Creating Data: the Wright Brothers

Orville and Wilbur Wright are most celebrated for the first powered and controlled flight and their subsequent leadership in the emerging aircraft industry. However, it can be argued that their novel development mindset (and revolutionary use of data) should be equally celebrated. Previous attempts at human flight had been limited to, at best, unpowered gliding flight and, at worst, serious injury & death. This earliest phase of experimentalist designs failed to possess the necessary combination of power, lift, stability and control, mostly owing to the general lack of understanding about the physical environment governing flight. This lack of understanding could also be stated as a lack of the necessary information to produce successful design decisions. Within this reality, the Wright Brothers lacked the necessary elements from all three decision-making domains[127]:

- ***Data*** describing previous flight vehicles was non-existent as no vehicles had previously flown. There was a small amount of component performance data in the form of propeller and airfoil section aerodynamic data developed by Otto Lilienthal, but it later proved unreliable[132].
- ***Knowledge*** about how to build and design an aircraft emerged only from those select individuals with direct experience and published in a few relevant texts[128][129][130][131]. The evolving knowledge that was possessed was often based on unfounded scientific methodologies and ill-devised vehicle designs.
- ***Analysis*** techniques to predict the performance of the components or the holistic vehicle system were not available, and it would some time before a purely analytical approach would exist.

Table 3.1 – Wright Brothers' Key Publications

Title	*Year*
Some Aeronautical Experiments, Journal of the Western Society of Engineering	1901
Flying-machine (patent)	1906
The Relation of Weight, Speed and Power in Flyers, Navigating the Air; a Scientific Statement of the Progress of Aeronautical Science Up to the Present Time	1907
The Wright Brothers' Aeroplane	1908
How to Glide and Soaring Flight, Flight	1909
The Earliest Flights: A Letter from Wilbur Wright, Scientific American	1910
The Papers of Wilbur and Orville Wright, including the Chanute, Wright Letters and Other Papers of Octave Chanute	1953

Because the early designs realized that more supporting information was needed, the Wright Brothers sought to expand the quantity & quality of the design-relevant data available to them. They developed a small wind-tunnel where they could test candidate airfoils and propellers, thereby creating their own supporting dataset. They understood that by better understanding the aerodynamic performance characteristics of the vehicle design before it was tested in flight, they increased the likelihood of success and decreased their chances of physical & capital loss.

Between 1901 and 1903, the Wright Brothers tested approximately 200 potential[127] airfoil shapes measuring the force of the airfoil in the two principal directions (lift and drag) versus the inclination of the airfoil relative to the incoming flow (angle of attack); an example data table is reproduced in Figure 3.1. Design alternatives were tested in families of wing configurations with shared characteristics, but with single parameters varied independently. The Wright Brothers understood, and therefore pursued, the power of more extensive aerodynamic design data – Wilbur's later comment that *"…we possessed in 1902 more data on cambered surfaces, a hundred times over, than all of our predecessors put together…"*[127] illustrates their mindset. These direct physical insights gained through an accumulation and implementation of data allowed the Wright Brothers to make systematic, thus data-grounded, design decisions that ultimately led to their successful flight vehicle system.

3.1.2 Compiling Data: Hoerner's Lift & Drag

The expansion of aircraft design & engineering knowledge in the four decades between the Wright Brothers' success and the end of World War II can only be described as a step-change. What had been a revolutionary capability to lift one man for a matter of seconds had evolved into vehicle systems that were pushing the boundary of sound and carrying payloads across transoceanic distances. It was in this environment that the next example of aerospace data usage was thrust in one of the most field-defining disciplines of early aircraft design, aerodynamics[139].

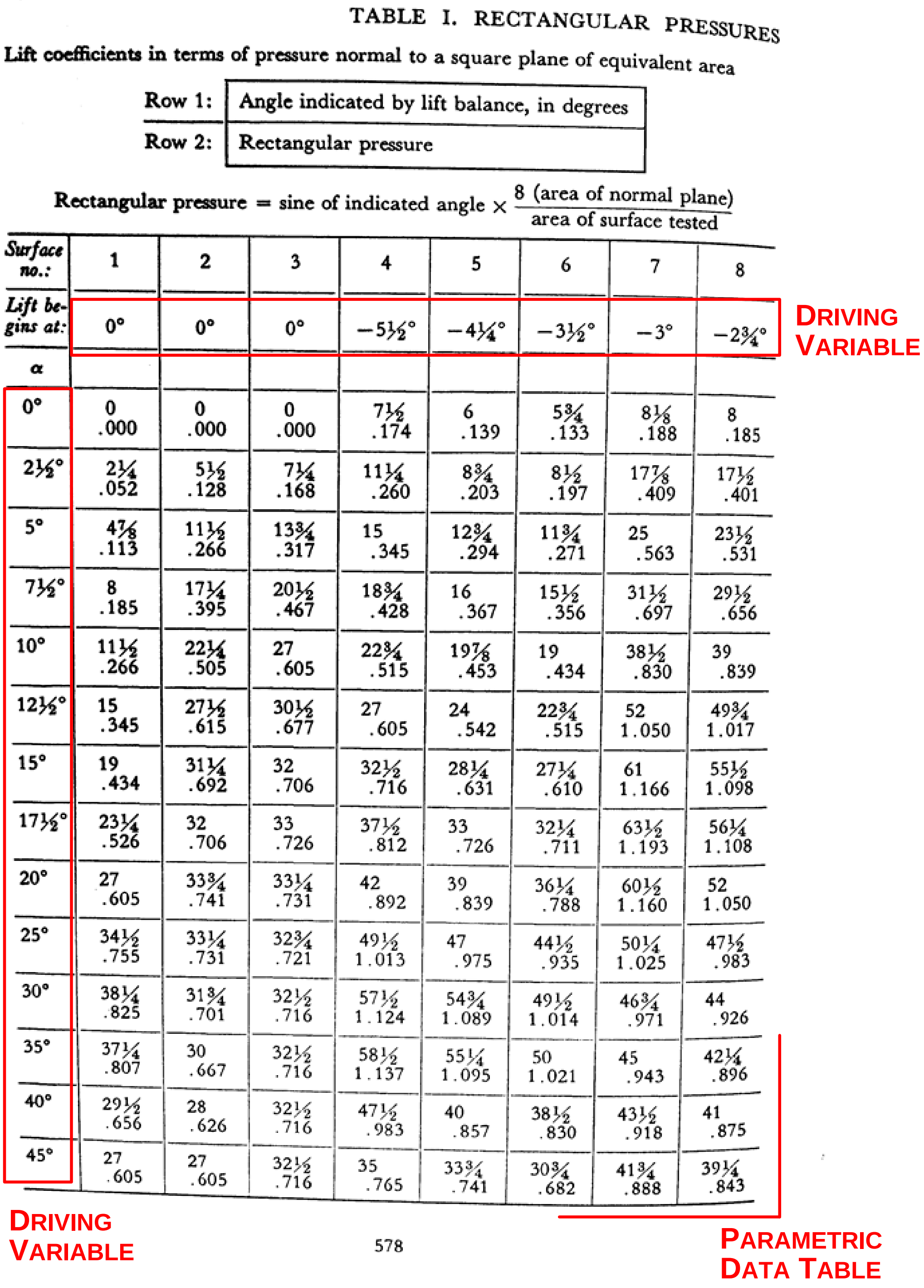


TABLE I. RECTANGULAR PRESSURES

Lift coefficients in terms of pressure normal to a square plane of equivalent area

Row 1:	Angle indicated by lift balance, in degrees
Row 2:	Rectangular pressure

Rectangular pressure = sine of indicated angle × $\frac{8 \text{ (area of normal plane)}}{\text{area of surface tested}}$

Surface no.:	1	2	3	4	5	6	7	8
Lift begins at:	0°	0°	0°	−5½°	−4¼°	−3½°	−3°	−2¾°
α								
0°	0 .000	0 .000	0 .000	7½ .174	6 .139	5¾ .133	8⅛ .188	8 .185
2½°	2¼ .052	5½ .128	7¼ .168	11¼ .260	8¾ .203	8½ .197	17⅞ .409	17½ .401
5°	4⅞ .113	11½ .266	13¾ .317	15 .345	12¾ .294	11¾ .271	25 .563	23½ .531
7½°	8 .185	17¼ .395	20½ .467	18¾ .428	16 .367	15½ .356	31½ .697	29½ .656
10°	11½ .266	22¼ .505	27 .605	22¾ .515	19⅞ .453	19 .434	38½ .830	39 .839
12½°	15 .345	27½ .615	30½ .677	27 .605	24 .542	22¾ .515	52 1.050	49¾ 1.017
15°	19 .434	31¼ .692	32 .706	32½ .716	28¼ .631	27¼ .610	61 1.166	55½ 1.098
17½°	23¼ .526	32 .706	33 .726	37½ .812	33 .726	32¼ .711	63½ 1.193	56¼ 1.108
20°	27 .605	33¾ .741	33¼ .731	42 .892	39 .839	36¼ .788	60½ 1.160	52 1.050
25°	34½ .755	33¼ .731	32¾ .721	49½ 1.013	47 .975	44½ .935	50¼ 1.025	47½ .983
30°	38¼ .825	31¾ .701	32½ .716	57½ 1.124	54¾ 1.089	49½ 1.014	46¾ .971	44 .926
35°	37¼ .807	30 .667	32½ .716	58½ 1.137	55¼ 1.095	50 1.021	45 .943	42¼ .896
40°	29½ .656	28 .626	32½ .716	47½ .983	40 .857	38½ .830	43½ .918	41 .875
45°	27 .605	27 .605	32½ .716	35 .765	33¾ .741	30¾ .682	41¾ .888	39¼ .843

578

Figure 3.1 – Example of the Wright Brothers' use of experimental databases[127]

Table 3.2 – Hoerner's Key Publications

Title	*Year*
Skin Drag of High Speed Aircraft	1936
Forces and Moments on Yawed Airfoil	1939
Base Drag and Thick Trailing Edges	1950
Aerodynamic Properties of Screens and Fabrics	1952
Aerodynamic shape of the Wing Tips	1952
The Effect of Roughness Concentration Upon the Frictional Drag	1954
Consideration of Size-speed-power in Hydrofoil Craft	1958
Commercial Hydrofoils	1964
Boat Hull and Hydrofoil Combination	1964
Fluid-Dynamic Drag: Practical Information on Aerodynamic Drag and Hydrodynamic Resistance	1965
Fluid-Dynamic Lift: Practical Information on Aerodynamic and Hydrodynamic Lift	1975

Sighard Hoerner, selected here as an exemplary case study in the collection, organization and compilation of data, was the head aerodynamicist at both the Junkers & Messerschmitt companies in Germany before coming to the United States after World War II as a researcher at what is now Wright-Patterson Air Force Base in Ohio. During this period of transition, he compiled his working knowledge of aerodynamics along with an expansive base of reference data into the seminally-titled *Fluid-Dynamic Drag*[150] in 1965, and the later counterpart *Fluid-Dynamic Lift*[151], completed and published posthumously in 1975.

In both texts, Hoerner sought to summarize state-of-the-art in topics that dominated different subcategories of flow phenomena. In each of these subcategories, he discusses individual topics, including the fundamental and theoretical basis, and then uses experimental and analytical data from a wide variety of sources to visualize trends that quantify the discussion. His work tends to overlays results from several references to provide the reader with a range of probable results and then additional comments are made on the validity and assumptions that underlie the composite figure, see Figure 3.2. In doing so, Hoerner succeeded in compiling a single version or best-practice from a variety of possible truths.

Even at the time of original compilation in 1945, Hoerner had access to roughly 20,000 available publications and technical reports with data describing aerodynamic phenomena, representing a staggering data pool, especially in a purely analogue world. Hoerner himself comments that "i*t soon became obvious that not all of these could be evaluated,…*" and that it would take considerable effort to sort the prime material from the *"…obsolete, unnecessary, repetitious, and…misleading…*"[150] Therefore, he applied a firm theoretical basis to correctly frame each of the discussions around the aerodynamic design process. He used his breadth of aerodynamic knowledge, along with supporting data points and research analyses, to quantify the theory and provide usable results and insights for further investigation.

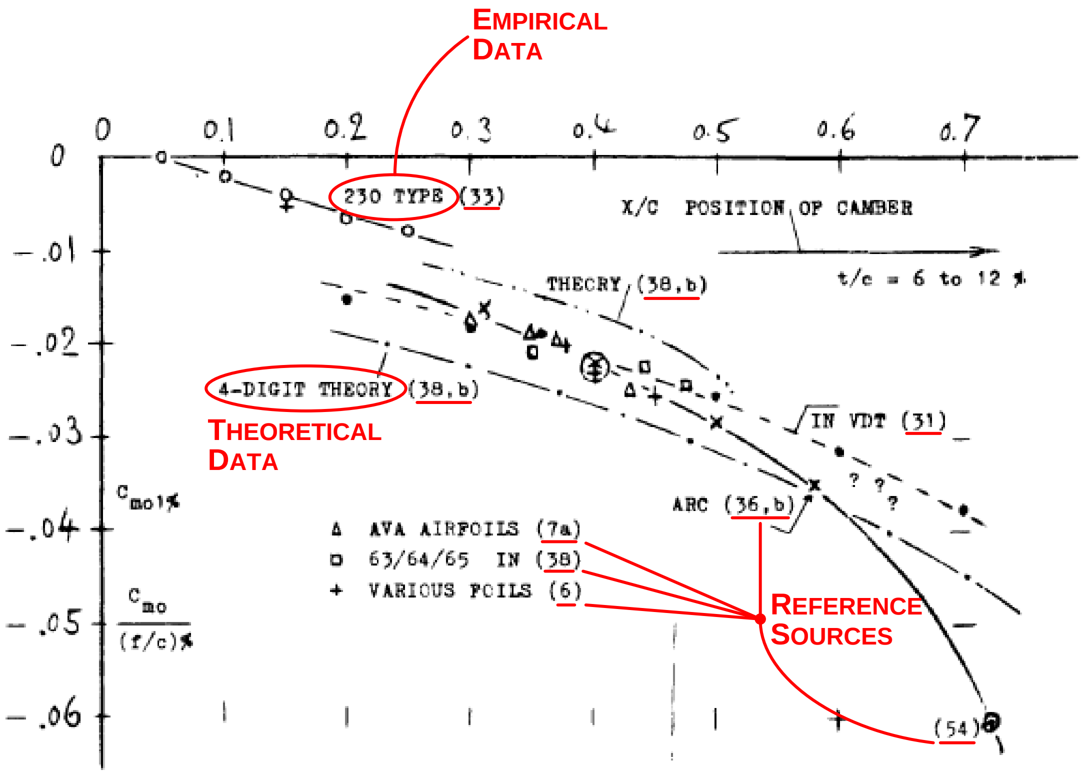


Figure 40. Pitching moment at zero lift caused by camber, as function of camber location.

Figure 3.2 – Example of Hoerner's use of multiple sources to visualize data trends[151]

The coverage of Hoerner's compendium on aerodynamics cannot be understated; no other single aerodynamic reference has achieved a parallel effort, even today. *Drag* spans 20 chapters discussing complex flow phenomena in a quantitative manner across aircraft, airships, missiles, land-borne vehicles, and satellites including a detailed breakout of drag over components of each class of vehicles. Rules of thumb, trend lines & empirical regressions bring the data to life. These two remarkable volumes do not only represent a bibliographic summary or a static encyclopedia of knowledge, but both practical guides for use in aerodynamic design of real vehicle systems.

3.1.3 Parameterizing Data: US Air Force Space Planners Guide

In 1965, the Space Systems Division of the Air Force Systems Command was tasked with producing a platform that would "…permit military planners with limited background in astronautics and the space sciences to evaluate mission concepts in terms of environmental, technological, economic factors…" Where only a few years prior space systems had not existed (Sputnik first flew in late 1957), the Space Planners Guide was written to jump head-first into 'Space Age' and bring guidance and comprehensiveness to an "…increasingly complex and difficult…" area[152].

Table 3.3 – Space Planner Key References

Title	*Year*
Space Planners Guide	1965
Evaluating the Space Planners Guide	1966
Assessing the Adaptability of the 1965 USAF Space Planners Guide for a Modern SpaceLiner-Type Hypersonic Point-to-Point Mission	2014

The Space Planners Guide was not intended to offer a complete solution to a well-formed technical problem, but to provide a 'first approximation' that would inform long-term mission planning. It was also required that the solutions possibilities be presented as parametric in both input & output – that is, the Guide offered structured processes that led from a series of user-defined inputs towards an assessment of the required vehicle system & its characteristics. The goal was not one answer, but a 'step-by-step procedure' that gave a family of answers to a family of questions. The availability of this comprehensive handbook methodology provided decision-making freedom the hands of the planner, designer or technical specialist.

In order to produce such a capability, there was a need to include contributions from all three decision-making elements: space vehicle data, top-level mission planning / design engineering knowledge, and parametric first-order analysis procedures. In the case of data, the relatively short history of space system development allowed the authors of the Space Planners Guide to consult "*…all space hardware programs and essentially the complete realm of space studies accomplished in this country since 1959…*" Because the authors were deeply involved within the space systems planning environment, they were able to apply their own knowledge when vetting and implementing data points. This embedded experience allowed for trends "*...derived from scattergraphs of experience points married to the latest accepted theories...*" The Space Planners Guide addresses a number of topics across its seven chapters, see Table 3.4.

Table 3.4 – Space Planners Guide Key Sections

Chapter	*Contents*
1	Space Operations
2	Space Payloads
3	Space Vehicle Synthesis
4	Launch Vehicles
5	Launch Sites
6	Ground Environment
7	Space System Cost Estimation

The user of the Space Planners Guide handbook methodology is presented with a series of worksheets, tables & figures that step through the process of designing a space vehicle system. The figures are often presented as nomographs, representing a series of interrelated charts that are able to graphically solve a series of equations. The underlying equations have been solved parametrically, allowing the user to obtain results in a simple & efficient process. Figure 3.3 shows an example of the nomograph system used in this handbook design guide; input (calculated from a previous section) are read in at the left of the top graph, the output is correlated along the horizontal axis and the final output comes from the separate graph at the bottom (the graphs are aligned and share the same axes to make this conversion possible).

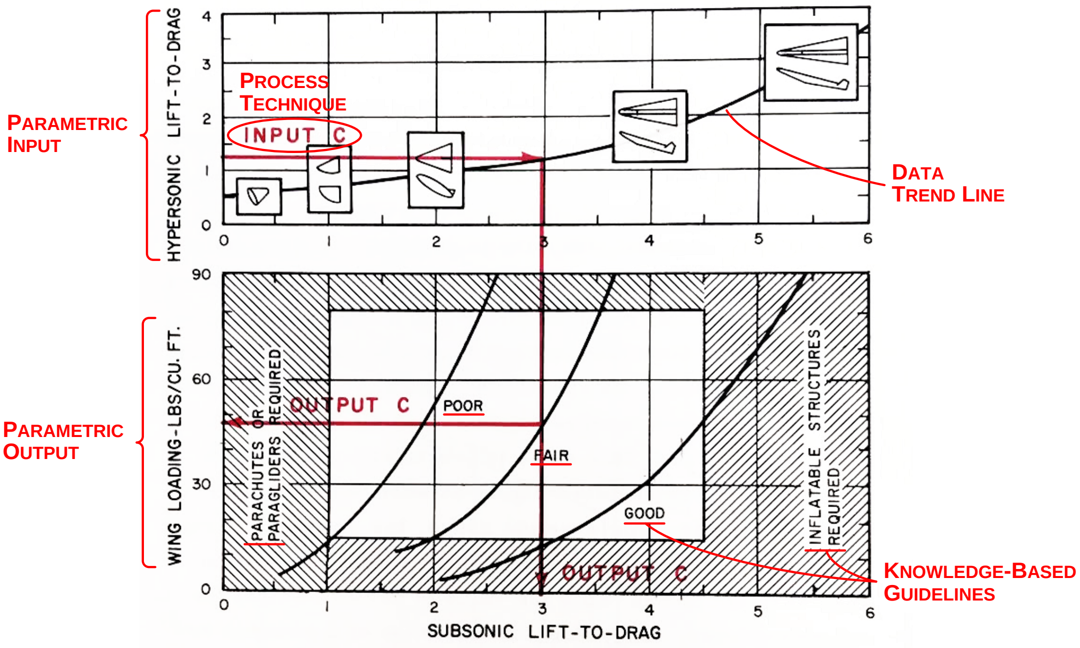


Figure IV.A-9 Approach and Landing Characteristics of Hypersonic Vehicles

Figure 3.3 – Space Planners Guide's use of nomographs of parametric data trends[152]

In this case, the hypersonic lift-to-drag ratio (a measure of the ability to change course & steer during atmospheric reentry among other characteristics) is correlated to the wing loading required to obtain safe landing. By using data in such a parametric approach, the Space Planners Guide ensures that it remain a relevant technique to quickly and correctly assess a broad range of space planning activities far in the future.

3.1.4 Synthesizing Data: Küchemann

Although it is not apparent from the sameness of modern commercial aircraft, subsonic aircraft design offers a tremendous amount of design flexibility. The payload-carrying tube, cantilevered lifting wing, pod-mounted engines and aft mounted control surface configuration is ubiquitous with the public perception of what an aircraft looks like. These commercial aircraft configurations evolved as a function of the freedom their subsonic operating environment permitted. By separating the operational functions of lift, payload volume, propulsion, and stability & control into distinct entities, coupling effects between functions can almost be eliminated. In fact, tube & wing aircraft are designed specifically to take advantage of this disintegrated mechanic – it allows the design process to be divided into the components & subcomponents, optimized for local performance, and then integrated into the total design of the vehicle. This system of division of function allows for a division of labor and a division of skills that greatly simplifies the early design process for a select group of vehicle types.

Table 3.5 – Küchemann's Key Publications

Title	*Year*
Design of Wing Junction, Fuselage, and Nacelles to Obtain the Full Benefit of Sweepback Wings at High Mach Number	1947
On the Chordwise Lift Distribution at the Centre of Swept Wings	1949
Concerning the Flow about Ring-Shaped Cowlings of Finite Thickness	1952
Aerodynamics of Propulsion	1953
Boundary Layer on Swept Wings. Their Effects and their Measurements	1955
A Proposed Research Programme on the Problems Associated with Flight at Low Supersonic Speeds	1956
A Method for Calculating the Pressure Distribution over Jet-Flapped Wings	1957
Hypersonic Aircraft and their Aerodynamic Problems	1965
The Overall Design Concept of Slender Wings for Supersonic Flight	1966
An Analysis of Some Performance Aspects of Various Types of Aircraft Designed to Fly Over Difference Ranges at Different Speeds	1968
The Physics of Airflows and the Design of Aircraft	1969
Some Future Possibilities in Air Transport	1970
The Aerodynamic Design of Aircraft	1978

This disintegrated paradigm, named after Sir George Cayley, a pioneer in aerodynamic research[139], does not hold true across all operating environments however. As the design speed of an aircraft increases, especially above and beyond the speed of sound, the operational functions are placed under increasingly-coupled restrictions. Volume, lift, propulsion and control become interdependent entities that can no longer be solved separately & then integrated, but must be integrated upfront throughout the analysis of the vehicle system.

It was in this design environment that Dietrich Küchemann, a German-born engineer who performed the majority of his research at the Royal Aircraft Establishment (RAE) in England, made his most significant. Küchemann was an aerodynamicist by functional specialty, but he is most well-known for his pioneering involvement in supersonic vehicle design leading to Concorde. From his perspective, aerodynamics was a means to an end – he always strove to tie results back to their overall effects on the aircraft, a necessary trait particularly with supersonic & hypersonic vehicles.

In his posthumously-published book, *The Aerodynamic Design of Aircraft*[167], Küchemann summarizes this mindset by providing the foundations for aerodynamic configuration design as applied to the subsonic, supersonic & hypersonic flight regimes while showing the overall operational efficiency of aircraft as a function of configuration and speed. In order to achieve this grand end-goal in a single view, he needed parametric descriptions for both aerodynamic and propulsive performance as well as a common factor that linked them to the geometric configuration of the aircraft.

Because the interest was in showing the correct sensitivities of the solution, Küchemann used the most base level of synthesis or disciplinary integration formulation available. The Breguet Range equation, shown in Equation 3.1, relates the theoretical range of an aircraft to the propulsion choice (through heat of formation & propulsion efficiency), the aerodynamic efficiency (lift-to-drag ratio), and the required fuel ratio. It should be noted that this relationship does not provide a basis for design since the final variable output is a weight ratio, and not an absolute weight or size. It does however allow different classes of vehicles to be gauged against one another within one analytic equation. The missing piece of the puzzle is the correlation of the Breguet terms to the aircraft configuration (vehicle shape).

$$R = H * \eta_P * \left(\frac{L}{D}\right) * \ln\left(\frac{1}{1 - \frac{W_F}{W}}\right)$$

Equation 3.1

Küchemann characterized this relationship through the geometric aircraft parameter he titled slenderness, the ratio of (half) wing span to overall length. By assuming characteristic shapes for each of the three distinct speed regimes (subsonic – swept wing, supersonic – slender body, hypersonic – waverider), he has been able to assess aerodynamic performance of each configuration throughout the text. By using physically based analytic expressions and known vehicle data points for correlation, he relates cruise speed and slenderness to the overall aircraft lift-to-drag ratio for each configuration. This required extensive reference to both experimental results and theoretical research specializing in aerodynamic phenomena in the specific flight regimes. In the end, this approach allowed Küchemann to illustrate the global solution possibilities for known aircraft configurations in a single graphical representation, shown in Figure 3.4.

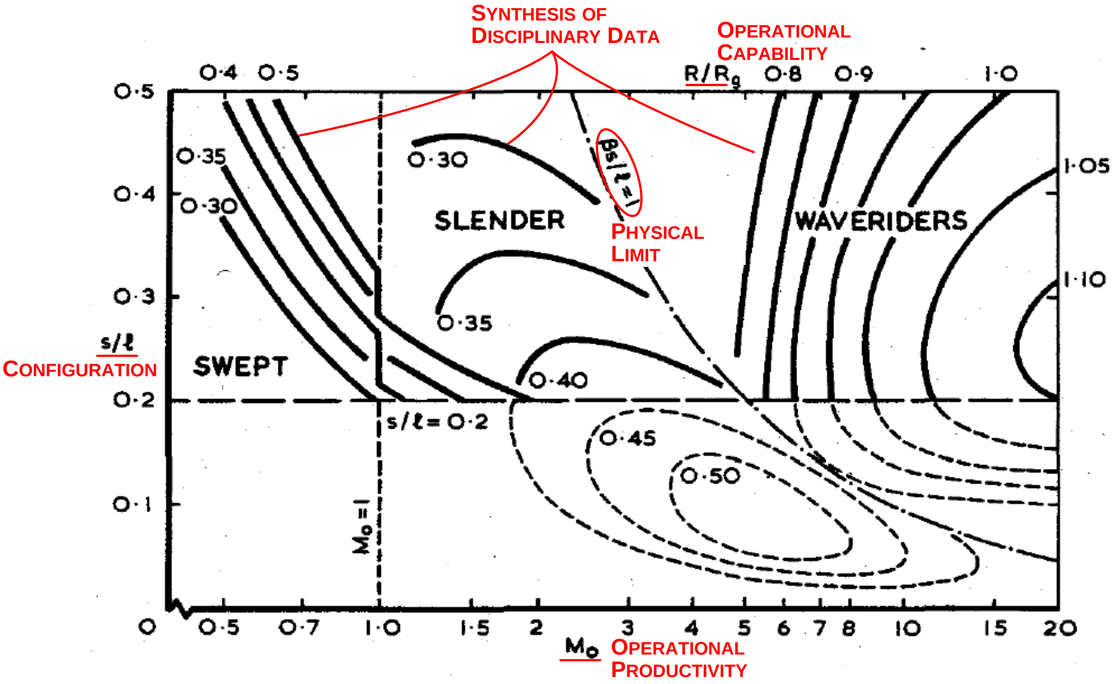


Figure 3.4 – Küchemann's synthesis of multidisciplinary data (modified from [167])

This solution-space topography, a figure presented as a summary towards the end of *The Aerodynamic Design of Aircraft*, illustrates the overall goal of Küchemann's approach. The horizontal & vertical axes represent the speed and slenderness of the aircraft, respectively. The contours within the graph represent the available range. Behind each data curve is a parametric equation for the aerodynamic efficiency, propulsive efficiency, and a data-correlated assumption for the weight ratio, refer above to Equation 3.1. In this single graph, the gross operational productivity, capability and performance of subsonic vs. supersonic vs. hypersonic commercial transportation paradigms is captured. Küchemann provides a birds-eye view of the solution space and provides information of where and where not to place resources for further investigation.

3.1.5 Analyzing Data: DATCOM

While the traditional archetype of data is a numeric quantity, according to the broadest definition of data, descriptive facts or statistics, a more diverse set of elements can be expected. The United States Air Force *Data Compendium* (DATCOM) challenges the data paradigm by treating methods of disciplinary analysis as data. The project did not seek out to create or improve a single method of analysis, but to "*…collect, correlate, codify, and record…*" the best available aerodynamic stability & control methods[168]. The DATCOM development goal has been to provide a streamlined access point for a wide range of aerodynamic analysis methods, or in terms of the present research, a functional data support system that provides stability and control of information to design and analysis engineers.

Table 3.6 – DATCOM Key Publications

Title	*Year*
USAF Stability and Control DATCOM	1960
The USAF Stability and Control Digital DATCOM, Volume I, Users Manual	1979
The USAF Stability and Control Digital DATCOM, Volume II, Implementation of DATCOM Methods	1979
The USAF Stability and Control Digital DATCOM, Volume III, Plot Manual	1979
Adaptation of Digital DATCOM into a Conceptual Design Process	2011

One of the reasons DATCOM remains in use today is the broad scope of aircraft configurations and flight regimes considered within the compendium of analysis methods. The life-cycle phase of vehicle development was also not taken as a given – DATCOM contains first-order methods described as 'very simple' to 'accurate and thorough procedures' that are applicable along a range of design life-cycle phases, all within a unified multi-fidelity toolbox. As supporting elements, DATCOM also provides a complete suite of geometry, weight, and inertia procedures that are needed within stability & control analysis. The end-product inputs base geometric & mission descriptions and outputs a complete suite aerodynamic stability & control derivatives. The user is given guidance on which methods are most applicable to the combination of aircraft configuration and flight envelope through a series of user's manuals[169][170][171].

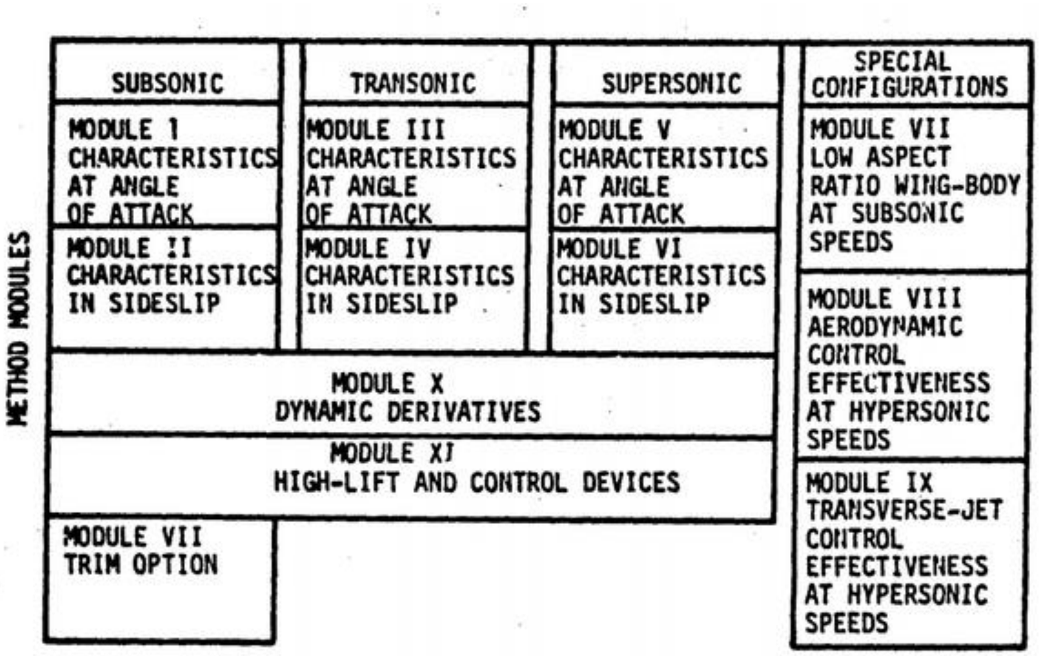
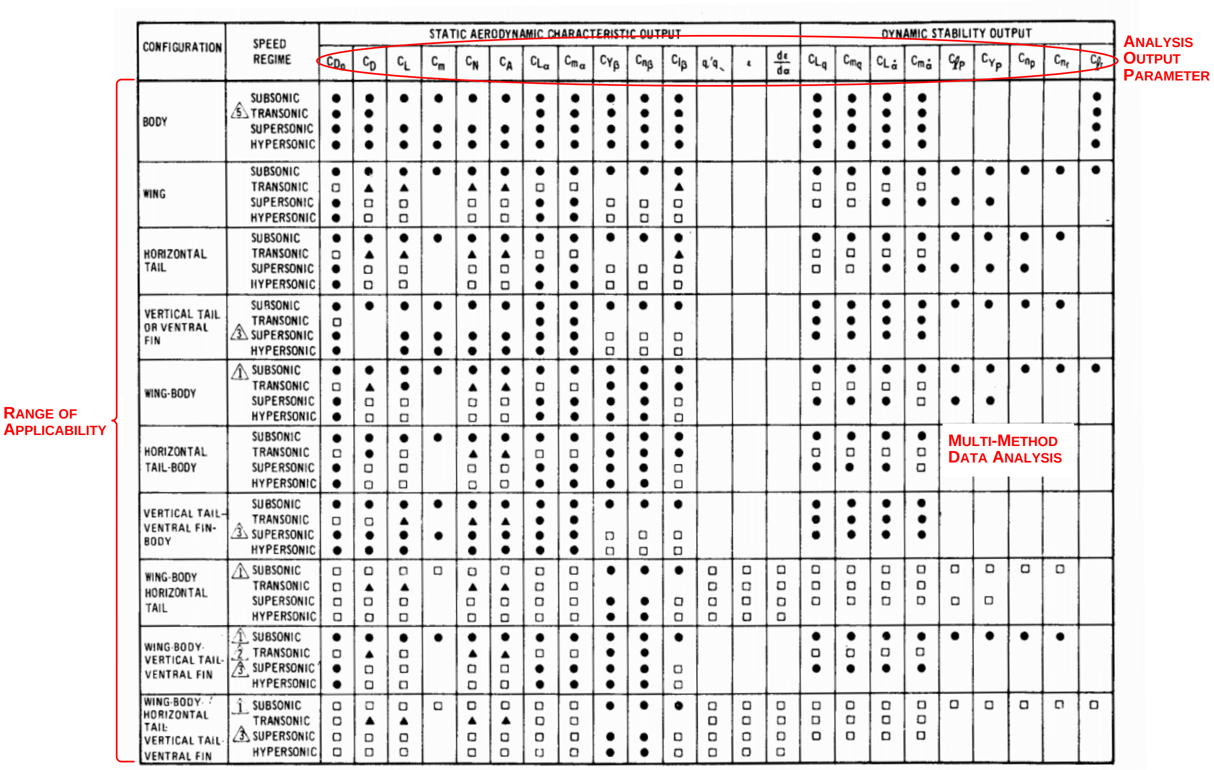


Figure 3.5 – DATCOM Modules across Flight Regimes & Aerodynamic Phenomena[169]



CONFIGURATION	SPEED REGIME	STATIC AERODYNAMIC CHARACTERISTIC OUTPUT														DYNAMIC STABILITY OUTPUT								
		C_{D_0}	C_D	C_L	C_m	C_N	C_A	C_{L_α}	C_{m_α}	C_{Y_β}	C_{n_β}	C_{l_β}	q'/q_∞	ϵ	$\frac{d\epsilon}{d\alpha}$	C_{L_q}	C_{m_q}	$C_{L_{\dot{\alpha}}}$	$C_{m_{\dot{\alpha}}}$	C_{l_p}	C_{Y_p}	C_{n_p}	C_{n_r}	C_{l_r}
BODY	SUBSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●					●
	△5 TRANSONIC	●	●					●	●	●	●	●				●	●	●	●					●
	SUPERSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●					●
	HYPERSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●					●
WING	SUBSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●	●	●	●	●	●
	TRANSONIC	□	▲	▲		▲	▲	□	□			▲				□	□	□	□					
	SUPERSONIC	●	□	□		□	□	●	●	□	□	□				□	□	●	●	●	●			
	HYPERSONIC	●	□	□		□	□	●	●	□	□	□												
HORIZONTAL TAIL	SUBSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●	●	●	●	●	
	TRANSONIC	□	▲	▲		▲	▲	□	□			▲				□	□	□	□					
	SUPERSONIC	●	□	□		□	□	●	●	□	□	□				□	□	●	●	●	●	●		
	HYPERSONIC	●	□	□		□	□	●	●	□	□	□												
VERTICAL TAIL OR VENTRAL FIN	SUBSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●	●	●	●	●	
	TRANSONIC	□						●	●							●	●	●	●					
	△3 SUPERSONIC	●		●	●	●	●	●	●	□	□	□				●	●	●	●					
	HYPERSONIC	●		●	●	●	●	●	●	□	□	□												
WING-BODY	△1 SUBSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●	●	●	●	●	●
	TRANSONIC	□	▲	●		▲	▲	□	□	●	●	●				□	□	□	□					
	SUPERSONIC	●	□	□		□	□	●	●	●	●	□				●	●	●	□	●	●			
	HYPERSONIC	●	□	□		□	□	●	●	●	●	□												
HORIZONTAL TAIL-BODY	SUBSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●					
	TRANSONIC	□	●	□		▲	▲	□	□	●	●	●				□	□	□	□					
	SUPERSONIC	●	□	□		□	□	●	●	●	●	□				●	●	●	□					
	HYPERSONIC	●	□	□		□	□	●	●	●	●	□												
VERTICAL TAIL-VENTRAL FIN-BODY	SUBSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●					
	TRANSONIC	□	□	▲		▲	▲	●	●							●	●	●	●					
	△3 SUPERSONIC	●	●	●	●	●	●	●	●	□	□	□				●	●	●	●					
	HYPERSONIC	●	●	●		●	●	●	●	□	□	□												
WING-BODY HORIZONTAL TAIL	△1 SUBSONIC	□	□	□	□	□	□	□	□	●	●	●	□	□	□	□	□	□	□	□	□	□	□	
	TRANSONIC	□	▲	▲		▲	▲	□	□				□	□	□	□	□	□	□					
	SUPERSONIC	□	□	□		□	□	□	□	●	●	□	□	□	□	□	□	□	□	□	□			
	HYPERSONIC	□	□	□		□	□	□	□	●	●	□	□	□	□									
WING-BODY-VERTICAL TAIL-VENTRAL FIN	△1 SUBSONIC	●	●	●	●	●	●	●	●	●	●	●				●	●	●	●	●	●	●	●	
	△2 TRANSONIC	□	▲	□		▲	▲	□	□	●	●					□	□	□	□					
	△3 SUPERSONIC	●	□	□		□	□	●	●	●	●	□				●	●	●	●					
	HYPERSONIC	●	□	□		□	□	●	●	●	●	□												
WING-BODY-HORIZONTAL TAIL-VERTICAL TAIL-VENTRAL FIN	1 SUBSONIC	□	□	□	□	□	□	□	□	●	●	●	□	□	□	□	□	□	□	□	□	□	□	□
	TRANSONIC	□	▲	▲		▲	▲	□	□				□	□	□	□	□	□	□					
	△3 SUPERSONIC	□	□	□		□	□	□	□	●	●	□	□	□	□	□	□	□	□					
	HYPERSONIC	□	□	□		□	□	□	□	●	●	□	□	□	□									

ANALYSIS OUTPUT PARAMETER

RANGE OF APPLICABILITY

MULTI-METHOD DATA ANALYSIS

Figure 3.6 – DATCOM's compilation of multiple analysis methods[169]

DATCOM remains in use today, because it was not built as a static tool purpose-built for a specific problem, but as a systematic framework to organize analysis methods, see Figure 3.6. Because the procedure of creating and executing the framework is very well documented, as well as the source code being openly available, the capabilities of DATCOM have constantly been refined and updated by various aerospace organizations. The framework has also been applied in a separate (security-restricted) tool *Missile DATCOM*[172], which also represents an industry standard, for the aerodynamic design of missile systems.

3.1.6 Normalizing Data: Hypersonic Convergence

As with the previous case of Küchemann in Europe, see section 0 above, engineers & researchers in the United States also sought to develop techniques that laid out broad vehicle system solutions for early design understanding. Paul A. Czysz championed this systems-level mindset during his career as a manager and chief engineer at McDonnell Aircraft Company working on programs varying from military fighter aircraft to supersonic & hypersonic transport concepts to space access vehicles. Using these experiences, he developed an educational course for the early design investigation of air and space vehicles, later published as a contractor report through the United States Air Force. *Hypersonic Convergence*[176][177][178] details Czysz's technique to normalize characteristic vehicle data in such a way as to create universal regressions, allowing the parametric sizing of any flight system to its mission requirements under a unified process.

Table 3.7 – Csysz's Key Publications

Title	*Year*
Supersonic Hydrogen Combustion Studies	1963
Thermographic Heat Transfer Measurement	1968
Hypersonic Convergence	1989
Energy Analysis of Propulsion Systems for High Speed Vehicles	1989
Energy Analysis of High-Speed Flight Systems	1991
Space Transportation System Requirements Derived from the Propulsion Performance	1992
Rocket Based Combined Cycle Engine – A Propulsion System for the 21st Century	1993
Interaction of Propulsion Performance with the Available Design Stage	1995
Transatmospheric Launcher Sizing	2000
Rocket-Based Combined-Cycle Power Spaceliner Concept	1996
Magnetohydrodynamic Coupled Ramjet Propulsion System – a Perspective	2001
Future Space Tourism Transportation Design Requirements	2005
Future Spacecraft Propulsion Systems: Enabling Technologies for Space Exploration	2009
Solution-Space screening of a Hypersonic Endurance Demonstrator	2012

Czysz defines system solution possibilities by the concept of a 'solution space'. The 'solution space' represents a system-converged multi-dimensional map of potential alternatives with a consistent numerical gauge. Its purpose is not to provide a "*…specific answer to a question in great detail, but [with] no comprehension of the surrounding area…*" but to "*…identify the strata and identify where to look for answers…*" In order to accomplish this utilitarian task, Czysz does not solely rely on theoretically-based analysis. Instead, relying on correlating normalized data-points to provide design trends weighted towards existing, thus well-researched and well-defined, air and space vehicle designs.

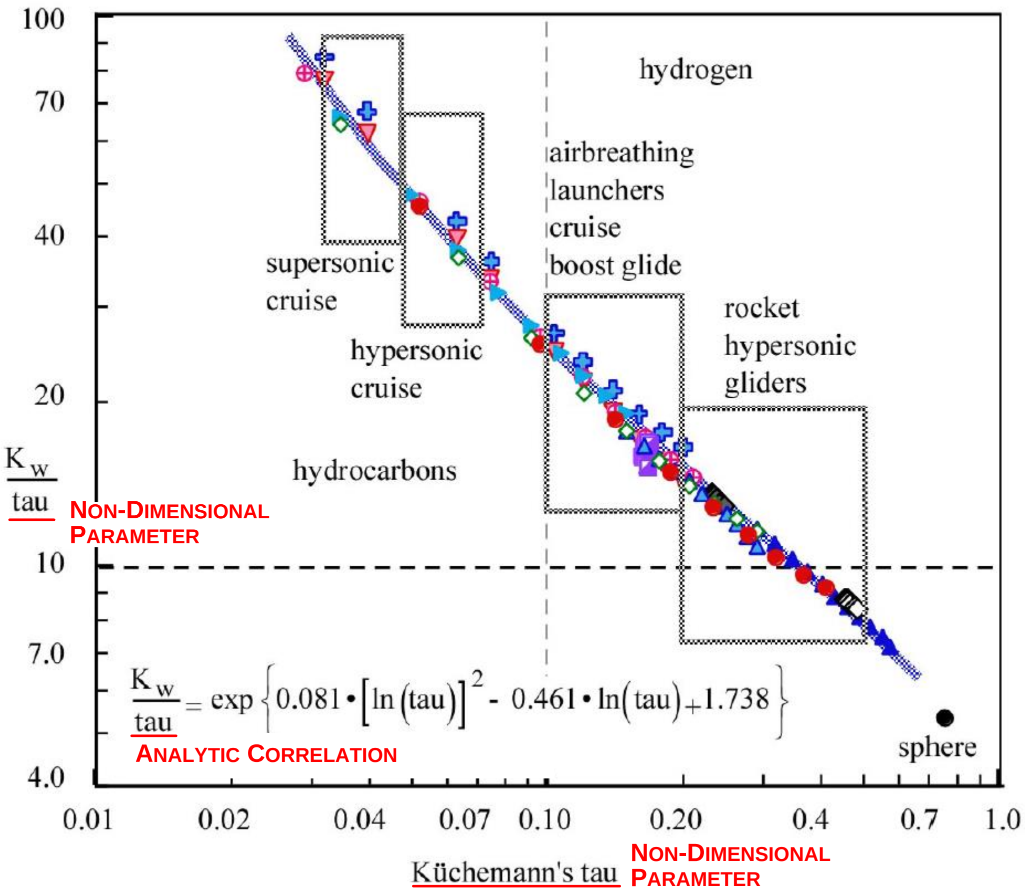


Figure 70. Determination of the Geometric Characteristics of Hypersonic Aircraft by Mission and Fuel

Figure 3.7 – Hypersonic Convergence usage of normalized parameters for design[176]

By normalizing data to create non-dimensional or scalable data-sets, Czysz successfully condenses entire families of similar correlation trends into a singular design trend lines, see Figure 3.7. This ultimately allows the end-user, ranging from vehicle design engineers, chief engineers and program managers, to identify the base size, weight and configuration required for a prospective mission by a series of interrelated analytic expressions. Note that these relations, of which Figure

3.7 is one example, are not found elsewhere. Design synthesis even at the earliest stages of design exploration and definition, requires integrated systems analysis and iteration between a series of disciplinary relationships. Explicit relationships validated with actual flight vehicles allow systems designers to frame the candidate solutions to a range of problems in an effective and efficient manner that would not be possible otherwise.

3.2 CURRENT STATE OF AEROSPACE INDUSTRY DATA SUPPORT SYSTEMS

While Chapter 2 provided a generalist view of effort in the data domain, the majority of the aerospace data tools available today, in contrast, do not support or encourage this type of data usage. The aerospace environment appears locked in around traditional passive databases & reference compendia, leaving data as something that is looked up when needed, used, and then discarded. A critical look at some of the most notable aerospace data sources shows patterns of how current engineers in the field use and misuse the available data resources.

3.2.1 Jane's All the World's Aircraft©

Founded in 1909 by Fred Jane, an aviation enthusiast and amateur pilot, *Jane's All the World's Aircraft*© has been a go-to-references for aircraft data for more than a century. Jane's provides technical and operational data of "*…all known powered aircraft…currently in, or anticipating, commercial production in all countries of the World…*"[191] This all-encompassing goal is accomplished through a methodical country-by-country, manufacturer-by-manufacturer catalogue of vehicles, their properties, and corresponding images. For major commercial and military programs, a timeline is presented along with a detailed breakdown of orders & deliveries. Aircraft derivative configurations are discussed in paragraph form & qualitatively compared where possible. Missiles & aircraft engine data is also reported but in a tabular format, as opposed to the single-entry view of full aircraft. All entries are encompassed in an index for search purposes.

Although *Jane's*, now owned by *IHS*[1], produces a number of different aerospace & defense information reference sources, it is most well-known version for the flagship *Aircraft* edition, now split between Development & Production, In Service, and Unmanned versions. *Aircraft* was traditionally offered as a print book, but recent editions have expanded to offer online digital access and improved search functionality.

---

[1] www.ihs.com/about/history.html

Table 3.8 – Representative Jane's All the World's Data Variables

Discipline	*Variables*
General	Country, Manufacturer, Vehicle Description
Weights	Gross Weight, Takeoff Weight
Geometry	Length, Width, Height, Reference Areas
Performance	Speed, Endurance, Range, Climb

3.2.2 IHS Engineering Sciences Data Unit

The *Engineering Sciences Data Units* (ESDU) is an online reference service, created in 1940 as a technical service by the Royal Aeronautical Society for design in engineers, is now also owned and hosted by *IHS*[2]. ESDU provides "*…validated design methods, data and software tools covering a wide range of engineering disciplines…*" in order 'improve the design process', 'reduce time to market', and 'complement in-house design manuals, codes, standards and analysis tools.' Aerodynamics, structures, aircraft noise, dynamics, fatigue, heat transfer, internal flow, performance, stress analysis, transonic aerodynamics, and vibration topics are all given their own topic summaries with detailed subchapters[192].

ESDU allows users to zero-in on topics of interest from a select list of engineering fields and are provided a condensed summary of the topic with relevant references, analysis procedures, and tool platforms. The content of each topic is overseen by a steering committee consisting of subject-matter industry and academic experts. Data and topic summaries are pulled from a variety of common aerospace sources including DATCOM (see section 3.1.5 above) and NASA Reports (see section 3.2.9.1 below), creating an encyclopedic summary with linked referencing to primary sources. Although closer to a rudimentary *Knowledge-Engineering System,* ESDU is included due to its close ties to industry leaders (Airbus, BAE, Boeing, Lockheed Martin, ESA, NASA, FAA, and the National Research Council, among others, serve on committee panels overseeing subject matter guides).

3.2.3 International Reference Guide to Space Launch Systems

The *International Reference Guide to Space Launch Systems* is a print document in its 4th edition published by American Institute of Aeronautics and Astronautics (AIAA) and authored by Stephen Isakowitz, Josh Hopkins, & Josh Hopkins Jr. The Guide presents technical statistics describing present & past expendable launch vehicle systems from around the world (30+ launch systems are detailed)[193]. The format of the reference guide has each vehicle system described in

---

[2] www.esdu.com

detail one-by-one with engineering drawings, flight manifests, performance figures, and technical data. Although the Guide provides a narrow band of data on launch vehicles only, the depth and completeness of data about each vehicle system have made it a go-to source of reference data in space system design and analysis.

Table 3.9 – Representative International Reference Guide to Space Launch Systems Data Variables

Discipline	*Variables*
General	Country, Manufacturer, Vehicle Description, Configurations, Flight Records
Weights	Gross Weight, Takeoff Weight, Fuel Weight, Payload Weight
Geometry	Length, Width, Height, Reference Areas
Performance	Thrust, Separation Altitude, Delivery Orbit
Cost	Acquisition Cost

3.2.4 Aviation Week & Space Technology Aerospace Source Book

Table 3.10 – Representative AW&ST Source Book Variables

Category	*Discipline*	*Variables*
Turbine Engine	General	Country, Manufacturer, Vehicle Description
	Propulsion	Stages, Power, Thrust, Combustor Details
	Geometry	Length, Diameter
	Weight	Dry Weight
Commercial Aircraft	General	Country, Manufacturer, Vehicle Description, Configurations
	Propulsion	Type, Thrust
	Geometry	Length, Width, Height, Wing Area
	Weight	Takeoff Weight, Empty Weight, Payload Weight, Fuel Weight
	Performance	Passenger Capacity, Cruise Speed, Altitude, Landing Distance, Range
Helicopter	General	Country, Manufacturer, Vehicle Description
	Propulsion	Thrust, Power
	Geometry	Length, Width, Height, Rotor Area
	Weight	Takeoff Weight, Empty Weight, Fuel Weight,
	Performance	Passenger Capacity, Cruise Speed, Altitude, Endurance
Launch Vehicles	General	Country, Manufacturer, Vehicle Description
	Propulsion	Propellant, Thrust
	Geometry	Height, Diameter, Payload Dimensions
	Weight	Takeoff Weight, Empty Weight, Payload Weight, Fuel Weight
	Performance	Separation Speed, Separation Altitude, Staging, Orbital Altitude

Aviation Week & Space Technology (AW&ST) is an aerospace industry magazine that has been in publication since 1916. Each year, AW&ST provides a special issue titled the *Aerospace Source Book* containing long-term outlooks for the major industry fields within aerospace, as well as a statistical summary of vehicle systems characteristics. The Source Book spans commercial, military, freight, rotorcraft, UAV, business and general aviation, engines, space launch systems, and missiles, each with their own qualitative market forecast and quantitative data table.

The formatting of the data tables across aerospace markets is roughly the same, with universal subsections for dimensions, weights, performance, and vehicle status being constant throughout. Within these subsections, data is broken out into market-specific parameters that are uniquely significant to their field (i.e. FAA landing field length for commercial, endurance for UAV's, propellant types for launch vehicles). Vehicles systems are grouped along their prime manufacturer & sorted alphabetically. Although no index or search capability is provided in the print edition, the Source Book has been made available online as a PDF in its current versions.

3.2.5 Aerospace America Worldwide UAV Roundup

The yearly-published *Worldwide UAV Roundup*[194] is created by *Aerospace America*, a sub-division of *AIAA*, and provides general information about global unmanned aerial systems. Vehicles are grouped by country and then sorted alphabetically by prime contractor. Overall performance data (endurance, range, & ceiling) are reported, along with a general mission description. The roundup document is published online on a bi-yearly basis in a search-able PDF format from Aerospace America's website (www.aerospaceamerica.org). Although broad coverage of vehicle systems is provided, the lack of depth and detailed data about each UAV makes the roundup an underwhelming resource for all but basic data collection requirements.

Table 3.11 – Representative Aerospace America Worldwide UAV Roundup Variables

Discipline	*Variables*
General	Country, Manufacturer, Vehicle Description, Status, Mission
Propulsion	Type
Performance	Endurance, Range, Service Ceiling

3.2.6 Defense & Aerospace Competitive Intelligence Service

The *Defense & Aerospace Competitive Intelligence Service* (DACIS) database, published by *InfoBASE Publishing*, provides program manager and executive-level aerospace program data. DACIS contains linked database modules focusing on Companies, Contracts, Programs, Customers and Mergers & Acquisitions. Public data from the US Government-run *FedBizOps* aerospace & defense contract portal and the yearly *Department of Defense* budget are included as additional modules. The separate databases are cross-linked and searchable, allowing users to improve their decision-making insight, reduce resources spent finding programmatic data, and ultimately, ‘gain a competitive advantage’[195].

3.2.7 RAND Military Vehicle Database

The RAND Corporation, a non-profit government-sponsored think-tank developed a database containing “…descriptive, historical, and numerical information on most fixed-wing and related military and commercial R&D programs undertaken by U.S. aerospace contractors after World War II…” during the course of research for their survey of the fighter research and development history[196]. The database focuses on programmatic data, see Table 3.12, and providing a complete catalogue of vehicle systems. Technical data about vehicle systems is not addressed with the database, nor is any reference to external sources presented.

Table 3.12 – Representative RAND Military Vehicle Database Variables

Discipline	*Variables*
General	Manufacturer, Vehicle Type, Dates of Design / Test / Development
Performance	Speed

3.2.8 Technology-Specific Databases

When examining an aerospace vehicle at a component or sub-component level for detailed design or technical information, it is required to have supporting technical data in order describe the physical phenomena governing the environment. Although the type of information varies greatly between total system design and sub-component analysis, the need for data management and support remains constant. A number of technology-specific databases are available that, within their specialized field, are go-to sources for data.

3.2.8.1 CINDAS Aerospace Structural Metals Database

The *Aerospace Structural Metals Database* (ASMD) is the digital embodiment of the *Aerospace Structural Metals Handbook* (ASMH)[197], which is a reference document commissioned by the U.S. *Department of Defense* to standardize material properties for engineering & technical usage. ASMD is maintained by *CINDAS LLC* as an online platform that provides scientific & technical personnel access to properties and relationships for “*...230 metal alloys with over 85,000 data curves...*”[198] Results of a property and material search engine can be visualized in an interactive graphical view. Data curves representing the same material-property combination can be overlaid from available reference sources. The graph may be resized to zoom in or out as needed, individual data points are selectable, and the axes units may be changed from a preset list. An attached view provides the reference citation for each data curve and a link to the full text of the ASMH.

3.2.8.2 C&R Technologies TPSX

The *Thermal Protection Systems Expert* (TPSX) *Materials Properties Database* was created by C&R Technologies in conjunction with NASA Ames Research Center. The database contains material properties for over 1500 materials provided by NASA and industry TPS experts with query-able property data formatted for export into thermal analysis software[199].

3.2.8.3 NIST Standard Reference Database

The US National Institute of Standard and Technology (NIST) is tasked by the Standard Reference Data Act of 1968 to provide "…reliable standardized scientific and technical reference data…" and make the it "…readily available to scientists, engineers, and the general public..." [200] Today, NIST provides the Standard Reference Database (SRD) online and through digital hard copy, pulling scientifically-vetted datasets across chemistry, biology, environmental data, material properties, atomic physics and others.

NIST has implemented a 'Data Gateway' that allows users to search for properties across the various reference databases creating a functionality that is especially powerful for accessing material, chemical, and atomic properties across source datasets. A search results in a link to each database in which the search object appears.

3.2.9 Report Servers

The majority of formalized aerospace information resides in books, technical reports, journal articles, conference proceedings, presentations, and academic theses[201]. The current paradigm of engineering information dissemination is to: **(1)** create data through focused research or development, **(2)** editorialize the results into a cohesive storyline that creates an intended informational conclusion, and then **(3)** publish the final product through one of the above mediums where it is stored for future information use.

In order to manage this paradigm of information, modern digital analogues to physical libraries have now become commonplace to collect, store, organize and recall data describing published technical documents. These report servers do not seek to extract the embedded data within the documents, but *seek only* to guide interested scientific and technology personnel to the correct *source* *of data*. As such, the data found in an online report server is data about sources of data, referred to as *meta-data* (see section 2.2.1).

The rise of the *Adobe Portable Document Format* (PDF) has greatly changed the medium through which digital documents are accessed. By offering a standardized reading experience across operating systems (including mobile and tablet devices), it has quickly spread as the go-to file format for technical documents. The built-in functionality to recognize text from a non-digital original document has also expanded the potential to search and access digital versions of documents. *Optical Character Recognition* (OCR) technology allows physical documents to be effectively *digitized* by scanning their contents to a digital format and then processing the digital image to recognize the text contents within[203]. This allows for search engines to search not only the meta-data, but also the text contents within the source document. OCR has expanded keyword searches to the contents of the documents within the report server thereby improving the likelihood of relevant search results[204].

The ability to search meta-data has become the central functionality for the majority of modern aerospace, and non-aerospace, digital report servers. Standardized bibliography fields (title, author, publisher, year, report / identification number, etc.) are indexed to allow for search for a specific source or to filter results based on desired criteria (i.e. all sources by author ‘John Anderson’ between 1985 & 1990 or conference proceedings about the topic ‘computer-aided design’).

Report servers specializing in sub-sets of technical documentation or sponsored by industry organizations are now a mandatory intermediary for accessing most data in aerospace. The design & functionality of these data systems is further investigated.

3.2.9.1 NASA Technical Report Server

The National Aeronautics & Space Administration hosts a report server (www.sti.nasa.gov) that seeks to collect “…facts, analyses, and conclusions resulting from scientific, technical, and related engineering research and development efforts, both basic and applied.” The NASA Technical Report Server (NTRS) is the by-product of the NASA Scientific and Technical Information (STI) Program that is dedicated to the “…advancement of aeronautics and space science…”, “…avoid[ing] duplication of research by sharing information…”, and “…ensur[ing] that the U.S. maintains its preeminence in aerospace-related industries and education.” Records are available to the public through the NTRS with a NASA-internal and contractor version holding more technically-sensitive information. This accessibility availability came under scrutiny in 2013 after NASA unexpectedly took the NTRS offline in response to a potential breach of data to a foreign national suspected of espionage[205].

NTRS allows users to search through the massive database of report bibliographies containing 4 million plus technical documents, with the ability to immediately view 500 thousand plus full-text PDF documents[9]. The remaining documented records are either not available in their entirety through NASA-sponsored sources, or must be requested through a built-in form that must be processed by the NASA *Center for AeroSpace Information* (CASI) before dissemination. The records have been indexed and are searchable by standard bibliographic fields, as well as topic-specific keywords. Documents from separate aerospace report servers, namely AIAA (see section 3.2.9.3 below), are included in search results, but their availability is limited to NASA-internal users. In order to add a document to the NTRS, it must first go through a bureaucratic editorial procedure administered by STI. NASA-authored research papers are automatically filed into the STI-approval system, while outside-authored documents must be entered and approved on a case-by-case basis.

3.2.9.2 Defense Technical Information Center

The *Defense Technical Information Center* (DTIC) is an online collection (www.dtic.mil) of engineering and scientific documents hosted by the U.S *Department of Defense* (DoD). It seeks to "*…maintain management systems for information storage, retrieval and access…*" to "*…provide essential, technical research, development, testing and evaluation (RDT&E) information rapidly*."

Over 2 million citations are available through a keyword and field-index search. Where available, the full-text is readily available in PDF format through the search-results. There is no procedure, however, to request documents that are listed only by citation, nor is there built-in functionality to trace these documents to a native source. The publicly-available online version is also granted access to approximately half of all document entries, with the other half holding an Unclassified, Limited or Classified document distribution designation[207].

3.2.9.3 AIAA Aerospace Research Central

Aerospace Research Central (ARC) is the online repository for technical journal and conference papers for the *American Institute of Aeronautics & Astronautics* (AIAA) technical organization (arc.aiaa.org). Documents that have been previously published in AIAA peer-reviewed journals or presented at AIAA peer-refereed conferences are available for bibliographic search. All documents have been digitized into PDF format, but require an individual or organizational subscription for access.

3.2.9.4 CSA Aerospace and High Technology Database

The *Cambridge Scientific Abstracts* (CSA) Aerospace and High Technology Database is an online catalogue for technical documents, journal articles, and government reports and seeks to offer "*…the most comprehensive bibliographic coverage of research, emerging technologies, applications and companies in the areas of aeronautics, [and] astronautics…*" The database is administered by *ProQuest*, a company that focuses solely on providing information products to a variety of research and technology fields[208].

The Aerospace and High Technology Database functions as standard bibliographic-search report server, but also has a number of unique features of particular interest[209].

- The 'Deep Indexing' feature allows searches to expand to include graphs, tables, figures, and their associated labels. These elements are available for viewing outside of the source document, directly in the search results.
- An adaptive search procedure suggests tangent search keywords and keyword combinations that may result in relevant documents.
- Personalized data management tools are embedded within the platform. Users may save search queries, documents, tables and figures, as well as add annotated notes to saved elements.
- Users may add their own tags to data elements that are then available to the general search community, creating an interactive and continually adapting set of meta-data.

3.2.9.5 Knovel

Knovel is an online reference source (app.knovel.com) for scientific and technical information with a subset for aerospace & defense topics. The platform seeks to allow engineers in product design and development to save time, increase efficiency, and sustain a competitive advantage by allowing access and navigation through 'multiple sources of information'[210]. Search results return standard bibliographic citations as well as full-text technical documents where available. Contents of technical textbooks is also made fully available to search and access online through cooperative publishers (Knovel is owned & operated by *Elsevier*[3]). Knovel has collaborative agreements with *AIAA*, *AIChE*, *ASME* and *NACE* to provide source documents through their platform.

---

[3] http://www.elsevier.com/online-tools/knovel

In addition, scientific reference tables (material properties are the most widely available currently) have been incorporated into the online system as search-able, query-able, and export-able elements through Knovel's *Data Search* feature. Users may search for desired properties to find matching materials, properties of a desired material, or any combination of the two. The search results return the source reference of the data, as well as an interactive embedded data-table that may be queried, sorted, and filtered to provide a condensed data bank of candidate materials. The final data table may be exported in standardized formats (Excel, PDF, csv) for further examination.

3.2.10 Integration Platforms

As a reaction to engineering and analysis tasks which require translation between multiple discrete platforms, support platforms have emerged with the goal of integrating data across systems. These integration platforms allow the user to set up some form of translation decoder between disciplinary analysis environments, which is thereafter an automated connection. Especially in organizations which traditionally segment tasks between specialists, standardized data integration systems promote collaborate design and forecasting activities in a single environment.

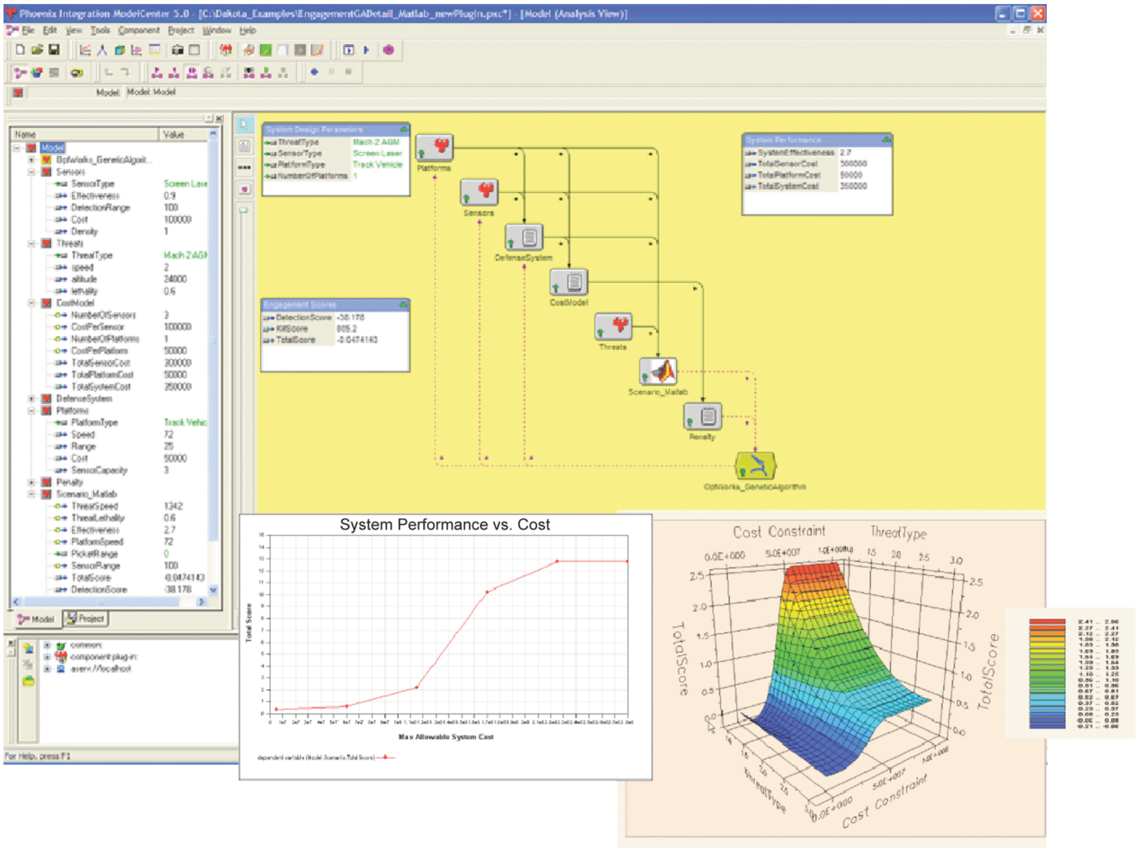
3.2.10.1 Adaptive Modeling Language

TechnoSoft Inc. (in collaboration with the Air Force Research Laboratory and NASA Langley[211]) has developed on object-oriented integration platform, *Adaptive Modeling Language* (AML), for use in aerospace vehicle design & analysis. AML "*...provides a geometry-centric environment...*" that allows disciplinary engineers to integrate all analysis tasks into a single AML environment description of the system. AML facilitates this centralization by linking variables between analysis models with the aid of native data handling functions and an adaptive GUI[212].

The object-oriented nature of AML ensures that analysis processes are interchangeable within the larger model construct as long as they provide the needed data. By allowing for analysis integration independent of analysis fidelity, this characteristic allows AML to be flexibly used throughout the design and development cycle. This multi-fidelity freedom is a distinguishing feature of the AML platform.

3.2.10.2 Phoenix ModelCenter & AnalysisLibrary

Phoenix Integration, Inc. has developed a suite of integration platforms that tackle distinct issues within multi-disciplinary and multi-system engineering, design and analysis. *ModelCenter* is Phoenix's commercial sand-box integration platform for multi-source analysis methods. Built as a means to perform *multi-disciplinary design analysis & optimization* (MDAO), ModelCenter provides a GUI-driven environment for linking variables between existing analysis procedures, wrapping systems-level frameworks with built-in optimizer functions, and viewing multivariate output. Modular analysis integration, especially of existing legacy analysis codes, and native MDAO capabilities has made ModelCenter a preferred platform for some aerospace & defense design forecasting organizations[213].



Name	Value
Model	
OptWorks_GeneticAlgorit...	
Sensors	
SensorType	Screen Lase
Effectiveness	0.9
DetectionRange	100
Cost	100000
Density	1
Threats	
ThreatType	Mach 2 AGN
speed	2
altitude	24000
lethality	0.6
CostModel	
NumberOfSensors	3
CostPerSensor	100000
NumberOfPlatforms	1
CostPerPlatform	50000
TotalSensorCost	300000
TotalPlatformCost	50000
TotalSystemCost	350000
DefenseSystem	
Platforms	
PlatformType	Track Vehic
Speed	72
Range	25
Cost	50000
SensorCapacity	3
Penalty	
Scenario_Matlab	
ThreatSpeed	1342
ThreatLethality	0.6
Effectiveness	2.7
PlatformSpeed	72
PicketRange	0
SensorRange	100
TotalScore	-0.0474143
DetectionScore	-38.178

System Design Parameters

ThreatType	Mach 2 AGM
SensorType	Screen Laser
PlatformType	Track Vehicle
NumberOfPlatforms	1

Engagement Scores

DetectionScore	-38.178
KillScore	805.2
TotalScore	-0.0474143

System Performance

SystemEffectiveness	2.7
TotalSensorCost	300000
TotalPlatformCost	50000
TotalSystemCost	350000

Figure 3.8 – Phoenix ModelCenter Analysis Canvas[213]

As seen above in Figure 3.8, each analysis module is represented within an integrated canvas by an icon with each analysis module (possibly) having its own software programming environment; FORTRAN, C++, Excel and MATLAB programs are directly interface-able, with standardized text-based connections available for more complex data constructs (e.g. 3-D geometry structures for finite element analysis or computational fluid dynamics). The GUI-based integration platform also allows the connection of variable dependencies between modules, including recursive convergence and optimization routines. Once executed, results can be visualized in-line within the ModelCenter environment.

3.2.11 Assessment of Data-Engineering Performance in Aerospace Design Forecasting

As expected from anecdotal experience within the aerospace design industry, the collection of aerospace-specific data platforms confirms the notion that data and knowledge are siloed within disciplines, require significant effort to extract into a usable format, and are not inherently compatible with systems-level analysis required during design forecasting efforts. The introduction of knowledge-based features is being adopted, although slowly and with varied consistency within industry niches. Analysis integration platforms have been generalized to accommodate variable fidelity and variable discipline design methodologies, but fail to address *Data-Engineering* tasks that precede (or supersede) systems analysis in a structured processes. Overall, the current aerospace data systems do not offer a unified data-knowledge-analysis approach to traditional vehicle systems design problems, and provide insufficient structure for non-traditional data & knowledge-driven forecasting approaches required in the modern information environment. The key missing elements from aerospace data systems are categorically listed below in Table 3.13.

Table 3.13 – Pitfalls of Existing Aerospace Data Systems

Data System Category	*#*	*Pitfall(s)*
Vehicle DBs	1	Reference data is only practical in design analysis if it can be digitized and implemented with minimal effort.
	2	Data is presented as a static entity, not to be adjusted between publishing iterations.
Report Servers	3	Data is presented in its raw form with the onus for extraction placed on the data user, and not on the data system.
	4	Reliance on external factors (e.g. classification, membership, digitization) for user accessibility.
	5	Do not account for the functional information requirements of practicing engineers.
Technology-Specific DBs	6	Data is stored in topic-specific databases that are only known within their defined community.
Overall	7	User lacks ability to influence data and-or data system with project and personal experience
	8	Platforms are discrete entities along continuous Data-Engineering tasks.
	9	Man-data interactions are treated as personal responsibilities, and not as organizational investments.

An overarching thread within current aerospace data systems is the consistent treatment of data as a second-class entity to the engineering definition, design and development processes. The data domain, tasked with capitalizing on the stockpiled progress of 100 plus years of aerospace research and development, is fragmented from the technical analysis domain. Front-end DE tasks at the industry and organizational levels are left as responsibilities of historians[214][215] and information and library scientists[201][202] – the personnel and processes that operate the remaining *DE* and information tasks (data analysis, data visualization, system-level synthesis, and communication of information) have little influence in how data is handled and presented at an organizational level, shown in Figure 3.9.

Data-Engineers, then, are forced to create personal libraries, file systems, and data processes that supplement existing traditional data systems, dragging static and ill-prepared data systems towards implementation in technical analysis, design and forecasting activities. Without the formal definition and education of *Data-Engineering* principles, the bridging of internal data systems and interfacing with analysis platforms remains a task left to the individual engineer. Because of this isolation away from organizationally standardized and unified processes, the capability to re-purpose data gathered and learn from experiential knowledge gained during engineering information tasks rests untapped. In this paradigm the engineer is the sole repository of the knowledge required to operate these data and information processes, with no formal outlet to inform future efforts by other personnel.

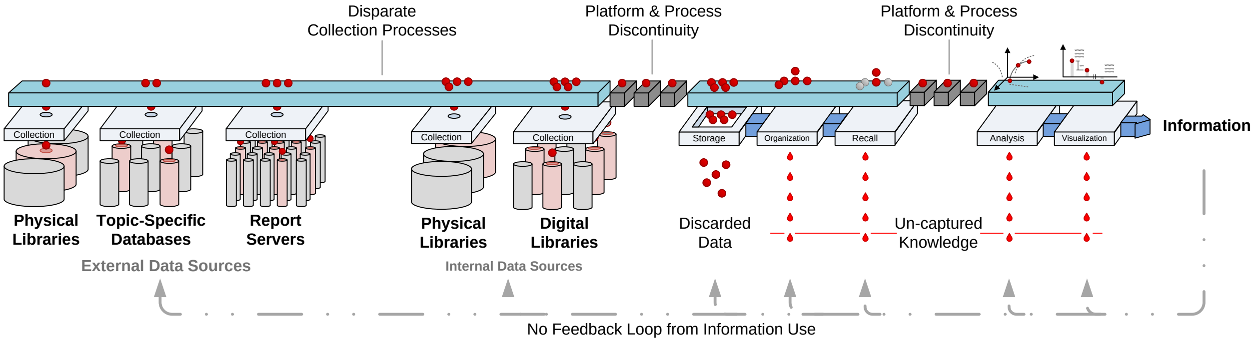


Figure 3.9 – Representative Pitfalls of Current Aerospace Data Processes

As seen in the above aerospace profiles, presented in Section 3.1 , ad-hoc personal data processes can be beneficial, industry-leading tools. However, these cases have been presented as the exception in the aerospace design forecasting industry, and not the rule. In an environment where engineers spend an ever-increasing amount of time on data and information tasks[216], formalizing the new discipline of *DE* takes the substantially powerful domain of data (and data integration in larger decision-making processes) away from personal intuition and practices, and elevates *DE* as a foundational educational discipline that is implemented and executed as a structured tool in aerospace design forecasting organizations.

3.3 RESEARCH IN AEROSPACE DATA SYSTEMS

Although tangential to the traditional engineering and analysis focus of the aerospace industry, some government organizations[201][202][206][207], academic institutions[223][226] and private companies[217][218][219] have realized the need for an increase in data system capability and have begun investing in research & development within the field.

3.3.1 Government Research in Aerospace Data Systems

NASA, specifically, has been particularly interested in managing data both inside and outside of project-based engineering tasks. Carvalho et al[220] discuss the development and integration of a 'Data Aggregator' configuration management data system to support space programs (e.g. Constellation and International Space Station). Their top-level goals of "*…improving data accuracy,…improving data accessibility over the full program lifecycle,…[and] providing efficiencies in data management…*" are reached by allowing access of system and sub-system level data for the entire program within one unified data system. However, the data system is focused on the detail design and operational life-cycle phases of the aerospace programs only, offers no insight into uses of the platform for data tasks earlier in the life-cycle, such as feasibility analysis, sizing and conceptual design.

Vander Kam & Gage, also of NASA, have created a standardized object-oriented data structure to handle multi-disciplinary integration of launch vehicle analysis. Their *Launch Vehicle Language* (LVL) standardizes input and output structures between analysis toolsets in conjunction with use of Phoenix ModelCenter (a tool integration platform). This system requires a 'one-time link definition activity' to define the connections between analysis code and LVL variable definition[221]. Expansion of the LVL to other vehicle categories or in a generic setting outside of ModelCenter is not discussed.

NASA Headquarters has led a research effort into the forecasting process of technology R&D projects. The basis of their task was creating a unified database of technology development programs from disparate sources and identifying the key driving parameters to cost and time schedules[222]. In addition to semi-standardized governmental databases of programmatic details, the researchers extracted variable data, by hand, through supporting documents and contacted personnel previously involved with the project for subject-matter expert input. They identified technology papers to "*…consistently contain rich information with respect to the 20 parameters of interest,…*" of which many are programmatic and managerial-level data. The resultant database is used as a backend to feed an Excel GUI where users can search, view statistical trends, and drill-down to individual technology R&D project. The approach of forecasting technology development efforts through data-centric processes is novel, however, the lack of attached analytical capabilities and clear guidance to inform decision-making detract from its practical applicability.

Pinelli et al are a team of NASA engineers and information scientists commissioned to study the interaction of aerospace technologists with data, information and knowledge, published in two parallel volumes[201][202]. They provided a broad survey of tendencies of domestic and international engineers and scientists with respect to data tasks and information requirements. Their results identified the current structure for static report servers as not "*...incorporating an understanding of the communication practices and information-related activities of U.S. aerospace engineers and scientists*." They go on to posit that "*...the need for interpretation and analysis is critical because there is less time for decisionmaking and the half-life of knowledge is getting shorter*." Their research also suggest that the next generation of aerospace engineering information scientists command an understanding of the 'technical domain', 'information-seeking and use behaviors' and the 'tasks, organizational norms and constraints' of aerospace engineers. The integration of engineer and information scientist's responsibilities will push both professions towards becoming equally cognizant of data, information and knowledge demands in aerospace.

3.3.2 Academic Research in Aerospace Data Systems

The *EXTROVERT,* program sponsored by Georgia Tech, attempted to create a 'design-centered portal to aerospace engineering' by condensing lessons learned and case studies into a functional online resource. Reverse-engineering and student-based design case studies are presented by topic and linked within the website. Although the basis of EXTROVERT is to "…*empower the learner with the knowledge and skills necessary for the conceptual design of aerospace vehicles,*…"[223] the current system offers more student-created documents than professional engineering documents, and the knowledge-based lessons offer only introductions to flight vehicle concepts.

Danner, in his doctoral research of technology growth in aerospace systems forecasting, outlines a need to compile historical data to 'identify system level metric(s)' and form regressions to bound growth curves. The process of finding and extracting data from native sources for use in his methodology is not covered[224].

In his doctoral research of strategic planning of aerospace programs at Georgia Tech, Raczynski[225] outlines the broader decision-making process and within it, the need for introduction and management of data. In the 'Gathering Information' phase of decision-making (defined as the process of collecting "…*information necessary to generate and evaluate the concepts proposed to accomplish the vision*...*"*), the author outlines the need for central data system to manage program planning but stops short of development and implementation within a functional design process. He states that "…*ideally, programmatic information would be stored in a database which is readily accessible to both the planner as well as those responsible for day to day action*." Data may be in the form "…*numerical data from experimentation or modeling & simulation... [or] the knowledge of Subject Matter Experts*."

Lu, also of Georgia Tech, provides an implementation scheme for data management in an aircraft conceptual design environment[232]. While the research effort is primarily concerned with the storage and communication of design data variables within the actual synthesis platform, he does make particular note of the 'data intensive' nature of early design tasks. The preparation of data for use in conceptual design nor the broader use of data in aerospace forecasting activities is not addressed.

Mason (a former professor at Virginia Tech) led a research effort to gather information sources relevant during the aircraft design process. The end result is the *Aircraft Design Information Sources*[226] compendium, an online bibliography of aircraft design references, as well as bibliography of bibliographic sources. Although significant effort has gone into collecting meta-data about sources, there are few opportunities to directly access documents – most entries are bibliographic only. There is no advanced search feature to find documents or to sort the entries beyond the predefined categories given, creating a static warehouse of data sources that fails to capitalize on its potential transfer of data and knowledge.

3.3.2.1 Other Research Impacting Aerospace Data Systems

Harvey and Holdsworth of Boeing Australia suggest introduction of formal data and knowledge management systems may "…improve the quality, quantity and accessibility of the information available to authorities and decision makers…" and "…facilitate retention of knowledge/skills of key employees…", but offer no substantive formulation to its functional implementation[228].

Morris et al[229], in conjunction with NIST and DARPA, provide a survey of data management in engineering, offering the following key distinctions for engineering data.

"Database technology has evolved in parallel to the evolution of software to support engineering. Target applications for database technology have traditionally been data intensive business applications. In these applications relatively simple operations are performed on large volumes of data with uniform structure. The term data processing refers to these types of applications. The engineering world, on the other hand, is full of computationally intensive, logically complex applications requiring sophisticated representations."

Power defines key functionalities of modern decision support systems[230], agnostic of the applied field, as 1) user flexibility in data recall, analysis and visualization, 2) introduction of knowledge-based practices through user-driven meta-data, and 3) automated integration with outside platforms for further analysis.

Wu et al of RAND Corporation, applied a broad survey of decision support systems towards focused recommendations in clinical health care data systems[233]. Their resulting recommendations for decision support (DS) design, however, are universal: *"...providing broad, system-level perspectives; customizing interfaces to specific users and roles; making the DS reasoning transparent; presenting data effectively; generating multiple scenarios covering disparate outcomes; allowing for contingent adaptations; and facilitating collaboration.*"

Heisig provides a survey of managers and engineers in product development on their data, knowledge and information requirements[234], the results of which suggest that making "…*all the data available in one place*…". "…*electronically on a file server*…", and incorporating a "…*web-based design database…that captures designer criteria, solutions, and software*…" are key needs in design data management. Additionally, navigation from a 'big picture' overview to component-specific details and traceability of information were common attributes practicing engineers and managers desired.

3.3.3 Assessment of Research in Aerospace Design Forecasting

Although academic and private industry research has begun to acknowledge that formalized information support will be necessary for the next generation of aerospace engineers, designers and forecasters, the practical steps towards realizing a heightened level of execution in data- and knowledge-centric aerospace tasks have yet to be addressed. In the unique cases where data tasks have been systematically integrated in research and development environments, implementation has been limited towards configuration data management applicable only in mature design cycle phases – the early forecasting tasks of providing decision-maker situational awareness, defining systems requirements and multi-domain socio-technical conceptual design studies have been left only as theoretical sidebars.

Research efforts in aerospace data systems have, to this point, segmented themselves into two tracks: 1) those efforts that focus on collecting source data for future use and 2) those efforts that focus on the inter-platform data requirements of aerospace analysis and detailed development. The first track has considered collecting relevant data sources and minimally extracting data values as sufficient process outputs, but without consideration of data and information requirements in practical aerospace tasks. The second track, on the other hand, has taken a hyper-focused view of the data requirements within an organizational environment to produce information for a particular aerospace field. In relation to a unified approach of *DE* applied to uncertain early design and forecasting problems, both research tracks fall short.

Design forecasting engineering, in contrast, is tasked with highly varying data and information requirements (e.g. situational awareness, feasibility analysis, competition analysis, strategic planning, requirements definition, vehicle sizing, system architecture planning), subject to an expansive range of topics (e.g. subsonic-to-hypersonic-to-space access vehicle systems; market, environmental, societal, political and economic considerations; chief engineer, program manager and executive-level decision makers). Figure 3.10 illustrates the decision-making realm and *Data-Engineering* tasks required for aerospace forecasting contrasted with those aerospace research efforts previously discussed, highlighting the fact that the practicing *Data-Engineer* requires a unique and separate research approach. Developing multi-domain, multi-fidelity environments built around adaptable, dynamic processes and supported by integrated data and knowledge systems is the only approach keeping pace with the requirements for modern aerospace decision-making.

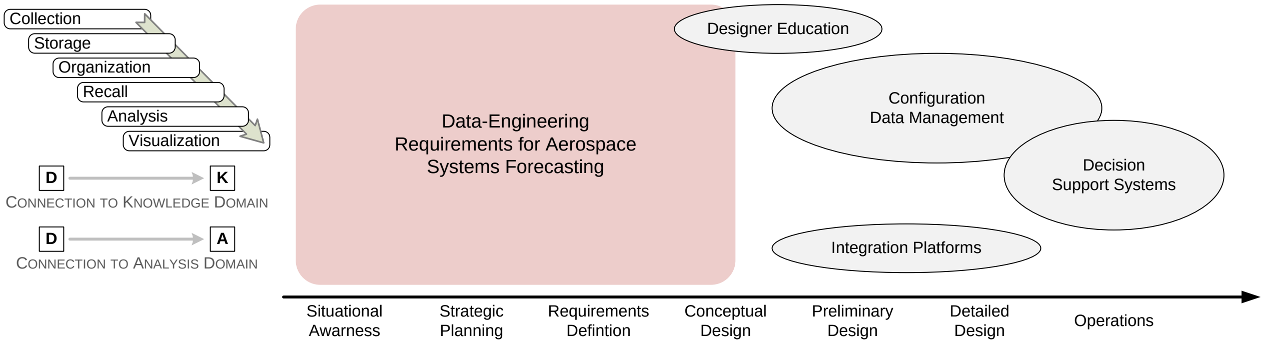


Figure 3.10 – Aerospace Data Research Efforts across Development Life-Cycle

3.4 CONTRIBUTION SUMMARY

This chapter has contributed the following towards the dissertation research topic:

- An *anatomy of data* use by aerospace industry-leading individuals and organizations. Common traits and mindsets extracted for future implementation of a structured *Data-Engineering System*.

- An *assessment* of content & capability for current data platforms specific to the aerospace and defense industry.
- Survey of current and ongoing research of underlying *Data-Engineering* principles.

REFERENCES

[127] Wright, W., Wright, O., Chanute, O., and McFarland, M., "The papers of Wilbur and Orville Wright, including the Chanute-Wright letters and other papers of Octave Chanute," Arno Press, 1953.

[128] Cayley, G., “On Aerial Navigation,” Nicholson’s Journal of Natural Philosophy, 1809.

[129] Lilienthal, O., “The Carrying Capacity of Arched Surfaces in Sailing Flight,” excerpt from ‘The Flying Man’, 1893.

[130] Lilienthal, O., “Der vogelflug als grundlage der fliegekunst: Ein beitrag zur systematik der flugtechnik,” Gaertner, 1889.

[131] Langley, S., “Experiments in Aerodynamics,” University of Wisconsin, 1902.

[132] Dodson, M., "An Historical and Applied Aerodynamic Study of the Wright Brothers' Wind Tunnel Test Program and Application to Successful Manned Flight," US Naval Academy, 2005.

[133] Wright, W., “Some Aeronautical Experiments,” Journal of the Western Society of Engineers, 1901.

[134] Wright, O., and Wright, W., “Flying Machine,” United States Patent, 1906.

[135] Ludlow, I., “Navigating the Air: The Relation of Weight Speed and Power of Flyers (Chapter 2),” Aero Club of America, 1907.

[136] Wright, O., and Wright, W., “The Wright Brothers’ Aeroplane,” United States Patent, 1908.

[137] Wright O., and Wright, W., “How to Glide and Soaring Flight,” Flight, 1909.

[138] Wright, W., “The Earliest Wright Flight: A Letter from Wilbur Wright,” Scientific American, 1910.

[139] Anderson, J., “A History of Aerodynamics: And Its Impact on Flying Machines,” Cambridge Aerospace Series, 1999.

[140] Hoerner, S., “Skin Drag of High Speed Aircraft,” Aircraft Engineering 1936.

[141] Hoerner, S., “Forces and Moments on a Yawed Airfoil,” NACA TM 906, 1939.

[142] Hoerner, S., “Base Drag and Thick Trailing Edges,” Journal of the Aeronautical Sciences, 1950.

[143] Hoerner, S., “Aerodynamic Properties of Screens and Fabrics,” Textile Research Journal, 1952.

[144] Hoerner, S., “Aerodynamic Shape of the Wing Tips,” Air Force Material Command Technical Report No. 5752, 1952.

[145] Hoerner, S., “The Effect of Roughness Concentration Upon The Frictional Drag,” Journal of the American Society of Naval Engineers, 1954.

[146] Hoerner, S., “Consideration of Size-speed-power in Hydrofoil Craft,” Gibbs and Cox Inc New York, 1958.

[147] Buermann, T.M., and Hoerner, S., “Commercial Hydrofoils,” Naval Engineers Journal, 1964.

[148] Hoerner, S., “Boat hull and hydrofoil combination,” United States Patent, 1964.

[149] Hoerner, S., “Fluid-dynamic drag : practical information on aerodynamic drag and hydrodynamic resistance,” 1965.

[150] Hoerner, S., "Fluid-Dynamic Drag: Theoretical, Experimental and Statistical information," 1965.

[151] Hoerner, S., "Fluid-Dynamic Lift: Practical Information on Aerodynamic and Hydrodynamic Lift," 1985.

[152] Anon., "Space Planners Guide," United States Air Force Systems Command, ISBN 1114772070, 1965.

[153] Risher, J.F., “Evaluation of the Space Planners Guide,” United States Air Force, 1966.

[154] Coley, D., and Chudoba, B., “Assessing the Adaptability of the 1965 USAF Space Planners Guide for a Modern SpaceLiner-Type Hypersonic Point-to-Point Mission,” AIAA 2014-4412, 2014.

[155] Küchemann, D., "Design of Wing Junction, Fuselage, and Nacelles to Obtain the Full Benefit of Sweepback Wings at High Mach Number,” Ministry of Supply, 1947.

[156] Küchemann, D., "On the Chordwise Lift Distribution at the Centre of Swept Wings,” Royal Aeronautical Society, 1950.

[157] Küchemann, D., "Concerning the Flow about Ring-Shaped Cowlings of Finite Thickness,” NACA-TM-1325, 1952.

[158] Küchemann, D., and Weber, J., "Aerodynamics of Propulsion,” Mc-Graw-Hill, 1953.

[159] Küchemann, D., "Boundary Layer on Swept Wings. Their Effects and their Measurements,” Royal Aircraft Establishment, 1955.

[160] Küchemann, D., "A Proposed Research Programme on the Problems Associated with Flight at Low Supersonic Speeds,” 1956.

[161] Küchemann, D., "A Method for Calculating the Pressure Distribution over Jet-Flapped Wings, “ R and M, 1957.

[162] Küchemann, D., "Hypersonic aircraft and their aerodynamic problems," Progress in Aerospace Sciences, 1965.

[163] Küchemann, D., "The Overall Design Concept of Slender Wings for Supersonic Flight,” RAE Technical Memo, 1966.

[164] Küchemann, D., and J. Weber. "An analysis of some performance aspects of various types of aircraft designed to fly over different ranges at different speeds," Progress in Aerospace Sciences, 1968.

[165] Küchemann, D., "The Physics of Airflows and the Design of Aircraft,” RAE Technical Memo, 1969.

[166] Küchemann, D., "Some Future Possibilities in Air Transport,” RAE Technical Memo, 1970.

[167] Küchemann, D., "The Aerodynamic Design of Aircraft," Pergamon Press, 1978.

[168] Fink, R., "USAF Stability and Control DATCOM," United States Air Force Flight Dynamics Laboratory, USAF Technical Report AFWAL-TR-83-3048, 1978.

[169] “The USAF Stability And Control Digital Datcom, Volume I, Users Manual,” USAF Technical Report AFFDL-TR-79-3032 (AD A086557), 1979.

[170] “The USAF Stability And Control Digital Datcom, Volume II, Implementation of Datcom Methods,” USAF Technical Report AFFDL-TR-79-3032 (AD A086558), 1979.

[171] “The USAF Stability And Control Digital Datcom, Volume III, Plot Manual,” USAF Technical Report AFFDL-TR-79-3032 (AD A086559), 1979.

[172] Blake, W., “Missile DATCOM: User’s Manual-1997 FORTRAN 90 Revision,” United States Air Force, 1998.

[173] Watters, B., “Adaptation of Digital DATCOM Into a Conceptual Design Process,” University of Texas at Arlington, 2012.

[174] Burnet, DR., and Czysz, P., “Supersonic Hydrogen Combustion Studies,” Aeronautical Systems Division Wright-Patterson AFB, 1963.

[175] Czysz, P., and Dixon, W.P., “Thermographic Heat Transfer Measurement, “ Instr. Cont. Syst., 1968.

[176] Czysz, P., "Hypersonic Convergence: Volume I," Air Force Research Laboratory, USAF Technical Report AFRL-VA-WP-TR-2004-3114, 2004.

[177] Czysz, P., "Hypersonic Convergence: Volume II," Air Force Research Laboratory, USAF Technical Report AFRL-VA-WP-TR-2004-3115, 2004.

[178] Czysz, P., "Hypersonic Convergence: Volume III," Air Force Research Laboratory, USAF Technical Report AFRL-VA-WP-TR-2004-3116, 2004.Wang, R., and Strong, D., "Beyond Accuracy: What Data Quality Means to Consumers," Journal of Management Information Systems, Vol. 12, No. 4, pp. 5-33, 1996.

[179] Czysz, P., and S. N. B. Murthy. "Energy analysis of propulsion systems for high speed vehicles," AIAA, Aerospace Sciences Meeting, 1989.

[180] Czysz, P., and S. N. B. Murthy. "Energy analysis of propulsion systems for high speed vehicles," AIAA, 1991.

[181] Czysz, P., “Space Transportation System Requirements Derived from the Propulsion Performance,” International Astronautical Federation, 1992.

[182] Czysz, P., and Little, M., “Rocket Based Combined Cycle Engine – A Propulsion System for the 21st Century,” AIAA-93-5056, 1993.

[183] Czysz, P., "Interaction of propulsion performance with the available design stage," International Symposium on Air Breathing Engines, 1995.

[184] Czysz, P., “Rocket-Based Combined-Cycle Power Spaceliner Concept,” AIAA, 1996.

[185] Czysz, P., and Vandenkerckhove, J., "Transatmospheric launcher sizing." Scramjet propulsion, AIAA, 2000.

[186] Bruno, C., and Czysz, P., “Magnetohydrodynamic Coupled Ramjet Propulsion System – a Perspective,” International Symposium on Air Breathing Engines, 2001.

[187] Chudoba, B., et al. "Future space tourism transportation design requirements." *AIAA/CIRA 13th International Space Planes and Hypersonic Systems and Technologies,* 2005.

[188] Csysz, P., and Bruno, C., “Future Spacecraft Propulsion Systems: Enabling Technologies for Space Exploration,” Springer Science & Business Media, 2006.

[189] Askham, N., Cook, D., Doyle, M., Fereday, H., Gibson, M., Landbeck, U., Lee, R., Maynard, C., Palmer, G., and Schwarzenbach, J., "The Six Primary Dimensions for Data Quality Assessment: Defining Data Quality Dimensions," Data Management Association UK, 2013.

[190] Mayer-Schoenberger, V., and Cukier, K., "Big Data: A Revolution That Will Transform How We Live, Work and Think," Houghton Mifflin Harcourt, ISBN 978-0-544-00269-2, 2013.

[191] Jackson, P., Peacock, L., and Munson, K., “Jane's All the World's Aircraft, 2001-2002,” Jane's Information Group, 2001.

[192] “ESDU Aerospace: Aerospace Industry Decision Support Tool,” IHS, 2006.

[193] Isakowitz, S., Hopkins, J., and Hopkins, J., "International Reference Guide to Space Launch Systems - Fourth Edition," American Institute of Aeronautics and Astronautics, ISBN 1-56347-591-X, 2004.

[194] “Worldwide UAV Roundup – 2013,” Aerospace America, 2013.

[195] DACIS Information Sheet, InfoBASE Publishing. 3/11/14
URL: http://docs.dacis.com/public/DACIS_Information%20Sheet_082012.pdf

[196] Lorell, M., Levaux, H., “The Cutting Edge: A Half Century of U.S. Fighter Aircraft R&D,” RAND Project Air Force, 1998.

[197] "Aerospace Structural Metals Handbook," Department of Defense, A062553, 1978.

[198] “ASMD Brochure,” CINDAS LLC, 2014.

[199] "TPSX: Thermal Protection System Expert and Material Property Database," Fourth International Conference on Composites Engineering, 20020051080, 1997.

[200] "Standard Reference Data Act of 1968," 90th US Congress, P.L. 90-396; 15 U.S.C. 290-290f, 1968.

[201] Pinelli, T., Barclay, R., Kennedy, J., and Bishop, A., "Knowledge Diffusion in the U.S. Aerospace Industry: Part A," Ablex Publishing Corporation, ISBN 1-56750-225-3, 1997.

[202] Pinelli, T., Barclay, R., Kennedy, J., and Bishop, A., "Knowledge Diffusion in the U.S. Aerospace Industry: Part B," Ablex Publishing Corporation, ISBN 1-56750-225-3, 1997.

[203] Hahn, S., “A Study on Utilizing OCR Technology in Building Text Database,” Database and Expert Systems Applications, 1999.

[204] Sharma, O., Ghose, M., Shah, K., and Thakur, B., “Recent Trends and Tools for Feature Extraction in OCR Technology,” International Journal of Soft Computing and Engineering, 2013.

[205] Mazzetti, M., "Database is Shut Down by NASA for a Review," The New York Times, March 22, 2013.

[206] NASA Scientific and Technical Information (STI) Program: About. 2/28/2014
URL: http://www.sti.nasa.gov/about-us/#.UxIwQPldW-M

[207] Pitts, S., and Rike, J., "Defense Technical Information Center Overview," U.S. Department of Defense, 2008.

[208] Leverette, A., "CSA Aerospace and High Technology Database Guide," CSA, 2006.

[209] "ProQuest Advanced Technologies and Aerospace Collection," ProQuest, 2014.

[210] Knovel Aerospace & Defense. 3/1/2014
URL: why.knovel.com/industries/aerospace.html

[211] "Modeling Languagues Refine Vehicle Design," NASA Office of the Chief Technologist, 2009.

[212] "TechnoSoft Solutions," TechnoSoft, 2014.

[213] "Simulation Driven Design: Creating an Environment for Managing Simulation Tools, Processes, and Data," Phoenix Integration, 2010.

[214] “The Jay Miller Aviation History Collection,” Central Arkansas Library System, 2015.

[215] Jenkins, D., Landis, T., and Miller, J., “American X-Vehicles: An Inventory, X-1 to X-50,” NASA Office of External Relations, History Office, 2003.

[216] James, L., Kreisman, R., and Erickson, J., “IM Report: Outsell’s End-User Study: Engineering and Science Professionals, Outsell, 2014.

[217] "Intelligent Information Factory: Knowledge Management," Lockheed Martin, 2003.

[218] Brenes, D., "Leveraging Technical Expertise via Boeing Library Services," Transportation Librarians Roundtable, 2010.

[219] Kelsey, S., and Porter, M., "Best Practices for Corporate Libraries," The Libraries Unlimited Library Management Collection, 2011.

[220] Carvalho, R., Bell, D., Tollinger, I., and Berrios, D., "Integrating Engineering Data Systems for NASA Spaceflight Projects," NASA, 20120011105_2012010766, 2012.

[221] Vander Kam, J., Gage, P., Sohn, J., "The Launch Vehicle Language Data Model Applied to Analysis Tool Connectivity," 42nd AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2004-206, 2004.

[222] Cole, S., Reeves, J., Williams-Byrd, J., Greenberg, M., Comstock, D., Olds, J., Wallace, J., DePasquale, D., and Schaffer, M., "Technology Estimating: A Process to Determine the Cost and Schedule of Space Technology Research and Development," NASA Headquarters, NASA TP-2013-218145, 2013.

[223] Komerath, N., "EXTROVERT: Learning to Innovate Across Disciplines," Georgia Tech, 2013.

[224] Danner, T., "A Formulation of Multidimensional Growth Models for the Assessment and Forecast of Technology Attributes," Georgia Institute of Technology, 2006.

[225] Raczynski, C., "A Methodology for Comprehensive Strategic Planning and Program Prioritization," Georgia Institute of Technology, 2008.

[226] Mason, W.H., "Aircraft Design Information Sources," VPI Aircraft Design Program and the NASA/USRA Advanced Design Program, 2005.

[227] Connolly, T., and Begg, C., "Database Systems: A Practical Approach to Design," Pearson Education Limited, ISBN 0201708574, 2002.

[228] Harvey, D., and Holdsworth, R., "Knowledge Management in the Aerospace Industry," Proceedings International Professional Communication Conference, ISBN 0780390288, 2005.

[229] Morris, K., Mitchell, M., Dabrowski, C., and Fong, E., "Database Management Systems in Engineering," NIST, NISTIR 4987, 1992.

[230] Power, D., "Understanding Data-Driven Decision Support Systems," Information Systems Management, doi 10.1080/10580530801941124, 2008.

[231] Bryan, M., "The Use of an Engineering Database for System Integration," IEEE, 0263-9327, 1984.

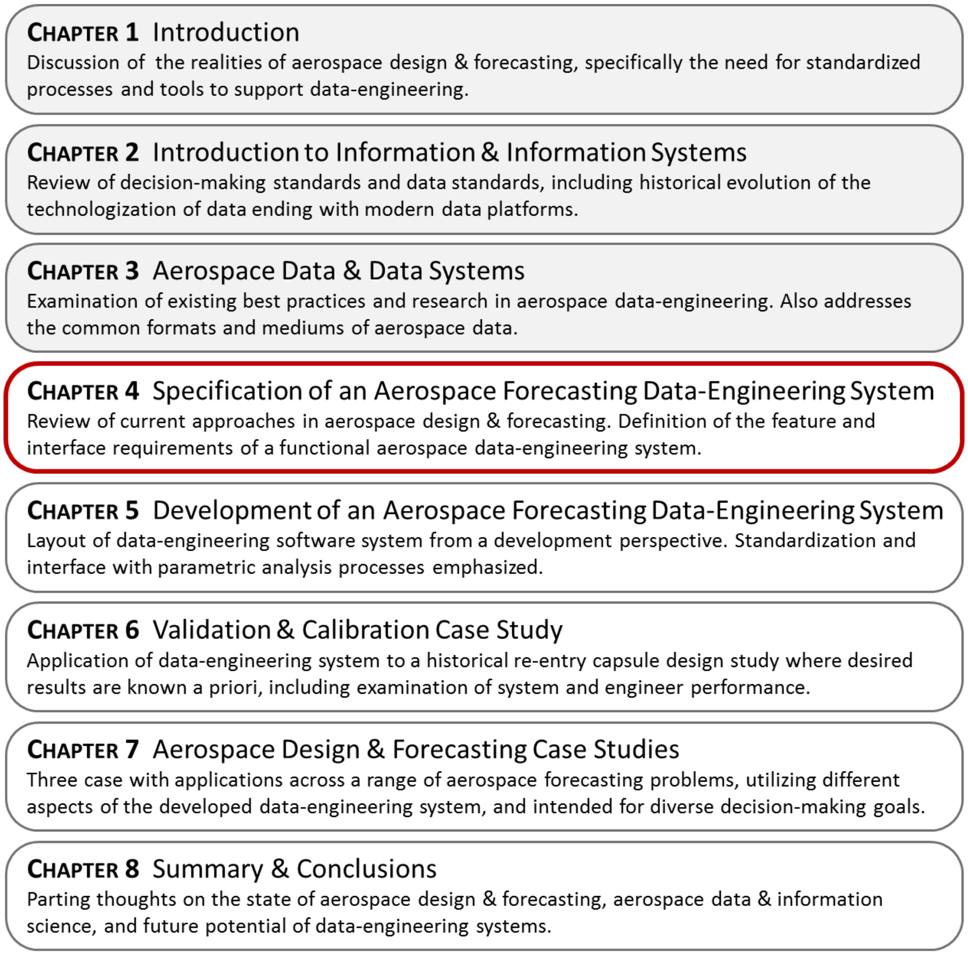
[232] Lu, Z., "Data Management in an Object-Oriented Distributed Aircraft Conceptual Design Environment," Georgia Institute of Technology, 2007.

[233] Wu, H., Davis, P., and Bell, D., "Advancing Clinical Decision Support Using Lessons from Outside of Healthcare: An Interdisciplinary Systematic Review," RAND, doi:10.1186/1472-6947-12-90, 2012.

[234] Heisig, P., Caldwell, N., Grebici, K., and Clarkson, P., "Exploring knowledge and information needs in engineering from the past and for the future - results from a survey," Design Studies, DOI:10.1016/j.destud.2010.05.001, 2010.

CHAPTER 4

SPECIFICATION FOR AN AEROSPACE DESIGN AND FORECASTING DATA-ENGINEERING SYSTEM



CHAPTER 1 Introduction
Discussion of the realities of aerospace design & forecasting, specifically the need for standardized processes and tools to support data-engineering.

CHAPTER 2 Introduction to Information & Information Systems
Review of decision-making standards and data standards, including historical evolution of the technologization of data ending with modern data platforms.

CHAPTER 3 Aerospace Data & Data Systems
Examination of existing best practices and research in aerospace data-engineering. Also addresses the common formats and mediums of aerospace data.

CHAPTER 4 Specification of an Aerospace Forecasting Data-Engineering System
Review of current approaches in aerospace design & forecasting. Definition of the feature and interface requirements of a functional aerospace data-engineering system.

CHAPTER 5 Development of an Aerospace Forecasting Data-Engineering System
Layout of data-engineering software system from a development perspective. Standardization and interface with parametric analysis processes emphasized.

CHAPTER 6 Validation & Calibration Case Study
Application of data-engineering system to a historical re-entry capsule design study where desired results are known a priori, including examination of system and engineer performance.

CHAPTER 7 Aerospace Design & Forecasting Case Studies
Three case with applications across a range of aerospace forecasting problems, utilizing different aspects of the developed data-engineering system, and intended for diverse decision-making goals.

CHAPTER 8 Summary & Conclusions
Parting thoughts on the state of aerospace design & forecasting, aerospace data & information science, and future potential of data-engineering systems.

This chapter will portray the aerospace *Data-Engineering* research specification through the following steps: 1) characterize the aerospace design forecasting decision-making environment, 2) illustrate current industry-standard approaches towards information production within the early development phase, 3) highlight deficiencies in data-knowledge-analysis integration leading to mis-represented or under-represented information, and finally 4) produce a specification for a *Data-Engineering* structure that will improve these deficiencies for a broad range of aerospace design forecasting tasks. As illustrated in Figure 4.1, this specification can only be derived with a firm understanding of the supporting fields, provided in previous chapters, as well as required capabilities from design forecasting efforts examined below.

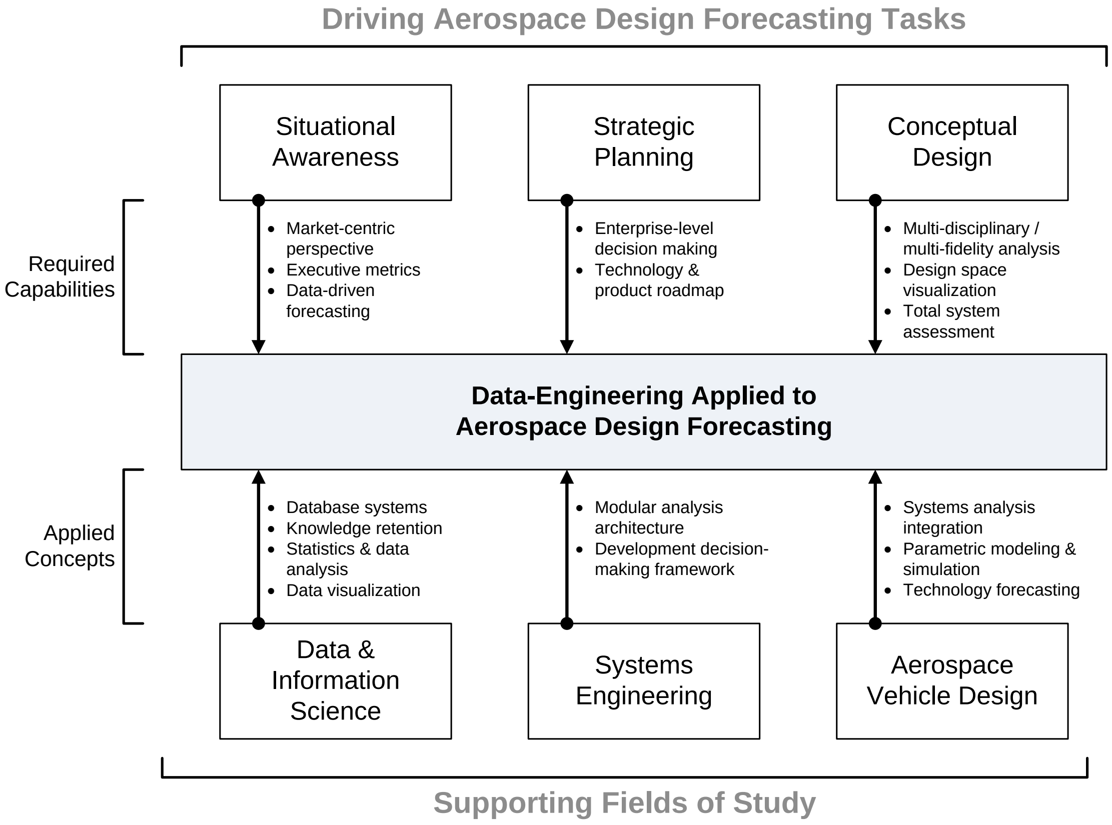


Figure 4.1 – Drivers and Influencers of Aerospace Data-Engineering

4.1 ANATOMY OF AEROSPACE DESIGN FORECASTING

One of the key distinctions that characterize aerospace engineering design apart from less technically-complex decision-making environments is the level of multi-disciplinary, multi-domain consideration which must be reflected in systems-level analysis. Due to the enormous time, human and fiscal investments required for development of air and space vehicle systems, the difference to an organization's bottom line between a successful and unsuccessful program is substantial – the consequences of these investments decisions must be paralleled in the scrutiny of the early design decision-making processes.

As an example, the Airbus A380[4] and Boeing 787[5] were designed in the same time period, share a similar range and cruise speed, only differing substantially on passenger capacity (544 vs

---

[4] http://www.airbus.com/aircraftfamilies/passengeraircraft/a380family/

[5] http://www.boeing.com/commercial/787/

242 typical seating, respectively). The products have not been met with a similar market response, however – the Boeing aircraft has *doubled* the revenue of the Airbus product to date (estimated by orders and sticker price), and discussions have emerged of closing the A380 production line preemptively[235]. Determining these driving system characteristics at the earliest phases of product definition (Airbus launched the A3XX program that became the A380 in 1993[236], 14 years before first delivery) and their impact on ever-shifting market, environmental, social, political, economic and social considerations is a necessity that requires an integrated approach and tool suite incorporating data, knowledge, and multi-disciplinary analysis domains.

Integrating coupled disciplinary analysis concepts into a unified model of a vehicle system is referred to as *vehicle synthesis*, and is primary technique for assessing design of aerospace vehicle systems. At the highest level of abstraction, aerospace synthesis systems receive operating environment, mission constraints and design characteristics as inputs and produce a vehicle system with associated performance as the output. This is achieved by dissecting the major disciplines relevant to the vehicle (e.g. aerodynamics, weight, propulsion, etc.), the major hardware components (e.g. fuselage, wing, tail, etc.) and determining the coupled hardware-discipline effects through a structured set of functional dependencies.

The level of detail with which each discipline and its intra-system relationships is referred to as the *level of fidelity* (i.e. a high fidelity method represents a more accurate-less uncertain model of the actual phenomena, whereas a low fidelity method produces a less accurate and more uncertain model of the actual). Low fidelity methods, however, trade certainty and accuracy for lower complexity and less input-intensive operation. Additionally, if the method is well-calibrated to the phenomena being analyzed, the centralized result will tend towards the actual outcome regardless of underlying uncertainty. This quality, referred to as the *correctness*, is much more important than accuracy at the development stages of design and forecasting – the undefined or under-defined requirements, unknown system characteristics, and the inherent uncertainty of the future operating environment emphasize fast, efficient, and dynamic methods, that still maintain general correctness, over more accurate, but slower and more cumbersome, high-fidelity methods.

As the complexity of the synthesis models grow, so too does the amount of input data required to operate the model – the matching of the model fidelity (and therefore required data) with the amount of data known about the design concept requires a sliding, multi-fidelity approach, shown in Figure 4.2. As the design progresses, concepts mature, requirements are more established, and constraints are made firm – higher-fidelity modelling is required from here onwards to lower the uncertainty, and thus increase accuracy, between the design concept and what will soon be a prototype leading to production and operation[259].

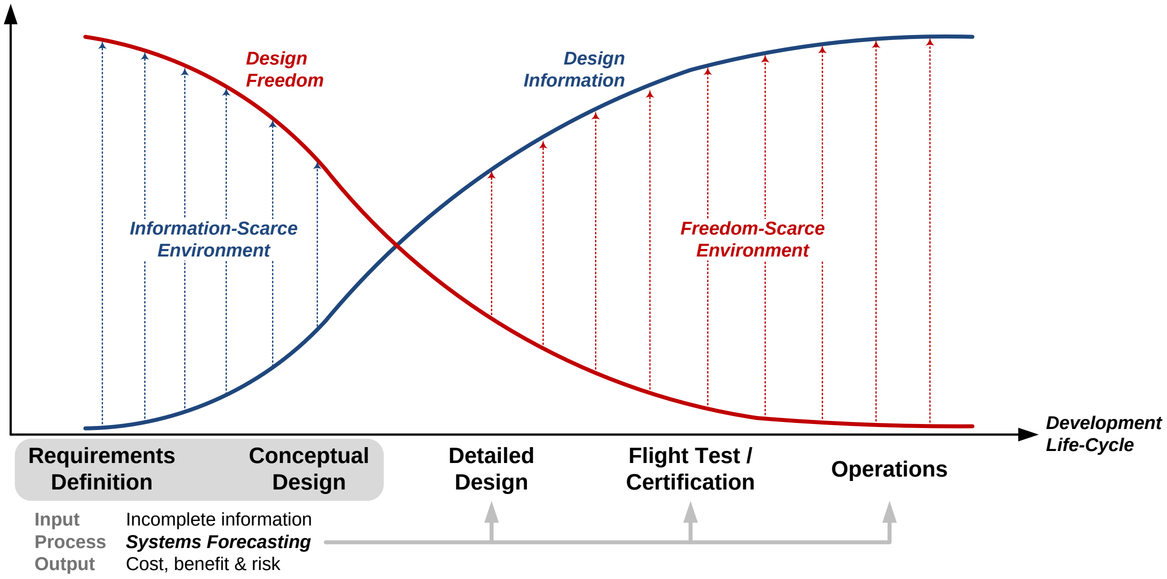


Figure 4.2 – Aerospace Vehicle System Design Cycle

Early design and pre-design tasks necessitate a forecasting-centered approach and therefore have fundamentally different process requirements than traditional engineering processes. The problems in forecasting are ill-defined or are not yet defined at all, whereas the problem requirements in engineering are assumed as a known and given quantity[2]. Non-technical factors must be addressed in forecasting and may even outweigh technical considerations, whereas engineering processes are often technical discipline-focused. Lead times for forecasting decisions are often on the order of weeks and months, whereas modern engineering processes span years or even decades. Process requirements vary significantly to match the unique problem and information needs in forecasting, whereas engineering problems tend to have well-defined and stable processes.

Creating a system, then, that addresses early design and development questions and also addresses the interaction with those decision-makers that rule this domain (e.g. program managers, executives, high-ranking military officers, politicians) requires elevating both the inputs and outputs of a forecasting system away from technical detail-oriented descriptions found in the engineering realm. The inputs must reflect the uncertain and unknown data that is available at such an early point in the development effort, and the outputs must reflect the high-level socio-technical variables that are relevant to the decision-makers. Detailed technical analyses, by themselves, offer no information at the forecasting level – the speed of execution and ability to model interdependencies with other socio-technical factors is a more driving indicator of the value of information produced. Rigorous engineering methods can, and should, be included in forecasting and early design efforts, but the process by which they are applied must reflect the time, cost, uncertainty, and benefit realities of these high-level decisions.

Today, there is wide variety of organizations across academic, government and industry settings, see Table 4.1, which produce early design and forecasting studies. These organizations produce information that directly supports design, development, and planning of aerospace vehicle systems. Although some of these listed organizations are responsible for producing information through a product's life-cycle (i.e. prime manufacturers for their own commercial product), early design activities are often performed under collaboration between organizations (i.e. industry-research university partnership) or as customer-developer partnership (i.e. government-led requirements definition with input from potential industry companies) – this variety in design forecasting organizations inherently drives variation in approaches for early design forecasting information production.

Table 4.1 – Representative Aerospace Design Forecasting Organizations

Sector	*Category*	*Representative Organizations*
Academic	Vehicle Design and Forecasting Research	Georgia Tech, MIT, University of Texas at Arlington, Cranfield University, TU Braunschweig
Government	Technology Development and Integration	NASA, ESA, DLR, Air Force Research Laboratory
	Oversight	Government Accountability Office
	Non-profit Think-tank	RAND Corporation, Aerospace Corporation, Battelle
Industry	Prime Manufacturers	Boeing, Airbus, Lockheed Martin
	For-profit Think-tank	McKinsey, Deloitte, PricewaterhouseCooper

In addition to requiring tailored synthesis processes, forecasting tasks also increase the influence of data- and knowledge-driven processes. Both data and knowledge are often required as inputs to operate analysis methods (i.e. empirical regression of weight trends) or to provide direct inputs for systems analysis (i.e. subject matter expert elicitation of future technical performance of a subsystem). Additionally, data and knowledge domains are frequently operated independently from systems-level analysis under some circumstances (e.g. Delphi methods for aggregating expert knowledge to inform technology policy decisions without providing any explicit analysis are prevalent in National Research Council forecasting studies[237]; defense system requirements are derived as a direct counter to adversary capabilities[238]). These approaches are employed in order to narrow solution space possibilities and focus design options before significant investments of time, human and fiscal investments are required for more in-depth analyses – however, the significance of these decisions demands at least the same level of process scrutiny as analysis-driven solutions produced later in the development cycle.

4.1.1 Examination of Status Quo Aerospace Design and Forecasting

If the early design and development of a product is taken as a continuum from initial concept through conceptual engineering design (the detailed design, testing, manufacturing, and operations is out-of-scope for this discussion), common tasking threads can be extracted, see Figure 4.3. These tasks have been segmented based on their commonality in the organizations that produce them, the design forecasting deliverables output, and the quasi-structured decision-gates that dissect them – this breakdown is not meant as a *de facto* linear standard of how all design forecasting decisions are made, but does provide a representative set of tasks for discussion purposes.

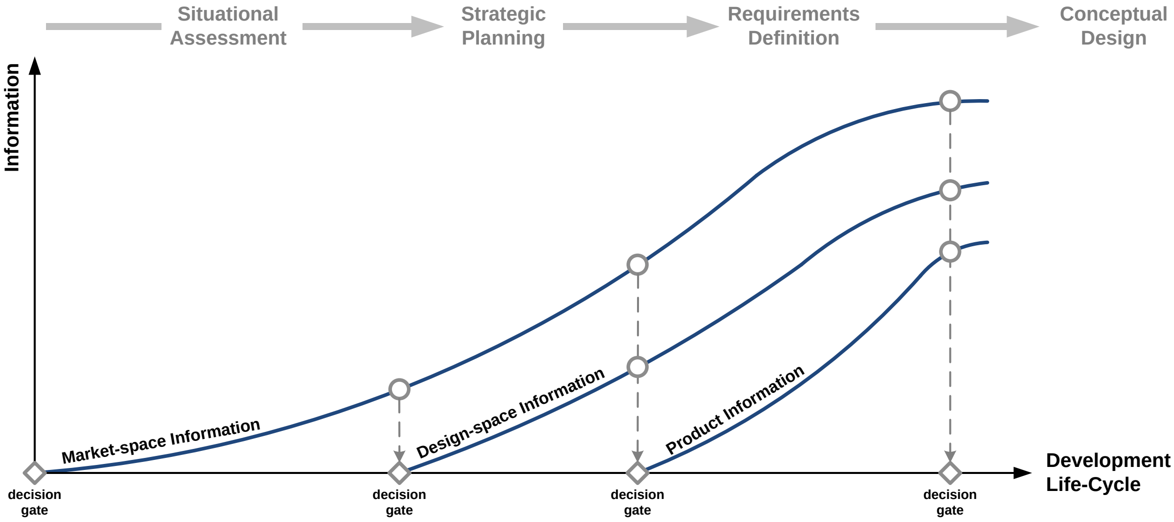


Figure 4.3 – Market, Design and Product Information Development

As these tasks are performed, the information surrounding the potential vehicle system is better understood: initial *situational assessment* provides information into the potential benefit of a solution concept and the existing systems that occupy the market-space, *strategic planning* aligns any potential system design with the realities of the organization's development and operations by bounding the feasible design space, and the *requirements definition* task explores the impact of specific capabilities and technical approaches on the proposed vehicle system. Each task, defined and discussed with representative example information efforts below, is progressively more complex in terms of information produced and required analysis fidelity, thereby also larger implied investments of resources – the decision to continue on with research towards development and operation of a vehicle system requires conclusive information of a the system's cost, benefit, uncertainty and risk to the organization at each gate.

4.1.1.1 Situational Assessment

Table 4.2 – Defining Traits of Situational Assessment Forecasting Tasks

Targeted Decision-Maker	Policy makers, executives, program managers
Information Produced	The formal awareness of efforts undertaken in the past, present and future within a distinct market, including market survey, analysis of competitors, and industry trend analysis.
Related Tasks	Competition analysis, market forecast
Proceeding Decision Gate	Investment decision to further investigation pushing towards a desired system capability (i.e. a weapon system that counteracts a known adversary system; a space architecture that takes a payload to Mars).

Situational assessments are forecasting efforts undertaken often independent of a specific product in order to better understand a potential market-space and communicate the current and future realities towards both internal and external stakeholders, see Table 4.2. The goal is to provide visibility and context for a broad category of products (i.e. global aerospace and defense research & development assessment; trends in U.S. military acquisition programs) with the desire to highlight market inefficiencies, over- and under-extended product categories and potential growth markets. The term market here does not necessarily convey viability of a monetary return – it is also used to convey a system capability that provides a significant military advantage, research potential or international political prestige that is of value to potential decision-makers.

The necessity to provide an ultra-enterprise level perspective means situational assessment forecasting tasks are often performed by organizations and organizational sub-divisions several layers removed from the development and operationalization of aerospace vehicle systems. Therefore, the tools, personnel and techniques applied to situational assessment tasks are similarly distinct from those analysis-driven approaches that dominate the later development cycle – knowledge-driven subject matter expert (SME) assessment and economic data-driven forecasts heavily influence the information these organizations produce. While these approaches provide some level of insight into the top-level trends expected, the lack of analytical connection to the underlying technical and non-technical variables means the forecasted information often only communicates the, most times deterministic, result and not the causational effects that will drive the future reality.

Situational Assessment Examples

Battelle[6], a non-profit science and technology research and development (R&D), provides a yearly assessment of trends in global R&D along with near-term forecasts, with a focused sub-section for the aerospace industry[235]. The stated goal is to provide an "…annual forecast of global research and development funding, which is a public service for use by policy makers, corporate research leaders, researches, educators, and economists." Through collection of historical investment figures for national and international aerospace and defense organizations, Battelle provides a short-term trend analysis and forecast for investment expenditures, see Figure 4.4 and Figure 4.5. However, the impacts of even macro-level industry trends (i.e. sequestration; major commercial airliner development programs) are left only as qualitative discussion points. Additionally, the underlying technologies that are being funded are not discussed nor is the impact success or failure of these R&D investments on future capabilities.

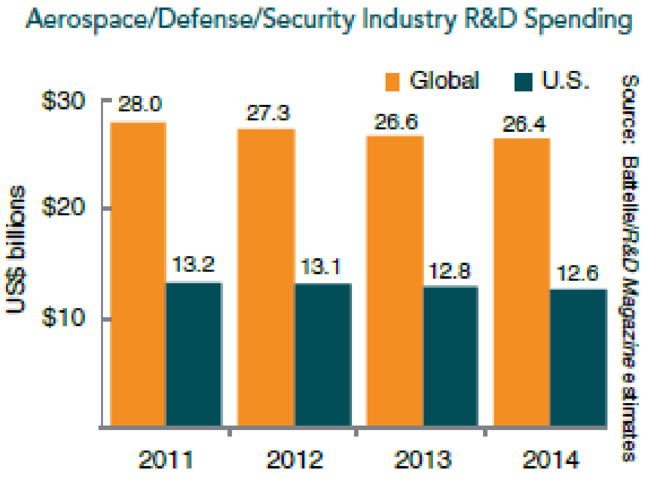


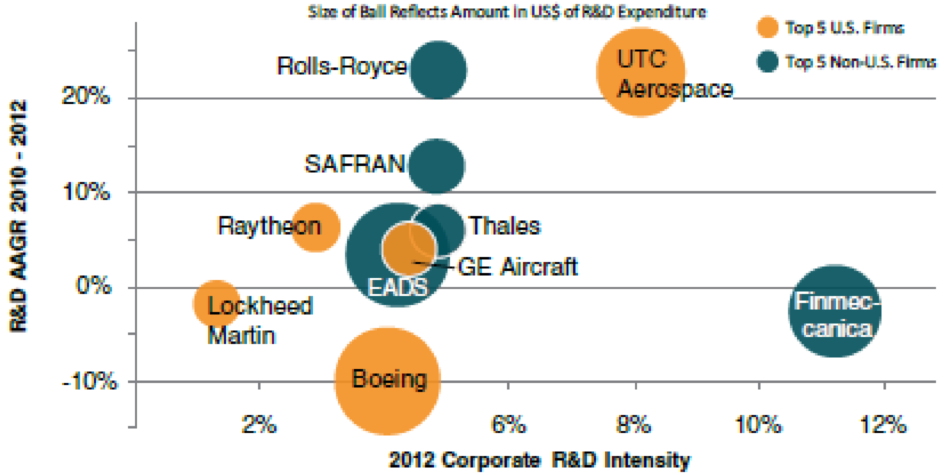
Figure 4.4 – Global and US Aerospace R&D Investment[235]

In a more directed study, McKinsey & Company provides a publically-available report for defense acquisitions in a geographically-targeted market[243]. In their Southeast Asia defense report, they "…outlin[e] the opportunities, highlight the nuances among the diverse markets in the region and offer insights into what is required to succeed…" Although the region spends substantially less than the United States and Western Europe, they have a high investment growth rate and a robust

---

[6] www.battelle.org

defense import market, see Figure 4.6 – the report is geared towards those executive and program manager level decision-makers in western aerospace and defense organizations with potential product cross-over or one-off development and export potential.

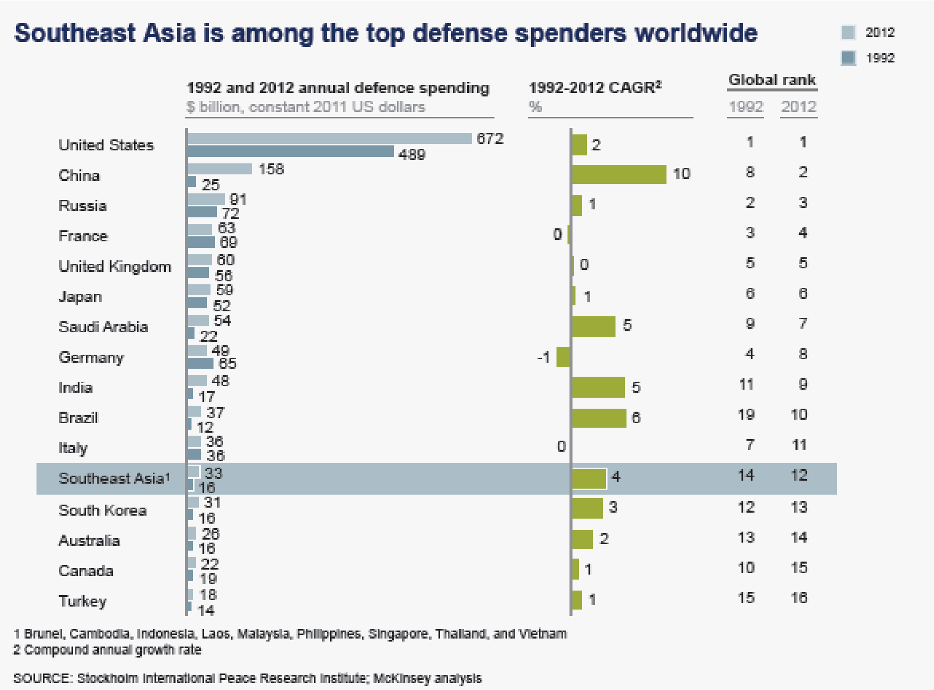


Source: Battelle/*R&D Magazine*, Schonfeld & Associates, European Commission-JRC/EIRI

Figure 4.5 – Relative Expenditures & Growth Rate of Aerospace R&D Investment[235]

The report pulls together several substantial datasets to derive a collective data-centric information viewpoint: country and region-level socio-demographic data, fiscal budgeting data, defense system acquisition data, and existing military force data for each country within the region are all collected. The result is a rich portrayal of the types of weapon systems being imported, their manufacturing origin, see Figure 4.7, and the emphasis the country is placing on maintaining a modern defense force. The report is lacking however, to tie these vehicle systems to operational capabilities (i.e. there is no quantitative discussion of the types of mission capabilities that are, or will be required, to defend against expected military threats) – this missing connection leaves a hole in the decision-making potential of the global defense organization executive decision-makers the report is geared towards.

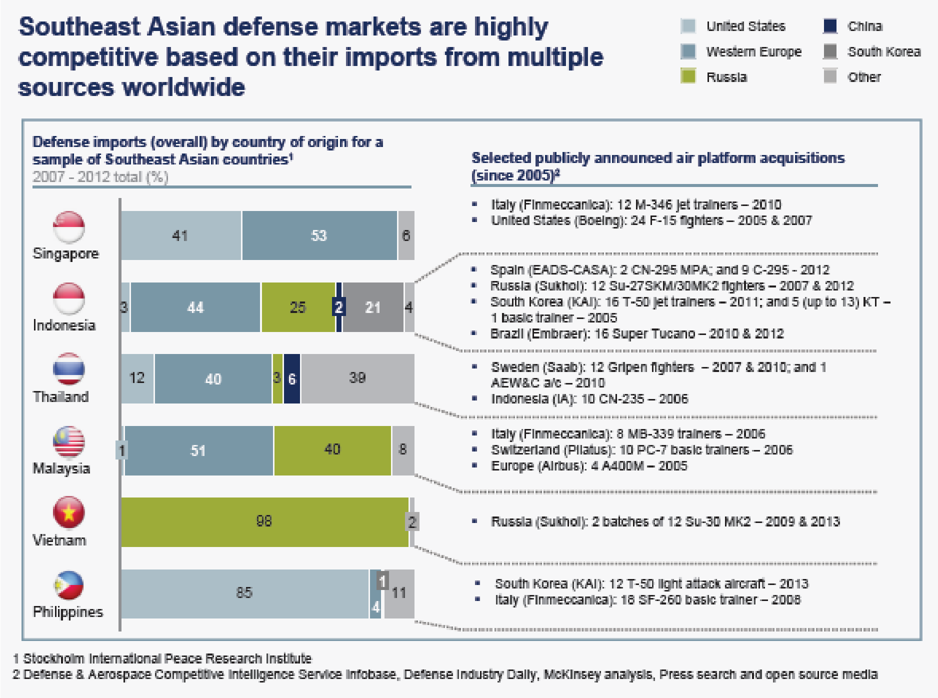
Large aircraft manufacturers have taken it as an industry responsibility to produce regular market forecasts with the goal of delivering long-term view "…of the demand for civil passenger and freighter aircraft that will serve as a reference for airlines, airports, investors, government and non-government agencies, air transport and economic planners world-wide..."[242]. Airbus[242], Boeing[240], Bombardier[241], and Embraer[244] all produce independent market assessments, each assessing the present and projected demand for air vehicle systems. The use of economic indicators and long-term historical growth-rates to provide forecasted demand is prevalent.



1 Brunei, Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, and Vietnam
2 Compound annual growth rate

SOURCE: Stockholm International Peace Research Institute; McKinsey analysis

Figure 4.6 – Country-level Defense Investments Deliverable[243]



- Italy (Finmeccanica): 12 M-346 jet trainers – 2010
- United States (Boeing): 24 F-15 fighters – 2005 & 2007

- Spain (EADS-CASA): 2 CN-295 MPA; and 9 C-295 - 2012
- Russia (Sukhoi): 12 Su-27SKM/30MK2 fighters – 2007 & 2012
- South Korea (KAI): 16 T-50 jet trainers – 2011; and 5 (up to 13) KT – 1 basic trainer – 2005
- Brazil (Embraer): 16 Super Tucano – 2010 & 2012

- Sweden (Saab): 12 Gripen fighters – 2007 & 2010; and 1 AEW&C a/c – 2010
- Indonesia (IA): 10 CN-235 – 2006

- Italy (Finmeccanica): 8 MB-339 trainers – 2006
- Switzerland (Pilatus): 10 PC-7 basic trainers – 2006
- Europe (Airbus): 4 A400M – 2005

- Russia (Sukhoi): 2 batches of 12 Su-30 MK2 – 2009 & 2013

- South Korea (KAI): 12 T-50 light attack aircraft – 2013
- Italy (Finmeccanica): 18 SF-260 basic trainer – 2008

1 Stockholm International Peace Research Institute
2 Defense & Aerospace Competitive Intelligence Service Infobase, Defense Industry Daily, McKinsey analysis, Press search and open source media

Figure 4.7 – Defense Imports by Source Country Deliverable[243]

The commercial airline manufacturers, Airbus and Boeing, both heavily base their projections on airline figures of merit (revenue passenger kilometers (RPK), freight ton kilometers (FTK), see Figure 4.9, average seats, load factors, number of routes, route frequencies), geo-political and economic trends (GDP, population and their growth rates), and forecasted fuel prices – the resulting assessment is a primarily broken down by perceived demand of aircraft classes (e.g. freight, single-aisle, twin-aisle) by geographic region, see Figure 4.8. The forecasts rely on constant, deterministic growth rates applied year over year, with no variability or uncertainty implied for the underlying causal factors.

Business jet market assessments[241][244] similarly use broad economic indicators and historical aircraft delivery rates to forecast future growth rates by vehicle category and geographic region. Due to the discretionary nature of many of business jet purposes, the business jet market assessments also include analysis of global stock market movements as an indicator of order volumes, as well as providing trend analysis of ultra-minority populations (i.e. those individuals beyond the upper 1% of wage earners) that drive the niche market volume. In addition, competition analysis between airframers across market segments is addressed to some level, see Figure 4.10 – however, the interaction between market position and the quantitative driving capabilities (range, payload, cabin volume, operating cost) is left unexplored.

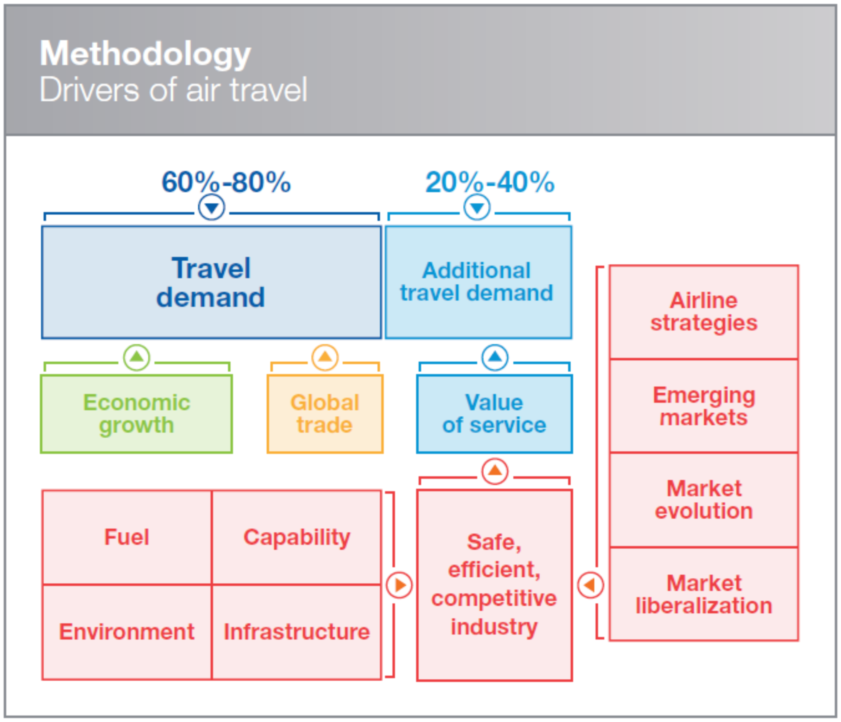


Figure 4.8 – Qualitative Representation of Demand Forecast Model[240]

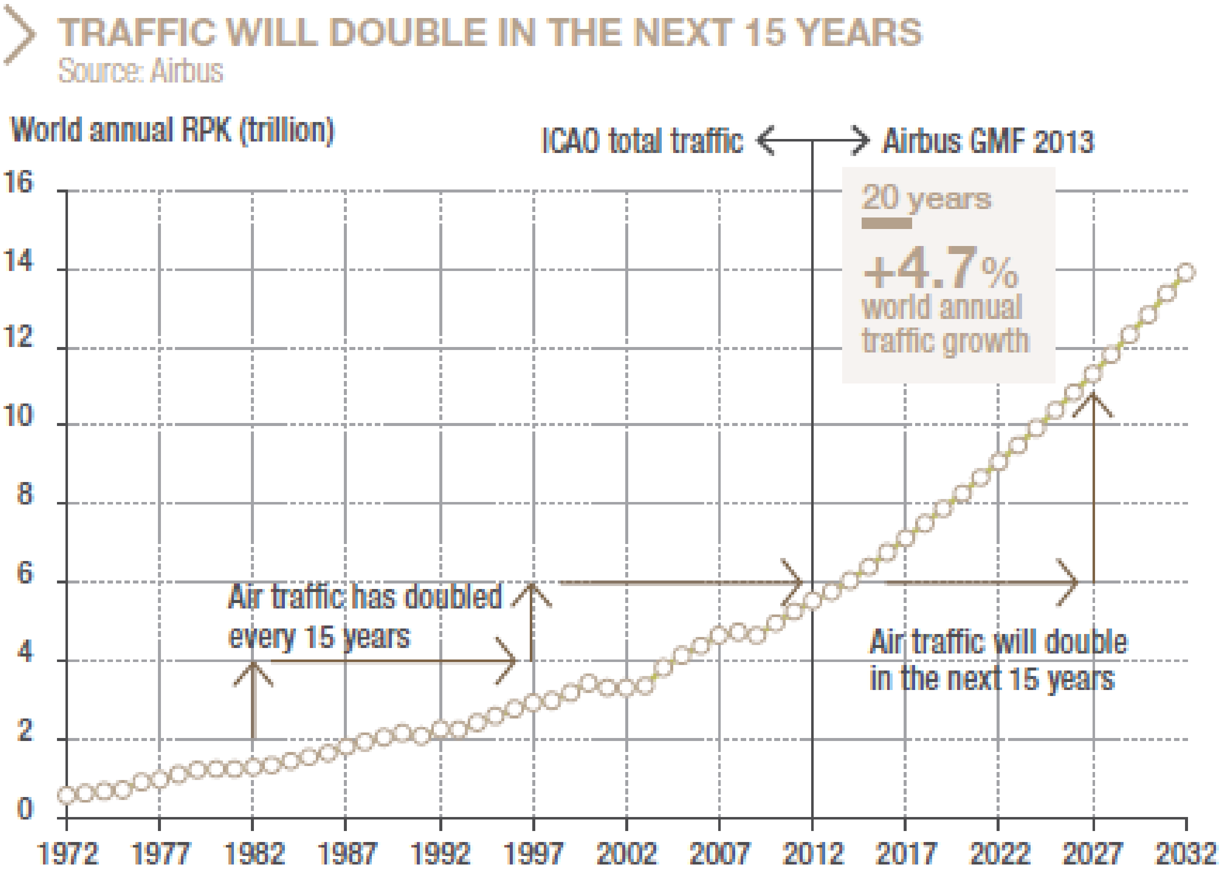


Figure 4.9 – Long-term Demand Forecast Example[242]

BUSINESS JET MARKET SEGMENTATION(1)

In Prod. 37

In Dev. 14

	VERY LIGHT	LIGHT	MEDIUM	LARGE	LARGE CORPORATE AIRLINERS
Bombardier		L70 L75 L60XR L85	CL350 CL605 CL850	G5000 G6000 Global 7000 Global 8000	
Cessna	Mustang CJ2+ M2 CJ3/CJ3+	CJ4 XLS+ Latitude Sovereign+	Citation X+ Longitude		
Dessault			F2000S F2000LXS F900LX	F7X F8X F5X	
Embraer	Phenom 100	Phenom 300 Legacy 450	Legacy 500 Legacy 600 Legacy 650		Lineage 1000E
Gulfstream		G150	G280 G450	G550 G650 G650ER	
Others	Hondajet SJ30-2 Eclipse 550	PC-24			ACJ 318/319 BBJ 1/2/3 BBJ Max 8/9

(1) Segmentation is largely determined by a combination of cabin volume, range and price.

Source: Bombardier Business Aircraft.

Figure 4.10 – Competition Analysis Example[244]

Summary of Situational Assessment Forecasting

Overall, aerospace design forecasting situational assessments reflect their intended purpose to act as a starting information source for further investigation by decision-makers both internal and external to the forecasting organization and not as information specific to a system development program. The reliance on top-level data-driven information, supplemented with SME testimony of qualitative market trends produces assessments that are convincing, if not lacking on back-end analytical rigor. In summary, current aerospace situational assessment forecasting efforts have the following traits.

- Emphasis on historical budgets and economic indicators
- Requires compilation of datasets across political, economic and market domains
- Forecasted market growth rate determined from historical trends
- Connection of market demands to underlying causal factors not addressed quantitatively
- Effect of future product development and technology advancements on market behavior not addressed

4.1.1.2 Strategic Planning

Table 4.3 – Defining Traits of Strategic Planning Forecasting Tasks

Targeted Decision-Maker	Executives, program managers, chief engineers, research technologists
Information Produced	The definition of prioritized concepts for investigation and the resources required to bring match the desired systems-level capability.
Related Tasks	Cost-benefit analysis, analysis of alternatives
Proceeding Decision Gate	Determination if there is both a market need and if the required resources, technology included, are available under the realities of the developing organization.

Where situational assessment forecasting divorces itself from a specific product approach or development course of action, strategic planning is the first point at which an organization is committing resources, made in the form of prioritizing time, fiscal and information investment, towards a refined collection of vehicle system concepts, see Table 4.3 – the concepts are not necessarily defined here, but the underlying mission classes, system capabilities, market feasibility, and required technologies are framed in the context of the organizational enterprise.

Although these strategic planning tasks can often provoke investment of enormous sums of money (e.g. President Kennedy’s declaration of putting a man on the moon driving a current-day translated \$109B investment[245]), the degree of rigor within the information production process has often been suspect. Long-term uncertainty in internal and external factors coupled with uncertainty in complex vehicle system interaction has led to a difficult planning environment in which to consistently apply analytical frameworks – forecasting organizations have responded by either a) reducing the amount of analysis performed, leaving the information dependent on the data, or increasingly, the knowledge domains, or b) reducing the breadth of analytical demands by down-selecting missions, vehicle concepts, technologies and considered interactions even at the strategic planning level.

The conclusions of strategic planning tasks, especially those laying out long-term planning across market segments, are inherently sensitive information to an aerospace development organization – published results of enterprise planning efforts are very rarely made publicly for private organizations. In contrast, public government organizations are often required to provide the results of their strategic planning efforts – the below examples are representative of the publically available strategic planning efforts and the assumption is made that private organizations, many of which are in close-collaboration with the public forecasting organizations, take a similar approach to enterprise and technology planning.

Strategic Planning Examples

In 2010, NASA initiated the development of a long-term prioritization of technologies, mission capabilities and technical challenges to be addressed within their enterprise-wide *NASA Space Technologies Roadmap and Priorities* document[246], conducted by the National Research Council (NRC) government organization under close collaboration with military and academic personnel. The report summarily produced a prioritized list of technical research areas, see Figure 4.11, and their connection to desired long-term space capabilities.

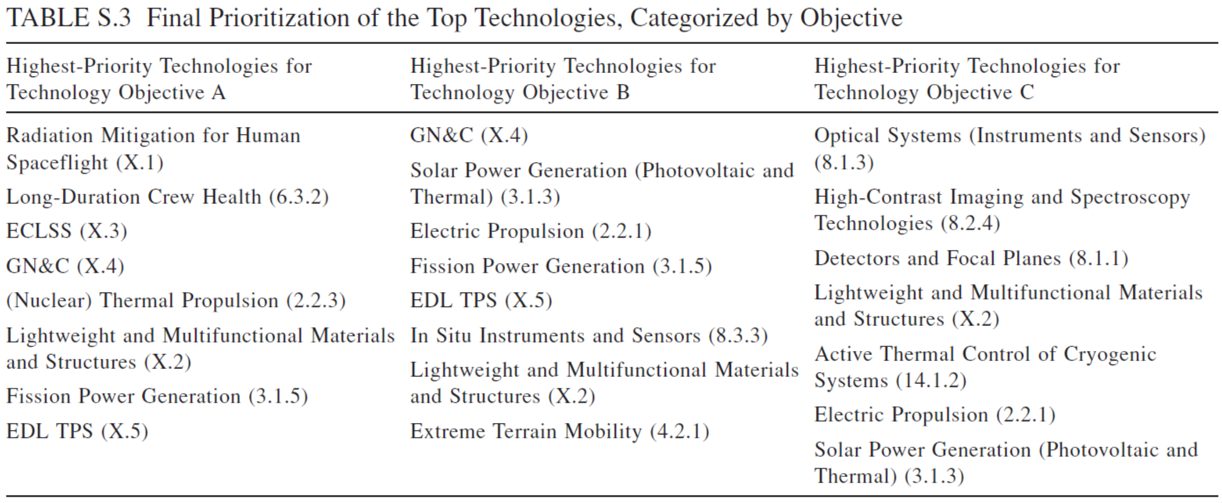


TABLE S.3 Final Prioritization of the Top Technologies, Categorized by Objective

Highest-Priority Technologies for Technology Objective A	Highest-Priority Technologies for Technology Objective B	Highest-Priority Technologies for Technology Objective C
Radiation Mitigation for Human Spaceflight (X.1)	GN&C (X.4)	Optical Systems (Instruments and Sensors) (8.1.3)
Long-Duration Crew Health (6.3.2)	Solar Power Generation (Photovoltaic and Thermal) (3.1.3)	High-Contrast Imaging and Spectroscopy Technologies (8.2.4)
ECLSS (X.3)	Electric Propulsion (2.2.1)	Detectors and Focal Planes (8.1.1)
GN&C (X.4)	Fission Power Generation (3.1.5)	Lightweight and Multifunctional Materials and Structures (X.2)
(Nuclear) Thermal Propulsion (2.2.3)	EDL TPS (X.5)	Active Thermal Control of Cryogenic Systems (14.1.2)
Lightweight and Multifunctional Materials and Structures (X.2)	In Situ Instruments and Sensors (8.3.3)	Electric Propulsion (2.2.1)
Fission Power Generation (3.1.5)	Lightweight and Multifunctional Materials and Structures (X.2)	Solar Power Generation (Photovoltaic and Thermal) (3.1.3)
EDL TPS (X.5)	Extreme Terrain Mobility (4.2.1)	

Figure 4.11 – Technology Investment Recommendations Deliverable[246]

The basis for the recommendations produced by the roadmap are solely driven by subject matter expert (SME) elicitation of the *benefit*, *alignment*, and *technical risk* of each technology identified for further investigation, see Table 4.4. Panels specific to a research or capability topic (e.g. Launch Propulsion; Entry, Descent & Landing) were convened and asked to provide their expert assessment of each technology in relation to explicit elicitation questions – the discrete responses (four possible answers, ranging from purely negative to purely positive) were given non-linear numeric ratings and combined along with SME-defined weighting criteria to arrive at a quantitative estimate of the merit in initiating research in each technical area.

Table 4.4 – Example Elicitation Categories from NRC Knowledge-Driven Approach

Category	*Example Elicited Question*
Benefit	Would the technology provide game-changing transformational capabilities in the timeframe of the study?
Alignment	How does NASA research in this technology improve NASA's ability to meet its long-term needs?
Technical Risk and Challenge	Is the proposed timing of the development of this technology appropriate relative to when it will be needed?

The problems with the approach of the NRC-produced NASA roadmap, and other strategic planning documents that rely solely on knowledge domain SME assessment, are many. The lack of analytical framework connecting the assessed technologies with system capabilities (i.e. not *that* the they are related, but *how* they are related) leads to a subjective assessment of priorities that is anchored to the socio-technical conditions at the time of the forecast and does not provide an adaptable forecast that can easily be updated to assess changes in assumptions and realities. Although a wide cross-section of experts were paneled, only consensus (i.e. deterministic) ratings of benefit, alignment and technical risk are used to influence the investment priorities – the future research and development environment is inherently uncertain and therefore the technical approaches to meet them should also be inherently uncertain (i.e. stochastic or parametric).

The National Aerospace Initiative (NAI) was a collaborative effort from US military commanders, the Department of Defense, and NASA to study the interrelationships of research and development programs and their impact on national high-speed vehicle goals, see Figure 4.12[247]. The NAI committee is not given power to direct investment budgets, but is tasked with producing a cohesive source of information to determine if the long-term goals are technically feasible, financially feasible, and operationally relevant.

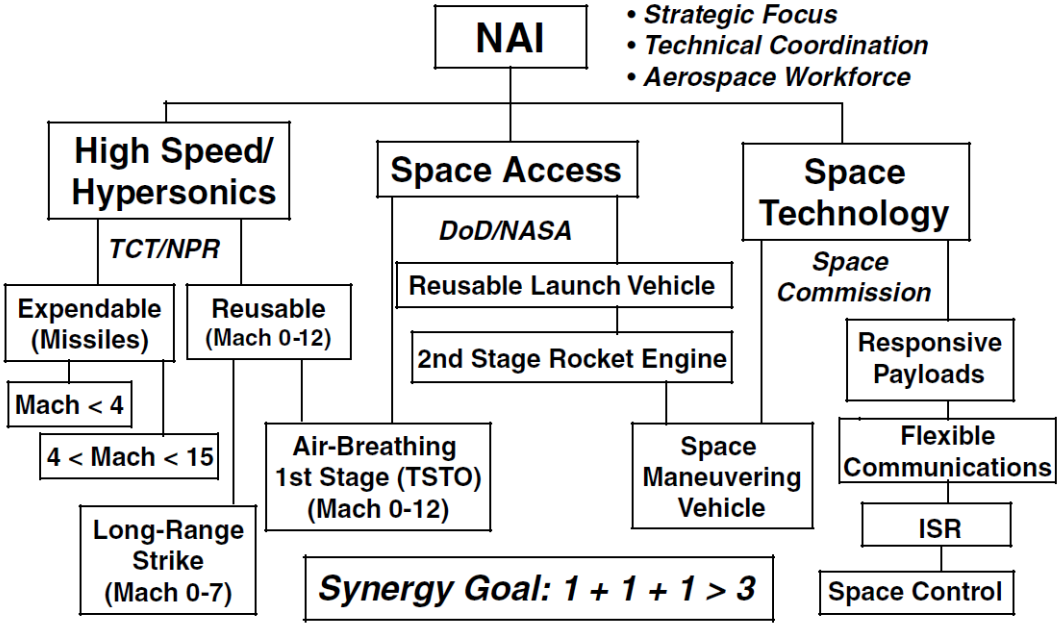


Figure 4.12 – National Aerospace Initiative Research Framework Deliverable[247]

Due to the disintegrated funding and development programs of the involved organizations, a significant hurdle in aligning research efforts was simply to gather and synthesize program data from the technical level to the budgeting and scheduling level. However, the lack of transparency into current budgets and the uncertainty into future investment budgets has made this a difficult task. While the NAI study concludes that "…sound system engineering principles to determine the objectives, technical challenges, and enabling technical, and the fundamental research, technology development, ground testing, and flight demonstration plans required to mature enable technologies..." is required, the lack of structured connection between the data and knowledge the NAI committee has and the analytical approach desired is apparent. The production of unified roadmap for technology and vehicle development, idealized in Figure 4.13, is left only as an exercise of expert opinion of scheduling, technical risk, and development prioritization, with self-admittedly no underlying analytical framework.

After the conclusions of NASA's High Speed Research (HSR) program[344], the National Research Council was commissioned to "…identify breakthrough technologies for overcoming key barriers to the development of an environmentally acceptable economically viable commercial supersonic aircraft..."[248] – the HSR program had failed to produce a formal vehicle development program, and NASA desired informational insight into where technology investment resources should be allocated to make future high-speed vehicle system possible. Their summary findings, that only small less than Mach 2 business jet capability is obtainable in the foreseeable future and still requires significant technology advances, rely on residual data and knowledge from the HSR program and assessment by the NRC committee.

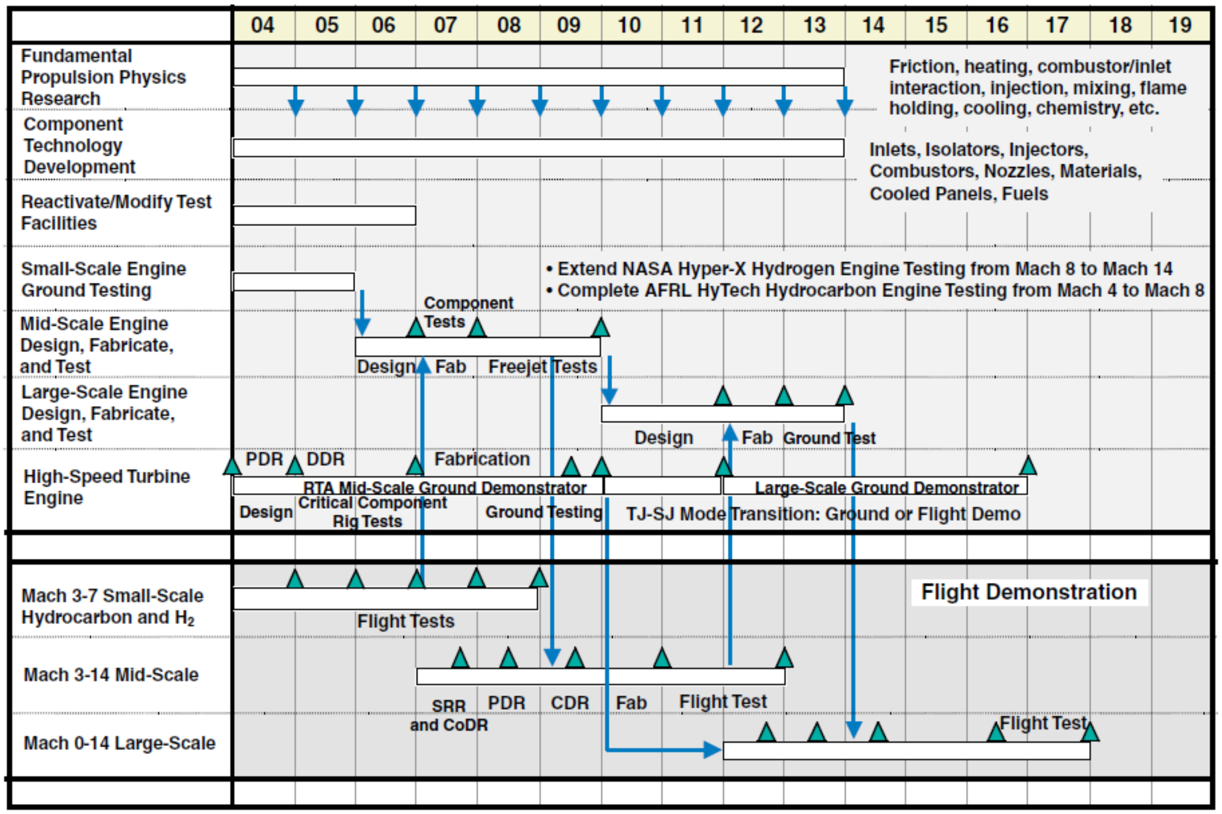
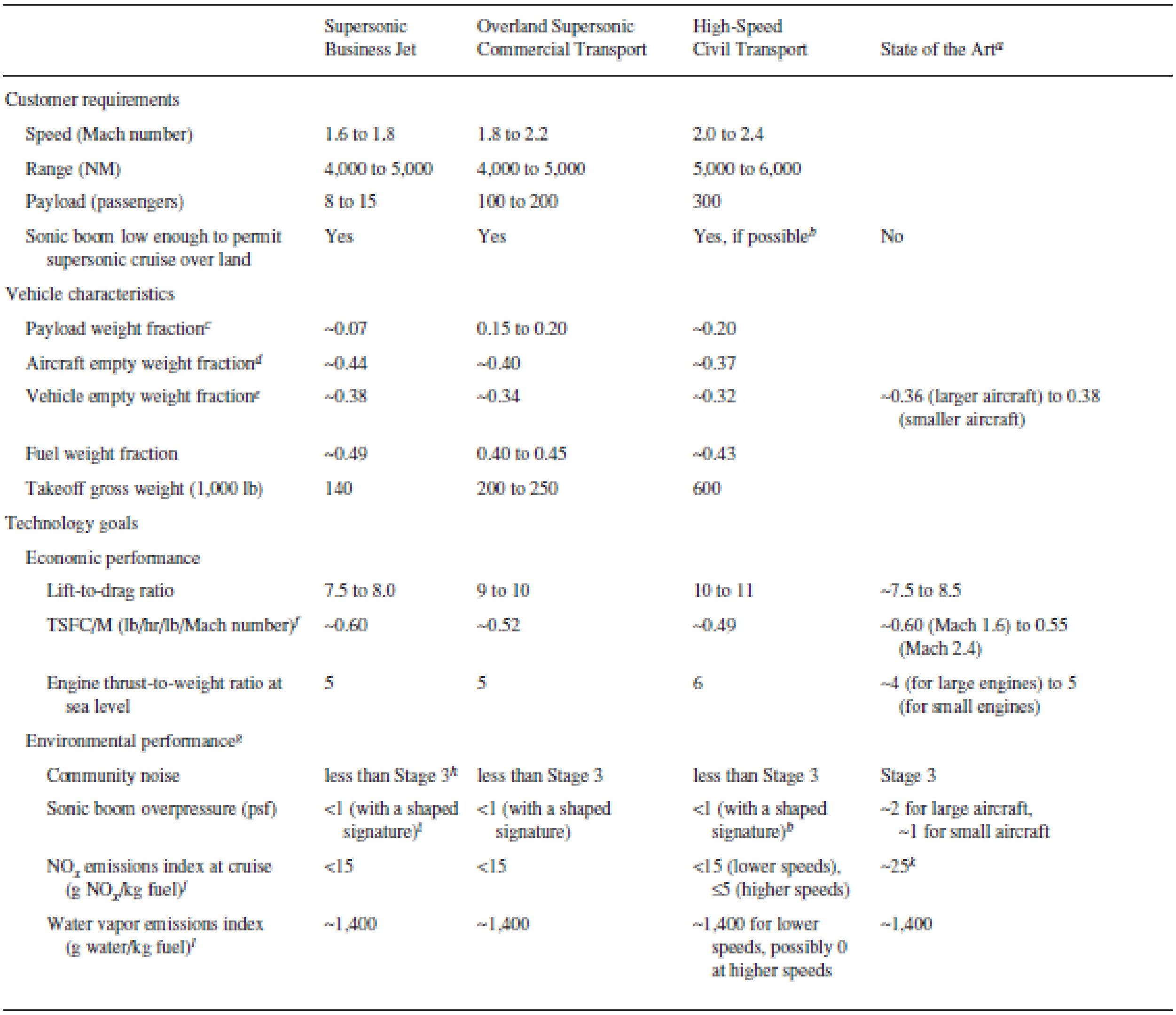


Figure 4.13 – National Aerospace Initiative Technology Roadmap[247]

Although the ending of the HSR program without hardware development was largely due to the benefit of the production vehicle not outweighing the incurred cost, risk and uncertainty, the NRC study only addresses the potential demand through reference and qualitative discussion, and no mention is made of how the three potential roles of considered categories of vehicle systems (business jets, commercial aircraft, and strike aircraft, see Figure 4.14) may change in the 25 year time period under consideration. The problem is acknowledged as an integrated socio-technical issue, but the connection between the defined mission categories, supporting technology research areas and their operational viability is not provided.



	Supersonic Business Jet	Overland Supersonic Commercial Transport	High-Speed Civil Transport	State of the Art[a]
Customer requirements				
Speed (Mach number)	1.6 to 1.8	1.8 to 2.2	2.0 to 2.4	
Range (NM)	4,000 to 5,000	4,000 to 5,000	5,000 to 6,000	
Payload (passengers)	8 to 15	100 to 200	300	
Sonic boom low enough to permit supersonic cruise over land	Yes	Yes	Yes, if possible[b]	No
Vehicle characteristics				
Payload weight fraction[c]	~0.07	0.15 to 0.20	~0.20	
Aircraft empty weight fraction[d]	~0.44	~0.40	~0.37	
Vehicle empty weight fraction[e]	~0.38	~0.34	~0.32	~0.36 (larger aircraft) to 0.38 (smaller aircraft)
Fuel weight fraction	~0.49	0.40 to 0.45	~0.43	
Takeoff gross weight (1,000 lb)	140	200 to 250	600	
Technology goals				
Economic performance				
Lift-to-drag ratio	7.5 to 8.0	9 to 10	10 to 11	~7.5 to 8.5
TSFC/M (lb/hr/lb/Mach number)[f]	~0.60	~0.52	~0.49	~0.60 (Mach 1.6) to 0.55 (Mach 2.4)
Engine thrust-to-weight ratio at sea level	5	5	6	~4 (for large engines) to 5 (for small engines)
Environmental performance[g]				
Community noise	less than Stage 3[h]	less than Stage 3	less than Stage 3	Stage 3
Sonic boom overpressure (psf)	<1 (with a shaped signature)[i]	<1 (with a shaped signature)	<1 (with a shaped signature)[b]	~2 for large aircraft, ~1 for small aircraft
NO_x emissions index at cruise (g NO_x/kg fuel)[j]	<15	<15	<15 (lower speeds), ≤5 (higher speeds)	~25[k]
Water vapor emissions index (g water/kg fuel)[j]	~1,400	~1,400	~1,400 for lower speeds, possibly 0 at higher speeds	~1,400

Figure 4.14 – Initiation of Requirements in Strategic Planning[248]

Summary of Strategic Planning Forecasting

The current status quo approach seen in strategic planning tasks shows a consistent lack of analytical framing of the design space. The complexity of the vehicle systems and their socio-technical influences is not a sufficient reason to pass the responsibility solely to the judgement of experts, no matter how experienced – these decisions can and should be supported with data-driven and analysis-driven information promoted by *DE* principles. In summary, the qualities of current strategic planning forecasting are:

- Requirement to synthesize data across socio-technical and decision-making domains

- Need to define a functional relationship between time, cost, and capability
- Reliance on knowledge domain to produce information where data and analysis sources are insufficient
- Uncertainty artificially reduced to assess future outcomes

4.1.1.3 Requirements Definition

Table 4.5 – Defining Traits of Requirements Definition Forecasting Tasks

Targeted Decision-Maker	Program managers, chief engineers, research technologists, operational and manufacturing engineers
Information Produced	Formal set of requirements that should be satisfied for a product to satisfy the desired capabilities, often focused towards a specific product concept or set of concepts.
Related Tasks	Feasibility study, sensitivity analysis
Proceeding Decision Gate	The initiation of a formal development program and investment of organizational resources towards definition of the vehicle system product.

The definition of design requirements is the point at which an organization's strategic visions meet with the realities of the development and operational environment to coalesce into concrete expectations for a vehicle system. This includes defining the mission the vehicle is to satisfy, specifying the regulatory constraints that must be met, identifying the desired return on investment, and refining the expected solution approaches. This forecasting task should, in theory, only be executed after the market space for the vehicle system is well understood and the feasibility of the proposed design space has been verified. As shown in the examples below system requirements definition, however, often occurs with incomplete supporting information that does not take advantage of available data and built around holistic analytical description of the problem.

Requirements Definition Examples

In 2008, NASA sponsored a collaborative effort with industry and academic team to study potential operational aspects for future supersonic commercial transport aircraft in both the mid-term[251] (N+2) and long-term[252] (N+3). The overall goal is to define the baseline requirements and objectives on which NASA should direct their technology investment budget dollars. In order to define the top-level capability requirements, the study must examine the influence of an interrelated combination of socio-technical variables on the operational performance, requiring both a combination of datasets across multiple domains and an integration of multi-disciplinary analysis into decision-making information.

Within the N+2 and N+3 studies, the definition of the operational mission requirements is largely substantiated by historical air travel data – route distance, number of passengers transported, and numbers of premium passengers transported are used to define cutoffs in required vehicle range and potential demand for long-distance transport, see Figure 4.15. In addition, market trends in business jet deliveries are also used as an indicator for the potential demand of supersonic transports in the case that the design passenger payload is small enough to compete in the personal or fractional ownership market. Unfortunately, no connection is made to the underlying geopolitical influences driving neither the route demands nor the potential changes in demand from the requirements phase to the entry into service phase, ~2035, is made – the requirement definition is treated as a deterministic, one-time event with no sensitivity shown to changes in future events.

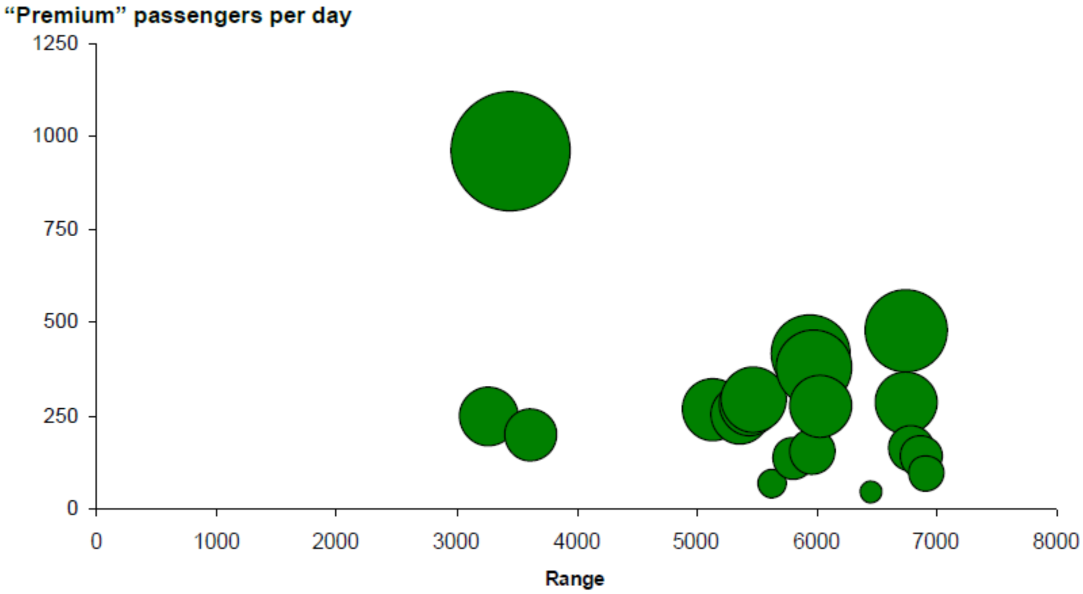
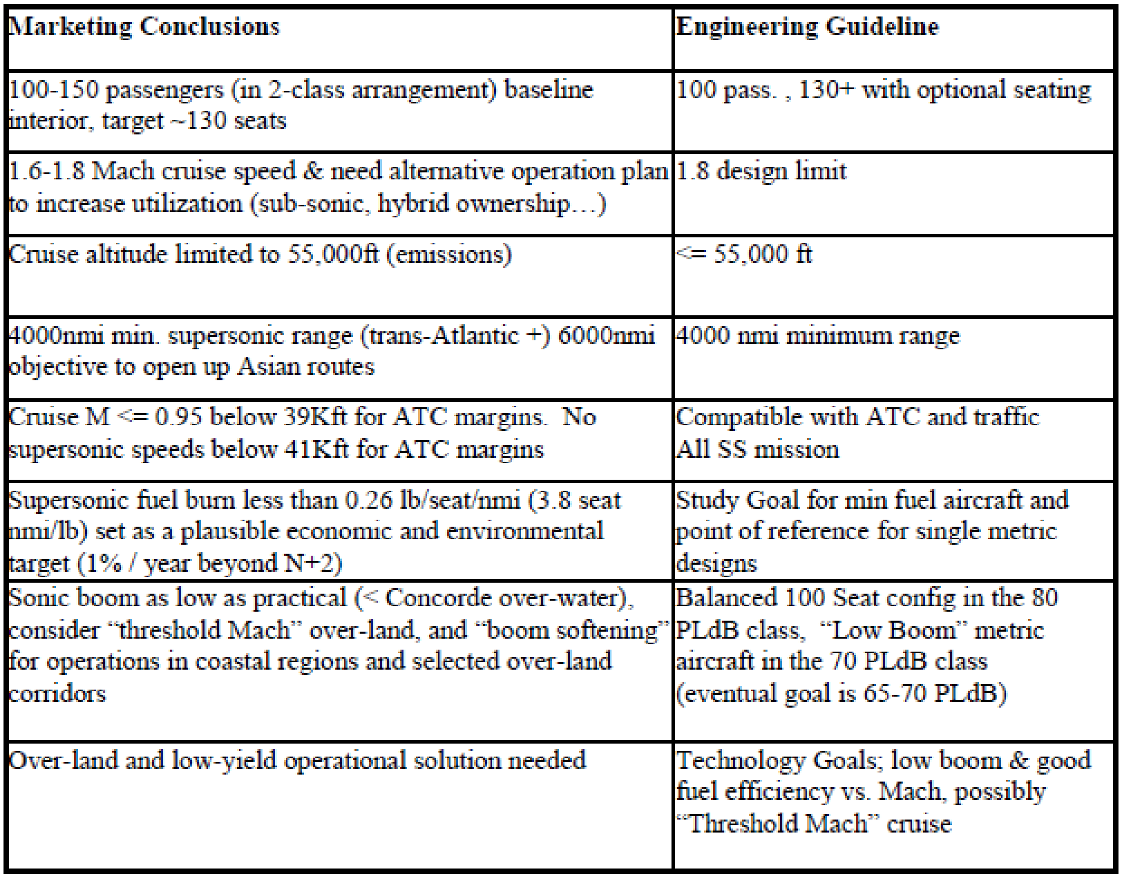


Figure 4.15 – Using Current Market Data to Drive Future Requirements[251]

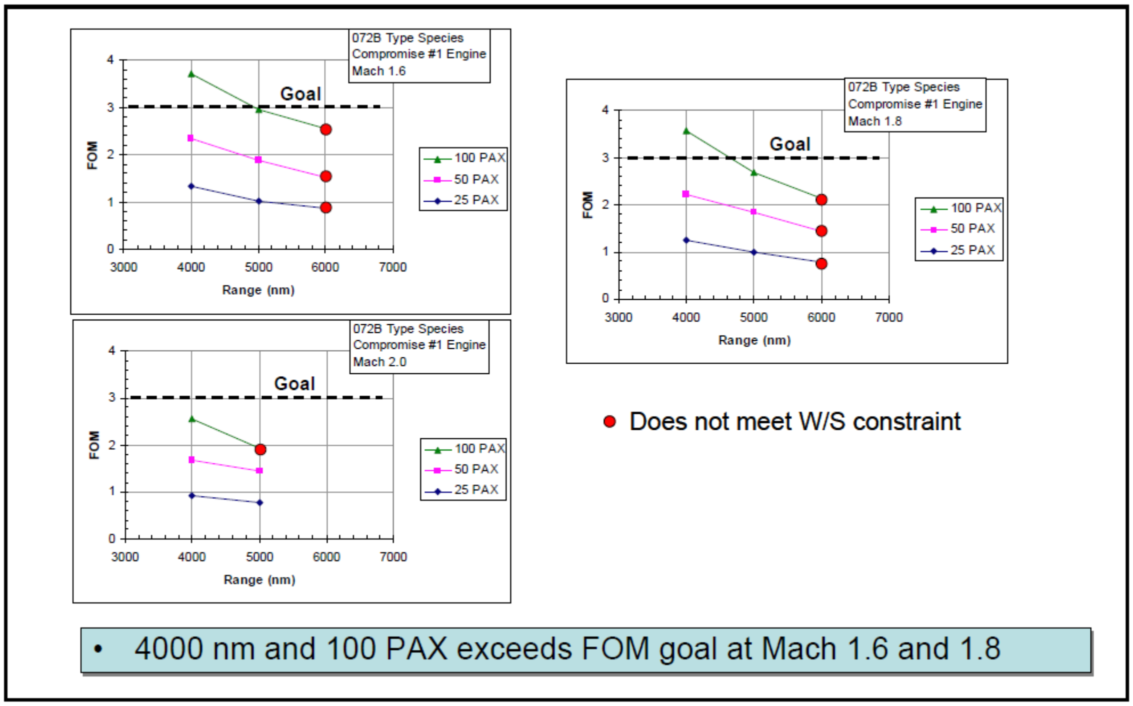
The definition of other vehicle requirements are driven by a combination of expert estimates of regulatory and environmental constraints at entry into service and analytically-derived information, see Figure 4.16. The constriction of the design space through narrow ranges of requirements (e.g. 100 passenger payload, Mach 1.8 design limit, .26 lb/seat/nmi fuel efficiency) place a very deterministic viewpoint on an inherently uncertain future scenario. If the actual operating environment varies from the expected outcomes, these guidelines for directing future research investments and vehicle system development may be misdirected – it is inherent to human decision-making to define a most likely future scenario, but the restriction of vantage point to only the most likely whilst ignoring the bound of uncertainty is an incorrect portrayal of long term forecasting.



Marketing Conclusions	Engineering Guideline
100-150 passengers (in 2-class arrangement) baseline interior, target ~130 seats	100 pass. , 130+ with optional seating
1.6-1.8 Mach cruise speed & need alternative operation plan to increase utilization (sub-sonic, hybrid ownership…)	1.8 design limit
Cruise altitude limited to 55,000ft (emissions)	<= 55,000 ft
4000nmi min. supersonic range (trans-Atlantic +) 6000nmi objective to open up Asian routes	4000 nmi minimum range
Cruise M <= 0.95 below 39Kft for ATC margins. No supersonic speeds below 41Kft for ATC margins	Compatible with ATC and traffic All SS mission
Supersonic fuel burn less than 0.26 lb/seat/nmi (3.8 seat nmi/lb) set as a plausible economic and environmental target (1% / year beyond N+2)	Study Goal for min fuel aircraft and point of reference for single metric designs
Sonic boom as low as practical (< Concorde over-water), consider "threshold Mach" over-land, and "boom softening" for operations in coastal regions and selected over-land corridors	Balanced 100 Seat config in the 80 PLdB class, "Low Boom" metric aircraft in the 70 PLdB class (eventual goal is 65-70 PLdB)
Over-land and low-yield operational solution needed	Technology Goals; low boom & good fuel efficiency vs. Mach, possibly "Threshold Mach" cruise

Figure 4.16 – Deriving Engineering Requirements from Non-technical Considerations[252]

In order to produce vehicle system information for the N+2 and N+3 studies through the use of existing vehicle synthesis software, detailed operational and performance characteristics of the system (e.g. velocity, time and altitude profiles of baseline mission) have been designated *a priori* (i.e. before sufficient supporting vehicle system information should be known) – this adaptation of vehicle description to match an existing analytical framework instead of vice versa (i.e. adapting the analysis fidelity and framework to match the uncertainty of a future vehicle system) have not been addressed. While parametric evaluation of design variables within an MDA framework has been used to justify design requirements, see Figure 4.17, the development time and cost (i.e. program risk) has not been included for further decision-making.



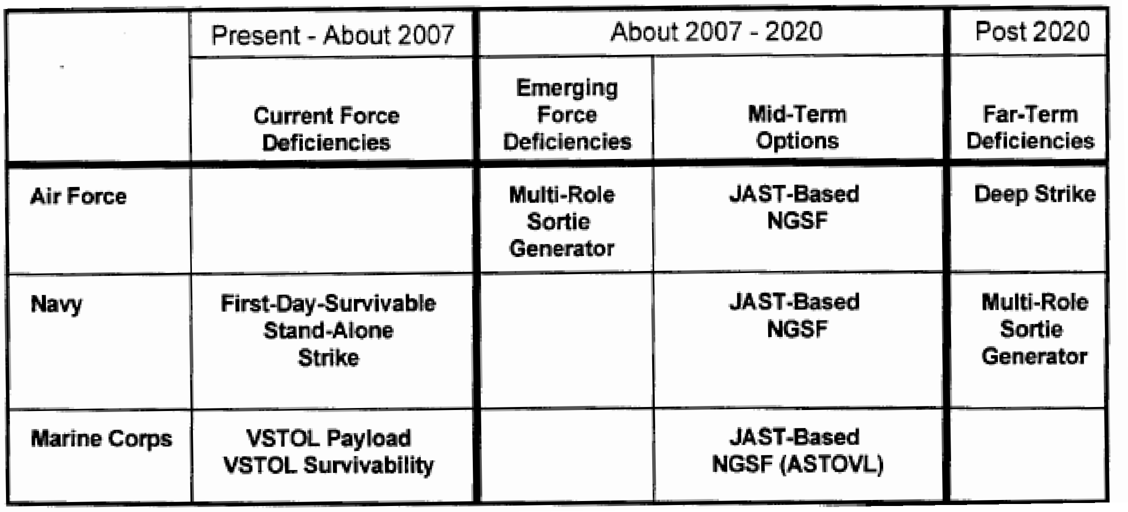
- 4000 nm and 100 PAX exceeds FOM goal at Mach 1.6 and 1.8

Figure 4.17 – Parametric Analysis of Design Space to Derive Requirements[252]

Although the recent problems with the F-35 Joint Strike Fighter (JSF) aircraft program have involved sub-system engineering, software design and supply-chain logistics[258], many of the issues in budget and schedule overrun can at least be partially attributed to the initial definition of system capability requirements in the early 1990s[253].

One of the key tenets of the JSF program has been the accommodation of Air Force, Navy and Marine Corps capability requirements, see Figure 4.18, with the joint nature due to the contraction of acquisition and development programs due to capability the collapse of the Soviet Union, and therefore an expected dearth of high-technology adversaries. Although the changing nature of engagements is acknowledged by the joint program, the expected operating environment in future engagements throughout the life-cycle of the weapon system is missing. In addition, the connection between these requirements and the feasibility and performance characteristics of the aircraft is not made – solution-space narrowing requirements are being defined without consideration of their effect on the technical risk and cost of the vehicle system.

In particular, the requirement by the Marine Corps for a Vertical / Short Takeoff Landing (VSTOL) capability has proven to not only be a technical challenge, but has degraded the estimated in-theatre performance of even the Navy and Air Force F-35 variants that do not directly have the capability, but share airframe commonality – a strategic air-to-air war gaming analysis has concluded that even with superior training, sensor and detection systems, and missile systems, the slow speed, short range, and degraded maneuvering characteristics of the F-35 make it largely ineffective in a relevant engagement[257]. The deficiency of forecasted insight into the future operational realities (i.e. renewed and growing Chinese Air Force, advances in stealth-sensing capabilities, advances in unmanned vehicles, network-centric warfare), as well as the insistence on capabilities without an understanding of the impact on system feasibility continues to follow the JSF program.



	Present - About 2007	About 2007 - 2020		Post 2020
	Current Force Deficiencies	**Emerging Force Deficiencies**	**Mid-Term Options**	**Far-Term Deficiencies**
Air Force		**Multi-Role Sortie Generator**	**JAST-Based NGSF**	**Deep Strike**
Navy	**First-Day-Survivable Stand-Alone Strike**		**JAST-Based NGSF**	**Multi-Role Sortie Generator**
Marine Corps	**VSTOL Payload VSTOL Survivability**		**JAST-Based NGSF (ASTOVL)**	

Figure 4.18 – Capabilities-based Requirements for Joint Military Vehicle System[254]

Summary of Requirements Definition Forecasting

The definition of vehicle system requirements in current aerospace research and development programs shows an inconsistent application of *DE* principles leading to mischaracterized operating environments and constriction of design possibilities before sufficient information is known. Current requirements definition forecasting efforts have the following characteristics:

- Adaptation of the information process to match accepted analysis techniques
- Narrow definition of requirements for uncertain future scenarios
- Capability expectations made without assessment of impact on system viability

4.1.2 Impact of Data-Engineering Systems on Aerospace Design and Forecasting

From this assessment of design forecasting approaches across the research and development cycle, it is hypothesized that the introduction of *Data-Engineering* principles in the form of integrated *Data-Engineering Systems* has the potential to positively impact the efficiency at which information is produced, as well as improve the level of market-space and design-space understanding available to the decision-makers. Current design forecasting efforts produce inconsistent information outputs that stem from their unstructured integration of data, knowledge and analysis domains – introduction of process structure through a *DES* is needed to ensure design and forecasting organizations have an avenue to channel their efforts, facilitating cohesive studies that provide better information with more integration of both decision-making perspectives and the socio-technical-domains that influence them.

Implementing *DES* principles within aerospace design forecasting environments requires the derivation of specifications from both a functional data system and aerospace design engineering perspectives. The proposed approach is stretching the responsibilities of the aerospace engineering and design community to transition from engineering analysis of vehicle systems and subsystems towards application of engineering principles to forecasting tasks – this requires a supplemental structured *Data-Engineering* education foundation and applied toolsets in addition to their technical expertise.

4.2 DATA-ENGINEERING RESEARCH SPECIFICATION

Using this accumulated understanding of the decision-making process, theoretical and practical treatment of data within larger information processes, and aerospace-specific integration of data into design & forecasting tasks, the specifications for aerospace *Data-Engineering* research can objectively be addressed.

4.2.1 Defining Characteristics of Data-Engineering Systems

Before defining a specification for an aerospace forecasting-specific *Data-Engineering System* (DES), a formal definition of *DESs* and their characteristics provides a tangible anchoring point for further discussion, see Table 4.6. These properties of *DES*s are intentionally left at a generic, universal level. In addition to aerospace design forecasting-specific functions, discussed below, it is the author’s intent that development of the proceeding *DES* be constantly grounded with best-practices and guidelines outside of the aerospace field. This approach is adopted in an attempt to elevate the development away from a parochial platform with narrow focus and applicability only within the native organization and sub-field, but towards a research effort that is applicable to a broader class of design, forecasting, and integration engineers.

Table 4.6 – Defining Properties of Data-Engineering Systems

#	*Property*
1	Derives value only by improving the quantity, quality and efficiency of information provided for decision-making.
2	Executes along a structured process flow that is independent of the topic or the information requirements.
3	Measures its performance as a function of both the attributes of the data utilized and the platform used to process data.
4	Addresses its role in larger information production processes requiring knowledge and analysis-driven tasks.
5	Provides a collaborative environment for dissemination and retention of data pertaining to past and present organizational efforts.

4.2.2 Ideal Design Forecasting Environment

The development of a complete, holistic aerospace forecasting environment able to accommodate all levels of decision-making across all aerospace vehicle spectra is a massive undertaking, and one that will be produced incrementally across the careers of many researchers and practitioners. It is, however, beneficial to produce an idealistic viewpoint of the theoretical end-goal – this provides a yardstick by which existing systems may be gauged, and the incremental improvements may be judged for merit.

An ideal forecasting system, at the highest level, would be an inverse-information production engine. The final information product desired is taken as the input and the engine determines, through artificially intelligent inference, the data, knowledge, and analytical approach required to produce that information product. Under scenarios where all data, knowledge and analysis elements presently exist within the system, the information is produced inherently with no additional input required. Where data, knowledge, or analysis elements do not exist, the engine defines explicitly what elements are needed and accepts input from the user under any format or mechanically searches external sources for possible inclusion. A baseline synthesis process is produced automatically from information requirements and the available analysis methods.

Within this idealized goal, the research and development goals of the current dissertation topic are a sub-segment. The outcome of a fully implemented *Data-Engineering System*, illustrated in Figure 4.19, is to provide a single unified platform that enables all data tasks, incorporates organizational knowledge processes and provides a direct interface towards the analysis domain. This development sub-goal and the idealized end-state are mutually exclusive outcomes – in order to advance towards an intelligent inverse information-production paradigm, the information elements and processing platforms must be more readily be integrated, as proposed by this *DE* research.

4.2.3 Aerospace Data-Engineering Specification Requirements

From this top-level definition of a *DES*, a functional specification for a *DES* in an aerospace design forecasting environment can be applied (the development of a prototype *DES* platform built to these specifications is discussed in the following Chapter 4). These specifications have been further decomposed into 1) functional requirements, and 2) user interface requirements.

functional requirement:
task a platform is required to perform, subject to any defined constraints

user experience (UX) requirement:
attribute of a system that impacts how a user performs a functional task

The specification requirements, following the general order in which they would be encountered in a developed *DES* (shown in Table 4.7), represent the intersection of the above research in data, data systems, and the unique data and information requirements for aerospace design forecasting as internalized by the author. Each requirement guides the development of design features in a practical *DES* software platform and is referred to through the derivation process.

Table 4.7 – Specification of an Aerospace Design Forecasting Data-Engineering System

#	*Requirement*	*Fnct'l Req.*	*UX Req.*
1	Develop an open architecture to be continually improved.	X	X
2	Provide a transparent flow of data from source documentation to implementation.		X
3	House source, process and result data in organizationally-communal network.	X	
4	Allow the collection, viewing and editing of original source documentation.	X	X
5	Allow the integration of non-standardized data formats.	X	
6	Interface with multi-domain existing internal and external data sources	X	
7	Provide access to source, process and result data of previous organizational efforts.	X	
8	Provide the opportunity to add, edit and manipulate data organization schema.	X	X
9	Allow for user-defined aggregation, filter and query across any dataset(s).		X
10	Provide ability to identify and visualize trends in data.	X	
11	Provide a suite of data visualization outputs with corresponding applicability.	X	
12	Allow view, edit and add of knowledge guidelines to support future efforts.	X	X
13	Provide a standardized process interface between the DES and synthesis platform.	X	
14	Integrate data processes required for execution of aerospace synthesis.	X	

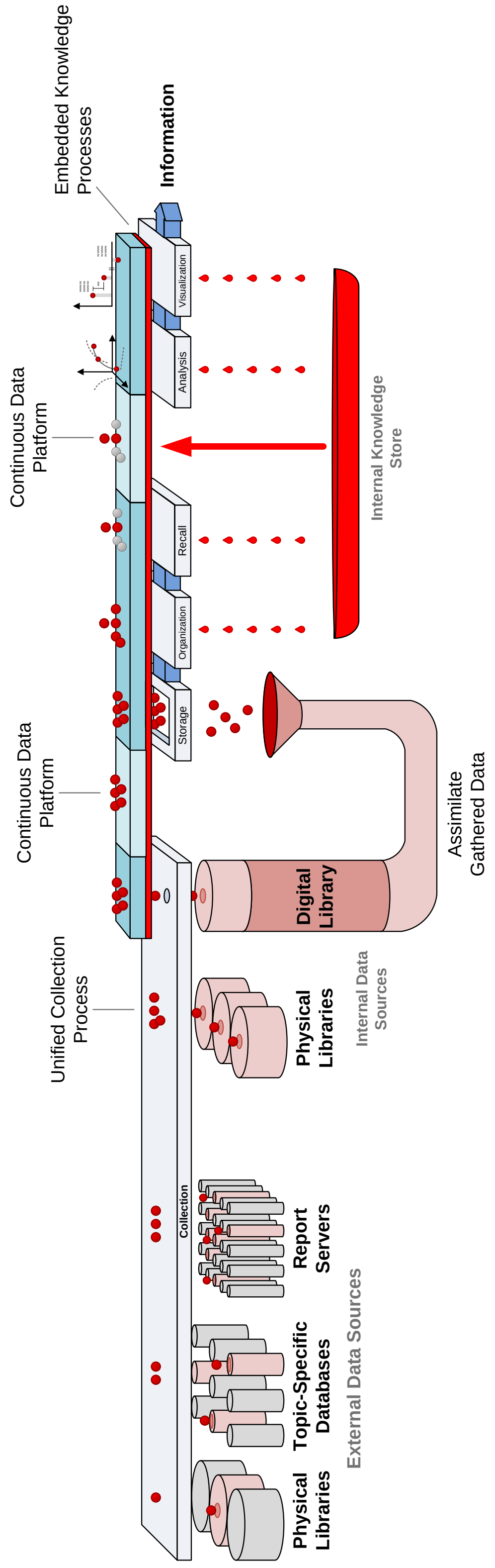


Figure 4.19 – Developmental Goal State of Data-Engineering System

Table 4.8 – Data and Data Systems Performance Metrics

ID	*Data Metric*	*Category*	*Meaning*
A	Scope	Data Quality	Breadth of data
B	Density	Data Quality	Depth of data
C	Meta-Data Ratio	Data Quality	Understanding of data
D	Completeness	Collection, Storage & Organization	Lack of holes in data
E	Capacity	Collection, Storage & Organization	Storage limit
F	Accessibility	Collection, Storage & Organization	Openness to user change
G	Adaptability	Collection, Storage & Organization	Effort to meet changing requirements
H	Time Cost	Recall	Temporal access investment
I	Economic Cost	Recall	Dollar access investment
J	Precision	Recall	Applicability of results
K	Sensitivity	Recall	Wholeness of results
L	Multiplicity	Analysis & Visualization	Visualization 'field of view'
M	Degrees of Freedom	Analysis & Visualization	Solution space options
N	Interoperability	Analysis & Visualization	Interface with outside processes

4.3 CONTRIBUTION SUMMARY

This chapter has contributed the following towards the dissertation research topic:

- An assessment of aerospace design forecasting principles.
- Discussion and examples of current status quo approaches towards early design forecasting efforts along *situational assessment*, strategic planning and *requirements definition* archetypes.
- Definition of an ideal state design forecasting environment, along with the impact of *DE* research on advancements towards this ideal.
- Definition of *DES* specification requirements reflecting the deficiencies in current data use in aerospace design forecasting.
- Correlation of *DES* specification requirements towards the *DE* component and specific performance metric in which they are intended to improve the information process.

Table 4.9 – Impact of Research Specification Requirements on Data-Engineering Performance

Req. #	*Data Quality Metric*			*Data System Metric*										
				Collection, Storage & Organization				*Recall*				*Analysis & Visualization*		
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*
1						X	X	X				X	X	
2			X	X		X		X		X	X			
3	X	X		X	X	X	X	X	X	X	X			
4	X	X	X											
5	X	X		X										
6	X	X	X	X										
7	X	X		X										
8						X	X							
9						X	X							
10												X	X	
11												X	X	
12			X	X				X	X	X	X			
13														X
14							X							X

REFERENCES

[235] Rothman, A., “Airbus Raises Prospect of Ditching A380 as Orders Vanish,” Bloomberg Business, 2014.
URL: http://www.bloomberg.com/news/articles/2014-12-10/airbus-at-crossroads-as-a380-jumbo-faces-spendorfade-conundrum

[236] Simons, G., “The Airbus A380: A History,” Replika Press, 2014.

[237] National Research Council, "Evaluation of the National Aerospace Initiative," National Academy of Sciences, ISBN 0-309-53107-1, 2004.

[238] National Research Council, "Review and Evaulation of the Air Force Hypersonic Technology Program," National Academy Press, ISBN 0-309-06142-3, 1998.

[239] "2014 Global R&D Funding Forecast," Battelle, 2013.

[240] "Current Market Outlook: 2011-2030," Boeing, 2011.

[241] "Business Aircraft Market Forecast 2013-2032," Bombardier, 2013.

[242] "Future Journeys: Global Market Forecast," Airbus, 2013.

[243] Dowdy, J., Chinn, D., Mancini, M., and Jonathan, N., "Southeast Asia: The next growth opportunity in defense," McKinsey & Company, 2014.

[244] "Embraer Market Outlook: 2014-2033," Embraer, 2014.

[245] Orloff, R., “Apollo by the Numbers: A Statistical Reference,” NASA SP-4029, 2001.

[246] "NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technology Edge and Paving the Way for a New Era in Space," National Research Council, 2012.

[247] National Research Council, "Evaluation of the National Aerospace Initiative," National Academy of Sciences, ISBN 0-309-53107-1, 2004.

[248] Committee on Breakthrough Technology for Commercial Supersonic Aircraft, "Commercial Supersonic Technology: The Way Ahead," National Research Council, 2001.

[249] "An Update of the Nation's Long-Term Strategic Needs for NASA's Aeronautics Test Facilities," RAND Corporation, 2009.

[250] Bartis, J., and Van Bibber, L., "Alternative Fuels for Military Applications," RAND Corporation, 2011.

[251] Welge, H., and et. al, "N+2 Supersonic Concept Development and Systems Integration," NASA Langley Research Center, NASA CR-2010-216842, 2010.

[252] Welge, R., and et al, "N+3 Advanced Concept Studies for Supersonic Commercial Transport Aircraft Entering Service in the 2030-2035 Period," NASA, NASA CR-2011-217084, 2011.

[253] "Balance and Affordability of the Fighter and Attack Aircraft Fleets of the Department of Defense," Congressional Budget Office, 1992.

[254] Heebner, D., "Report of the Defense Science Board Task Force on Joint Advanced Strike Technology (JAST) Program," Office of the Under Secretary of Defense for Acquisition & Technology, 1994.

[255] Steidle, C., "The Joint Strike Fighter Program," Johns Hopkins APL Technical Digest, Vol. 18, No. 1, 1997.

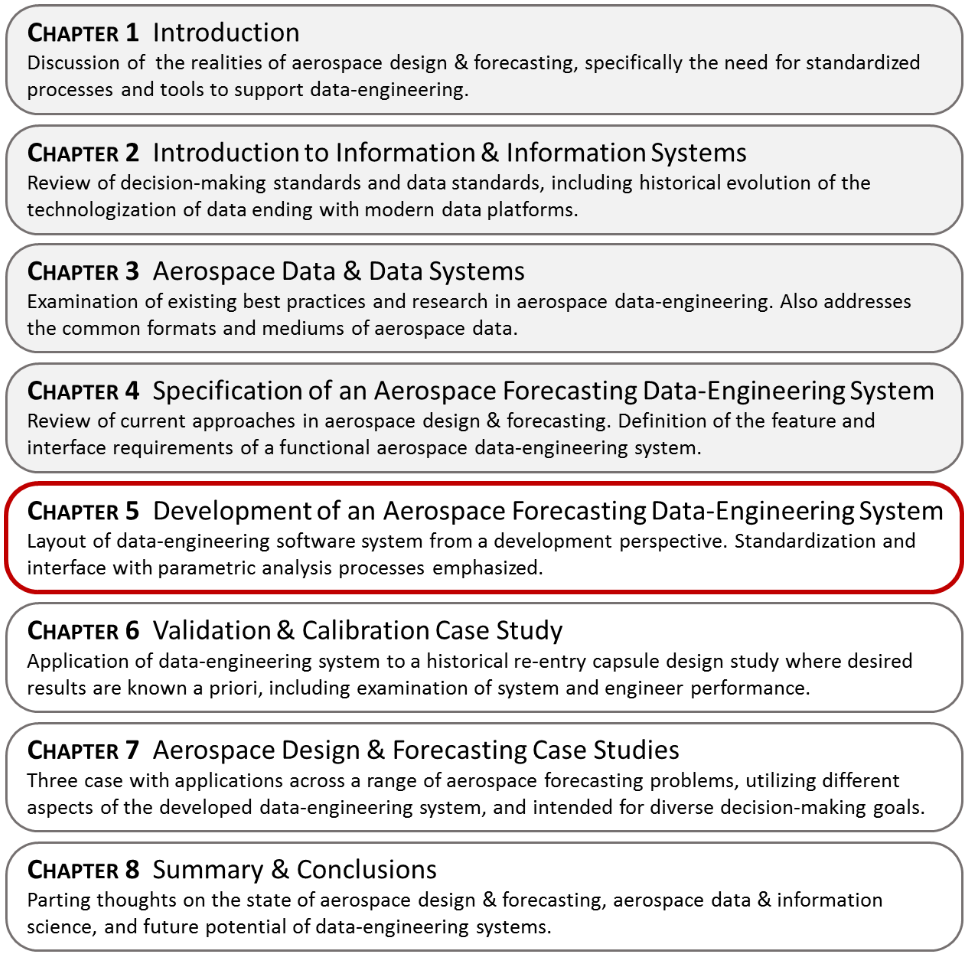
[256] "Joint Strike Fighter (JSF) Program: Background, Status, and Issues," Congressional Research Services, 2003.

[257] Stillion, J., and Perdue, S., "Air Combat Past, Present and Future," RAND Corporation, 2008.

[258] Axe, D., "F'd: How the U.S. and Its Allies Got Stuck with the World's Worst New Warplane," War is Boring, 2013.

Chapter 5

Development of Aerospace Data-Engineering System



Chapter 1 Introduction
Discussion of the realities of aerospace design & forecasting, specifically the need for standardized processes and tools to support data-engineering.

Chapter 2 Introduction to Information & Information Systems
Review of decision-making standards and data standards, including historical evolution of the technologization of data ending with modern data platforms.

Chapter 3 Aerospace Data & Data Systems
Examination of existing best practices and research in aerospace data-engineering. Also addresses the common formats and mediums of aerospace data.

Chapter 4 Specification of an Aerospace Forecasting Data-Engineering System
Review of current approaches in aerospace design & forecasting. Definition of the feature and interface requirements of a functional aerospace data-engineering system.

Chapter 5 Development of an Aerospace Forecasting Data-Engineering System
Layout of data-engineering software system from a development perspective. Standardization and interface with parametric analysis processes emphasized.

Chapter 6 Validation & Calibration Case Study
Application of data-engineering system to a historical re-entry capsule design study where desired results are known a priori, including examination of system and engineer performance.

Chapter 7 Aerospace Design & Forecasting Case Studies
Three case with applications across a range of aerospace forecasting problems, utilizing different aspects of the developed data-engineering system, and intended for diverse decision-making goals.

Chapter 8 Summary & Conclusions
Parting thoughts on the state of aerospace design & forecasting, aerospace data & information science, and future potential of data-engineering systems.

With the specification for an aerospace design & forecasting data system formalized, this chapter will detail the functional development of a practical system. Although it has been necessary to articulate a firm theoretical basis behind *Data-Engineering Systems*, the end goal is to augment practical data processing in actual aerospace information-production tasks. The development of capabilities has directly followed requirements from design and forecasting projects supporting actual aerospace industry decision-makers with substantial information requirements, see Chapters 6 & 7.

The preceding research of *Data-Engineering* platforms, processes and objectives in a generic fashion has provided a key research objective: to specify the problem and define solution requirements. The ensuing objective of the scientific approach, then, is to provide a derivation of the experimental system, presented here. The following discussion is focused solely on development of a *Data-Engineering System* as applied to the early design and forecasting decision process for aerospace vehicle research and development.

5.1 AEROSPACE SYNTHESIS PLATFORM ASSESSMENT

Due to the integrated and complex nature of air and space vehicle systems, dedicated aerospace multi-disciplinary analysis (MDA) platforms have been developed to provide parametric systems analysis. By receiving mission, operational and hardware definition, requirements and constraints from the platform operator, the MDA platform synthesizes the multi-domain interdependencies to arrive at a defined vehicle system. The level of consideration of disciplinary analysis, scope of multi-domain effects, process integration scheme, and output information is solely dependent on the specific implementation of the *synthesis platform*. To date, most synthesis platforms have been developed and operated in provincial settings (i.e. developed for specific types of air or space vehicles at specific design stages for specific organization or decision-making scope), see Table 5.1.

Table 5.1 – List of Aerospace Synthesis Platforms[264]

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

18	**ASCENT**	(-)	Lockheed Martin Skunk Works	AeroSpace Vehicle	1993
19	**ASSET**	Advanced Systems Synthesis and Evaluation Technique	Lockheed California Company	Aircraft	Before 1993
20	**Altman**	Design Methodology for Low Speed High Altitude UAV's	Cranfield University	Unmanned Aerial Vehicles	Paper 1998
21	**AVID**	Aerospace Vehicle Interactive Design	N.C. State University, NASA LaRC	Aircraft and AeroSpace Vehicle	1992
22	**AVSYN**	?	Ryan Teledyne	?	1974
23	**BEAM**	(-)	Boeing	?	NA
24	**CAAD**	Computer-Aided Aircraft Design	SkyTech	High-Altitude Composite Aircraft	NA
25	**CAAD**	Computer-Aided Aircraft Design	Lockheed-Georgia Company	Aircraft	1968
26	**CACTUS**	(-)	Israel Aircraft Industries	Aircraft	NA
27	**CADE**	Conceptual Aircraft Design Environment	McDonnel Douglas Corporation	Fighter Aircraft (F-15)	1974
28	**CAP**	Configuration Analysis Program	North American Rockwell (B-1 Division)	Aircraft	1974
29	**CAPDA**	Computer Aided Preliminary Design of Aircraft	Technical University Berlin	Transonic Transport Aircraft	1984-
30	**CAPS**	Computer Aided Project Studies	BAC Military Aircraft Devision	Military Aircraft	1968
31	**CASP**	Combat Aircraft Synthesis Program	Northrop Corporation	Combat Aircraft	1980
32	**CASDAT**	Conceptual Aerospace Systems Design and Analysis Toolkit	Georgia Institute of Technology	Conceptual Aerospace Systems	late 1995
33	**CASTOR**	Commuter Aircraft Synthesis and Trajectory Optimization Routine	Loughborough University	Transonic Transport Aircraft	1986
34	**CDS**	Configuration Development System	Rockwell International	Aircraft and AeroSpace Vehicle	1976
35	**CISE**	(-)	Grumman Aerospace Corporation	AeroSpace Vehicle	1994
36	**COMBAT**	(-)	Cranfield University	Combat Aircraft	
37	**CONSIZ**	CONfiguration SIZing	NASA Langley Research Center	AeroSpace Vehicle	1993
38	**CPDS**	Computerized Preliminary Design System	The Boeing Company	Transonic Transport Aircraft	1972
39	**Crispin**	Aircraft sizing methodology	Loftin	Aircraft sizing methodology	1980
40	**DesignSheet**	(-)	Rockwell international	Aircraft and AeroSpace Vehicle	1992
41	**DRAPO**	Définition et Réalisation d'Avions Par Ordinateur	Avions Marcel Dassault/Bréguet Aviation	Aircraft	1968
42	**DSP**	Decision Support Problem	University of Houston	Aircraft	1987
43	**EASIE**	Environment for Application Software Integration and Execution	NASA Langley Research Center	Aircraft and AeroSpace Vehicle	1992
44	**EADS**				
45	**ESCAPE**	(-)	BAC (Commercial Aircraft Devision)	Aircraft	1995
46	**ESP**	Engineer's Scratch Pad	Lockheed Advanced Development Co.	Aircraft	1992

47	**Expert Executive**	(-)	The Boeing Company	?	
48	**FASTER**	Flexible Aircraft Scaling To Requirements	Florian Schieck		
49	**FASTPASS**	Flexible Analysis for Synthesis, Trajectory, and Performance for Advanced Space Systems	Lockheed Martin Astronautics	AeroSpace Vehicle	1996
50	**FLOPS**	FLight OPtimization System	NASA Langley Research Center	?	1980s-
51	**FPDB & AS**	Future Projects Data Banks & Application Systems	Airbus Industrie	Transonic Transport Aircraft	1995
52	**FPDS**	Future Projects Design System	Hawker Siddeley Aviation Ltd	Aircraft	1970
53	**FRICTION**	Skin friction and form drag code			1990
54	**FVE**	Flugzeug VorEntwurf	Stemme GmbH & Co. KG	GA Aircraft	1996
55	**GASP**	General Aviation Synthesis Program	NASA Ames Research Center	GA Aircraft	1978
56	**GPAD**	Graphics Program For Aircraft Design	Lockheed-Georgia Company	Aircraft	1975
57	**HACDM**	Hypersonic Aircraft Conceptual Design Methodology	Turin Polytechnic	Hypersonic aircraft	1994
59	**HADO**	Hypersonic Aircraft Design Optimization	Astrox	?	1987-
60	**HASA**	Hypersonic Aerospace Sizing Analysis	NASA Lewis Research Center	AeroSpace Vehicle	1985, 1990
61	**HAVDAC**	Hypersonic Astrox Vehicle Design and Analysis Code	Astrox		1987-
62	**HCDV**	Hypersonic Conceptual Vehicle Design	NASA Ames Research Center	Hypersonic Vehicles	
63	**HESCOMP**	HElicopter Sizing and Performance COMputer Program	Boeing Vertol Company	Helicopter	1973
64	**HiSAIR/Pathfinder**	High Speed Airframe Integration Research	Lockheed Engineering and Sciences Co.	Supersonic Commercial Transport Aircraft	1992
65	**Holist**	?	?	Hypersonic Vehicles with Airbreathing Propulsion	1992
66	**ICAD**	Interactive Computerized Aircraft Design	USAF-ASD	?	1974
67	**ICADS**	Interactive Computerized Aircraft Design System	Delft University of Technology	Aircraft	1996
68	**IDAS**	Integrated Design and Analysis System	Rockwell International Corporation	Fighter Aircraft	1986
69	**IDEAS**	Integrated DEsign Analysis System	Grumman Aerospace Corporation	Aircraft	1967
70	**IKADE**	Intelligent Knowledge Assisted Design Environment	Cranfield University	Aircraft	1992
71	**IMAGE**	Intelligent Multi-Disciplinary Aircraft Generation Environment	Georgia Tech	Supersonic Commercial Transport Aircraft	1998
72	**IPAD**	Integrated Programs for Aerospace-Vehicle Design	NASA Langley Research Center	AeroSpace Vehicle	1972-1980
73	**IPPD**	Integrated Product and Process Design	Georgia Tech	Aircraft, weapon system	1995
74	**JET-UAV CONCEPTUAL DEISGN CODE**		Northwestern Polytechnical University, China	Medium range JET-UAV	2000
75	**LAGRANGE**			Optimization	1993

76	**LIDRAG**	Span efficiency			1990
77	**LOVELL**				1970-1980
78	**MAVRIS**	an analysis-based environment	Georgia Institue of Technology		2000
79	**MELLER**		Daimler-Benz Aerospace Airbus	Civil aviation industry	1998
80	**MacAirplane**	(-)	Notre Dame University	Aircraft	1987
81	**MIDAS**	Multi-Disciplinary Integrated Design Analysis & Sizing	DaimlerChrysler Military	Aircraft	1996
82	**MIDAS**	Multi-Disciplinary Integration of Deutsche Airbus Specialists	DaimlerChrysler Aerospace Airbus	Supersonic Commercial Transport Aircraft	1996
83	**MVA**	Multi-Variate Analysis	RAE (BAC)	Aircraft	1991
84	**MVO**	MultiVariate Optimisation	RAE Farnborough	Aircraft	1973
85	**NEURAL NETWORK FORMULATION**	Optimization method for Aircrat Design	Georgia Institute of Technology	Aircraft	1998
86	**ODIN**	Optimal Design INtegration System	NASA Langley Research Center	AeroSpace Vehicle	1974
87	**ONERA**	Preliminary Design of Civil Transport Aircraft	Office National d’Etudes et de Recherches Aérospatiales	Subsonic Transport Aircraft	1989
88	**OPDOT**	Optimal Preliminary Design Of Transports	NASA Langley Research Center	Transonic Transport Aircraft	1970-1980
89	**PACELAB**	knowledge based software solutions	PACE	Aircraft	2000
90	**Paper Airplane**	(-)	MIT	Aircraft	
91	**PASS**	Program for Aircraft Synthesis Studies	Stanford University	Aircraft	1988
92	**PATHFINDER**		Lockheed Engineering and Sciences Co.	Supersonic Commercial Transport Aircraft	1992
93	**PIANO**	Project Interactive ANalysis and Optimization	Lissys Limited	Transonic Transport Aircraft	1980-
94	**POP**	Parametrisches Optimierungs-Programm	Daimler-Benz Aerospace Airbus	Transonic Transport Aircraft	2000
95	**PrADO**	Preliminary Aircraft Design and Optimization	Technical University Braunschweig	Aircraft and AeroSpace Vehicle	1986-
96	**PreSST**	Preliminary SuperSonic Transport Synthesis and Optimization	DRA UK	Supersonic Commercial Transport Aircraft	
97	**PROFET**	(-)	IABG	Missile	1979
98	**RAE**	Artificial Intelligence Supported Design of Aircraft	Royal Aircraft Establishment, Farnborough	Aircraft conceptual design	Early1970’s.
99	**RAM**		NASA	geometric modeling tool	1991
100	**RCD**	Rapid Conceptual Design	Lockheed Martin Skunk Works	AeroSpace Vehicle	
101	**RDS**	(-)	Conceptual Research Corporation	Aircraft	1992
102	**RECIPE**	(-)	?	?	1999
103	**RSM**	Response Surface Methodology			1998
104	**Rubber Airplane**	(-)	MIT	Aircraft	1960s-1970s
105	**Schnieder**				
106	**Siegers**	Numerical Synthesis Methodology for Combat Aircraft	Cranfield University	combat aircraft	Late 1970s
107	**Spreadsheet Program**	Spreadsheet Analysis Program	Loughborough University	Aircraft Design Studies	1995

108	**SENSxx**	(-)	DaimlerChrysler Aerospace Airbus	Transonic Transport Aircraft	
109	**SIDE**	System Integrated Design Environment	Astrox	?	1987-
110	**SLAM**	Simulated Language for Alternative Modeling	?	?	
111	**Slate Architect**	(-)	SDRC (Eds)	?	
112	**SSP**	System Synthesis Program	University of Maryland	Helicopter	
113	**SSSP**	Space Shuttle Synthesis Program	General Dynamics Corporation	AeroSpace Vehicle	
114	**SYNAC**	SYNthesis of AirCraft	General Dynamics	Aircraft	1967
115	**TASOP**	Transport Aircraft Synthesis and Optimization Program	BAe (Commercial Aircraft) LTD	Transonic Transport Aircraft	
116	**TIES**	Technology Identification, Evaluation, and Selection	Georgia Institute of Technology		1998
117	**TRANSYN**	TRANsport SYNthesis	NASA Ames Research Center	Transonic Transport Aircraft	1963- (25years)
118					
119	**TRANSYS**	TRANsportation SYStem	DLR (Aerospace Research)	AeroSpace Vehicle	1986-
120	**TsAGI**	Dialog System for Preliminary Design	TsAGI	Transonic Transport Aircraft	1975
121	**VASCOMPII**	V/STOL Aircraft Sizing and Performance Computer Program	Boeing Vertol CO.	V/STOL aircraft	1980
122	**VDEP**	Vehicle Design Evaluation Program	NASA Langley Research Center	Transonic Transport Aircraft	
123	**VDI**				
124	**Vehicles**	(-)	Aerospace Corporation	Space Systems	1988
125	**VizCraft**	(-)	Virginia Tech	Supersonic Commercial Transport Aircraft	1999
126	**Voit-Nitschmann**				
127	**WIPAR**	Waverider Interactive Parameter Adjustment Routine	DLR Braunschweig	AeroSpace Vehicle (Waverider)	
128	**X-Pert**	(-)	Delft University of Technology	Aircraft	Paper 1992

In the context of the author's research, the level of integration of *Data-Engineering* capabilities is the primary feature used for further platform investigation. Operating a synthesis model of an aerospace vehicle requires the definition of design data inputs, the quality of which directly affect the quality of information produced (i.e. 'garbage in, garbage out'). The scope and depth of data inputs varies substantially from low-fidelity synthesis systems (e.g. the Breguét range equation, shown in Figure 5.1, requires only four technology inputs to produce an overall vehicle weight ratio) to high-fidelity synthesis systems created for preliminary design and detailed configuration evaluation (i.e. PrADO requires thousands of input values dependent on the vehicle configuration[262]).

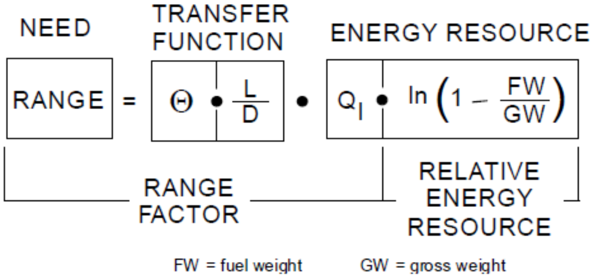


Figure 5.1 – Breguét Range Equation as Interpreted as Synthesis Equation[176]

As also observed in the survey of aerospace data research, aerospace synthesis systems have also sporadically addressed the suite of *DE* tasks, illustrated in Table 5.2. These representative synthesis systems tend to only provide storage of previous synthesis project data and allow native visualization of the output solution space within a pre-defined format (i.e. AAA provides the default solution space as thrust loading versus wing loading, but does not allow the user to modify this view). Other data tasks, especially those in the front end of the *DE* process steps (e.g. collection of data from native sources into a format suitable for synthesis input) are left as ad-hoc pre-synthesis activities.

Table 5.2 – Assessment of Data-Engineering Requirements in Aerospace Conceptual Design Sizing Platforms

Platform	*Developer*	*Research Specification Requirement*													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
AAA[260]	DAR Corporation					X		X				X			
FLOPS[261]	NASA LaRC					X		X				X			
PrADO[262]	Technical University Braunschweig	X				X		X				X			
RDS[263]	Conceptual Research Corporation							X				X			
VDK/HC[176][177][178]	MacDonnell Douglas, Hypertec					X		X							

In addition to lacking fundamental *DE* capabilities, the closed software architecture of these systems does not allow for the adaptability and flexibility of analysis approaches required for forecasting and early design tasks. Introducing new analysis methods, MDA frameworks, or information visualization outputs to address novel technological, mission, and operational concepts is not possible to an end-user of these synthesis platforms.

It is hypothesized that the introduction of a structured *DES* into any of the above synthesis systems would improve the *efficiency*, *quality* and *consistency* of information production, while also decreasing the *effort* required to operate the holistic system. It is also hypothesized that, although the approach to synthesis varies between platforms and organizations, the principle *DES* functions developed for a representative platform are universally applicable to other environments across vehicle specialties and intended development phase. As such, the most important aspects of the selected representative synthesis platform for further *DES* development are its 1) adaptability to a broad range of information tasks and 2) open architecture to interface with external data processes.

5.2 BASELINE FORECASTING ENVIRONMENT

The Aerospace Vehicle Design (AVD) Laboratory is an aerospace design, forecasting & consulting organization based at the University of Texas at Arlington (the author has been a contributing member throughout the presented research from 2010 through 2014). As part of the research and consulting efforts undertaken by the AVD Laboratory, see Table 5.3, a functional multi-fidelity aerospace synthesis system has been developed[264] along with semi-standardized processes supporting a broad range of design and forecasting tasks. The formalization and development of the current *Data-Engineering System* is directly aligned with complementing the existing systems to expand the overall AVD capabilities to produce information for forecasting activities.

Table 5.3 – AVD Design & Forecasting Projects

Project	*Ref.*	*Customer*	*Year*
Commercial Transport	[265]	NASA LaRC, NIA	2004-2005
Rocketplane XP Space Tourism	-	Rocketplane	2004-2005
SpiritLear SSBJ	[266]	SpiritWing	2005-2006
Reusable Space Access Vehicle	-	NASA LaRC	2006
N+3 Transonic Transport	[267]	NASA	2008-2009
Hypersonic Transport	-	ESA	2009
Truss-Braced Wing Aircraft	-	NASA	2009
Hypersonic X-Plane	[268]	NASA LaRC	2010
Manned Satellite Servicing	[269]	NASA, DARPA	2010-2011
Electric Aircraft	-	Lindbergh Foundation	2011-2012
Hypersonic Vehicle Database	[270]	NASA	2011-2012
Transport Aircraft Mission Research	-	NASA	2013

As illustrated with the above table, the organizational experience of AVD has a broad range of aerospace and information applicability – subsonic, supersonic, hypersonic and space access vehicle efforts produced for technologist, chief engineer, program manager, and C-level executive decision-makers are all represented. As such, the information requirements of the AVD environment are representative of needs in other aerospace design and forecasting organizations. It is desired that the development of a structured *DES* to support AVD processes would be applied in parallel across the aerospace forecasting industry.

Before introducing the derivation of a *DES* to support AVD forecasting processes, an assessment of the historical data, knowledge, and synthesis analysis capabilities of the AVD environment provides a baseline deviation point for further development. The capabilities described below are a broken down by their contribution to the data, knowledge, and analysis domains, respectively.

5.2.1 Previous AVD Data Domain Research

In addition to data supporting defined design and forecasting tasks, significant effort been expended to collect, organize and store data for future academic, research and contractual support tasks. These tangential data sets are part of the always-increasing communal data-set that are applied whenever applicable to a design forecasting effort. By investing time and resources outside of a task-specific environment, the up-front effort required to recall and apply domain-specific data during a forecasting project is greatly reduced.

Table 5.4 – Legacy AVD Data Collection Efforts

Research Effort	*Year*	*Focus*	*Data Collected*
Chudoba[273]	1999	Aerospace synthesis systems	Vehicle system focus, development timeframe
Chudoba[273]	1999	Air and space vehicles	Program history, gross characteristics
Coleman[264]	2010	MDA methods	Source, applicability, algorithm
Mansouri[275]	2013	Structural design methods	Applicability, accuracy
Walker[276]	2014	Weight estimation methods	Source, applicability, accuracy

Chudoba, in his doctoral dissertation, provides a comprehensive database of air and space vehicle systems including their research and development histories and gross characteristics[273]. In particular, focus is placed on the stability and control characteristics in the longitudinal, directional, and lateral axes to support design analysis of ‘conventional and unconventional’ vehicle configurations.

Mansouri presents a survey of analytic, numerical, and empirical structural analysis methods and their application towards aerospace vehicle conceptual design[275].

Walker, now a weight engineer with the Lockheed Martin Skunkworks advanced design organization, has produced an extensive review of weight estimation methods including their implementation scheme, applicability ranges, and expected variance from actual vehicle systems[276].

Coleman, in the course of defining and developing a generic air and space vehicle system conceptual sizing platform[264], has also collected a substantial database of multi-discipline analysis methods spanning aerodynamics, weight and balance, stability and control, cost, geometry, propulsion and performance. In addition, multi-disciplinary analysis (MDA) frameworks from existing synthesis platforms have been collected and analyzed for applicability towards classes of aerospace systems.

The AVD forecasting environment is also in possession of a substantial physical library of textbooks, journal articles, conference proceedings and technical reports – additionally, several one-of-a-kind collections of company internal reports, presentations, drawings, and manuscripts have been inherited from a range of aerospace engineers and organizations, see Table 5.5. This collection represents 30+ years of concerted effort to gather unique articles of data that have shaped the history of air and space vehicle development.

Table 5.5 – Size, Scope and Content of AVD Library

Library Category	*Approximate Size of Database**	*Comment*
Textbooks	2.5 GB	Organized by discipline
Journal Articles, Conference Proceedings & Technical Reports	2 GB	Organized by discipline and applicable speed regime
Space Shuttle Library	100 MB	
Vought Design Library	250 MB	Organizational library of Vought Aircraft, specializing in military Vertical Takeoff and Landing (VTOL) and carrier-based design configurations
Czysz Library	500 MB	Personal library of Paul Czysz, McDonnell supersonic and hypersonic vehicle design engineer
NASP Library	100 MB	Documentation of research, design and development of National AeroSpace Plane (NASP)
Supersonic Commercial Design Library	100 MB	Concorde design documentation, FAA supersonic regulations, Advanced Supersonic Transport (AST) design documentation
Total AVD Library	5.5 GB	-

*Assumed standard digital convention - 1 book ~ .001 GB; 1 report ~ .0005 GB

5.2.2 Previous AVD Knowledge Domain Research

Coleman[264] and Walker[276] both integrate within their disciplinary analysis methods library fields a discussion of method applicability, assumptions, operating performance, and accuracy, shown below in Figure 5.2. This approach has allowed these research efforts to not only provide a reference of available analysis methods, but also as a guide towards understanding how a method will perform in a MDA synthesis setting before it has been implemented. Providing these general guidelines has increased the learning rate and efficiency of other analysts when selecting and implementing analysis methods.

Chudoba[273] has collected and organized a comprehensive set of knowledge guidelines for stability and control implications of a wide range of conventional and unconventional aircraft configurations (e.g. tail first, flying wing, oblique flying wing, three surface, etc.). General stability and control guidelines, as well as phenome specific to unique configurations are tabulated and presented as a formal knowledge entity.

Additionally, the aggregated knowledge from past AVD design forecasting efforts, shown in Table 5.3, has been continually embedded within tools and processes. The understanding of how to decompose information requirements into a functional synthesis description and communicated in a format relevant to aerospace decision-makers is iterated during the course of each forecasting effort.

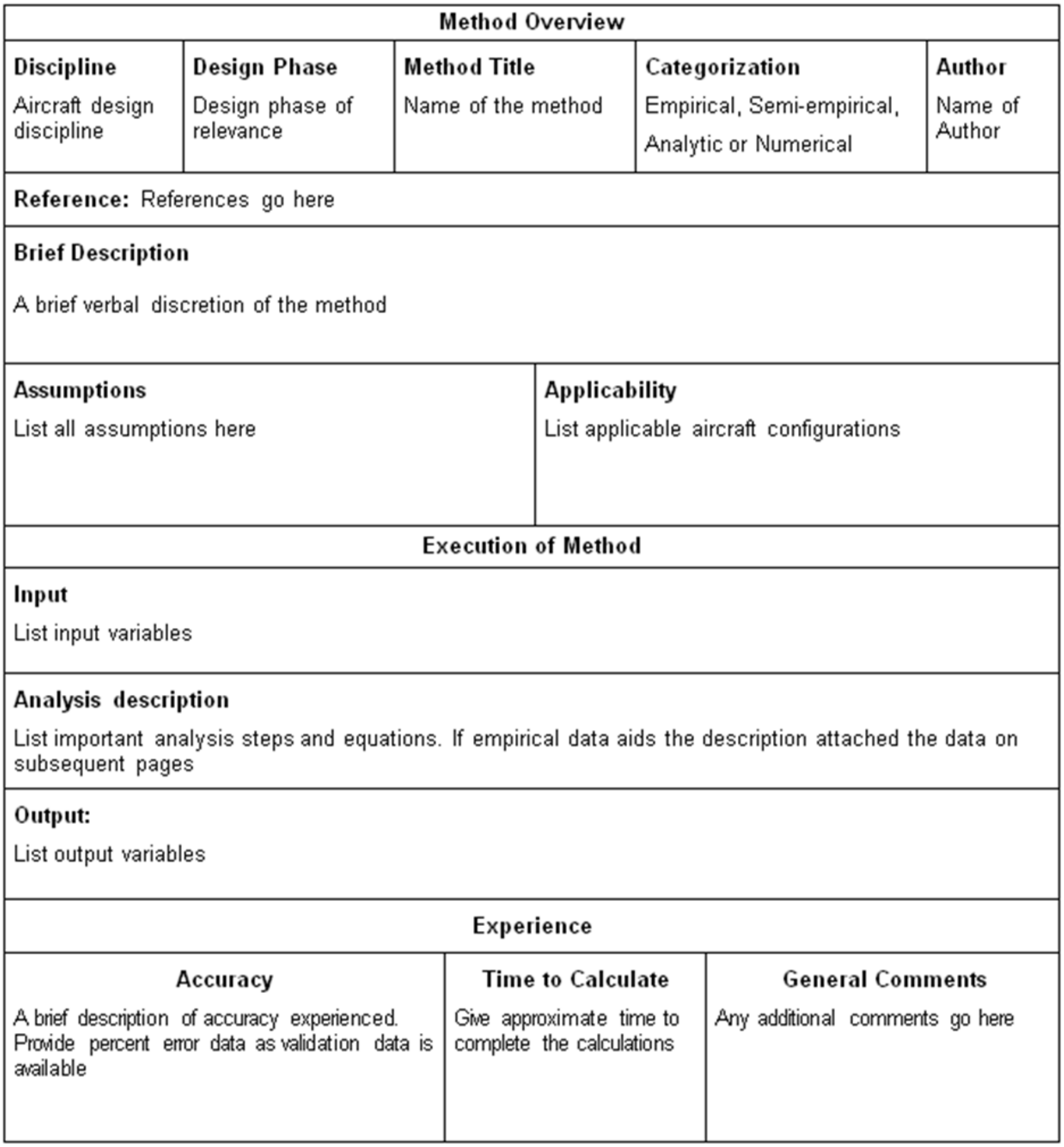
5.2.3 Previous AVD Analysis Domain Research

The analysis domain capabilities of AVD, like most aerospace design forecasting organizations, have been historically under the most research and development. A conceptual design synthesis software program, AVD Sizing, had been created after an extensive development program[264] and had been applied to general aviation, subsonic commercial, space tourism[266], hypersonic cruise[268] and space launch design projects. Subsequent research efforts have expanded the aerodynamic analysis[274], structural analysis[275], guidance & control[267] and weight estimation[276] capabilities impacting the operation of the central synthesis environment. The result is an expansive library of methods and infrastructure for aerospace system analysis.

Table 5.6 – Summary of AVD Sizing Methods and Coding Effort

Discipline	*Number of Methods*	*Approximate Lines of Code*
Aerodynamics	22	6000
Cost	11	2000
Flight Mechanics	3	500
Geometry	10	1000
Performance Matching	16	2000
Propulsion	24	2500
Weight & Balance	17	2000
Utility / Overhead	-	5000
Total	**103**	**21,000**

AVD Sizing was initially compiled in FORTRAN source code under a modular disciplinary framework. A master input file houses all variable inputs, the analysis method integration procedure, and the overall convergence logic. Based on the selection of disciplinary methods in the input file, AVD Sizing computes the disciplinary performance, feeding the inputs of the preceding disciplines into the following disciplines, see Figure 5.3. Once converged, a user-defined selection of system characteristics was output into a text-based output file. In order to create design spaces for parametric analysis, looping scripts of design variables had to be created within the input file. Once executed, the results of AVD were manually uploaded to MS Excel for data analysis and visualization tasks.



<table>
<tr><th colspan="6">Method Overview</th></tr>
<tr><td>Discipline
Aircraft design discipline</td><td>Design Phase
Design phase of relevance</td><td>Method Title
Name of the method</td><td colspan="2">Categorization
Empirical, Semi-empirical,
Analytic or Numerical</td><td>Author
Name of Author</td></tr>
<tr><td colspan="6">Reference: References go here</td></tr>
<tr><td colspan="6">Brief Description
A brief verbal discretion of the method</td></tr>
<tr><td colspan="3">Assumptions
List all assumptions here</td><td colspan="3">Applicability
List applicable aircraft configurations</td></tr>
<tr><th colspan="6">Execution of Method</th></tr>
<tr><td colspan="6">Input
List input variables</td></tr>
<tr><td colspan="6">Analysis description
List important analysis steps and equations. If empirical data aids the description attached the data on subsequent pages</td></tr>
<tr><td colspan="6">Output:
List output variables</td></tr>
<tr><th colspan="6">Experience</th></tr>
<tr><td colspan="2">Accuracy
A brief description of accuracy experienced. Provide percent error data as validation data is available</td><td colspan="2">Time to Calculate
Give approximate time to complete the calculations</td><td colspan="2">General Comments
Any additional comments go here</td></tr>
</table>

Figure 5.2 – AVD Methods Library Template before Data-Engineering[264]

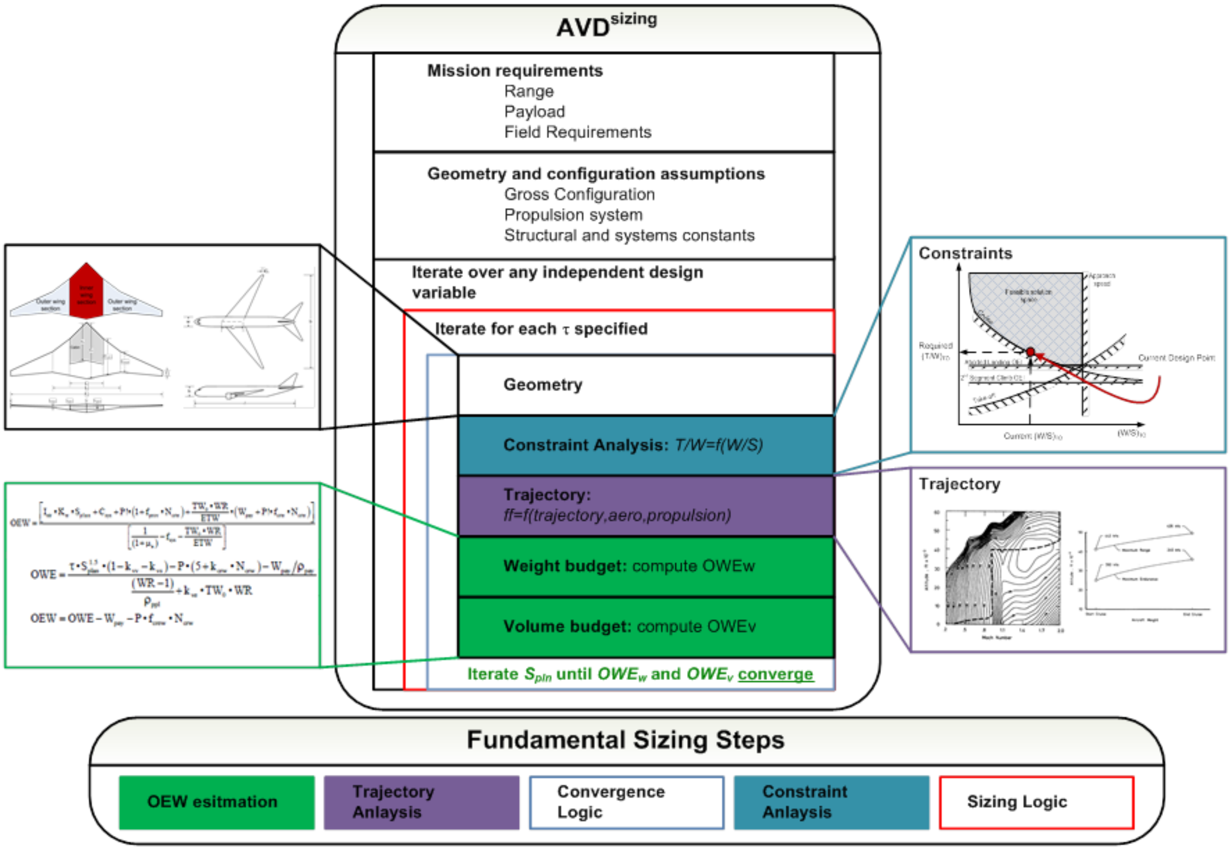


Figure 5.3 – AVD Sizing Synthesis Logic [264]

After base-lining a vehicle system model for a specific forecasting study, AVD Sizing provides a stable and adaptive platform for assessing design trade spaces and parameter analysis. However, initializing the synthesis platform for new vehicle concepts, adding new disciplinary methods, or adapting the disciplinary integration procedure required a significant upfront time and resource investment with the native low-level FORTRAN programming language playing a substantial debugging and integration barrier. Introducing new personnel to synthesis operations required a primer not only on synthesis operations, but on the programming language as well – the advantages of FORTRAN (e.g. computational power and speed) were mute in comparison to average run time (~10 seconds), the lack of previous knowledge the majority of entering personnel had with FORTRAN, and the resources required to adapt the synthesis framework.

5.3 DATA-ENGINEERING SYSTEM HARDWARE-SOFTWARE ACCESSIBILITY

The specific implementation of the prototype *Data-Engineering* platform was chosen to directly fit the needs and constraints of the AVD forecasting environment, including the integration of existing systems. This selection of hardware and software systems, then, is specific to this organization at this time – as the scale of the forecasting organization grows and / or the scale of data expands, these selections can and should be revisited.

5.3.1 Software Selection

Function: Provide native functionality to ease DES development burden.

Specification Requirement(s):

1. Develop an open architecture to be continually improved.
5. Allow the integration of non-standardized data formats.
6. Interface with multi-domain existing internal and external data sources.
8. Provide the opportunity to add, edit and manipulate data organization schema.
9. Allow for user-defined aggregation, filter and query across any dataset(s).
10. Provide ability to identify and visualize trends in data.
13. Provide a standardized process interface between the DES and synthesis platforms.

Targeted Data-Engineering Metric(s):

E. Capacity
F. Accessibility
G. Adaptability
H. Time Cost
I. Economic Cost
N. Interoperability

The *Data-Engineering System* is a prototype platform, built for use in a relatively small aerospace consulting organization, approximately 10 users. This allow flexibility in software choice to include less efficient, but more flexible, options that may not be available to large organizations. It is also desired that the main focus of the current and ongoing *DES* development effort be the institution and improvement of functionality, and not solely on continued operations. This drives towards a selection that favors ease-of-development and built-in native features over extensive enterprise-level data management platforms.

In particular, the system must provide a level of user interactivity (i.e. be GUI-based). Although platform development and maintenance should be transparent and made available to all members of the design organization, common operations should not require significant experience with platform-specific syntax. A high-level data platform with native analytic functions, data-user interfaces and visualization suites is preferred.

For data-to-data system interface, the platform should at least be scalable to integrate several datasets on the order of thousands of records per dataset. Larger datasets may drive information tasks in the future, but to-date, synthesizing a broad number of ‘small’ datasets has been a more common design forecasting requirement. Incorporating datasets with millions of records (i.e. 1 GB+ data tables) generally introduces a reduction in performance for high-order data management systems and therefore requires a more lean platform.

Table 5.7 – Performance Estimation of Prospective Data Platforms

Data Platform	*Description Section*	*Collection, Storage & Organization**	*Recall**	*Analysis & Visualization**	*Total*	*Comment*
MS Excel	2.5.1.1	3	3	4	10	Low performance with larger datasets
SQL	2.5.1.2	2	4	1	7	Syntax knowledge required
MS Access**	2.5.1.2	4	4	4	12	Low performance with larger datasets
Oracle	2.5.1.2	4	5	3	12	Cost-prohibitive
NoSQL	2.5.1.2	4	4	1	9	Lack of native analysis and visualization
R	2.5.1.4	1	2	5	8	Syntax knowledge required
MATLAB	2.5.1.4	2	2	5	9	Additional add-on required
SAS	2.5.1.4	2	3	4	9	Cost-prohibitive
SPSS	2.5.1.4	2	3	4	9	Cost-prohibitive

* 1 – 5 Likert scale; 1 = insufficient functionality, 3 = average functionality, 5 = superior functionality
** Selected Platform

An assessment of the potential data platforms, presented in Table 5.7, provides a rough guidelines to the platforms that should and should not be considered for prototyping. In general, the enterprise commercial software (Oracle, SAS, SPSS) provide sufficient performance, but the cost-per-seat plus system maintenance fee structure is prohibitive for a non-commercial organization. The programming languages (SQL, R, MATLAB) offer all required data capabilities, but generating user-friendly interfaces requires optionally-purchased add-ons or is not feasible without a secondary software interface. Of the remaining general data systems, MS Access provides superior structure for querying of datasets and user interface than MS Excel, and at the same time provides more analytical and visualization capabilities than a NoSQL database.

The specification requirements and adequate platform performance has led to the selection of *MS Access* as a prime prototyping platform. The ease of use, adaptability, SQL framework, graphic output integration and open coding environment provided a satisfactory fit for the constantly developing AVD research processes.

5.3.2 Forecasting Team Network Structure

Function: Link organizational storage infrastructure.

Specification Requirement(s):
3. House source, process and result data in an organizationally network.

Targeted Data-Engineering Metrics:
A. Scope
B. Density
E. Capacity
F. Accessibility
H. Time Cost
I. Economic Cost
J. Precision
K. Sensitivity

The ability to seamlessly share, collaborate and build off previous and current work within the forecasting organization is a highly impactful, desirable trait. A significant downfall in a non-network-enabled organization is the siloed work and file storage tendencies of the forecasting team. Because of a lack of shared computing and digital storage, files tend to aggregate on a user's computer storage, compartmentalizing data and knowledge for current and future dissemination. In order to advance towards a more collaborative development environment, a shared intra-network server must be implemented. Source documentation, process data, working files and synthesis platform base files should be made accessible to all personnel within the organization both on site, and through cloud-based remote access.

Moving towards a shared network, illustrated in Figure 5.4, makes collaborate development of project documents possible and encourages a 'single version of the truth'. Additionally, communal file structures create an organizational standardization of file access protocol that ensures personnel know where data, processes and platforms are stored. Especially during project development periods, a shared storage medium helps extensively with version control and open collaboration. Having direct access to the entirety of an organization's data at each analyst terminal provides a positive benefit that flows throughout *DE* task performance.

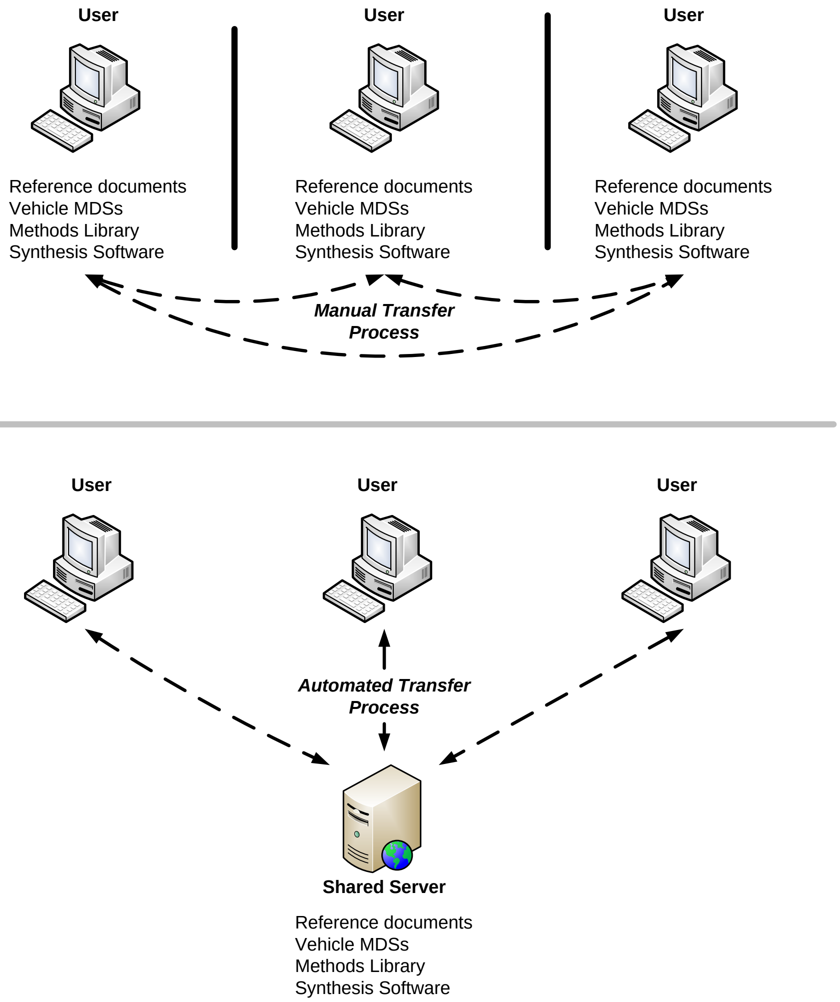


Figure 5.4 – File Sharing Structure before (Top) and after (Bottom) Data-Engineering Implementation

5.4 DATA-ENGINEERING SYSTEM PLATFORM DEVELOPMENT

Development of the prototype DES lies at the intersection of theoretical specifications and practical aerospace forecasting use-cases. From these two primary sources, a proposed work-flow can be defined – along with requisite user interfaces – for implementation on distinct classes of aerospace information production tasks.

5.4.1 Desired Aerospace Data-Engineering System Work-Flow

The final AVD DES will be a broad, expansive system of connected user-interfaces across multiple software environments. However, not all features of the DES will be required, or even suggested, for some forms of aerospace forecasting. This may be due to time / resource constraints, a lack of available data to initiate detailed analysis, the decision only requiring high-level assessment, or any combination of these factors.

Identifying the generalized potential use-cases allows the specific user-interface DES sub-components to be designed such that they are applicable to all desired use-cases. Incorporating multi-faceted influence during software design ensures that the DES is extensible the broadest spectrum of potential research efforts – a necessity if data and information is to be accumulated under a central software kernel.

5.4.1.1 Data Domain Only Work-Flow

Under circumstances when the amount of available data is low, the project is ill-defined or under-defined, the output information requirements are not heavily technical in nature, and the required turn-around time is short, it is envisioned that the Data-Engineering System be operated singularly – see Figure 5.5. This approach requires the collection, storage, and organization of source documentation, extraction of underlying data to DES data libraries, and generation of deliverables through data comparison and analysis – the user-facing components required for these interactions are labelled in the below schematic.

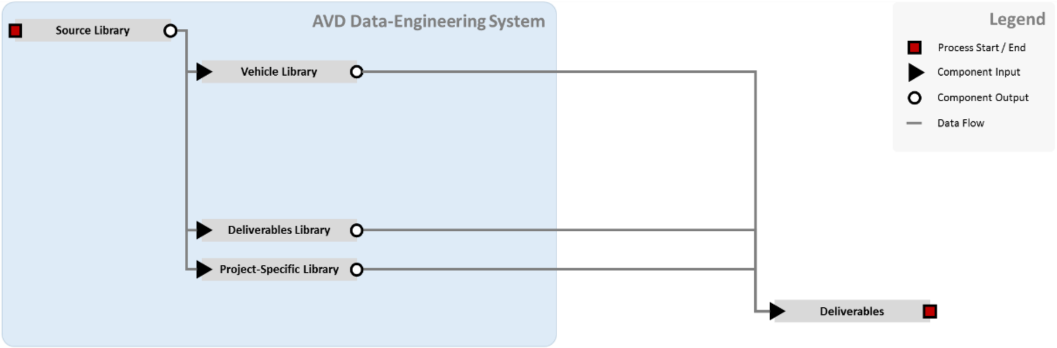


Figure 5.5 – Work-Flow for DES: Solo Operation

The generation of project deliverables happens outside of the Data-Engineering System due to the relatively weak visualization capabilities of the chosen software (MS Access). Therefore, the DES final output under most use-cases will be a standardized data file which can then be adapted for visualization in a separate software environment more suited for the task (e.g. Excel or MATLAB). In select circumstances, however, the MS Access DES environment is optimal for deliverable generation – i.e. when a standardized deliverable is to be generated for a large record-set, or an executive dashboard is to be refreshed on a persistent basis.

5.4.1.2 Data+Analysis Domain Work-Flow

In relation to Data-only operation, supplementary interface with the AVD Sizing parametric analysis environment is necessary when the research effort is better defined and the output information requirements include an assessment of potential design options. AVD Sizing can quickly and correctly analyze a number of possible designs, but adds an additional layer of software interface (AVD Sizing is written in MATLAB) and places data requirements on the data collection and organization processes in order to execute correctly.

Shown below in Figure 5.6, the schematic depicts the functional components for a Data+Analysis domain interfaced operation. Included are additional user-interfaces not required for a Data-only approach – an Analysis Methods library that characterizes different approaches to system analysis and an Analysis Definition library that characterizes the multi-disciplinary analysis methodology for assessing a vehicle system. Both of these under-lying sub-components are required within the DES to generate an executable AVD Sizing input file. An additional requirement is a functional interface between the MS Access and relational database-based DES and the MATLAB vector-based AVD Sizing.

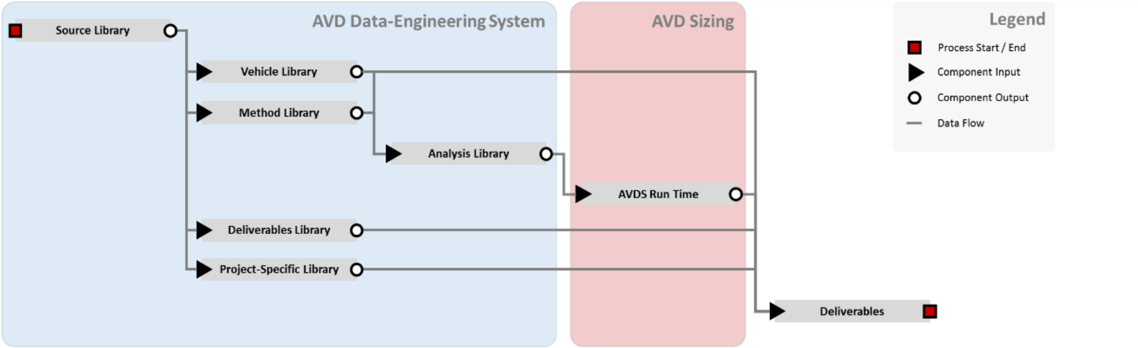


Figure 5.6 – Work-Flow for DES: Operations with Parametric Sizing

As with the Data-only approach, the Data+Analysis integrated approach ends with the generation of information Deliverables through a DES user-interface. Additional requirements must be put in place, however, to align AVD Sizing result outputs alongside supplementary data from the DES (i.e. comparing solution space analysis results to existing vehicle designs).

5.4.1.3 Data+Knowledge+Analysis Domain Work-Flow

Addition of Knowledge-based components is envisioned as a solely parallel effort to complement already-defined Data and Analysis domain user-interfaces, see Figure 5.7. Practical interface between a Knowledge System and the prototype and DES is not addressed here, but is discussed in other research[279].

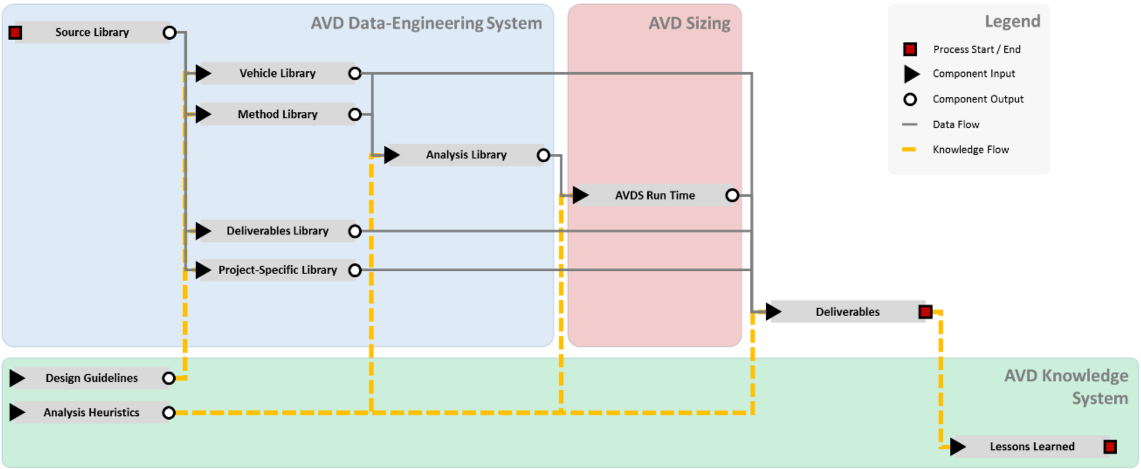


Figure 5.7 – Work-Flow for DES: Operations with Parametric Sizing and Knowledge-Based System

5.4.1.4 Data+Knowledge+Analysis Domain + Intelligent Feedback Work-Flow

The standardization of input and output data across the Data and Analysis domains offers multiple opportunities for automated feedback loops. Viewed from a larger perspective, the prospect of a system that can generate data and then adapt future processes based on the results is an inherent property of Artificially Intelligent (AI) systems. Within the prototype aerospace forecasting environment, both the AVD Sizing parametric analysis results and the output project Deliverables are readily available to integrate within existing processes to inform future system analyses, see Figure 5.8. This feedback loop serves two distinct purposes: 1) to iterate the existing analyses for more informative results, and 2) to serve as an additional reference point for future analyses.

With this digitized feedback in place, it is difficult to imagine an incremental approach towards a fully capable AI system. For example, a first-generation AI forecasting system may suggest alternative design approaches to a static user-defined mission. A second-generation AI may refine missions, technologies and alternative designs to maximize an objective function. And a fully-operational AI forecasting system may assess the underlying objective functions themselves. Implementing features towards this end will require significant codification of engineer experience and design knowledge, but will result in systems which are more agile to the growing needs and capabilities within aerospace vehicle design.

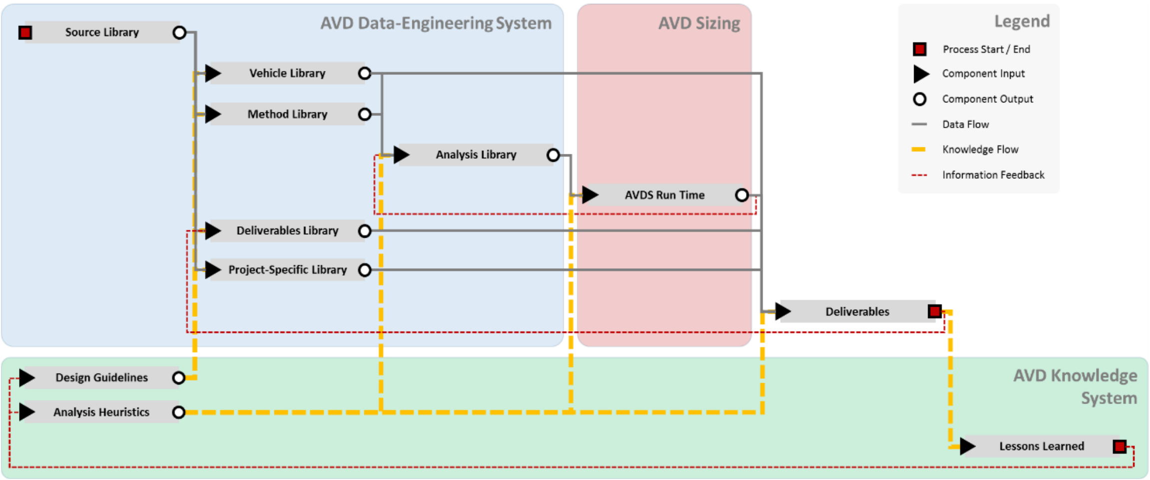


**Figure 5.8 – Work Flow for DES:
Operations with Parametric Sizing, KBS and Information Feedback**

5.4.2 *Aerospace Data-Engineering System Subcomponents*

The following section details the development of a software platform that formalizes and standardizes each *Data-Engineering* task (*collection* through *visualization*) within the AVD aerospace design forecasting environment. The central focus is on those functionalities that are needed most often, and are most transferable across forecasting projects, and therefore applicable to outside design forecasting organization education. As forecasting activities have demanded integration of novel datasets, incorporation of new disciplinary datasets, or unique information decision-making outputs, additional capabilities have been added to the data system. Because the platform is part of working, evolving, and growing process, its capabilities are also constantly expanding – the following discussion details the capabilities as they stand at the time of publication.

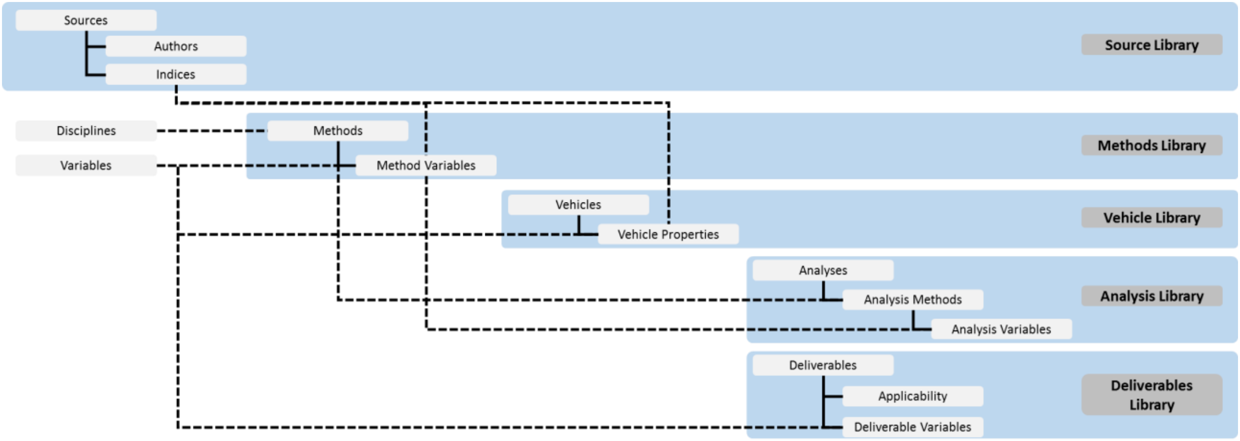


Figure 5.9 – Data-Engineering System Interface Diagram

5.4.2.1 Source Library

Function: Provide an open-architecture document repository.

Specification Requirement(s):

2. Provide a transparent flow of data from source documentation to implementation.
4. Allow the collection, viewing and editing of original source documentation.
6. Interface with multi-domain existing internal and external data sources.
7. Provide access to source, process and result data of previous organizational efforts.
12. Allow view, edit and addition of knowledge guidelines to support future efforts.

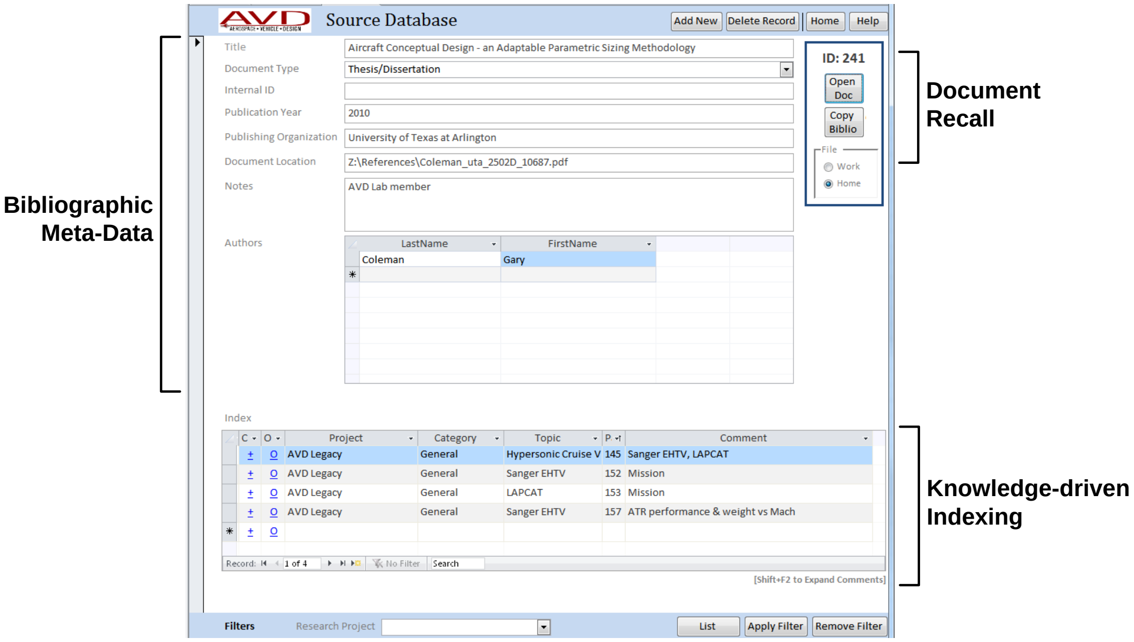
Targeted Data-Engineering Metric(s):

A. Scope
B. Density
C. Meta-Data Ratio
F. Accessibility
H. Time Cost
I. Economic Cost

The most base-level task for data-centered processes is the collection of source documentation to provide a clear foundation for all further information production. Reference collection is a foundational task in design forecasting – the quality of the proceeding work is directly impacted by an organization's ability to collect high quality data and extract the correct elements for the information effort at hand. In addition to provide a launching pad for the extraction of useful data, the source collection effort is a significant generator of subject-matter knowledge – care should be taken to gather this parallel knowledge growth for future use here, and throughout the entirety of the information production process.

The *Source Library* provides a framework to catalogue physical and digital files within a central, networked repository. While no restrictions have been placed on the format of the source entity, a generalized systematic set of meta-data is collected for each entry. Structure has been developed that allows the entire forecasting organization to read, write, add and edit entries directly – this functionality is in direct response to the prescribed *DE* specification requirements and is a departure from standard bibliographic report servers with restricted editing and introduction capabilities. All operational interfacing with the source library is within a formatted GUI form, shown below in Figure 5.10.

As users research a new topic, external sources are collected and bibliographic data is entered through the main source library form for the meta-data fields shown below in Table 5.8. If digital, the location of the document within the shared network is also entered. The location is treated as a generic file path and is therefore agnostic of format – the open file command button opens the document in its native program (i.e. allows written documents, spreadsheets, presentations, drawings, graphics, models and websites to be stored through the same system and dynamically opened from the source library interface). Direct access to native source files is required to provide data transparency for both the forecasting team and the external decision-making entity – this functionality will be reused repeatedly through the other *DES* tasks as a constant reminder of the existence, and immediate substance, of supporting documentation.



Title	Aircraft Conceptual Design - an Adaptable Parametric Sizing Methodology
Document Type	Thesis/Dissertation
Internal ID	
Publication Year	2010
Publishing Organization	University of Texas at Arlington
Document Location	Z:\References\Coleman_uta_2502D_10687.pdf
Notes	AVD Lab member

ID: 241

File: ○ Work ● Home

Authors

LastName	FirstName
Coleman	Gary

Index

C	O	Project	Category	Topic	P	Comment
+	O	AVD Legacy	General	Hypersonic Cruise V	145	Sanger EHTV, LAPCAT
+	O	AVD Legacy	General	Sanger EHTV	152	Mission
+	O	AVD Legacy	General	LAPCAT	153	Mission
+	O	AVD Legacy	General	Sanger EHTV	157	ATR performance & weight vs Mach
+	O					

Record: 1 of 4 No Filter Search

[Shift+F2 to Expand Comments]

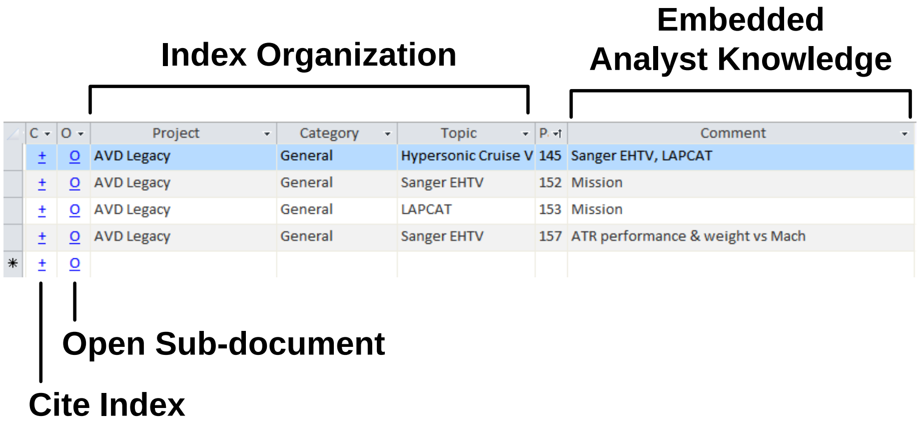
Filters Research Project

Figure 5.10 – Reference Source Library

Table 5.8 – Source Library Fields

Field	*Format*	*Description*
Title	Text	Document name
Document Type	List	Format of source
Internal ID	Text	Outside reference ID
Date	Number	Publication year
Organization	Text	Publishing organization
Notes	Text	Abstract / overview
Author	Text	Last Name
	Text	First Name

Once a source reference has been added to the source library, a knowledge-driven outlet is provided for identifying key items of interest within a source through an indexed tagging feature. Each index is given its own taxonomy structure to represent the project the analyst is currently engaged, as well as a project-unique set of index categories that describe major themes of interest during the collection phase (i.e. a project studying the design of a space access capsule may provide categories for the capsule and launch vehicle, with subcategories for sub-hardware groups of each). Index categories within a research project can be added and edited as new topics arise within the same user form. In addition to a broad category, the entry also contains a freeform specific topic that describes key aspects of the index as well as a memo-length comment field – the index system is meant to extract the complete thought-process knowledge from the individual at the time of entry, shown in Figure 5.11 and itemized in Table 5.9.



	C	O	Project	Category	Topic	P	Comment
	+	O	AVD Legacy	General	Hypersonic Cruise V	145	Sanger EHTV, LAPCAT
	+	O	AVD Legacy	General	Sanger EHTV	152	Mission
	+	O	AVD Legacy	General	LAPCAT	153	Mission
	+	O	AVD Legacy	General	Sanger EHTV	157	ATR performance & weight vs Mach
*	+	O					

Figure 5.11 – Document Index Sub-Library

The topic field has become a natural place for shorthand notation about potential contents of the reference index (e.g. "F:" for figure, "E:" for equation, "T:" for table) that improves reliability of effective future recall. Additional functionality has been added to reference indices in the form of linked sub-files and automated citation. Within the comment field of an index, a clarifier of "L:" denotes a file location – clicking the open index command will open the file of the specific index in question. For some decision-making outputs (see Data-Only case study of Chapter 5), this functionality has been used to directly link images of graphics, tables and images within larger documents and has proved very efficient for repeated use. The source library, including all individual indices, are made communally available to the organization to provide collaborative and transparent data collection in line with the prescribed *DES* specification requirements.

Table 5.9 – Index Table Fields

Field	*Format*	*Description*
Project	List	Research project
Category	List	Project-specific tag grouping
Topic	Text	Subject of tag index
Page	Number	Location of tag index
Comment	Text	Discussion of tag contents; analyst insight

5.4.2.2 Variables Library

Function: Provide a universal set of design variables.

Specification Requirement:

1. Provide an open architecture to be continually improved.
2. Provide a transparent flow of data from source documentation to implementation.
5. Allow the integration of non-standardized data formats.
13. Provide a standardized process interface between the *DES* and synthesis platform.
14. Integrate data processes required for execution of aerospace synthesis.

Targeted Data-Engineering Metrics:

B. Density
D. Completeness
L. Multiplicity
N. Interoperability

In order to unify object characteristic data for all *DE* tasks, including integration into systems-level synthesis discussed below, a standardized *Variables Library* is required. During the course of an integrated systems analysis project the flow of data from its native source, through interim processing steps, interfacing with analysis methods, and finally incorporated into visualizations requires that the identification of the data entity be uniquely represented and known at all times. By standardizing variable descriptions, assigning unique clarifiers to data fields, and consistently applying the same definitions through the information-production process, the opportunity for lapses in data quality diminishes. An attribute of an object has one defining name description and is used universally in all data, knowledge and analysis processes. Attributes used to instantiate variables, shown in Table 5.10, have been adapted from standard data attribute protocols established previously by standardization bodies[34].

Table 5.10 – Variable Table Fields

Field	*Description*
Variable	Shorthand name; direct reference to synthesis convention
Units	Default units
Description	Longhand name

The variable table acts as the *central nervous system* for the entire forecasting process – it provides a common interface between data, knowledge and analysis domains. As additional variable fields are introduced through novel research efforts, new analysis methods, or different information topics, the *DES* provides straight-forward framework to add variables to mold to the problem at hand. By standardizing the definition of variables, information-production tasks can begin to function as a single cohesive unit, instead of disparate platforms with their own native syntax.

5.4.2.3 Methods Library

Function: Catalogues synthesis analysis methods.

Specification Requirement:

2. Provide a transparent flow of data from source documentation to implementation.
3. House source, process and result data in organizationally-communal network.
6. Interface with multi-domain existing internal and external data sources.
7. Provide access to source, process and result data of previous organizational efforts.
12. Allow view, edit and add of knowledge guidelines to support future efforts.
14. Integrate data processes required for execution of aerospace synthesis.

Targeted Data-Engineering Metrics:

C. Meta-Data Ratio
D. Completeness
F. Accessibility
H. Time Cost
I. Economic Cost
J. Precision
K. Sensitivity
N. Interoperability

The diversity in aerospace flight vehicle systems (e.g. commercial, military, research; subsonic, supersonic, hypersonic, space access; manned, unmanned, autonomous) also drives a diversity in the techniques required to analyze and design these systems. The connection to physical systems that are subject to operational constraints and laws of physics drive modelling dependencies that, while complex, can be known – this ability to model causation of interdependencies is a requirement for aerospace system analysis, where correlation of characteristics is often sufficient with 'Big Data' approaches[14]. Identifying which methods of analysis are required as a function of vehicle system type, available data, MDA framework and final information requirements is a uniquely critical element for aerospace design forecasting.

When analyzing a vehicle system within a synthesis environment, the decomposition of the system into functional or disciplinary components is a key tenant of the systems engineering approach. Analysis methods must be chosen that are compatible with each other, reflect the operating environment of the system, and match the fidelity of the current analysis. The *Methods Library* seeks to organize the available disciplinary analysis methods available to the forecasting analyst and facilitates the implementation of a chosen collection of methods in further systems analysis by providing inputs, outputs, analysis details, range of applicability, and knowledge-based guidelines for use.

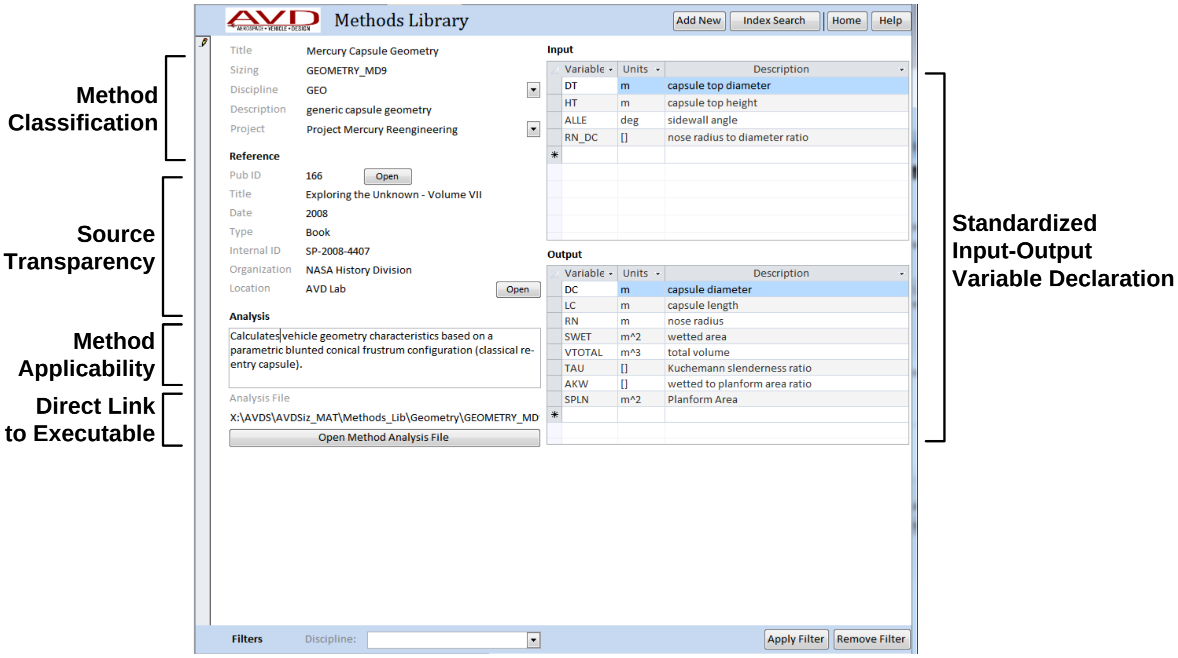
Previous approaches to building standardized methods libraries within the AVD environment[264][275][276] have resulted in substantial data and knowledge collections efforts and provide a reference benchmark for analyst user-interface. The implemented *DES* approach directly links the methods library to both the source documentation from which the method originated, as well as feeding directly into the synthesis environment – the actual disciplinary analysis file that is used in the synthesis process is provided within the *DES* methods library. The requisite input and output variables required by the analysis method are specified using the standardized variables table to provide consistency between data sources (i.e. using historical regression analysis to determine input values) and between analysis methods during the synthesis process.

Table 5.11 – Methods Library Fields

Field	*Format*	*Description*
Title	Text	Name of method
Synthesis Title	Text	Shorthand title of method used in synthesis environment
Discipline	List	Disciplinary category of method
Description	Text	Short explanation of method including applicability
Project	Text	Initial research project method has been applied
Reference ID	Number [Foreign Key]	Reference number from the source library entry that provides original documentation of the method
Analysis File	Text	File path of the analysis method within the synthesis environment
Input Variable*	List [Foreign Key]	Name of variable required as input into the method; naming convention defined in the variable library
Input Units*	Text	Required units of incoming input variable
Input Description*	Text	Description of method input variable
Output Variable*	List [Foreign Key]	Name of variable given as output from the method; naming convention defined in the variable library
Output Units*	Text	Units of the method output
Output Description*	Text	Description of method output variable

*Number of input & output variables unlimited

By collecting the meta-data, detailed in Table 5.11, needed for analyst understanding of when and why to implement a particular analysis method, the *DES* provides flexibility in the analysis approach to match information requirements. Defining new methods, either to model an existing interaction to a different level of fidelity or to introduce a new interaction, is handled through a structured user interface, shown in Figure 5.12. The inspection and selection of analysis methods is a prime candidate for implementation of knowledge-engineering practices (e.g. analysis method tutorials, inference of method selection by information requirements, correctness and accuracy of method applied to previous efforts, etc.), but have not been undertaken under the author's research and platform development process.



Title: Mercury Capsule Geometry
Sizing: GEOMETRY_MD9
Discipline: GEO
Description: generic capsule geometry
Project: Project Mercury Reengineering

Reference

Pub ID: 166
Title: Exploring the Unknown - Volume VII
Date: 2008
Type: Book
Internal ID: SP-2008-4407
Organization: NASA History Division
Location: AVD Lab

Analysis

Calculates vehicle geometry characteristics based on a parametric blunted conical frustrum configuration (classical re-entry capsule).

Analysis File: X:\AVDS\AVDSiz_MAT\Methods_Lib\Geometry\GEOMETRY_MD

Input

Variable	Units	Description
DT	m	capsule top diameter
HT	m	capsule top height
ALLE	deg	sidewall angle
RN_DC	[]	nose radius to diameter ratio

Output

Variable	Units	Description
DC	m	capsule diameter
LC	m	capsule length
RN	m	nose radius
SWET	m^2	wetted area
VTOTAL	m^3	total volume
TAU	[]	Kuchemann slenderness ratio
AKW	[]	wetted to planform area ratio
SPLN	m^2	Planform Area

Figure 5.12 – Disciplinary Analysis Methods Library

5.4.2.4 Vehicles Library

Function: Stores characteristic data about vehicle systems.

Specification Requirement:
2. Provide a transparent flow of data from source documentation to implementation.
3. House source, process and result data in organizationally-communal network.
5. Allow the integration of non-standardized data formats.
6. Interface with multi-domain existing internal and external data sources.

Targeted Data-Engineering Metrics:
A. Scope
B. Density
C. Meta-Data Ratio
D. Completeness
F. Accessibility
G. Adaptability
L. Multiplicity

The description of existing vehicle systems plays a pivotal role in design forecasting activities at a broad range of information levels. For example, vehicle systems data in a prospective market can be collected to perform an organizational competition analysis, vehicle data can provide a validation point to baseline MDA synthesis, component data can be used to develop subsystem-level trends for use in tangential applications, and time progression of vehicle characteristics can inform forecasting technology and growth factors.

Table 5.12 – Vehicle System Library

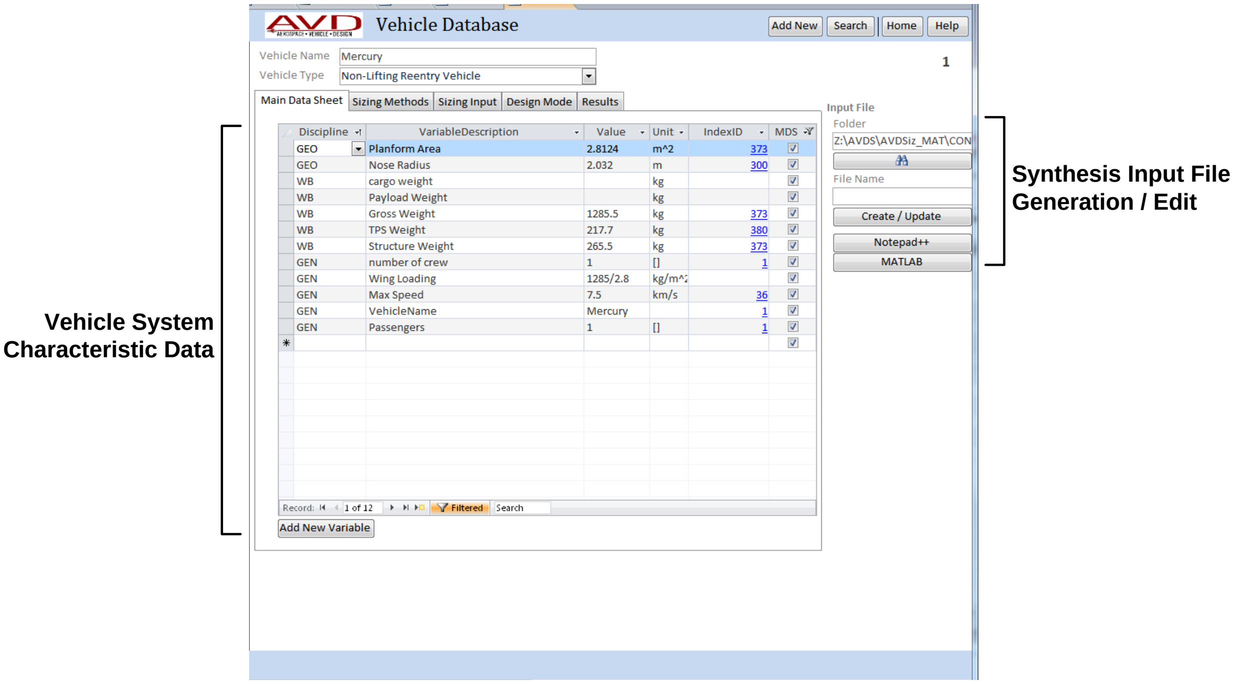
Tab	*Field*	*Format*	*Description*
Main Data Sheet	Discipline*	List	Discipline of variable that is describing vehicle characteristic
	Variable*	List	Description of variable characteristic; list determined by variable library
	Value*	Text	Value of vehicle characteristic data
	Unit*	Text	Units of variable
	Index ID*	Number [Foreign Key]	Location of index within source document that the value is referred
	Reference ID*	Number [Foreign Key]	Reference number from the source library entry that provides original documentation of the method

*Number of vehicle characteristics is unlimited

It should be apparent from these descriptions that characteristic data about a single vehicle system, if collected in a standardized and well-structured format, can be applied across all several use-cases. This directly mirrors the touchstone of data and information science advocates[11][14] that the majority of value in modern data will come, not from its original intended use, but its secondary and tertiary re-use towards new information problems.The *Vehicle Library,* described in Table 5.12, provides the user a standardized interface to collect characteristic data about vehicle system in a communal, structured environment and provide an interface with the synthesis environment. The library is segmented into five separate sub-forms, each of which perform a unique function.

Main Data Sheet

The *Main Data Sheet* sub-form provides a standard user interface to collect characteristic data about a vehicle system. In contrast to the relational data table format (i.e. all objects listed across one axis, all characteristic fields listed across the perpendicular axis, with the intersection holding the characteristic value), the *DES* main data sheet has been constructed borrowing influence from data structures found in NoSQL databases (section 2.5.1.2) and object-oriented programming (section 5.6.2). Vehicle object characteristics are collected and stored in a normalized dataset that grows and shrinks to fit the amount of data known about the object. This requires the user to only enter known and relevant characteristics (i.e. if a characteristic is not needed to describe an object or is not known, it is not required that user instantiate that characteristic or specify it as a null value). By constructing the characteristic data sheet in this manner, it is more-closely a ‘fit to size’ approach, as opposed to a ‘one size fits all’ – this approach is necessary to meet the specification requirements of meeting changing data topics and requirements and will allow the *DES* to scale for future use.



Vehicle Name: Mercury
Vehicle Type: Non-Lifting Reentry Vehicle

Folder: Z:\AVDS\AVDSiz_MAT\CON
File Name:

Discipline	VariableDescription	Value	Unit	IndexID	MDS
GEO	Planform Area	2.8124	m^2	373	☑
GEO	Nose Radius	2.032	m	300	☑
WB	cargo weight		kg		☑
WB	Payload Weight		kg		☑
WB	Gross Weight	1285.5	kg	373	☑
WB	TPS Weight	217.7	kg	380	☑
WB	Structure Weight	265.5	kg	373	☑
GEN	number of crew	1	[]	1	☑
GEN	Wing Loading	1285/2.8	kg/m^2		☑
GEN	Max Speed	7.5	km/s	36	☑
GEN	VehicleName	Mercury		1	☑
GEN	Passengers	1	[]	1	☑

Figure 5.13 – Vehicle System Library: Main Data Sheet

Specifying an object characteristic requires 1) the characteristic field being described, 2) the value of that object characteristic, and 3) meta-data describing the context and understanding behind the object characteristic. Characteristic fields are taken directly from the *variable library*, described above – linked disciplinary categories have been added to the form to provide dynamic filtering to clarify the selection of characteristic fields. Within the characteristic meta-data, the user is prompted to provide the source of the object characteristic – the value entered here is identification number that directly links towards an index ID specified in the *source library*. These two foreign keys, variable name and index ID, ensure consistency across forecasting projects and across *DES* users, as well as promoting the ‘transparent’ flow of data from source through implementation stated in *DES* specification requirements.

5.4.2.5 Analysis Library

Function: Defines system analysis and interfaces with sizing analysis code.

Specification Requirement:

2. Provide a transparent flow of data from source documentation to implementation.
3. House source, process and result data in organizationally-communal network.
5. Allow the integration of non-standardized data formats.
6. Interface with multi-domain existing internal and external data sources.
7. Provide access to source, process and result data of previous organizational efforts.
14. Integrate data processes required for execution of aerospace synthesis.

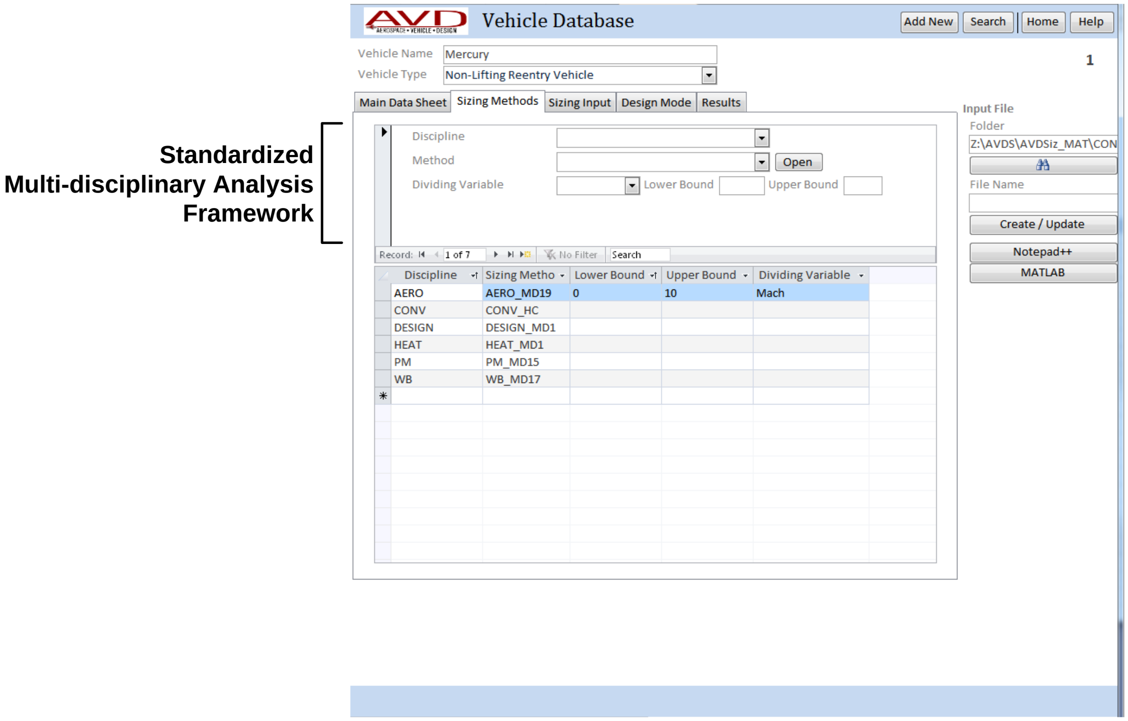
Targeted Data-Engineering Metrics:

A. Scope
B. Density
C. Meta-Data Ratio
D. Completeness
F. Accessibility
G. Adaptability
L. Multiplicity

For forecasting efforts that require formal system analysis, the Analysis Library is designed to facilitate the definition of analysis, formatting of data to match parametric analysis outside the DES, and the collection of both analysis inputs and results. This functionality is only available due to the standardization of all previous functions, but the highly-coupled nature offers the ripest opportunities for efficiency increases.

Synthesis Methods Selection

In order to select the disciplinary analysis methods needed to describe the vehicle system within the synthesis framework, the *synthesis method selection* sub-form is the first of four sub-forms required to implement a vehicle system in the synthesis environment, as specified in the foundational requirements. This sub-form connects to the previously defined *methods library* as a definition of disciplinary and domain-specific analysis methods – the meta-data describing inputs, outputs, analysis, applicabilities, and method performance are all made immediately available as the user is selecting methods. Additional functionality has been incorporated to dissect disciplinary methods that are only applicable within a defined range of operational variables (i.e. the user specifies one aerodynamic analysis method for subsonic Mach numbers, and a secondary method for all analysis at supersonic Mach numbers).



Vehicle Database

Vehicle Name: Mercury
Vehicle Type: Non-Lifting Reentry Vehicle
1
Folder: Z:\AVDS\AVDSiz_MAT\CON
Record: 1 of 7

Discipline	Sizing Metho	Lower Bound	Upper Bound	Dividing Variable
AERO	AERO_MD19	0	10	Mach
CONV	CONV_HC			
DESIGN	DESIGN_MD1			
HEAT	HEAT_MD1			
PM	PM_MD15			
WB	WB_MD17			

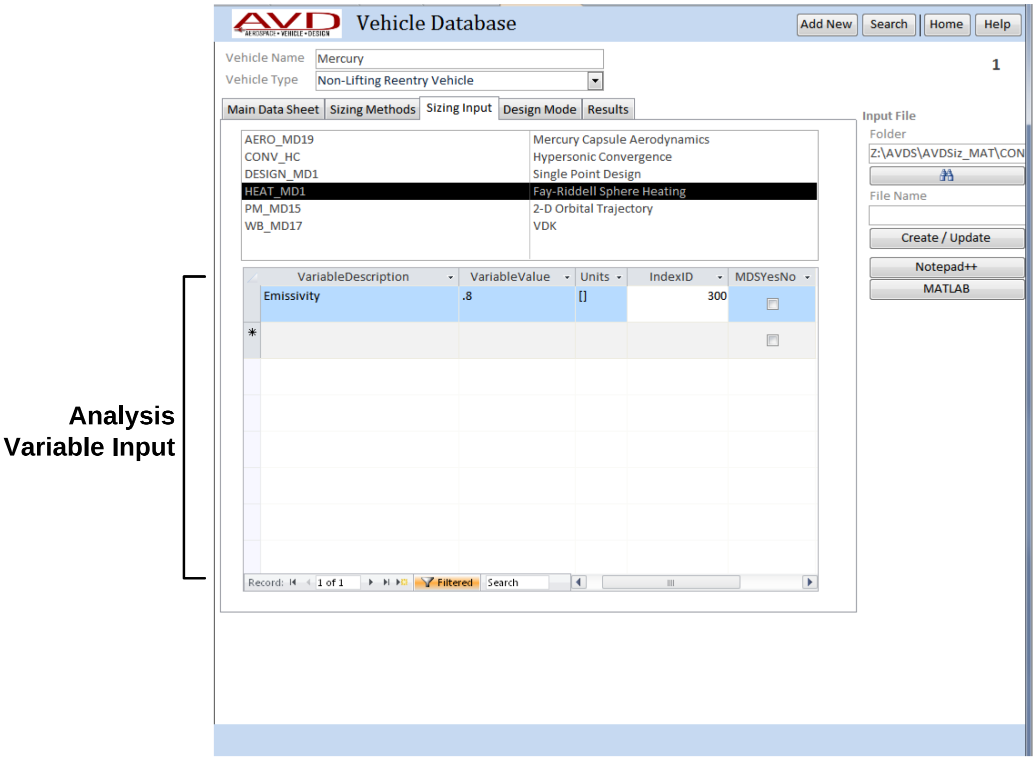
Figure 5.14 – Vehicle System Analysis Library: Synthesis Method Selection

Synthesis Input

The *synthesis input* vehicle sub-form, also optionally required for integration with synthesis, requires the user to provide all input variables required to execute the previously selected analysis methods, shown below in Figure 5.15. Distinction between which input variables are required for each disciplinary method is taken directly from definition of the method in the *methods library*. If a user has selected an analysis method to be included in the MDA structure and the characteristic is not currently known about the vehicle, the user is prompted about the discrepancy. Transparency in source documentation is provided here again, with a direct link to the index ID from the *source library* substantiating all input variables.

Synthesis Parameter Analysis

A separate sub-form titled *synthesis parameter analysis* is in place to define how the synthesis MDA will operate and what, if any, design parameter sweeps will be performed. Due to the uncertain nature of underlying input data, forecasted operational environment and disciplinary analysis methods, systems synthesis at the early stages of design should never be considered ‘point designs’. The goal of these information tasks is to define ranges or sets[30] of possible solutions which adhere to operational constraints and provide sufficient utility as defined by the decision-making entity.



Vehicle Name: Mercury
Vehicle Type: Non-Lifting Reentry Vehicle
1

Input File
Folder: Z:\AVDS\AVDSiz_MAT\CON
File Name:

AERO_MD19	Mercury Capsule Aerodynamics
CONV_HC	Hypersonic Convergence
DESIGN_MD1	Single Point Design
HEAT_MD1	Fay-Riddell Sphere Heating
PM_MD15	2-D Orbital Trajectory
WB_MD17	VDK

VariableDescription	VariableValue	Units	IndexID	MDSYesNo
Emissivity	.8	[]	300	☐
				☐

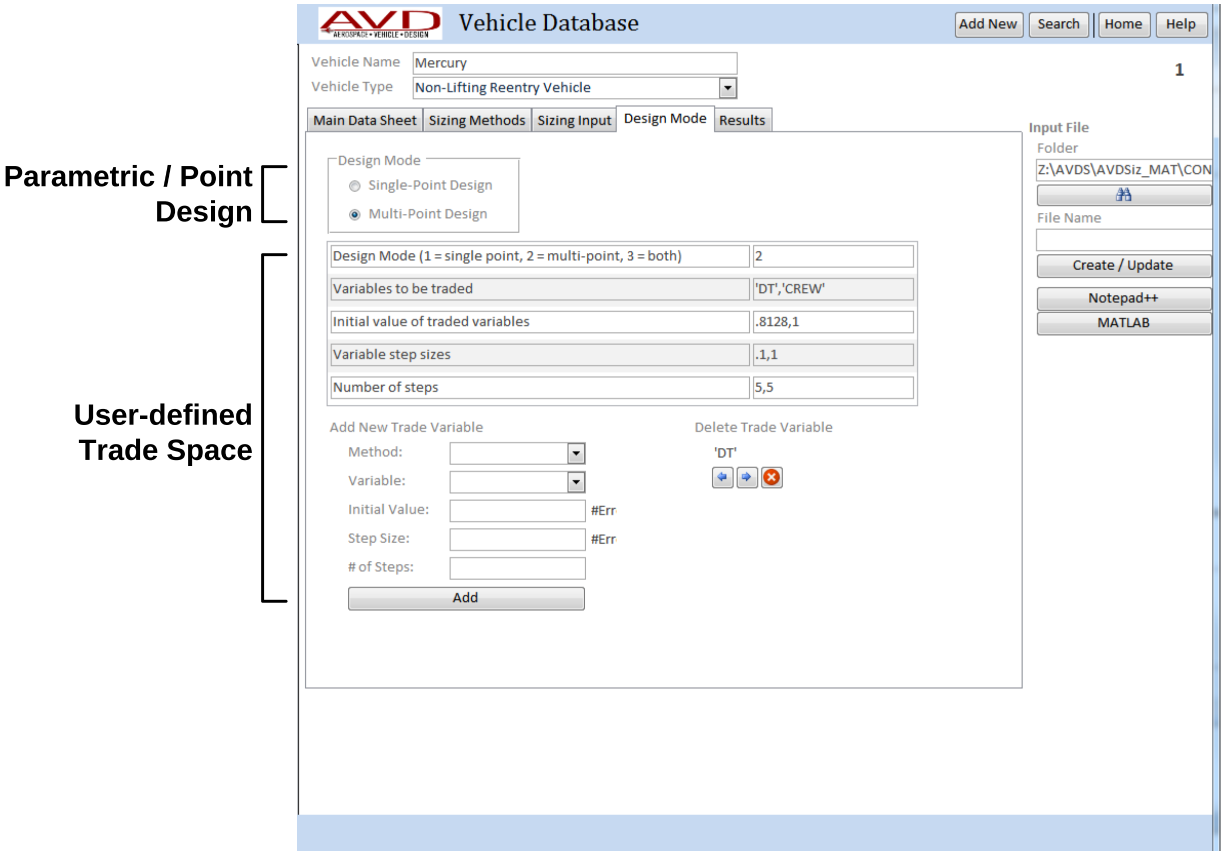
Figure 5.15 – Vehicle System Analysis Library: Disciplinary Analysis Inputs

In order to produce a ‘solution space’, independent design parameters are not given a deterministic value, but a set-based vector of potential values. By varying input parameters, analyzing the converged total vehicle system for each combination of design parameters, and visualizing the range of solutions on a single solution space allows the analyst to determine the system’s sensitivity to uncertainty in design variables and identify solution areas that warrant further analysis. Defining parameter variation in the synthesis parameter analysis is tied directly to the output of a synthesis input file, described in the following section.

Synthesis Input File

While the three previous sub-forms have been compiling the data required to operate the synthesis platform, the *synthesis input file* view provides a direct translation of data stored in the *DES* into programming syntax immediately executable with the synthesis environment. The specific formulation of the input file is specific to the AVD synthesis platform and is described below in section 5.6.4 and Appendix A.

Due the previous standardization of variables and methods, neither discipline-specific nor method-specific formatting syntax is required in the synthesis input file – all method inputs, definitions and analysis procedures adhere to a shared set of standards that can be defined in a generic fashion. This functionality allows the interface between the *DES* and the synthesis analysis software platform to scale with changing information requirements.



Vehicle Name: Mercury
Vehicle Type: Non-Lifting Reentry Vehicle

Design Mode
○ Single-Point Design
● Multi-Point Design

Design Mode (1 = single point, 2 = multi-point, 3 = both)	2
Variables to be traded	'DT','CREW'
Initial value of traded variables	.8128,1
Variable step sizes	.1,1
Number of steps	5,5

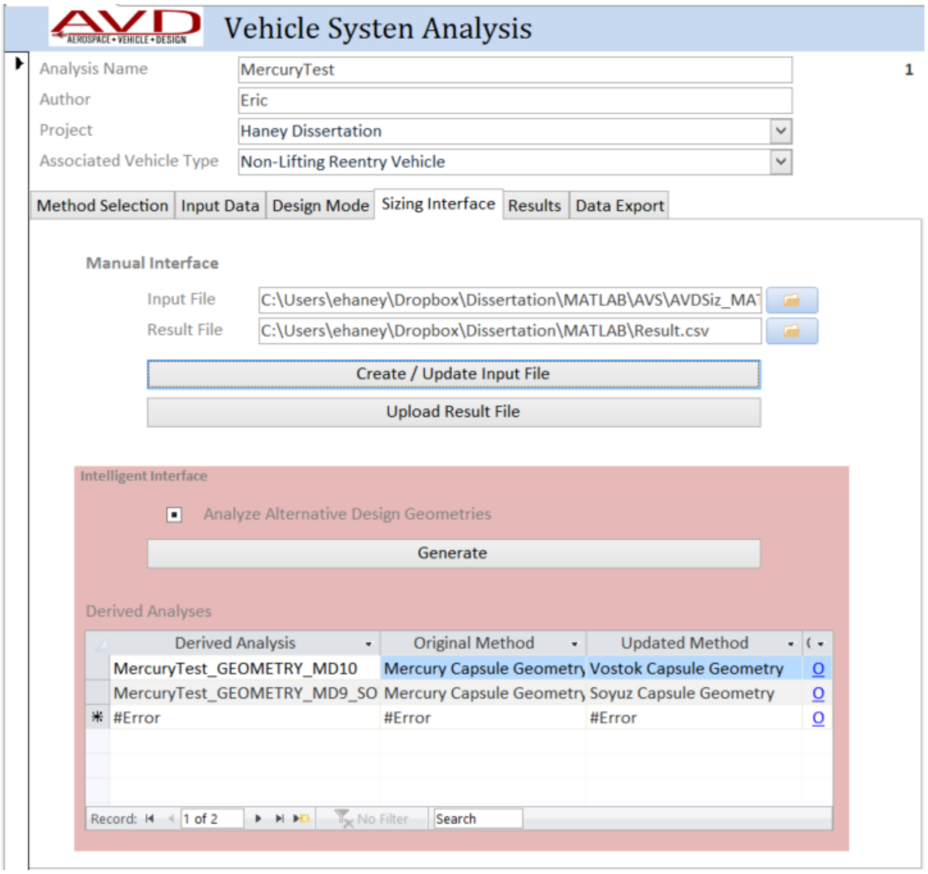
Folder: Z:\AVDS\AVDSiz_MAT\CON

Method:
Variable:
Initial Value: #Err
Step Size: #Err
\# of Steps:

Delete Trade Variable: 'DT'

Figure 5.16 – Vehicle System Analysis Library: Parametric Analysis Definition

As part of the interface a result file location is specified, in which all sizing analysis results are stored (the unique Analysis ID is used to cross-reference analyses defined in the DES and results produced by AVD Sizing). The DES then uploads the newly-created results back in the Analysis Library – the DES now has access to both the user-defined inputs and corresponding results from all analyses performed by the forecasting organization. This allows for unprecedented levels of data and knowledge accumulation which can, in the future, work towards an automated, self-learning environment.



Analysis Name: MercuryTest
Author: Eric
Project: Haney Dissertation
Associated Vehicle Type: Non-Lifting Reentry Vehicle
Input File: C:\Users\ehaney\Dropbox\Dissertation\MATLAB\AVS\AVDSiz_MA
Result File: C:\Users\ehaney\Dropbox\Dissertation\MATLAB\Result.csv
☑ Analyze Alternative Design Geometries

Derived Analyses

Derived Analysis	Original Method	Updated Method	(
MercuryTest_GEOMETRY_MD10	Mercury Capsule Geometry	Vostok Capsule Geometry	O
MercuryTest_GEOMETRY_MD9_SO	Mercury Capsule Geometry	Soyuz Capsule Geometry	O
#Error	#Error	#Error	O

Figure 5.17 – System Analysis Interface with AVD Parametric Sizing Code

5.4.2.6 Deliverables Library

Function: Collects example decision-making deliverables and provides a template for presenting information.

Specification Requirement:
2. Provide a transparent flow of data from source documentation to implementation.
7. Provide access to source, process and result data of previous organization efforts.
10. Provide ability to identify and visualize trends in data.
11. Provide a suite of data visualization outputs with corresponding applicability.

Targeted Data-Engineering Metrics:
L. Multiplicity
M. Degrees of Freedom

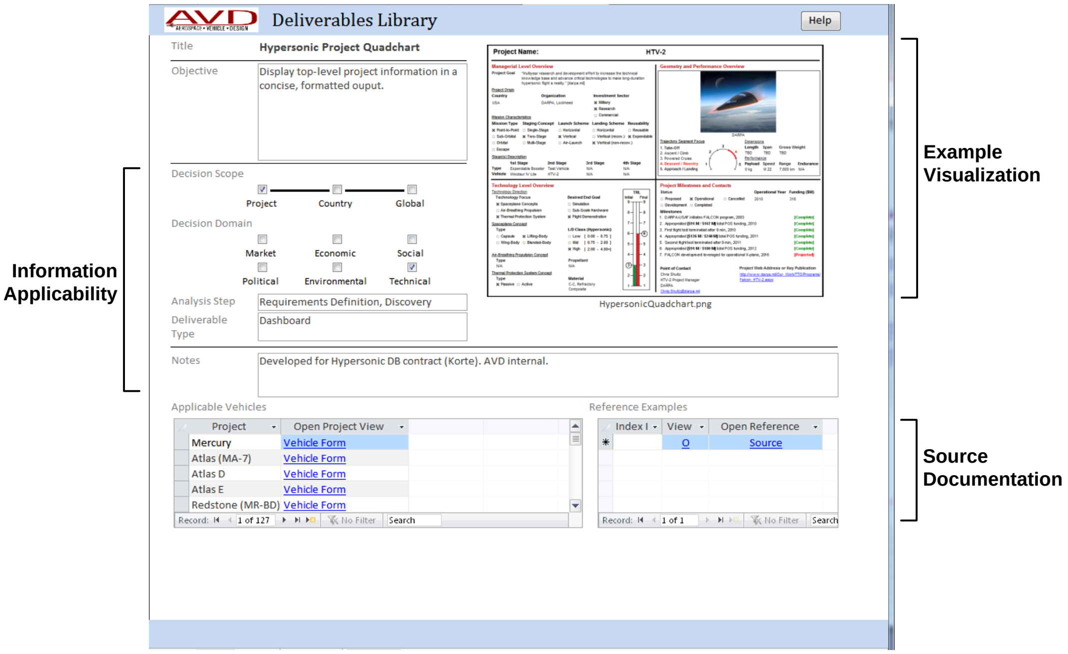
Capabilities for data visualization, the final *DE* task communicating information, have been collected in the *DES Deliverables Library*. Visualization techniques for aerospace forecasting have been collected and organized within the deliverables library with each visualization being decomposed by the variables required, the intended decision-making scope and domains, the point in decision-making at which the deliverable is applicable, as well as the overall objective of the deliverable, see Table 5.13. It is intended for the user to identify deliverable techniques from this library that are applicable to the design and forecasting task and specific decision-making needs and shape the information production process to achieve these visualization outputs.

Table 5.13 – Deliverables Library

Field	*Format*	*Description*
Title	Text	Deliverable name
Objective	Text	Purpose of deliverable in decision-making context
Scope	Yes/No	Micro- to macro-scale identifier
Domain	Yes/No	Socio-technical identifier
Variable*	List	Variables that are visualized or impacted by the deliverable
Index ID**	Number [Foreign Key]	Index detailing an example of the decision-making deliverable

*Number of influencing variables is unlimited
**Number of source references is unlimited

Currently, the deliverables library is primarily operated as a repository for deliverables meta-data and analyst knowledge about information applicability, see Figure 5.18. The capability to select pre-defined visualization deliverable and automatically generate a visualization from existing data within the *DES* is an ongoing development goal – an example case study detailing the development and integration of an executive dashboard deliverable for hypersonic research and development programs is presented in Chapter 5.



Title: Hypersonic Project Quadchart

Objective: Display top-level project information in a concise, formatted ouput.

Decision Scope: ☑ Project ☐ Country ☐ Global

Decision Domain: ☐ Market ☐ Economic ☐ Social ☐ Political ☐ Environmental ☑ Technical

Analysis Step: Requirements Definition, Discovery

Deliverable Type: Dashboard

Notes: Developed for Hypersonic DB contract (Korte). AVD internal.

Applicable Vehicles

Project	Open Project View
Mercury	Vehicle Form
Atlas (MA-7)	Vehicle Form
Atlas D	Vehicle Form
Atlas E	Vehicle Form
Redstone (MR-BD)	Vehicle Form

Record: 1 of 127 No Filter Search

Reference Examples

Index I	View	Open Reference
*	O	Source

Record: 1 of 1 No Filter Search

Figure 5.18 – Deliverables Library

5.4.2.7 Search

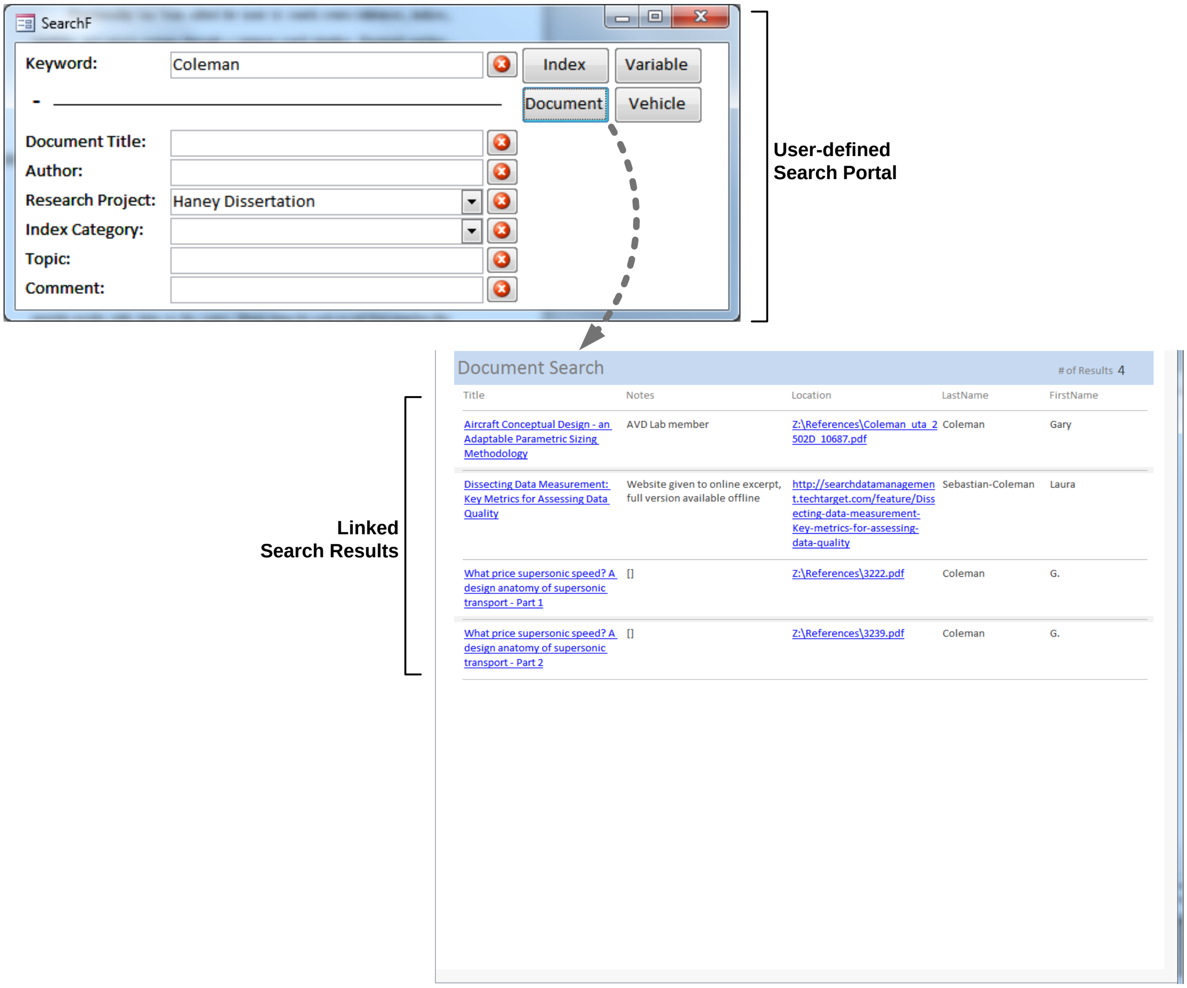
Function: Provides search and recall functionality across libraries.

Specification Requirement:

2. Provide a transparent flow of data from source documentation to implementation.
9. Allow for user-defined aggregation, filter and query across any dataset(s).

Targeted Data-Engineering Metrics:

F. Accessibility
H. Time Cost
I. Economic Cost
J. Precision
K. Sensitivity



Keyword: Coleman
Document Title:
Author:
Research Project: Haney Dissertation
Index Category:
Topic:
Comment:

Document Search

# of Results 4

Title	Notes	Location	LastName	FirstName
Aircraft Conceptual Design - an Adaptable Parametric Sizing Methodology	AVD Lab member	Z:\References\Coleman_uta_2502D_10687.pdf	Coleman	Gary
Dissecting Data Measurement: Key Metrics for Assessing Data Quality	Website given to online excerpt, full version available offline	http://searchdatamanagement.techtarget.com/feature/Dissecting-data-measurement-Key-metrics-for-assessing-data-quality	Sebastian-Coleman	Laura
What price supersonic speed? A design anatomy of supersonic transport - Part 1	[]	Z:\References\3222.pdf	Coleman	G.
What price supersonic speed? A design anatomy of supersonic transport - Part 2	[]	Z:\References\3239.pdf	Coleman	G.

Figure 5.19 – Search Portal

The capability to connect an analyst with desired data elements is the focus of the *DES Search* functionality where both formal and informal avenues for recall, sorting and filtering data have been implemented. Functionality has been added for users to search source references, indices, variables, and vehicle systems through a common search interface. Keyword searches, as well as targeted search within specific fields, is offered to the user – datasets from personnel throughout the organization are made searchable through the search portal, but may be focused to specific research and forecasting projects if desired..

The populated results provide a direct link to their native library (i.e. a document search will provide results with links to the *source library* form for each record that matches the search criteria), shown in Figure 5.19. The meta-data introduced at the source, method, variable and vehicle system levels plays a significant role in the ability to provide relevant search results, as measured by time cost, economic cost, precision and sensitivity and discussed in section 2.3.5.

In addition to a formal search portal, MS Access provides a native capability to search, filter, and sort entries within a form view – this provides the user the ability to perform natural search functions within the data system as the need arises. The capability also exists to define and save custom SQL queries, see section 2.5.1.2, to extract combined datasets subject to constraints with the unified relationships discussed previously for source, variable, method and vehicle data consistently carried throughout.

5.5 KNOWLEDGE SYSTEM PLATFORM INTEGRATION

Although formal *Knowledge-Engineering* implementation is, for the most part, taken as a parallel research and development path, elements of a knowledge-driven system have been implemented within the current data support architecture.

- Forecasting projects are given their own unique set of categories and index topics allowing data collection efforts to be retraced for transparency or as a learning tool for similar research projects at a future date.
- Index tagging within source documents allows individual analysts to distill the most impactful sections, offering ‘pre-digested’ knowledge for future research efforts.
- Methods library entries allow users to frame method applicability, as well as state general conclusions about when and how to use a disciplinary method.
- Deliverables library exists as a bridge between data and knowledge domains – visual decision-making deliverables from historical projects offer insight into the document authors’ expertise on the subject and provide forecasting analysts with condensed

situational awareness of how a problem has been conveyed to decision-makers in the past.

Overall, the storage of data and information production processes for inspection and reuse by future analysts on future projects is large step towards implementing formal Knowledge-Engineering principles.

5.6 ANALYSIS SYSTEM PLATFORM INTEGRATION

Function: Standardization of synthesis software, variable, and analysis method protocols.

Specification Requirement:

1. Develop an open architecture to be continually improved.
13. Provide a standardized process interface between the *DES* and synthesis platform.
14. Integrate data processes required for execution of aerospace synthesis.

Targeted Data-Engineering Metrics:

G. Adaptability
N. Interoperability

In order to provide a standard interface between the above-defined *DES* components and the aerospace synthesis platform has required several fundamental modifications to the aerospace synthesis platform – adjustment or complete changes in programming language, syntax standards, variable-naming protocol, and analysis function definitions have been completed. The following subsections detail the specific efforts and their overall impact on the data-to-analysis domain interface.

5.6.1 Synthesis Programming Language

AVD Sizing, the central synthesis program used by the AVD forecasting team, was originally written in FORTRAN 77[264], a low level programming language that offers exceptional computational speed, but lacks built-in functionality expected from modern programming languages. Because of the increases in modern computing power and already short software execution time, a higher-level programming language has been chosen for a migrated version of the original AVD Sizing.

An extensive translation effort was undertaken within the forecasting team to translate AVD Sizing from FORTRAN into MATLAB – over 150 disciplinary methods in total were hand-converted from FORTRAN syntax into MATLAB. The new programming language allows for significant portions of the heritage code to be dropped in favor of native MATLAB functions (e.g. declaration of variables, matrix functions, convergence logic). The reduction in complexity to edit and add new content was the driving factor in the decision to translate the software platform – exposure to FORTRAN was limited for most of the forecasting team members, limiting their ability to contribute to synthesis environment without learning syntax and operating peculiarities of the language. MATLAB's high-level architecture, extensive documentation, and user-friendly error logic allowed for more members to contribute to the synthesis and execution process.

5.6.2 Variable Standardization

Within the heritage FORTRAN synthesis code, disciplinary methods were given their own unique set of input, working and output variables. As variables were passed between methods, variable instantiation at the beginning of analysis processes converted the variables to the naming convention for that method. Because there was no standard variable database, analysts were offered no structured format for naming convention of input, working and output variables in new or edited disciplinary analysis methods. Although the implemented *Data-Engineering* protocol alleviates this issue, the existing analysis methods had to be updated for consistent variable naming convention and usage throughout each method file.

5.6.2.1 Object-Oriented Variables

Previously, variable values were stored independently and within a unique variable name. Because FORTAN does not have functionality to declare global variables, variables either had to be passed between functions in 'common blocks'[277] specified at the beginning of each analysis file or specified along with all other input variables (with consistent syntax) in the integration file. This second approach required *a priori* knowledge of the exact variables required for each analysis method, making the integration (referred to as Input) file specific to the analysis methods currently being used. 'Common blocks' were therefore widely used to pass variables between analysis methods, although this approach also posed issues if naming conventions changed due to change in synthesis methodology (i.e. new forecasting effort) or the addition of a new analysis method.

The solution within the new MATLAB architecture was to house all variables within discipline specific variables referred to as 'structures'[278], object oriented variables that can be passed and referred to as a whole, but which contain n-number of sub-variables (which may also themselves be structures). For instance, with structures all geometry data can be stored within the 'GEO' variable structure – instead of the wingspan being stored as its own independent variable 'B', it is now located within the 'GEO' structure and referenced in the software syntax as 'GEO.B'.

This approach, shown as an example in Figure 5.20, allows function calls to only refer to the disciplines required as inputs and outputs – the variables required for calculation are specified inherently by the method and only those variables needed are ‘unpacked’ from the structure. At the end of the analysis method, the output variables are then written into their corresponding disciplinary structures following the same convention specified in the *DES* variables library. Generalizing variables into a finite number of disciplinary structures allows the input convergence logic to remain largely unchanged for similar vehicle systems, even if the analysis methods are highly variable – this promotes a multi-fidelity mindset that is often necessary to adapt to changing decision-making needs during forecasting efforts.

	Unique Variable Programming	**Structures Programming**
Variable Declaration	B = … S = … A1 = … A2 = ...	**Input Module** INPUT.A1 = … INPUT.A2 = ... **Geometry Module** GEO.B = … GEO.S = …
Function Call	[W] = WB_MD1(B,S,A1,A2)	WB_MD1(GEO,INPUT,WB)
Function Execution		

Function Execution

Unique Variable Programming:

```
function [W] = WB_MD1(B,S,A1,A2)

        W = A1*B + A2*S

end
```

Structures Programming:

```
function = WB_MD1(GEO,INPUT,WB)

A1=INPUT.A1
A2=INPUT.A2
B=GEO.B
S=GEO.S

        W = A1*B + A2*S

WB.W = W

end
```

Figure 5.20 – Unique Variable vs MATLAB Structures Programming Comparison

5.6.3 Method Standardization

Disciplinary analysis methods previously followed a rough procedural formulation, but it was required for future development that the format of disciplinary analysis process files to be under a strict formatting structure, as discussed in the next sub-section. A description of the method including all input and output variables is now included at the beginning of each method file, followed by the instantiation of all input variables. Creating a well-defined structure allows for future platform development that automates the creation of disciplinary analysis method function files.

Meta-Data (Commented)

Method Description	WB_MD1: Description of this disciplinary analysis module. First clarifier states the discipline (Weight & Balance), second clarifier states the index number (1).	
Reference	REF:	States the source reference of the method.
Input Variables	A1	Input Design Variable
	A2	Input Design Variable
	B	Wing Span
	S	Reference Area
Output Variables	W	Weight
Structure Dependencies	INPUT GEO WB	

Function

```
function = WB_MD1(GEO,INPUT,WB)
```

Input Variable Unpacking

```
A1=INPUT.A1
A2=INPUT.A2
B=GEO.B
S=GEO.S
```

Analysis

```
      W = A1*B + A2*S
```

Output Variable Packing

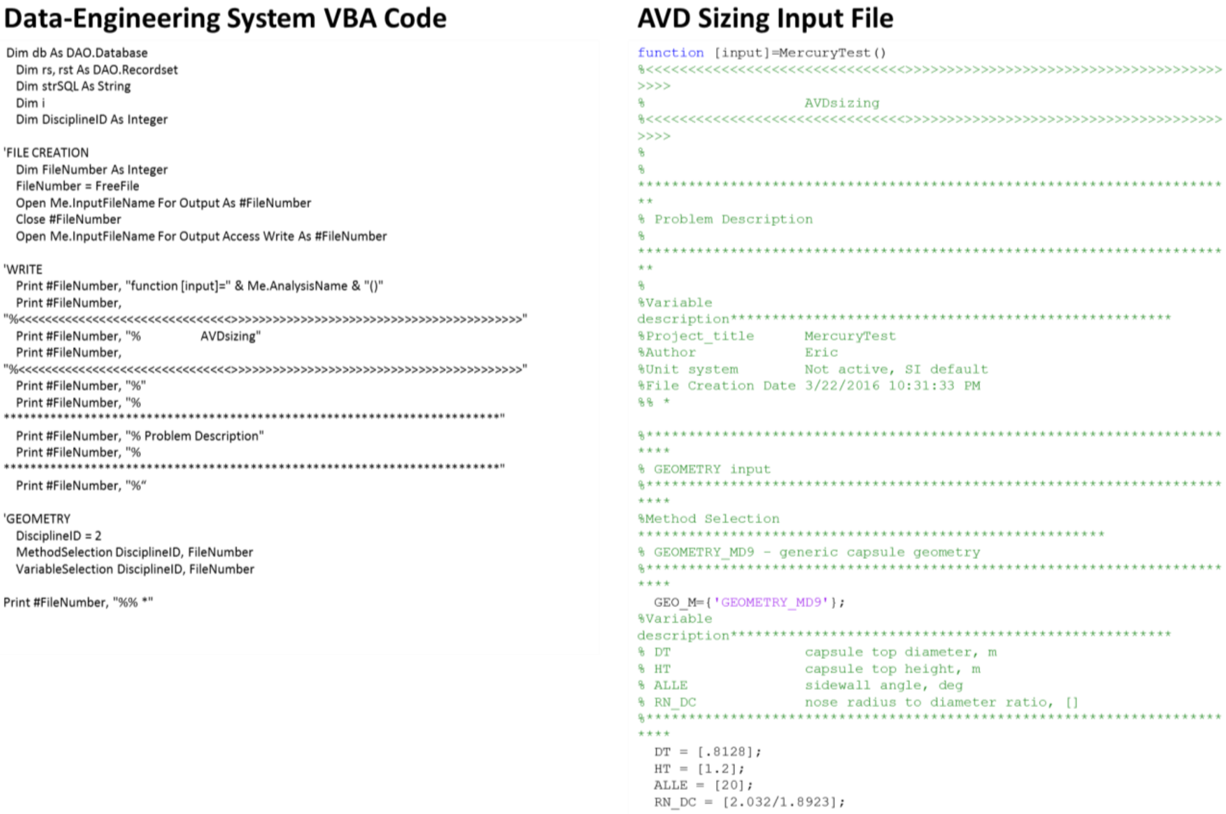
```
WB.W = W

end
```

Figure 5.21 – Standardized Disciplinary Analysis Method Definition (Example Method)

5.6.4 Input File Automation

The input file is the driving process file within the synthesis platform – it contains which disciplinary methods are going to be used, how the methods interact with each other, the user-defined input variables required for each method, and the overall convergence logic of the synthesis process. After the *Data-Engineering* process improvements, the synthesis input file is now a structured file format that can be completely written from the data support system interface. The declaration of each disciplinary analysis method, including the specification of which disciplines are required to describe the vehicle system, follows a structured pattern tying the above 'synthesis input' data directly into MATLAB-syntax code in the input file (Figure 5.22). See Appendix A for the details of the database-to-MATLAB translation coding process.



Data-Engineering System VBA Code

```
 Dim db As DAO.Database
   Dim rs, rst As DAO.Recordset
   Dim strSQL As String
   Dim i
   Dim DisciplineID As Integer

'FILE CREATION
   Dim FileNumber As Integer
   FileNumber = FreeFile
   Open Me.InputFileName For Output As #FileNumber
   Close #FileNumber
   Open Me.InputFileName For Output Access Write As #FileNumber

'WRITE
   Print #FileNumber, "function [input]=" & Me.AnalysisName & "()"
   Print #FileNumber,
"%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>"
   Print #FileNumber, "%              AVDsizing"
   Print #FileNumber,
"%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>"
   Print #FileNumber, "%"
   Print #FileNumber, "%
************************************************************************"
   Print #FileNumber, "% Problem Description"
   Print #FileNumber, "%
************************************************************************"
   Print #FileNumber, "%“

'GEOMETRY
   DisciplineID = 2
   MethodSelection DisciplineID, FileNumber
   VariableSelection DisciplineID, FileNumber

Print #FileNumber, "%% *"
```

AVD Sizing Input File

```
function [input]=MercuryTest()
%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
>>>>
%                   AVDsizing
%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
>>>>
%
%
**********************************************************************
**
% Problem Description
%
**********************************************************************
**
%
%Variable
description*******************************************************
%Project_title      MercuryTest
%Author             Eric
%Unit system        Not active, SI default
%File Creation Date 3/22/2016 10:31:33 PM
%% *

%*********************************************************************
****
% GEOMETRY input
%*********************************************************************
****
%Method Selection
*********************************************************
% GEOMETRY_MD9 - generic capsule geometry
%*********************************************************************
****
  GEO_M={'GEOMETRY_MD9'};
%Variable
description*******************************************************
% DT                capsule top diameter, m
% HT                capsule top height, m
% ALLE              sidewall angle, deg
% RN_DC             nose radius to diameter ratio, []
%*********************************************************************
****
  DT = [.8128];
  HT = [1.2];
  ALLE = [20];
  RN_DC = [2.032/1.8923];
```

Figure 5.22 – Data-Engineering System Input File Automation

5.7 ARTIFICIAL DESIGN INTELLIGENCE FEEDBACK

As a proof-of-concept, several design features have been developed within the DES that take advantage of the open interface availability of data across usually-siloed DE processes. These functions do not seek to allow the forecasting engineer to re-create existing data tasks more efficiently – their goal is to fundamentally alter the aerospace forecasting process, by producing artificially intelligent design feedback within the course of DES user-interface. Artificial design intelligence (ADI) features then, are analogous to receiving advice from an experienced senior engineer who is constantly scanning the organization’s dedicated encyclopedia. The information created with such an arrangement has no option but to increase in value.

5.7.1 Parameter Estimation

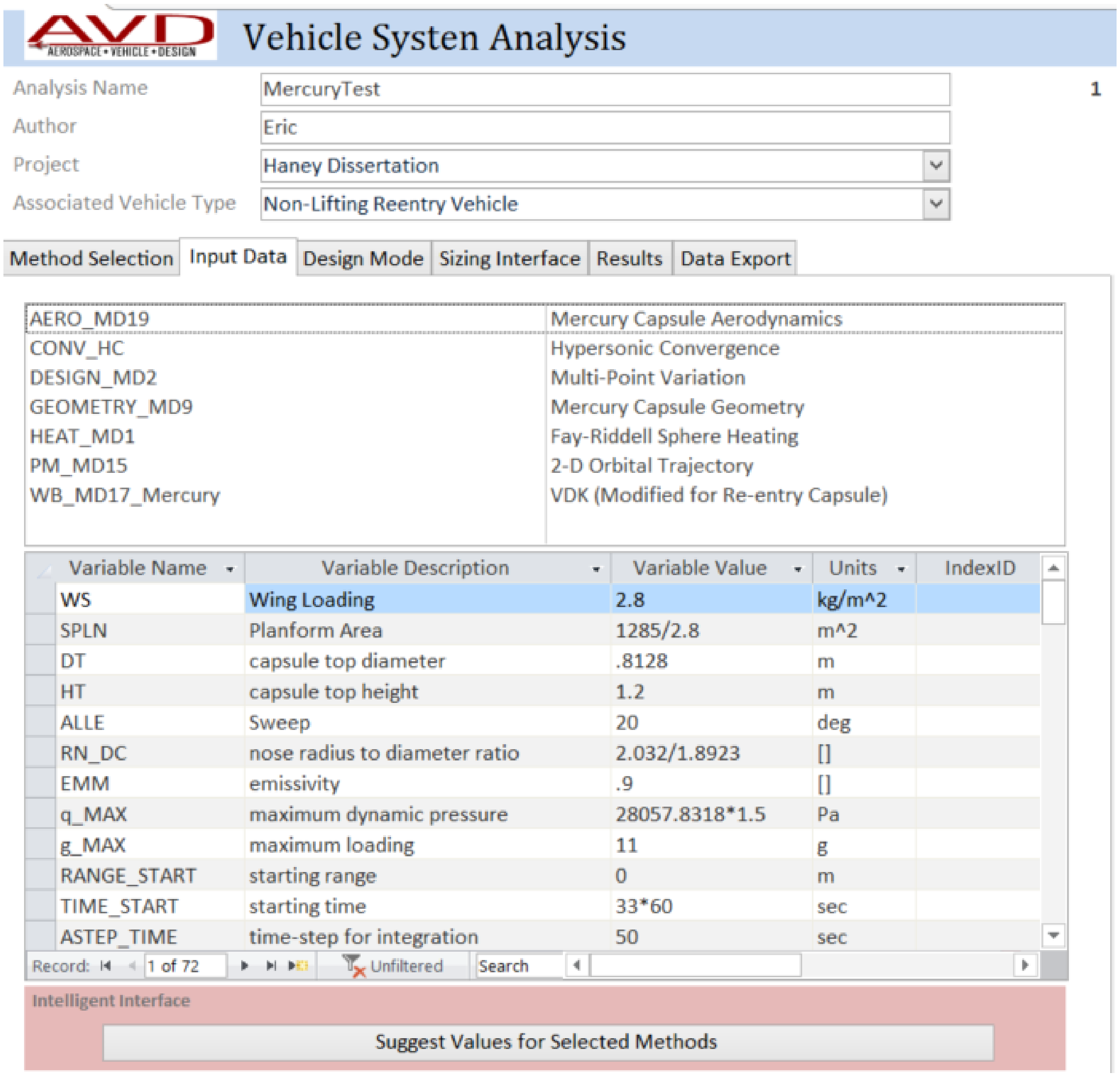
Within the process of characterizing vehicle systems and / or vehicle system analyses, not all variables have readily-available data. While some difficult-to-define values can be inferred tangentially (e.g. measure planform area from an aircraft sketch), some variables cannot be estimated accurately by only considering the data available about the current system. However, the integrated and compounding nature of the DES allows the *Parameter Estimation* ADI, trigged by a user prompt in Figure 5.23, to estimate a variable value by cross-referencing all other vehicle systems with similar operational or design traits. The resulting query (Figure 5.24) pulls all variable entries that are known, and provides the forecasting engineer a basis for estimating the variable value for the current system. A further step towards full artificial intelligence, could take this step of pulling relevant data and estimating parameters as an automated process – the user would simply identify which needed values are not known from source documentation, and the ADI would automatically introduce estimated parameter values.

5.7.2 Alternative Design Selection

The definition of a MDA to assess a vehicle system requires the user to select disciplinary analysis methods and their connection to each other. While the DES offers some context for the applicability of analysis methods, it is left as a user-responsibility to identify the vehicle configuration applicable to the defined reference mission. The *Alternative Design Selection* ADI harnesses the DES's collective memory to filter and identify alternative design concepts applicable to the mission, but not addressed in the current analysis – this feature expands the breadth of options from only those design options identified by the engineer, towards all potential alternatives ever previously considered within an organization. Not only does the *Alternative Design Selection* feature select alternative designs, but it automatically creates an additional analysis entry within the DES and transcribes all shared variables – the alternative analysis input can then generated and compared to the analysis results of the core design concept within a matter of minutes.

5.7.3 Deliverable Suggestion

The generation of deliverables is the primary interface between the design & forecasting process and the decision-making process – an analysis is only as productive as the method of communication resultant information. When the user selects the *Deliverable Suggestions* ADI, the DES selects deliverables that match both vehicle system category and one or more deliverable applicability criteria. The system then identifies the variables required to generate that deliverable, and marks them for export alongside all currently desired variables.

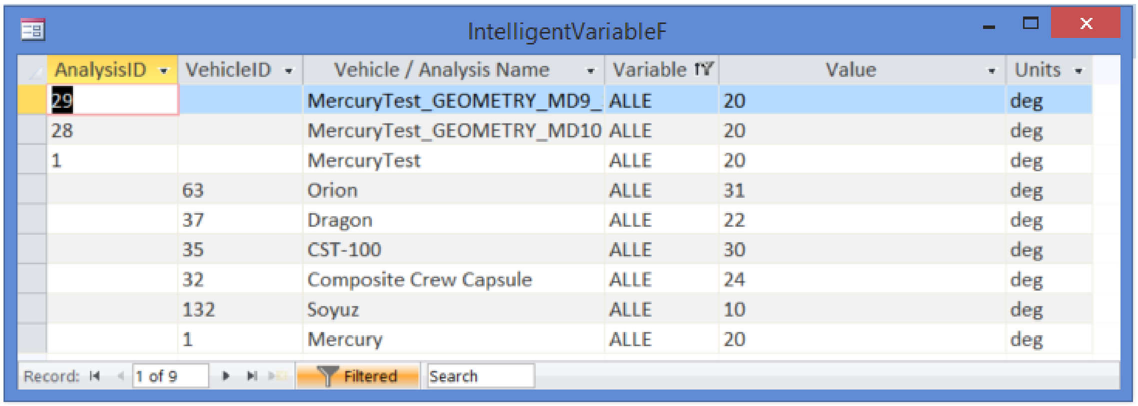


Analysis Name: MercuryTest
Author: Eric
Project: Haney Dissertation
Associated Vehicle Type: Non-Lifting Reentry Vehicle

AERO_MD19	Mercury Capsule Aerodynamics
CONV_HC	Hypersonic Convergence
DESIGN_MD2	Multi-Point Variation
GEOMETRY_MD9	Mercury Capsule Geometry
HEAT_MD1	Fay-Riddell Sphere Heating
PM_MD15	2-D Orbital Trajectory
WB_MD17_Mercury	VDK (Modified for Re-entry Capsule)

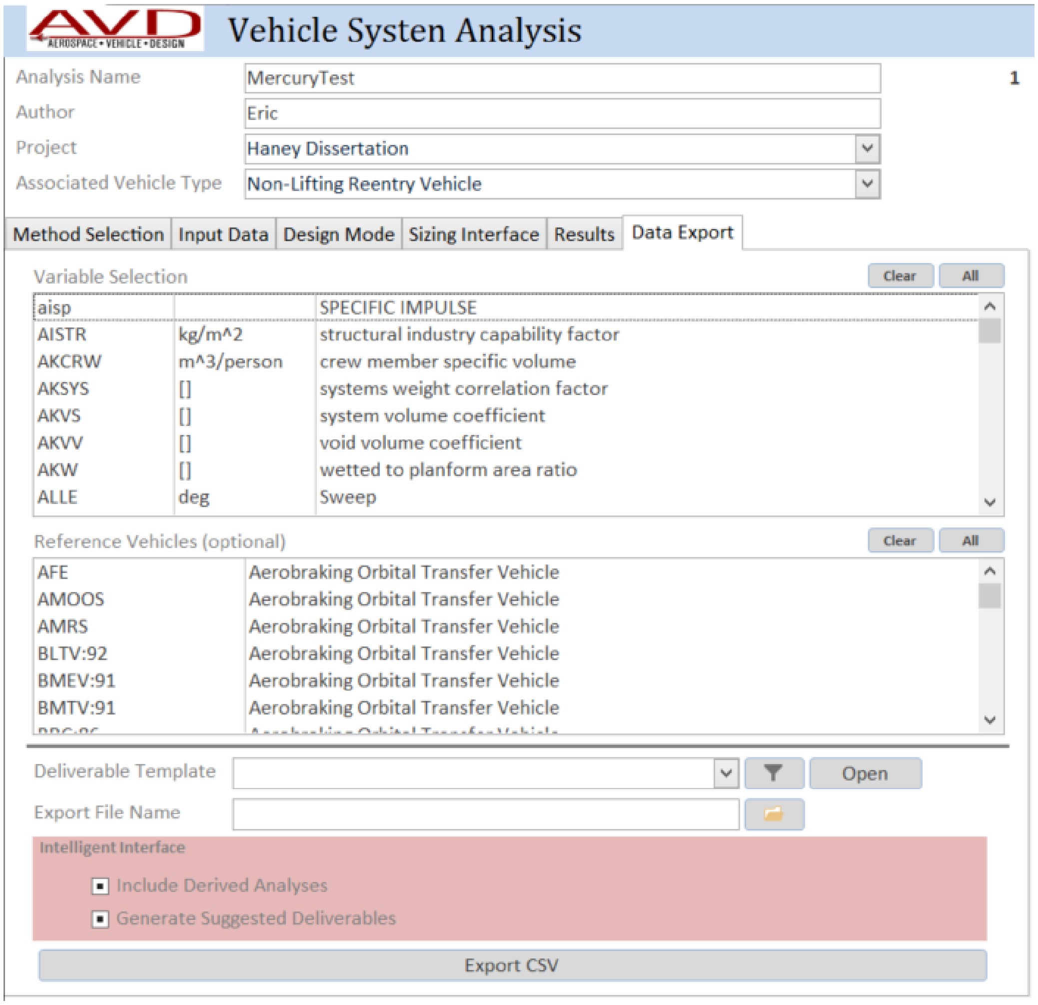
Variable Name	Variable Description	Variable Value	Units	IndexID
WS	Wing Loading	2.8	kg/m^2	
SPLN	Planform Area	1285/2.8	m^2	
DT	capsule top diameter	.8128	m	
HT	capsule top height	1.2	m	
ALLE	Sweep	20	deg	
RN_DC	nose radius to diameter ratio	2.032/1.8923	[]	
EMM	emissivity	.9	[]	
q_MAX	maximum dynamic pressure	28057.8318*1.5	Pa	
g_MAX	maximum loading	11	g	
RANGE_START	starting range	0	m	
TIME_START	starting time	33*60	sec	
ASTEP_TIME	time-step for integration	50	sec	

Figure 5.23 – Parameter Estimation Artificial Design Intelligence Feature



AnalysisID	VehicleID	Vehicle / Analysis Name	Variable	Value	Units
29		MercuryTest_GEOMETRY_MD9_	ALLE	20	deg
28		MercuryTest_GEOMETRY_MD10	ALLE	20	deg
1		MercuryTest	ALLE	20	deg
	63	Orion	ALLE	31	deg
	37	Dragon	ALLE	22	deg
	35	CST-100	ALLE	30	deg
	32	Composite Crew Capsule	ALLE	24	deg
	132	Soyuz	ALLE	10	deg
	1	Mercury	ALLE	20	deg

Figure 5.24 – Example Parameter Estimation Artificial Design Intelligence Query



Vehicle Systen Analysis

Analysis Name	MercuryTest	1
Author	Eric	
Project	Haney Dissertation	
Associated Vehicle Type	Non-Lifting Reentry Vehicle	

Variable Selection

aisp		SPECIFIC IMPULSE
AISTR	kg/m^2	structural industry capability factor
AKCRW	m^3/person	crew member specific volume
AKSYS	[]	systems weight correlation factor
AKVS	[]	system volume coefficient
AKVV	[]	void volume coefficient
AKW	[]	wetted to planform area ratio
ALLE	deg	Sweep

Reference Vehicles (optional)

AFE	Aerobraking Orbital Transfer Vehicle
AMOOS	Aerobraking Orbital Transfer Vehicle
AMRS	Aerobraking Orbital Transfer Vehicle
BLTV:92	Aerobraking Orbital Transfer Vehicle
BMEV:91	Aerobraking Orbital Transfer Vehicle
BMTV:91	Aerobraking Orbital Transfer Vehicle

Deliverable Template

Export File Name

☑ Include Derived Analyses

☑ Generate Suggested Deliverables

Figure 5.25 – Deliverable Suggestion Artificial Design Intelligence Feature

The *Deliverable Suggestion* ADI feature uses the DES's stored library of deliverables to identify those deliverables that have been used for similar system types or to support similar decision domains as the current analysis – i.e. how did the forecasting engineers of the Space Shuttle communicate the comparison between capsules and lifting bodies? Which metrics were used to justify the development of past supersonic transport aircraft? Tapping into this stored experience allows the forecasting engineer to learn from the victories, and the mistakes, of previous efforts to communicate information to decision-makers.

5.8 CONTRIBUTION SUMMARY

The following items have been completed in this chapter that provides a contribution to the dissertation research topic:

- Aerospace synthesis was introduced as a necessary component of design and forecasting environments. Existing best-in-class and representative synthesis systems are reviewed with a focus on their integration of *Data-Engineering* coverage.
- The AVD design forecasting environment is detailed and serves as the starting point for the implementation of a prototype *Data-Engineering* support system.
- Development of a software platform that incorporates *Data-Engineering* principles into conceptual design and managerial support tasks.
- Standardized I / O structure and configuration between MS Access *Data-Engineering System* and MATLAB AVD Sizing parametric analysis environment.
- Introduced *Artificial Design Intelligence* features that capitalize on the inherent standardization and availability of data across *Data-Engineering* tasks within the MS Access *Data-Engineering System*.

REFERENCES

[259] Choi, S., Alonso, J., and Kroo, I., “Two-Level Multifidelity Design Optimization Studies for Supersonic Jets,” AIAA Journal of Aircraft, 2009.

[260] Roskam, J. Anematt, W. “AAA (Advanced Aircraft Analysis): A user-friendly Approach to Preliminary Aircraft Design,” ICAS-90-2.10.2, ICAS, 1991.

[261] Lavelle, T., and Curlett, B., "Graphical User Interface for the NASA FLOPS Aircraft Performance and Sizing Code," NASA Lewis Research Center, NASA TM 106649, 1995.

[262] Strohmeyer, D., and Seubert, R., "Improvement of a Preliminary Design and Optimization Program for the Evaluation of Future Aircraft Projects," AIAA Symposium on Multidisciplinary Analysis and Optimization, AIAA 1998-4828, 1998.

[263] Raymer, D., "RDWwin: Integrated Windows Software for Aircraft Design, Analysis & Optimization," www.aircraftdesign.com, 2012.

[264] Coleman, G., "Aircraft Conceptual Design - an Adaptable Parametric Sizing Methodology," University of Texas at Arlington, 2010.

[265] Chudoba, B., Coleman, G.J., Smith, H., and Cook, M.V., “Generic Stability and Control for Aerospace Flight Vehicle Conceptual Design,” No. 1132, Vol. 112, The Aeronautical Journal, June 2008.

[266] Chudoba, B., Coleman, Czysz, P.A., and Butler, C.M., “Feasibility Study of a Supersonic Business Jet Based on the Learjet Airframe,” No. 1146, Vol. 113, The Aeronautical Journal, August 2009.

[267] Omorogbon, A., “An Integration of a Modern Flight Control System Design Technique into a Conceptual Design Stability and Controls Tool, AeroMech,” Master Thesis – University of Texas at Arlington, August 2010.

[268] Chudoba, B., Coleman, G., Oza, A., Gonzalez, A., Czysz, P., “Solution-Space Screening of a Hypersonic Endurance Demonstrator,” NASA CR-2012-217774, August 2012.

[269] Chudoba, B. Coleman, G., Oza, A., Gonzalez, L., Haney, E., Ricketts, V. and Czysz, P., “Manned GEO Servicing (MGS) Crew Return Vehicle Sizing,” Final Contract Report, National Institute of Aerospace (NIA), NASA LaRC and DARPA, Section in Final Report “Manned Geosynchronous Earth Orbit (GEO) Servicing (MGS) Joint NASA/DARPA Study,” NASA SP-2012-598, MGS Study Team, NASA Headquarters and DARPA Tactical Technology Office, Washington, DC, 27 April 2011.

[270] Chudoba, B., Haney, E., Gonzalez, L., Omoragbon, A., and Oza, A., “Strategic Forecasting in Uncertain Environments: Hypersonic Cruise Vehicle Research and Development Case Study,” Royal Aeronautical Society Aeronautical Journal, Vol. 119, No. 1211, 2015.

[271] Chudoba, B., Coleman, G., Oza, A., Gonzalez, L., and Czysz, P., “Solution-Space Screening of a Hypersonic Endurance Demonstrator,” NASA CR-2012-217774, 2012.

[272] Pirello, C.J., and Czysz, P., “Hypersonic Research Facilities Study: Research Requirements Analysis and Facility Potential,” Volume 4, Part3, Phase III Final Studies, NASA CR-114329, 1970.

[273] Chudoba, B., “Stability and Control of Conventional and Unconventional Aircraft Configurations: A Generic Approach,” Cranfield University Dissertation, 2001.

[274] Watters, B., “Adaptation of Digital DATCOM into a Conceptual Design Process,” The University of Texas at Arlington, 2011.

[275] Mansouri, R., “Structural Analysis at Aircraft Conceptual Design Stage,” The University of Texas at Arlington, 2014.

[276] Walker, A., “Development of a Conceptual Flight Vehicle Design Weight Estimation Method Library and Documentation,” The University of Texas at Arlington, 2014.

[277] “FORTRAN 77 4.0 Reference Manual,” Sun MicroSystems, 1995.

[278] “MATLAB Documentation” MathWorks, 2015.
URL: http://www.mathworks.com/help/matlab/

[279] Peng, X., “Formalization of the Engineering Science Discipline – Knowledge Engineering,” University of Texas at Arlington Dissertation, 2015.

CHAPTER 6

VALIDATION & CALIBRATION CASE STUDY: RE-ENTRY CAPSULE SOLUTION SPACE

CHAPTER 1 Introduction
Discussion of the realities of aerospace design & forecasting, specifically the need for standardized processes and tools to support data-engineering.

CHAPTER 2 Introduction to Information & Information Systems
Review of decision-making standards and data standards, including historical evolution of the technologization of data ending with modern data platforms.

CHAPTER 3 Aerospace Data & Data Systems
Examination of existing best practices and research in aerospace data-engineering. Also addresses the common formats and mediums of aerospace data.

CHAPTER 4 Specification of an Aerospace Forecasting Data-Engineering System
Review of current approaches in aerospace design & forecasting. Definition of the feature and interface requirements of a functional aerospace data-engineering system.

CHAPTER 5 Development of an Aerospace Forecasting Data-Engineering System
Layout of data-engineering software system from a development perspective. Standardization and interface with parametric analysis processes emphasized.

CHAPTER 6 Validation & Calibration Case Study
Application of data-engineering system to a historical re-entry capsule design study where desired results are known a priori, including examination of system and engineer performance.

CHAPTER 7 Aerospace Design & Forecasting Case Studies
Three case with applications across a range of aerospace forecasting problems, utilizing different aspects of the developed data-engineering system, and intended for diverse decision-making goals.

CHAPTER 8 Summary & Conclusions
Parting thoughts on the state of aerospace design & forecasting, aerospace data & information science, and future potential of data-engineering systems.

Portions of the work presented in this section have been presented at the American Society for Engineering Education Gulf Southwest Conference [280].

Results presented in Section 6.1.2 were developed as part of a team effort for graduate coursework at the University of Texas at Arlington during the Fall 2012 semester. The author was acting Chief Engineer and performed all capsule integration and sizing analysis for all presented results in Section 6.1.2. All other sections are original material.

Individuals Contributing (through Section 6.1.2): Lex Gonzalez, Amen Omoragbon, Doug Coley, Vincent Ricketts, Jon Crosley, Daniel Garcia, Amit Lalloobhai, Andy Walker, Thomas McCall, Xiao Peng, Tsung-yueh Chiang, Hung-chieh Wang

The previous chapter has detailed the derivation and development of a prototype Data-Engineering System, complete with user-interfaces intended to improve the efficiency and effectiveness of aerospace information production tasks. However, per the research charter laid out at the beginning of this dissertation, this approach must be tested experimentally before these hypothesis are verified. This chapter, then, proposes to create a controlled test of the prototype DES. The following subsections will outline the experimental design, underlying research and assumptions, and, finally, experimental test results. Comparison is detailed between a control group executed without any structured DES features and an experimental group with all prototype DES components functioning.

6.1.1 Experimental Test Definition

The experiment will, fundamentally, apply two separate data-engineering approaches to the same aerospace forecasting task with consistent metrics used to assess the performance of each approach. The first approach will be a control group that includes rudimentary data processes in place, meant to emulate the forecasting standard practices. The second, experimental group, approach will make use of the prototype Data-Engineering System developed for the current research. The forecasting task will require the use of both Data domain and Analysis domain processes – inclusion of Knowledge domain processes is supplemented where possible.

The following subsections will outline the details of the experiment, the characteristics of both the control group and the test group, and the hypotheses of the expected results.

6.1.1.1 Decision-Making Problem Statement

The forecasting task at hand is to assess the viability of the competing Mercury and Vostok re-entry capsule designs from the perspective of US aerospace forecasting organizations in the early 1950's. By re-engineering the prospective designs being considered at the time, this effort seeks to understand the systems-level decisions that were made early in the design cycle.

Both the Mercury and Vostok capsules are designed to support short-duration (hours to a few days mission length) Low Earth Orbit (LEO) missions with a single crew member. Both programs were used as stepping stones towards more ambitious orbital and extra-orbital missions, as well as providing an opportunity to grow technical, industrial and operational proficiency[280]. The capabilities of existing launch vehicles plays a substantial part in the available capsule designs and must be considered – both sides considered development of new launch vehicles to be time-prohibitive in an effort to be first to complete orbital operation.

From the perspective of US decision-makers, the analysis should provide an assessment of the Vostok capsule and how it relates to the Mercury capsule in terms of mission performance. The assessment should also include what underlying requirements or constraints are keeping the US from executing alternative Russian designs, if any. Due to this design exercise mirroring a quick-turn Situational Assessment of the design space, analysis efficiency will be prioritized over accuracy of detailed disciplinary analysis.

6.1.1.2 Determine Resources

The amount of data available, currently, about both the Vostok and Mercury capsule designs is relatively substantial. Several historical books and technical reports[282]-[300] have been produced characterizing the detailed designs of each system. The decision-making problem statement is primarily focused on the high-level viability of the design concepts (as opposed to detailed disciplinary analysis or sub-system design), and therefore some level of uncertainty is acceptable as long as the model results and sensitivities are correct.

6.1.1.3 Identify Options

The primary options available for capsule design are a blunted conical frustum geometry (Mercury) and a spherical capsule design (Vostok). Both the US and Soviet designers had inherent launch vehicle capabilities – which will be shown to be significant drivers in capsule design – that restrict overall capsule weight and size. While other design configurations are possible for reentry capsules, these two options provide distinct points with the overall solution space.

As a point of deviation, the test group will introduce another alternative Soviet design – this one being a rounded bell shape – to represent an early incarnation of the later Soyuz capsule. From the reverse-engineering perspective, introduction of this alternative design represents a leaked intelligence report of an engineering document or reports of a prototype. From the experimental perspective, inclusion of an additional design alternative is introduced in the test group to show the capabilities of the DES to highlight design concepts and generate multiple parallel analyses.

6.1.1.4 Establish Information Requirements

The analysis outputs should answer the following questions:

- Assuming 1950's technical capability, is the Mercury design point a converged design that does not violate operational constraints?
- Which constraints influenced the Mercury design and to what extent did they influence the design selection?
- Assuming static 1950's technical capability, is the Vostok design point a converged design that does not violate operational constraints?
- If the US team had desired the Vostok design concept, would it have been possible with existing operational constraints?

It should be noted that these informational queries are not overly technical in nature (i.e. as opposed to a request for the detailed aero-thermochemical environment on the leeward edge of the capsule during reentry). Therefore, the analyses should require the least possible complexity in order to answer the above questions – additional analysis complexity only serves to increase the overhead resources required for information generation, while not increasing the value of the information. The diameter and weight of the capsule are sufficient to impose launch vehicle constraints, and only slight more characteristics must be generated to allow for an assessment of the vehicle during re-entry

6.1.1.5 Control Group

The control group is executed by a collaborative team of graduate-level aerospace engineers, of which the author is one member, within the context of a space system design course. The collection, storage and organization of supporting documents, as well as the derivation of analysis methods is left to individual engineers, with integration left to a chief engineer. Formatting of analysis methods has been standardized to the extent of programming language and general input / output structure, but no other formatting restrictions have been put in place. There is no formal DES structure in place.

6.1.1.6 Test Group

The test group is executed solely by the author utilizing the prototype DES operating with full Data domain features, automated integration with the AVD Sizing Analysis domain, and design intelligence feedback components available. This experimental system will answer the same high-level decision-making problem statement, but may not necessarily recreate exact results – the control group does not represent the truth, but a baseline process against which to measure relative performance.

6.1.1.7 Experiment Hypothesis

The expected experimental outcome is highlighted by two key items, below.

Hypothesis #1:

Implementing a structured DES will reduce the time resources required to execute an aerospace forecasting task

Hypothesis #1 is the byproduct of the additional structure and standardization created by the formal DES environment. Layers of automation and codified best-practices allows the forecasting engineer to focus on collecting data, assessing the system design and communicating results towards the decision-maker. Mechanical operations that require significant resources, but do not necessarily add informational value have been relegated to automated functions – i.e. handing the engineer a calculator instead of a slide-rule.

Hypothesis #2:

Implementing a structured DES will increase the information quality produced during an aerospace forecasting task

Hypothesis #2 infers that the compounding nature of the DES will allow additional insights to be gained – each forecasting task does not exist in a vacuum, but is at the pinnacle of all organizational efforts before it. Although organizational experience is being artificially introduced through the manual addition of an alternative vehicle design with this experiment, an operational DES would have the full complement of organizational experience at its disposal. Due to the collective nature of the DES, there is an inherent ability to autonomously identify alternative designs, reference vehicle systems, methods of analysis, and decision-making deliverables. The intelligent feedback features within the DES automate these cross-correlation functions to force the forecasting engineer to consider alternative approaches to both the system design and analysis of the system.

6.1.2 Control Group Experiment

The following subsections detail the set-up and results of the control group – operating without implementation of a formal DES. Primary research and methodology that is common between the control group and test group is identified here, and not repeated with the test group documentation.

6.1.2.1 Retrieve / Create Information

Project Mercury was formally initiated in 1958 by the *Congressional Panel for Manned Space Flight* which required the following characteristics of the space system (emphasis by the author) –

> I. OBJECTIVES
> The objectives of the project are to achieve at the ***earliest practicable date orbital flight*** and successful recovery of a manned satellite, and to investigate the capabilities of man in this environment.
>
> II. MISSION
> To accomplish these objectives, the most ***reliable available boost system*** will be used. A nearly circular orbit will be established at an altitude sufficiently high to permit a 24-hour satellite lifetime; however, the number of orbital cycles is arbitrary. Descent from orbit will be initiated by the application of retro-thrust. Parachutes will be deployed after the vehicle has been slowed down by aerodynamic drag, and recovery on land or water will be possible.
>
> III. CONFIGURATION
> A. Vehicle
> The vehicle will be a ***ballistic capsule with high aerodynamic drag***. It should be statically stable over the Mach number range corresponding to flight within the atmosphere. Structurally, the capsule will be designed to ***withstand any combination of acceleration, heat loads, and aerodynamic force***s that might occur during boost and reentry of successful or aborted missions.
> …
>
> D. Retrograde System
> The retro-rocket system will supply sufficient impulse to permit atmospheric entry in less than 1⁄2 revolution after application of retro-thrust. The magnitude and direction of the retro-thrust will be predetermined on the basis of allowable declarations and heating within the atmosphere, and miss distance.
> …

Design Reference Mission

The design concept of operations, shown below in Figure 6.1, is described by A-B) launch a staged expendable rocket booster, C-D) detach the manned vehicle portion from the launch vehicle, E) execute one or more Low Earth Orbit (LEO) circuits, F-G) re-enter the atmosphere by decelerating aerodynamically, and H-K) land back on the Earth’s surface. All vehicle alternatives considered in both the control and experimental cases will operate according to this same design mission.

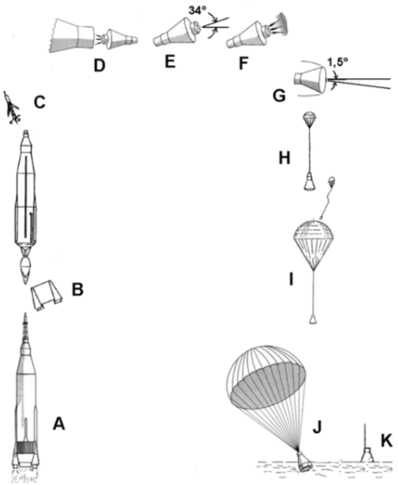


Figure 6.1 – Mercury Reference Mission Diagram[282]

Operational Constraints

Capsule design is driven largely by technical and operational constraints – see Table 6.1. Human limits on maximum sustainable forces constrains vehicle and mission designs to ensure atmospheric deceleration happens safely. Material capabilities also influence the available re-entry profiles by limiting the maximum peak energy absorption the vehicles thermal protection system (TPS) can withstand.

Table 6.1 – Reentry Capsule Constraints

Constraint Variable	*Value*	*Reason*
Longitudinal Acceleration	11 g	Maximum tolerable amount for astronaut
Maximum Heating Rate	300 W/cm^2	Approximate max. for ablative TPS of era
Capsule Diameter	1.78 m	Atlas max. payload diameter
	2.56 m	Vostok max. payload diameter
Orbital Mass	1400 kg	Atlas max. orbital mass [LEO]
	4400 kg	Vostok max. orbital mass [LEO]

Of particular note in this series of design studies is the influence of existing launch vehicle capabilities on capsule design space. Both the United States and Soviet governments had developed substantial Intercontinental Ballistic Missile (ICBM) systems, which were direct inspirations for the eventual launch vehicle systems. Launch vehicle limitations on size and weight do not restrict capsule designs that are independently feasible – i.e. it is possible to converge larger designs following the same configuration and operation, but these were not feasible at the time due to existing launch vehicle constraints. Relaxation of these constraints, by developing larger more capable launch vehicles, was the long term strategy. However quickness to market was a significant program driver, as outlined in the Congressional charter in the above section.

Table 6.2 – Constraining Characteristics of Launch Vehicles under Consideration

Launch Vehicle	*Maximum Diameter*	*Gross Weight to LEO*
Atlas (US)	1.9 m	1400 kg
Vostok (Soviet)	2.5 m	2700 kg

Identified Design Alternatives

Two design alternatives are considered within the control group: a blunted conical frustrum geometry (Mercury), and a spherical geometry (Vostok) – see Figure 6.2 and Figure 6.3. Although the design mission is held constant between these concepts, it is necessary to distinguish the weight and aerodynamic characteristics of each approach to understand the total system impacts of each configuration. The blunted Mercury design offers increased aerodynamic lift during reentry (which decreases maximum heating loads and normal forces). Comparatively, the spherical Vostok is a simpler design which requires increased TPS weight due to its symmetric geometry. Within these analyses, launch vehicles are considered as constraints on capsule size and weight and not as independent design considerations. This philosophy matches the realities of the time to operationalize a capsule design as quickly as possible.

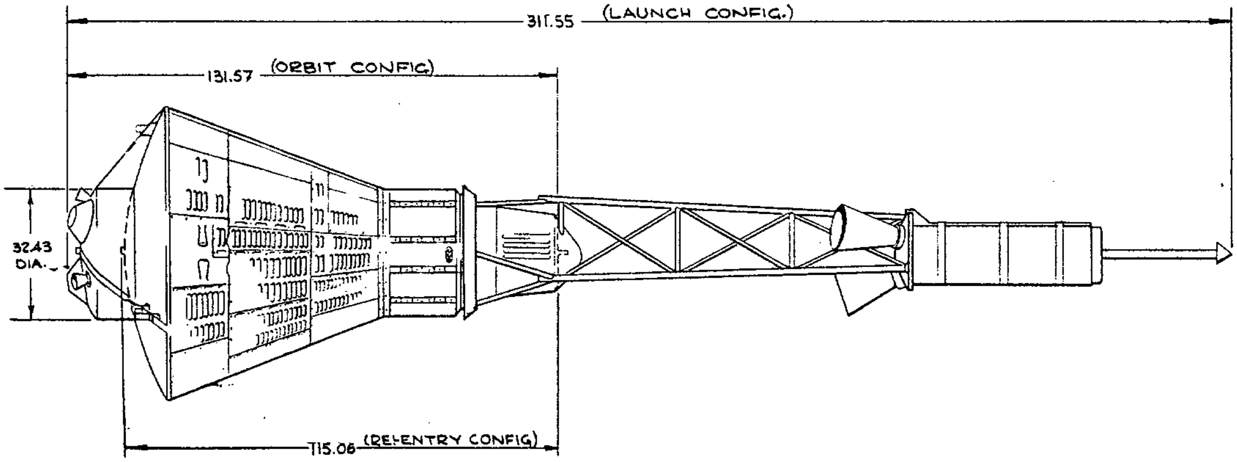


Figure 6.2 – Mercury Capsule Design

Multi-Disciplinary Analysis Definition

The multi-disciplinary analysis (MDA) approach chosen will dictate the number of analysis methods required, the interaction between design variables, and will generally dictate the information available for visualization and communication to the decision-maker. During conceptual design tasks (or even earlier in the design cycle), analyses are often predicated on generating a solution space around the proposed design – i.e. design parameters are specified as independent variables across a range of plausible values, with operational constraint boundaries used to dissect design combinations that are realistically feasible. The selection of independent design parameter must both have sufficiently sensitivity within the model and make sense within the context of the study.

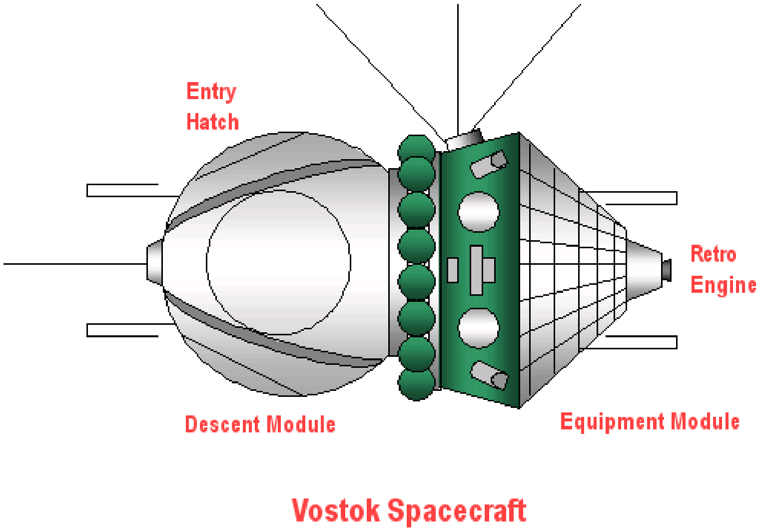


Figure 6.3 – Vostok Capsule Design

Figure 6.4, below, shows the MDA instituted for all current capsule system analyses with the mission definition being a constant across all scenarios. The amount of volume allocated for the astronaut has been selected as the independent design variable – as the volume increases, so does the size and weight of the capsule. Increasing size has the impact of alleviating re-entry constraints but intensifying launch vehicle constraints.

Within the capsule sizing, an internal convergence loop is required because the series of relationships that defines the MDA is not a determinate system – i.e. cannot be solved explicitly. Therefore, an initial estimate of solution must be taken as a starting point. The methodology iterates through vehicle size estimates until the input matches the output – the vehicle has reached a converged solution point.

Analysis Method Selection

The following methods were selected for a parametric analysis of the Mercury & Vostok capsule solution spaces.

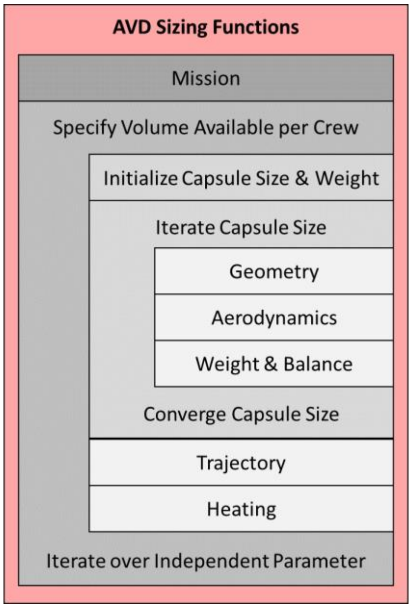


Figure 6.4 – Capsule Multi-Disciplinary Analysis Methodology

Table 6.3 – Method Summary for Re-entry Capsule Sizing

Discipline	*Method*	*Description*	*References*
Geometry	Analytical Capsule Geometry	Scaling of defined capsule configuration based on convergence variables.	Derived
Aerodynamics	Empirical Capsule Aerodynamics	Flight configuration-dependent lookup of aerodynamic characteristics. Based on existing historical data.	[305]
Weight & Balance	Hypersonic Convergence	Empirical weight and volume estimation of structure, systems, payload and propellant.	[302][303][304]
Trajectory	2D Re-entry	Time-integrated trajectory assuming only planar motion described by altitude, range, and velocity.	Derived
Heating	Fay & Riddell	Analytical nose point heating rate calculation assuming spherical body.	[301]

Geometry

The Mercury capsule geometry is described as a spherically-capped conical frustrum with a small cylinder extending from the top. This basic geometric shape is assumed to remain constant for all vehicle designs considered. The top adapter diameter is a fixed dimension and the ratio of total capsule diameter to nose radius is taken as a constant. With these assumptions, the geometry of the capsule can be described by knowing only the planform area (an input variable) – see Table 6.4.

The alternative Vostok geometry is also described analytically to match the same I / O structure. Before re-entry, the Vostok capsule sheds its asymmetric service module after the retro-rocket is fired, becoming a sphere during the reentry portion of the mission. Like Mercury, the planform area is sufficient to describe the Vostok geometry.

Table 6.4 – Primary I/O Variables for Capsule Geometry Analysis

Input Variables	*Output Variables*
Planform Area	Volume Wetted Area Volumetric Efficiency

Aerodynamics

Both the Mercury and Vostok capsule configurations were studied in great detail during the design phase of Project Mercury; therefore extensive wind tunnel data is available throughout the relevant Mach number range. In order to reduce the complexity and run time of the sizing program, the aerodynamic lift and drag coefficients as a function of Mach number and angle of attack are implemented as an empirical method directly from the experimental results (Table 6.5). Using actual vehicle aerodynamic data reduces the generic quality of the method, but this approach is simple to implement and allows for modularity between vehicles with similarly explored aerodynamic characteristics.

Table 6.5 – Primary I/O Variables for Capsule Aerodynamic Analysis

Input Variables	*Output Variables*
Mach	Drag Coefficient
Angle of Attack	Lift Coefficient

Trajectory

The in-orbit changes in velocity (ΔV's) for insertion and de-orbit are modeled as instantaneous changes in velocity that are accompanied by losses in mass (fuel burn and/or propulsion element jettison). Because of this assumption, a propulsion disciplinary method is not needed for the capsules. Only technology-related values for retro-rocket performance and weight are required in the input file.

The trajectory for the entire flight envelope is reduced to a 2-D, time-integrated series of equations. Because of the mission profile (no change of orbital plane) and the ballistic re-entry (no lift), the assumption is made that the trajectory can be adequately described by the altitude, range, velocity, flight path angle, and time. Integration is carried out numerically with a Runge-Kutta differential equation solution technique. The integration method requires drag coefficient from aerodynamics, thrust from propulsion, and weight history from weight & balance inputs, as well atmospheric and gravity models as a function of altitude, see Table 6.6.

The capsule trajectory is initialized from a design orbit and a specified retro-burn. This inserts the capsule into a re-entry trajectory. Both Mercury and Vostok missions have ballistic re-entry trajectories with a fixed zero degrees angle of attack. For sizing purposes, only the re-entry portion through the upper atmosphere is critical. Parachute deployment and landing is modeled as step changes in aerodynamic methods (calculation of drag coefficient), but is done only for completeness and parachute sizing. The landing flight phase does not produce any design-driving parameters for the capsule.

Table 6.6 – Primary I/O Variables for Capsule Trajectory Analysis

Input Variables	*Output Variables*
Initial State	Range
Propulsion Schedule	Altitude
Parachute Schedule	Velocity
Drag Coefficient	Time
Lift Coefficient	

Heating

Heating analysis is only performed for the capsule during the reentry phase of the mission on the capsule nose, where heating is highest. All other combinations of vehicle elements and mission phase are considered non-critical. Values for the heating rate are obtained by utilizing a semi-empirical engineering relation for stagnation-point heat transfer rate on a sphere developed by Fay and Riddell[301]. The inputs required are the geometry (nose radius) and the trajectory (velocity, density). Both the Mercury and Vostok capsules have spherical heat shields, therefore the method is directly applicable with the definition of the nose radius solved for in the respective geometry modules.

Table 6.7 – Primary I/O Variables for Capsule Geometry Analysis

Input Variables	*Output Variables*
Emissivity	Heating Rate
Nose Radius	Heat Load
Altitude	
Velocity	

Weight & Balance

Capsule weight is determined by using a weight and volume budget methodology from Hypersonic Convergence[302][303][304]. The methodology is generic in its formulation, and suited for a large range of supersonic and hypersonic vehicles. Because the re-entry capsule does not require weight and volume allocations for propulsion elements, the required variables to drive the method have been reduced to those shown below in Table 6.8. Each component of weight and volume is calculated using a combination of non-dimensional correlation factors and fixed values (i.e. Void Volume is specified in the input file as a fixed percentage of total vehicle volume, Crew Volume is input as a fixed, dimensioned design variable). This allows the weights and volumes to be divided between subsystems that are independent of the vehicle size and those that are dependent on the vehicle size.

Table 6.8 – Capsule Weight Method Variables of Merit

Variable	*Description*
WSTR	Structure Weight
WOPER	Operational Weight
WSYS	Systems Weight
WMARGIN	Empty Weight Margin
OEW_W	Empty Weight from Weight Budget
V_SYS	Systems Volume
V_PAY	Payload Volume
V_CREW	Crew Volume
V_VOID	Void Volume
OEW_V	Empty Weight from Volume Budget

Multi-Disciplinary Analysis Approach Validation

Generation of a parametric capsule solution requires the convergence of a family of design capsules utilization the same analysis methods. It is imperative, then, that analysis methodology reproduce known design point solutions when given inputs coinciding with the actual vehicle, whose characteristics are also known. If the results are sufficiently in agreement, the assumption can be made that other converged vehicle points away from the historical design point are valid and plausible vehicle designs.

When the primary independent design variable (volume allotted per crew member) is set at the historical value, the implemented MDA generates results within 10% of documented historical values for vehicle weight and geometry characteristics, see Table 6.9. Particularly, the overall gross weight of the vehicle is estimated at less than 1% error from the actual value. Additionally, when the configuration geometry calculated by the converged series of parametric equations is overlaid with the actual Mercury capsule mold line (Figure 6.5), little to no noticeable differences appear. These results are deemed sufficient validation that the MDA approach is appropriately implemented for decision-quality analysis of a capsule solution space.

6.1.2.2 Information Summary & Outcome

The above MDA is defined with the AVD Sizing parametric analysis environment, with all available vehicle data being used to form necessary input values. The volume allotted for the crew member is chosen as the independent design variable to drive capsule design points to grow or contract based on the input. The resulting solution space, shown below in Figure 6.6, is formed by a series of points representing a converged vehicle design that, without external constraints, could be feasibly be developed. On top of this family of possible Mercury capsules, the launch capabilities and re-entry performance requirements have been overlaid to determine the design concepts that were both feasible independently, as well as dependent on the operating realities of the Mercury program (the green shaded portions are feasible).

Table 6.9 – Mercury Capsule Design Point Validation

	Variable	*Sizing*	*Actual*	*Units*	*%Error*
Takeoff Gross Weight	TOGW	1241.6	1237.202	kg	-0.36%
Structure Weight	WSTR	422.21	409.78	kg	-3.03%
Systems Weight	WSYS	432.56	445	kg	2.80%
Propulsion Weight	WP_TJ	225.03	222	kg	-1.36%
Total Volume	V_TOTAL	3.3387	3.2	m^3	-4.33%
Systems Volume	V_SYS	0.93265	0.976	m^3	4.44%
Planform Area	SPLN	3.0531	2.81	m^2	-8.65%
Wetted Area	SWET	14.232	13.8	m^2	-3.13%
Capsule Diameter	DC	1.9716	1.8923	m	-4.19%

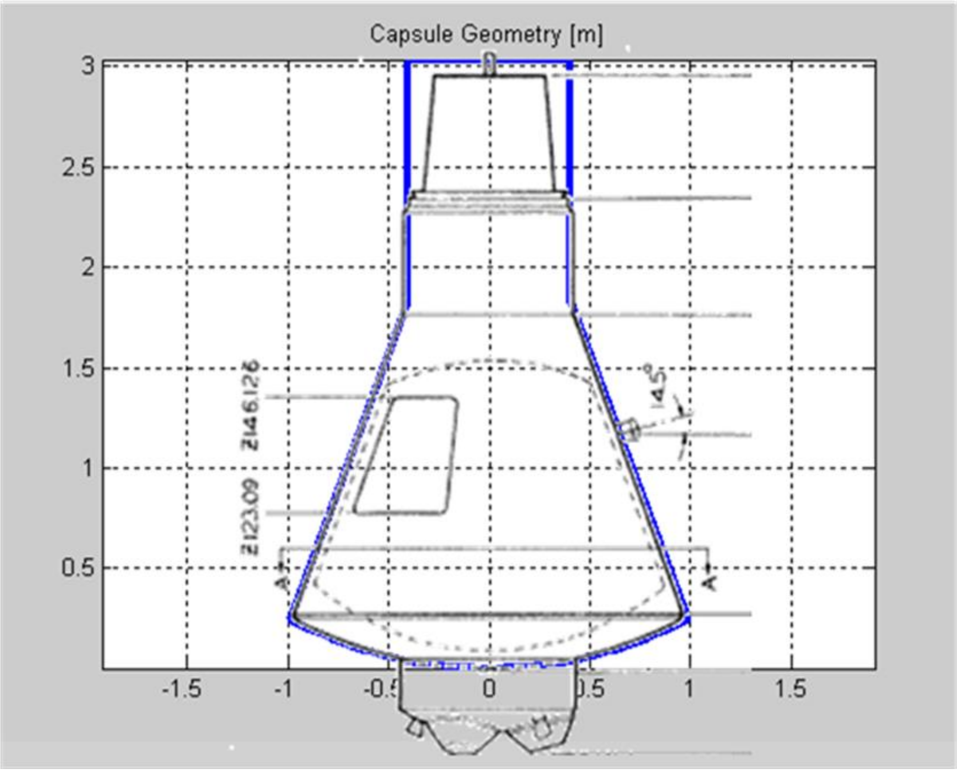


Figure 6.5 – Design Point Geometry Overlaid on Mercury Mold Line

The starting volume value of 1 m^3 is a rough estimate of the minimum volume an astronaut-sized human requires. As volume increases, the size and weight increases as expected. When the Atlas booster constraints are overlaid on the capsule results, it can be seen that the Mercury Capsule design point roughly corresponds to the widest vehicle that could fit as payload on the Atlas launcher. An adapter is required for the design point capsule with an increase in diameter of 10% over the standard payload section of Atlas. Increasing the potential adapter size past 10% would further decrease aerodynamic performance during the ascent phase, necessitating development of a more complex payload adapter system. It should be noted that the Atlas maximum payload constraint of 1,400 kg (not shown) will only allow the capsule diameter to grow to 2.2 m; this would have limited the design space even if a larger adapter could have been adequately designed.

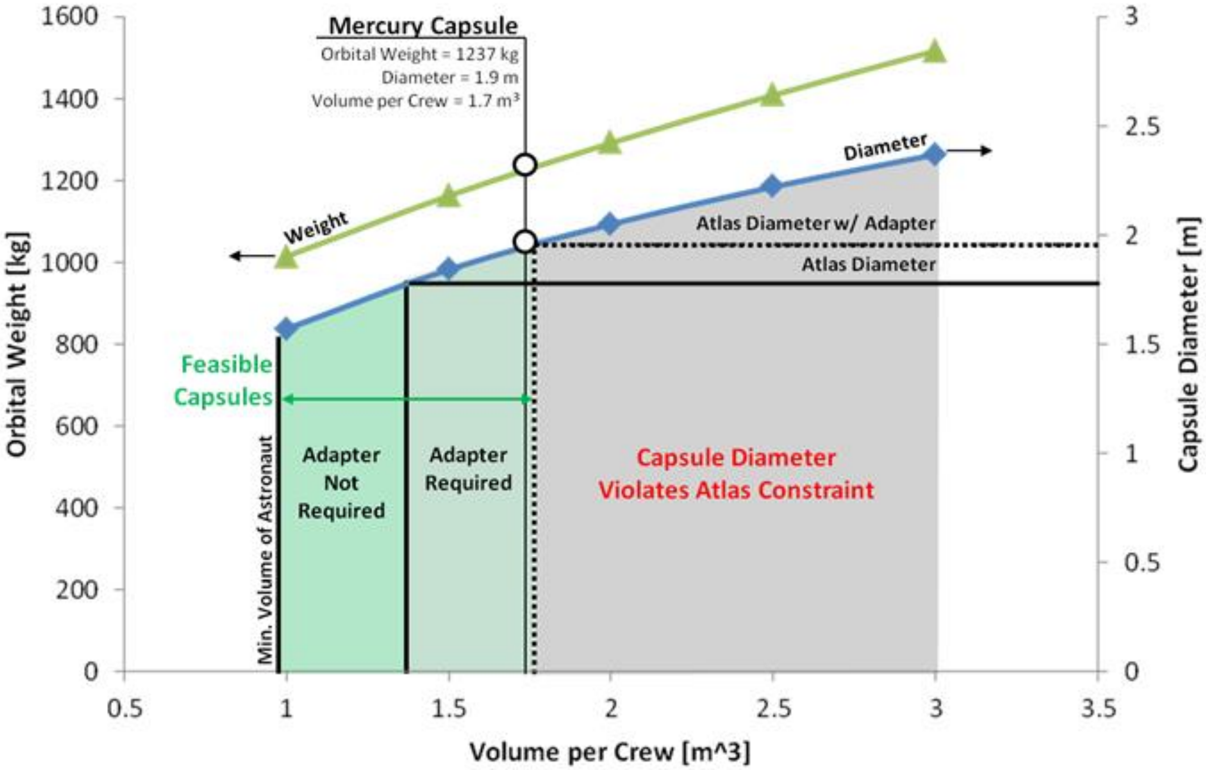


Figure 6.6 – Mercury Capsule Volume-Weight-Diameter Solution Space

Figure 6.7 shows the trend of heating rate and longitudinal acceleration as part of the same series of parametric volume analyses. The maximum heating constraint of approximately 300 W/cm^2 and the maximum loading constraint of 11 g's both appear off the top of each graph. This illustrates that the vehicle configuration choice has only a secondary effect on the aerodynamic and heating loads – the choice of design orbital altitude is the primary driver of re-entry characteristics, but is not considered in this course of analysis. Even still, the trends for the LEO-designed vehicles suggests that the largest possible capsule be selected to minimize undue stress on the thermal protection system and the astronaut.

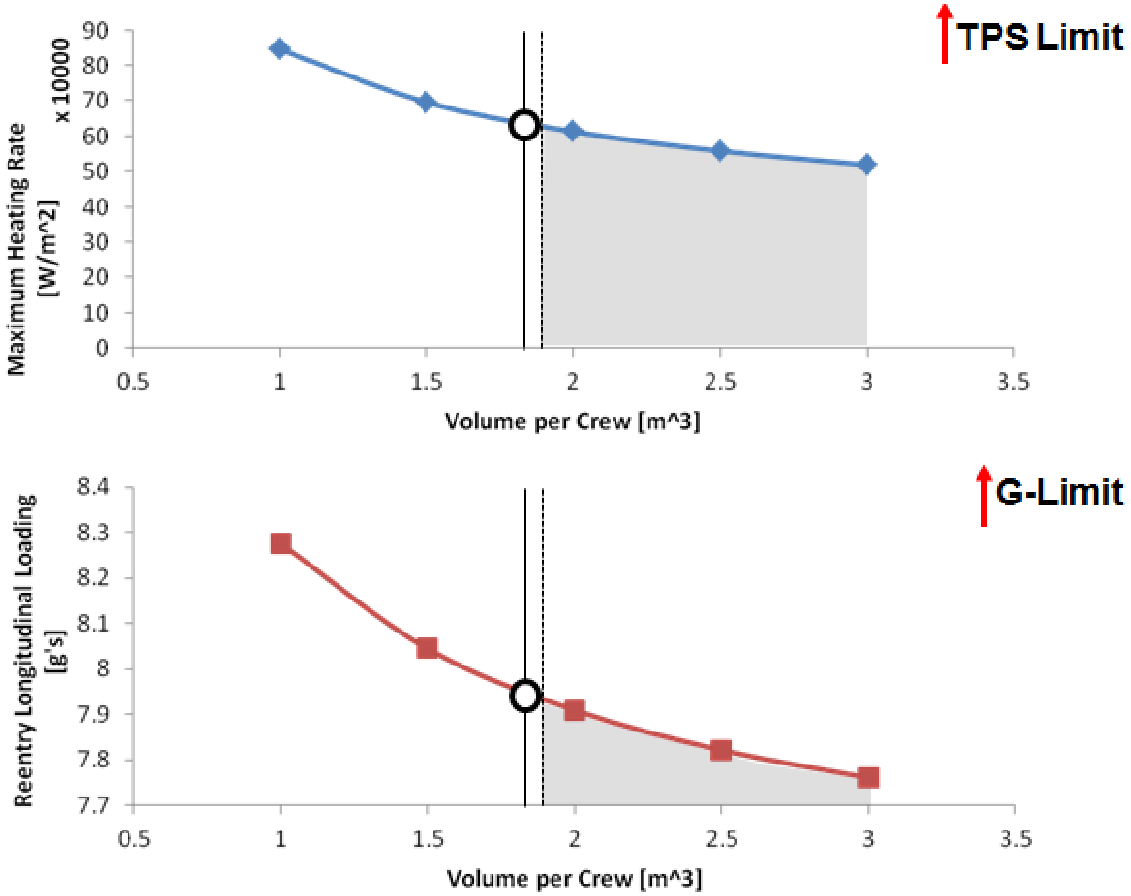


Figure 6.7 – Mercury Capsule Reentry Force Solution Space

The Vostok capsule is similarly evaluated by parametrically varying crew volume in Figure 6.8 with Soviet launch vehicle constraints overlaid. In order to compare systems of the same operational capability, the retrograde-rocket installed on the service module is modelled as a part of the manned capsule. Because of the much larger and more powerful Vostok launcher, a wider portion of the solution space is usable and the design point was able to shift a larger allowable volume within the capsule (4 m^3 Vostok vs 1.7 m^3 Mercury).

By overlaying the results of a spherical geometry with the Mercury capsule geometry design space, novel system versus system conclusions can be made, see Figure 6.9. The design space shows that with the Atlas launch capability available at the time of Project Mercury, a purely spherical capsule is not a feasible solution. While some of the spherical family of design pints are able to fit within the Atlas payload diameter, the stouter design increases weight past the maximum payload constraint of the existing booster. In general, the spherical design provides a more volumetrically efficient design, but at the cost of increased weight due to required TPS across a majority of the reentry body. Although the reentry characteristics of the spherical design, shown in Figure 6.10, are still within acceptable limits, they are significantly higher than the blunted conical design and therefore introduce more operational risk.

This analysis numerically illustrates that the US was launcher-constrained in their design possibilities at the time of Project Mercury. The diameter of the launcher is the primary constraint for a conical vehicle, while switching to a spherical design shifts the constraint to gross weight to LEO. Because the USSR had invested more heavily in a larger rocket booster system (initially for nuclear warheads), a more robust spherical capsule was possible. The US manned capsule had to be a smaller vehicle, but at the same time required to have a sufficiently large spherical forward section to handle the re-entry heating environment. This led to the Mercury spherically-capped conical frustrum configuration that maintains a wide spherical heat shield and reduces weight by decreasing useable volume within the capsule.

Responding to the original information request:

Q: Assuming static 1950’s technical capability, is the Mercury design point a converged design that does not violate operational constraints?

A: Mercury design point is proven feasible by the chosen analysis processes, see Figure 6.6.

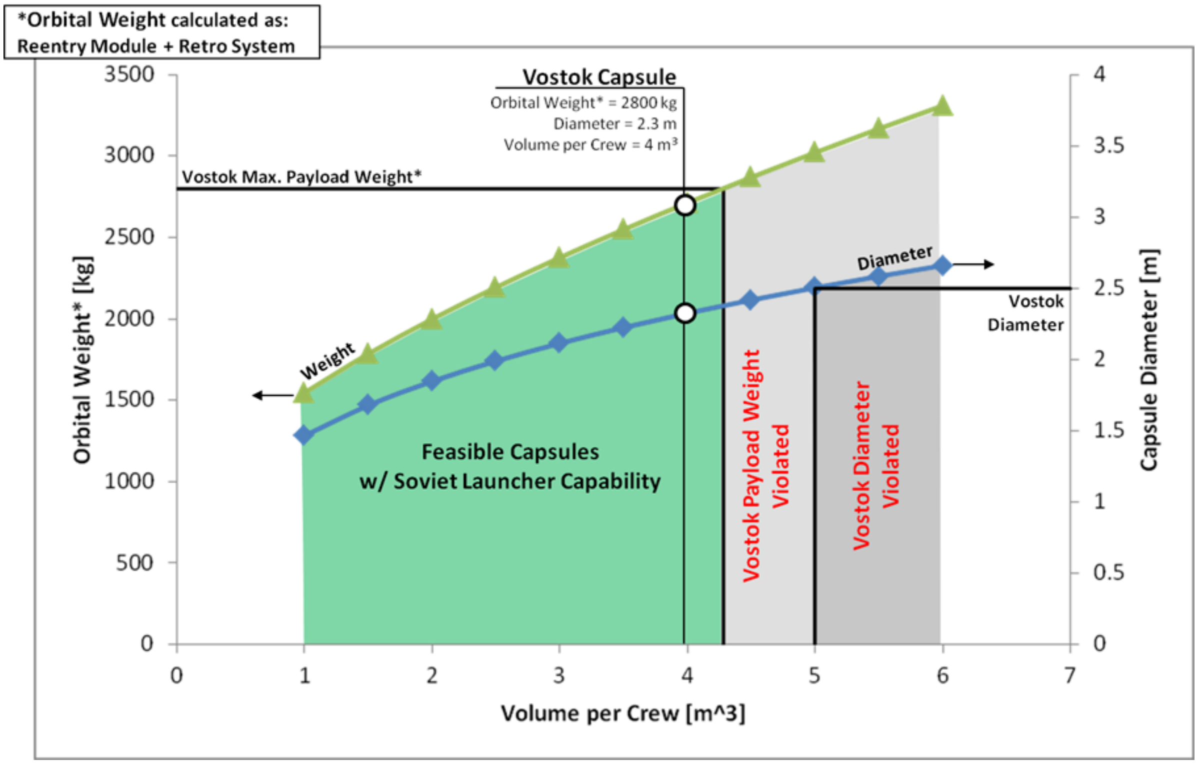


Figure 6.8 – Vostok Capsule Volume Solution Space

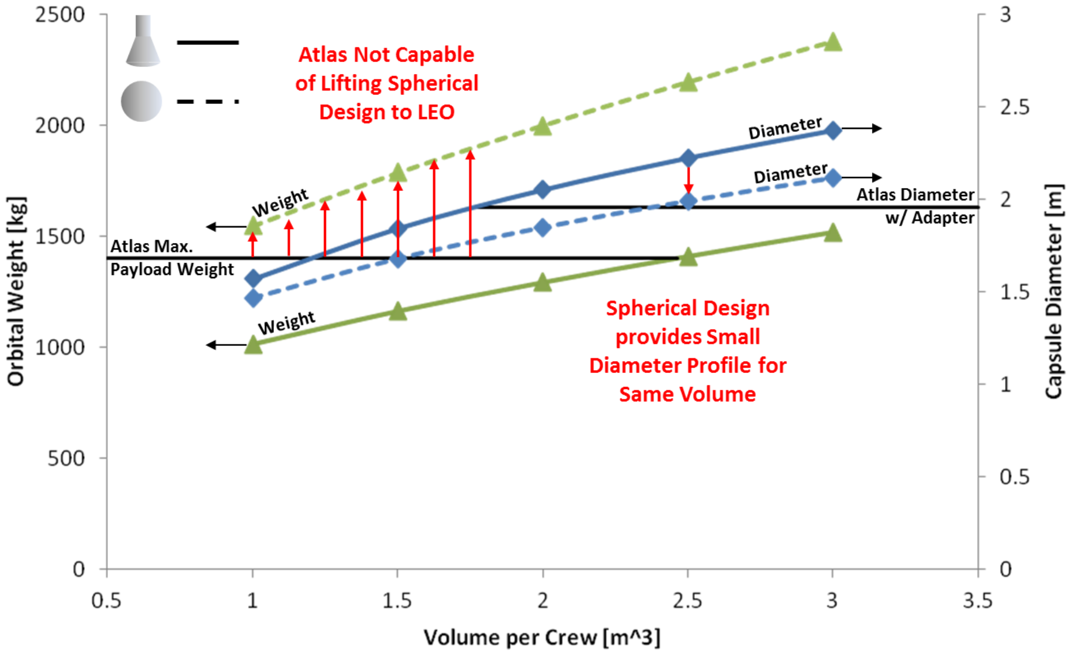


Figure 6.9 – Spherical versus Conical Design Impacts on Launch Capacity

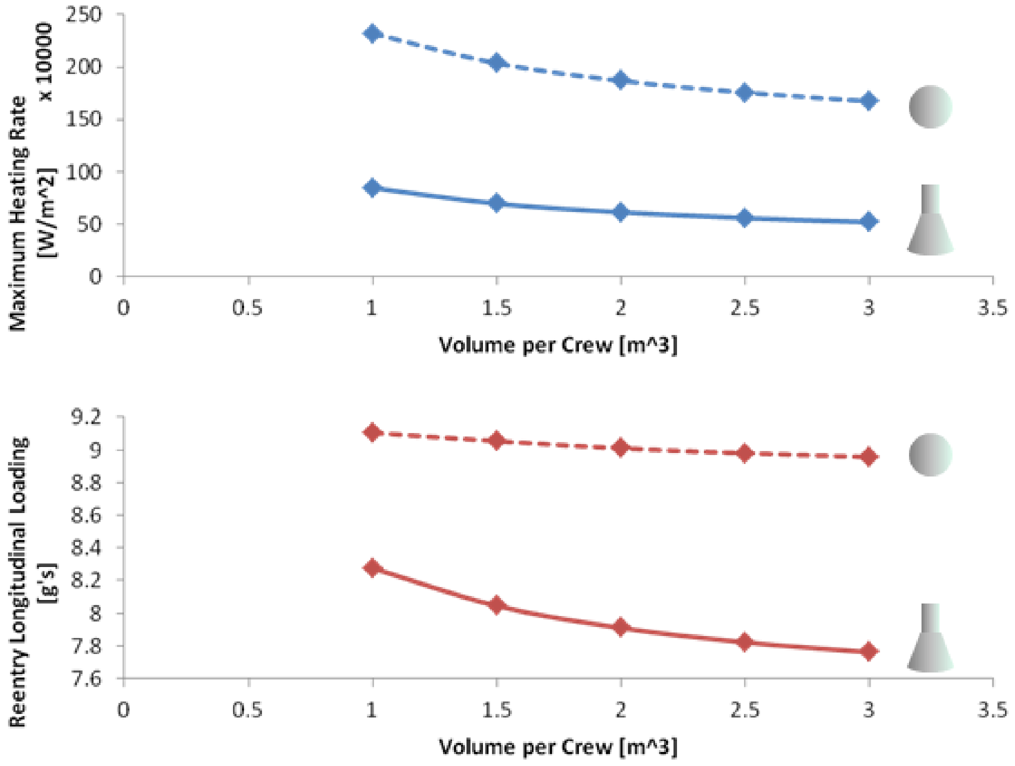


Figure 6.10 – Spherical versus Conical Design Impacts on Reentry Solution Space

Q: Which constraints influenced the Mercury design and to what extent did they influence the design selection?

A: Launch vehicle payload mass to LEO is the design constraining condition – subsequent space systems are predicated on more powerful launch vehicles.

Q: Assuming static 1950's technical capability, is the Vostok design point a converged design that does not violate operational constraints?

A: Vostok design point is proven feasible by the chosen analysis processes, see Figure 6.8.

Q: If the US team had desired the Vostok design concept, would it have been possible with existing operational constraints?

A: Vostok design concept not feasible due to Atlas payload mass constraints and minimum volume of astronaut constraint. Reentry constraints would have also been an issue in a minimum-size Vostok design with given US launch vehicle system.

6.1.2.3 Control Group Conclusion

The control group has established a relevant baseline for further comparison – decision-quality information has been produced with relatively little resources (approximately two man-weeks) and resulting deliverables can be used to demonstrably answer each of the driving information requests, as noted above.

Dissecting the amount of resources allocated to subtasks, shown in Figure 6.11, however, highlights that significant portions of time are spent on non-information-producing steps (highlighted in red). In general, these tasks are not seen as inefficiencies in from a status quo perspective – they are tasks an engineer is expected to perform in the course of a design forecasting task. However, from a purely value-added perspective, the following issues are providing waste within the forecasting processes:

- Data was collected by individual engineers in a semi-standardized format, but resources had to be constantly allocated to synthesize these sets into a collaborative database, redistribute and update.
    - Generating an AVD Sizing input file required non-value-added resources from multiple perspectives:
    - Data was collected on an individual semantic basis versus a standardized variable-list (i.e. data entered as "total vehicle weight" = X kg by one member; "gross weight" = Y kg by another member; neither specifies if this value

includes consumables, fuel, payload, etc.). Source documentation, which may or not be stored in a collective location, must be re-assessed to determine true value.

- Translation of available data to required variable inputs requires constant monitoring, additional data collection, and re-processing.
- Approximately 15 man-hours was resourced to connect analysis methods and standardize input / output structure in order to create a functioning AVD Sizing executable.

While the above resource-allocation inefficiencies are stated as known issues, there are several unknown risks to information quality due to manual processes (e.g. only those data items generated for this forecasting task are considering during analysis; no other alternatives considered). There are data points (i.e. other supporting documents, alternative capsule designs, substitute analysis methods) which may be applicable, or even better-suited, to the forecasting problem at hand, but are not known. Manual research is the only avenue offered to expand the research to include additional perspectives.

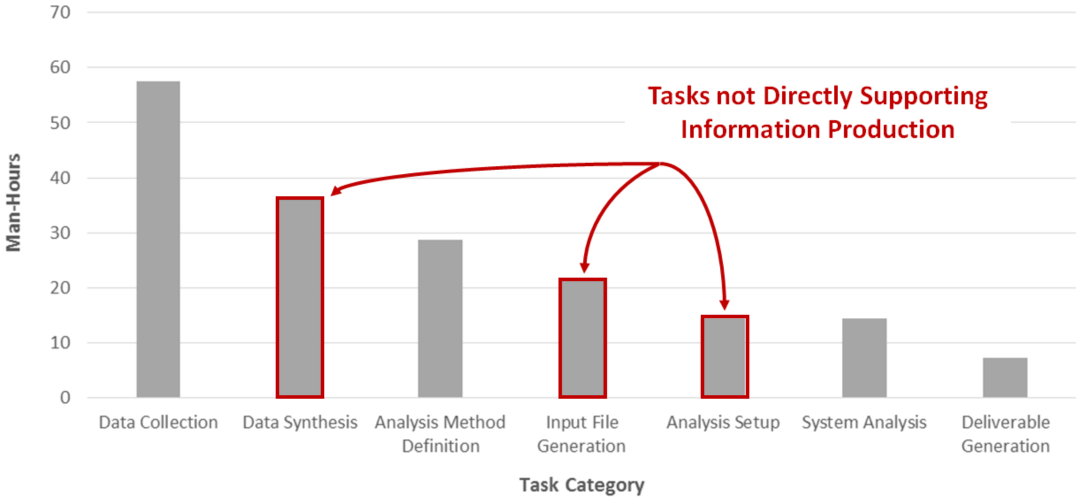


Figure 6.11 – Distribution of Time Resources on Capsule Analysis Control Group

6.1.3 Test Group Experiment

The experimental test group employs the DES components and interfaces developed in previous chapters, with the project-specific implementation shown below in Figure 6.12. As opposed to the control group, which did not employ any form of standardized data user environment, the proposed concept of operations provides a unified user interface for all DE tasks from Data Collection through Data Visualization. As another addition, the implemented DES provides feedback of analysis and deliverable data to provide a cumulative vantage point – this reentry capsule analysis will not exist in a vacuum, but will have complete access to all previously collected and analyzed data. Additionally, the data collected and created for the current analysis is saved with the DES environment to serve as an integrated reference point for future information tasks.

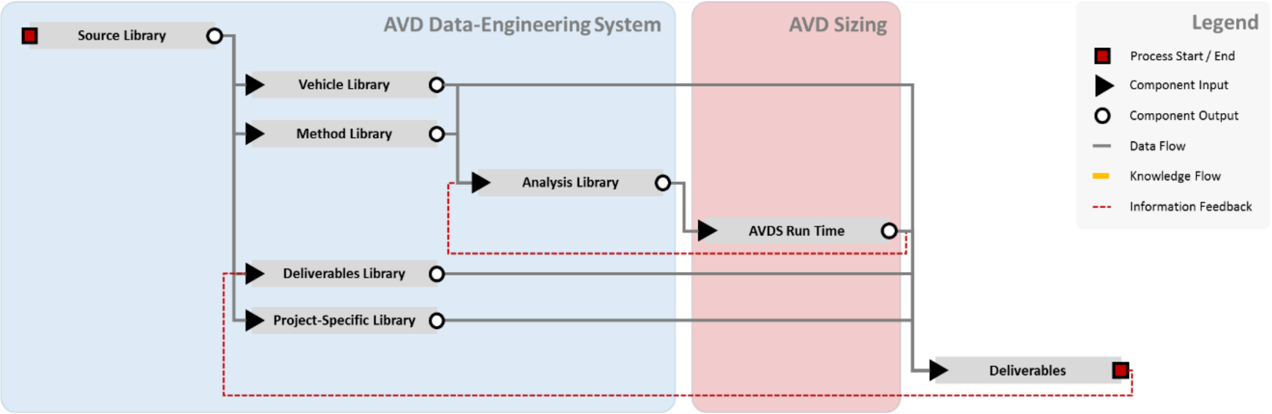


Figure 6.12 – Data-Engineering System Concept of Operations for Experimental Group

The experimental test group is tasked with providing the same information requests detailed in Section 6.1.1.4. That is, generally, assessing the feasibility of proposed internal and external design concepts for re-entry capsule configurations in the context of early 1960's US technical and operational capability.

In order to exercise the potential capability of the DES, not only will the test group be required to assess the Mercury and Vostok design points and corresponding solution spaces, but an additional configuration will be introduced into the series of analyses. This will serve two purposes: 1) to exercise the full capabilities of the DES, including Data Collection, Storage & Analysis, some of which have only been reproduced for the Mercury and Vostok analyses, and 2) exercise the design intelligence feedback features such that relevant alternatives are identified and assessed by the DES alongside user-selected configurations.

The selected additional alternative is the Soviet Soyuz design capsule, matching both the theme and context of the test design. This addition can be conceptualized as representative of an intelligence brief detailing a proposed design or release of prototype images to the press. The assessment will not emphasize a detailed analysis of the Soyuz design point, but will instead focus on the adaptation of the general Soyuz configuration to the Mercury reference mission. This approach is more representative of the conceptual circumstances (i.e. incomplete data available), as well as the intended impact of the DES intelligent feedback features (i.e. identifying and adapting relevant design alternatives to a user-defined mission).

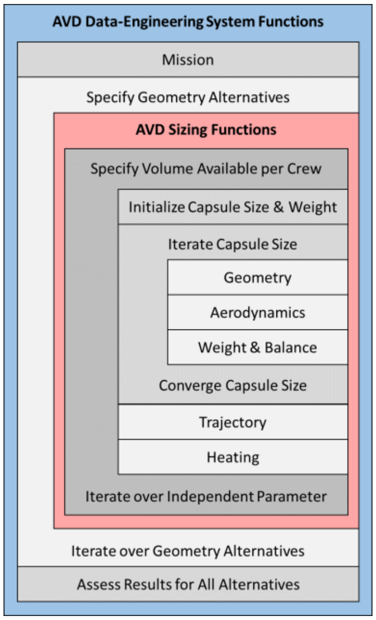


Figure 6.13 – Capsule Sizing Experimental Group Methodology

6.1.3.1 Retrieve / Create Information

All source documentation and vehicle data values collected as part of the control group have been entered within the DES. This data will serve as the basis for all further analysis, after being adapted to meet the DES data standardization and relational database structure. Collection of data to support an alternative analysis of the Soyuz design concept is carried out from initial discovery, however.

It is desired that the DES identify the Soyuz configuration as part of the control-group-parallel Mercury test, and adapt already-defined Mercury analysis data to match the required input data for a Soyuz analysis where possible. This experimental branch is not meant to be a design study of Soyuz, but an assessment of the Soyuz design to potentially influence the Mercury mission solution space.

The work-flow, shown below in Figure 6.14, will parallel the control execution from steps 1 through 5, although the process is now automated and should be, generally, more efficient. The new work-flow steps of identifying alternate design concepts and generating analysis data (items 7 & 8 in the diagram) are available only due to the integrated DES execution and produce purely supplemental decision-making information – i.e. the addition of alternative designs should provide a more complete view of the solution space.

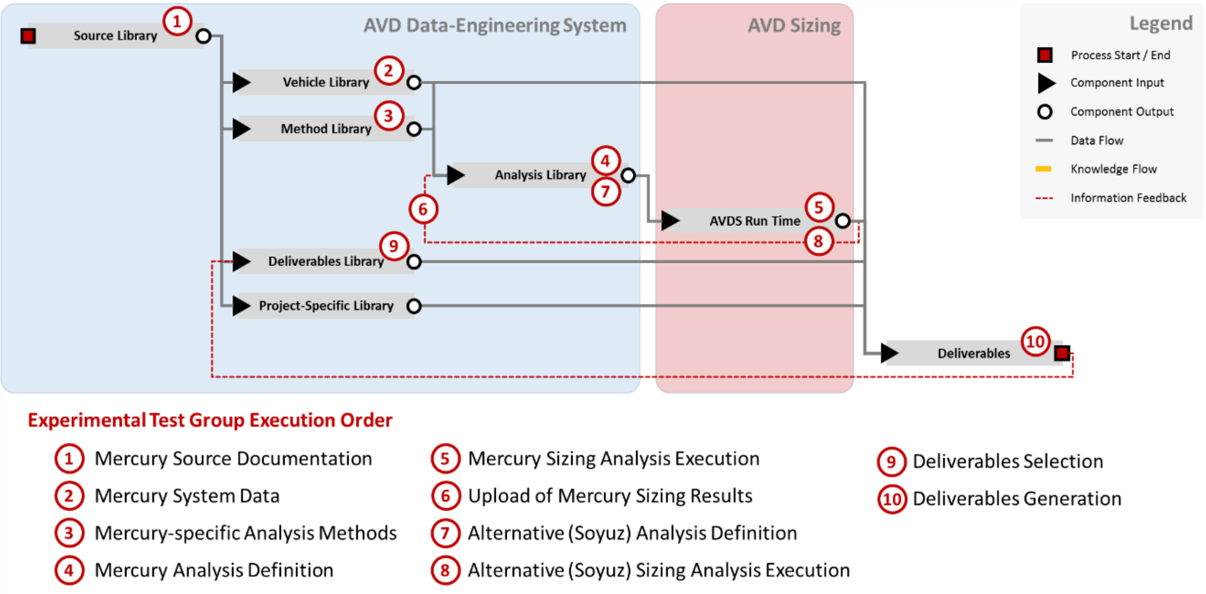


Figure 6.14 – Experimental Test Group Work-Flow within Prototype DES

In order to execute the alternative Soyuz design, the DES must have existing Vehicle Library and / or Method Library entries pertaining to Soyuz. Within the context of the MDA identified in the test group, this means that corresponding Geometry and Aerodynamics methods must be defined – Weight & Balance, Trajectory and Heating methods are generic and are not dependent on design configuration.

Geometry Method Definition

The geometry of the Soyuz capsule, shown below in Figure 6.15, is a bell-shaped design with a blunted nose to increase the effective vehicle radius[280]. This impacts the aerodynamic characteristics, which in turn increases the amount of lift that can be generated during re-entry which lessens both the normal force and heating environments. Under the same method I / O structure as the control group geometry methods, the Soyuz capsule method describes the volume, wetted area, and volumetric efficiency as a function of planform area.

Aerodynamic Method Definition

Aerodynamic characteristics for the alternative Soyuz concept have been described with empirical data[305] – this would contextually represent wind-tunnel data from an intelligence brief or re-created through analysis.

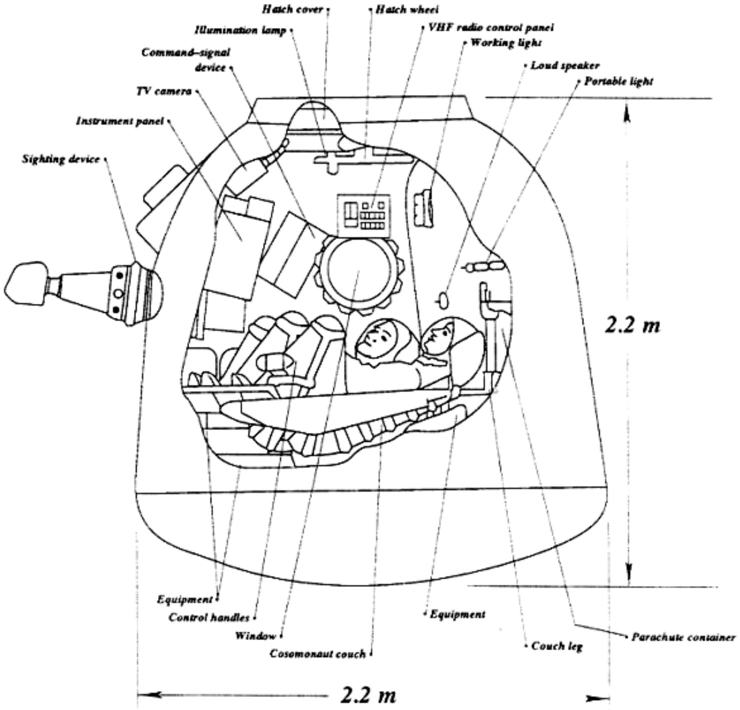


Figure 6.15 – General Soyuz Capsule Geometry[280]

6.1.3.2 Information Summary & Outcome

The test group produces two tracks of information to be assessed: 1) re-creation of the Mercury-Vostok solution space depicted in the control group, and 2) the capsule solution space with the Mercury, Vostok, and Soyuz design concepts overlaid. The first track will serve to verify that the DES produces consistent results with a manual system analysis process, and the second track will be used to assess the viability of the DES to autonomously produce beneficial information.

In order to assess the correctness of the overall analyses, results for both experimental groups have been compared to the actual vehicle data in Table 6.10 (the point values have been taken at the volume per crew equal to that of the actual vehicle). Comparing the results between the control and test groups, shown in the first two columns, it is seen that the DES is producing converged data points within 1% of the manual analysis. When assessed at the design volumes, both the Mercury and Vostok resulting design points are within 5% of the actual vehicle data, which is more than sufficient for decision-making within this information tasks.

Additionally, the Soyuz alternative design, which has only been defined as a generic geometry and aerodynamic configuration, has resulted in diameter and gross weight estimates within 3% of the actual vehicle data – i.e. populating the already-defined Mercury analysis with rudimentary parametric method descriptions of the Soyuz capsule enables the DES to accurately and correctly characterize the alternative vehicle.

Table 6.10 – Comparison of Re-entry Capsule Analyses Results to Vehicle Actuals

	Control	*Experiment*	*Actual*
Mercury (Central Design Node)			
Diameter [m]	1.9	1.9	1.9
Gross Weight [kg]	1214.0	1214.0	1237.0
Vostok (Alternative #1)			
Diameter [m]	2.4	2.3	2.3
Gross Weight [kg]	2719	2712.6	2800.0
Soyuz (Alternative #2)			
Diameter [m]	-	2.3	2.2
Gross Weight [kg]	-	2550.2	2480.0

Assessing the family of bell-shaped Soyuz configurations to the Mercury design mission, shown in Figure 6.16 below, shows the available solution space. Similar to the Vostok configuration solution space, overlaying the US Atlas launcher constraints provides little or no design space -- the values highlighted below (volume per crew < ~.7 m^3) are likely not feasible due to minimum volume constraints for a single crew member. Even with the compromised configuration, the Soviet concepts are too demanding from a weight perspective to operate with Atlas launch vehicles. The Soyuz design point, highlighted with a red circle, is the actual capsule dimensions and requires a substantially increased launch capability 1000 kg beyond the US capabilities, but which the Soviets already possessed.

While Figure 6.16 verifies that the Soyuz design is feasible given sufficient launch capability, Figure 6.17 illustrates the operational benefits gained from the bell-shaped configuration. By increasing the nose radius of the capsule, the maximum heating rate has been reduced drastically (approximately 100 W/cm^2 less than a spherical capsule of the same volume) and at the same time reducing force loading during re-entry. This underlines the fundamental design philosophy of the Soyuz capsule (which is still operational today) – emphasize volumetric efficiency of a spherical capsule design by compromising a more operationally-intensive, but repeatable, re-entry profile.

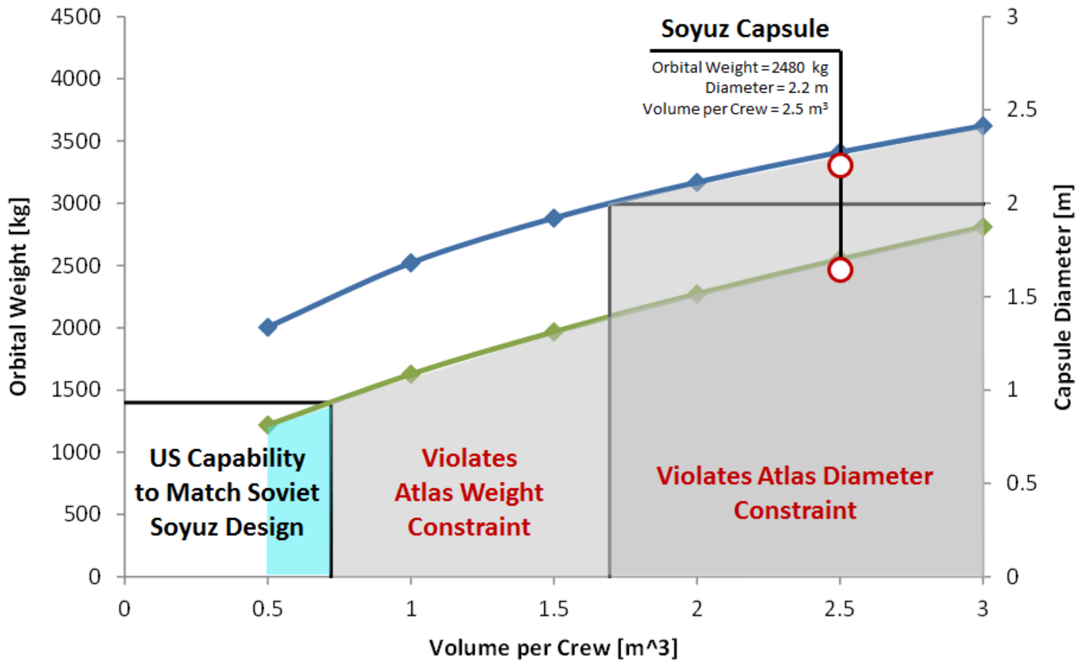


Figure 6.16 – United States Soyuz Geometry Volume Solution Space

6.1.4 Experimental Results

Although this historical case study has provided a snapshot of designs half a century old, the analysis concepts and even the design configurations have relevance now. Modern US capsule configurations have changed little from the Mercury concept, and even less from the evolutionary Apollo geometry – the Boeing CST-100, Lockheed Martin Orion, and SpaceX Dragon all share a similar profile. It is not difficult to imagine an early forecasting study within these organizations that default to the known US capsule solution – however, it is uncertain if modern internal processes within these organizations are prompted to consider alternative concepts in their early assessments.

However, if a DES was in place at the time of these studies, not only would the forecasting engineers have the ability to seamlessly assess alternatives integrated in the same analysis framework – artificial intelligence features should have ***forced*** alternatives to be addressed that were outside of the status quo. The power of a highly-functioning DES is that data and information is no longer piece-wise function, raising and lowering with the onset and drawdown of projects – the engineer has it their finger-tips the full weight of engineers and analysts that have endeavored before them.

Assessing the total forecasting environment, including the newly introduced *Data-Engineering System* and the revamped aerospace synthesis platform, after implementation of the *DE* research specification approach allows an assessment of the total efficiency, productivity and quality improvements of the holistic forecasting process. This section qualitatively depicts the overall capability improvements deltas in the AVD system process after *DE* implementation.

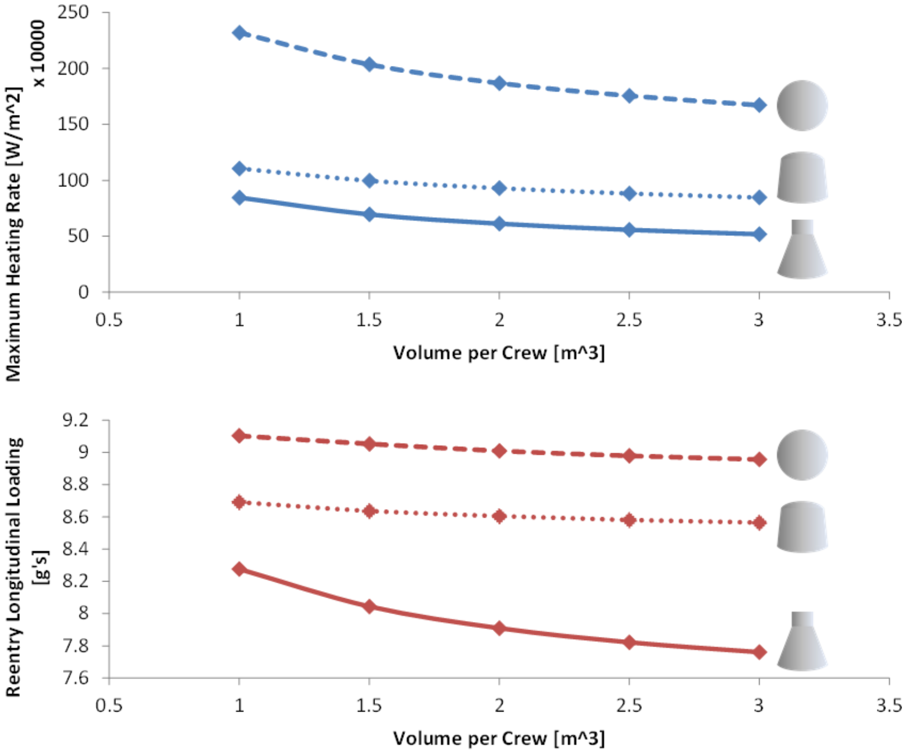


Figure 6.17 – Re-entry Characteristics for Three Alternative Capsule Designs

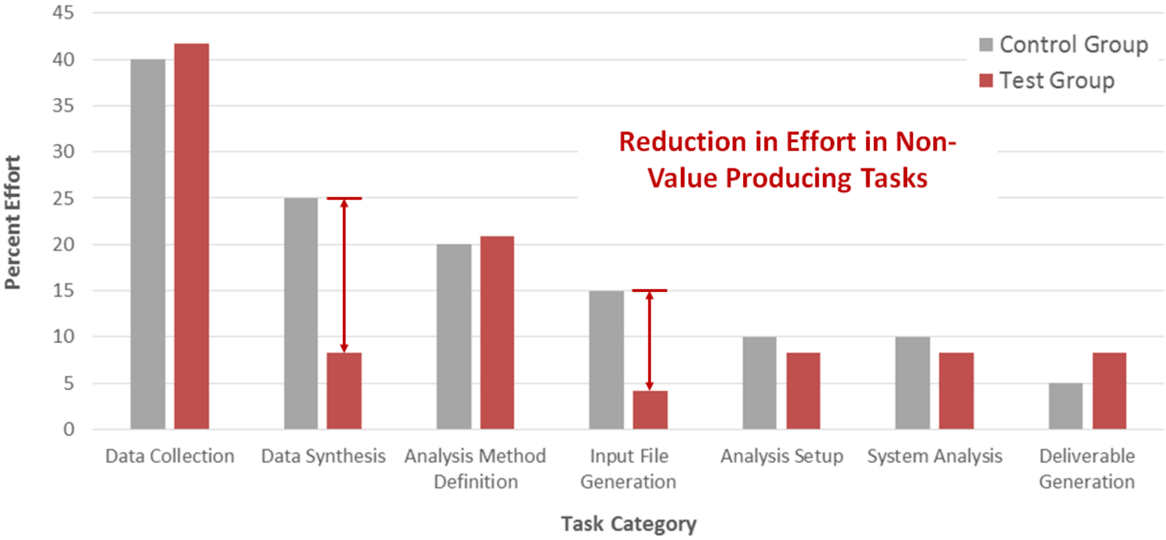


Figure 6.18 – Relative Effort for Control Group and Experimental Test Group

Looking at the relative amount of time resources allocated amongst data tasks between the control and test groups (Figure 6.18) shows a reduction in time spent on tasks which do not inherently add informational value (e.g. synthesizing data into a standardized format, formatting analysis input files). This allows the forecasting team to re-allocate relative time to more value-added tasks and to reduce overall time resources – the total time to produce the Soyuz alternative analysis employing the DES is ***2 man-days***, compared to ***2 man-weeks*** spent to produce the control group Mercury-Vostok analysis manually. Using the Data-Engineering metrics derived in Chapter 2, a detailed assessment of the Data-Engineering performance comparing the control group and test DES forecasting environments is detailed below.

6.1.4.1 Data Collection, Storage & Organization

The additional structure put in place through *Data-Engineering* constructs has improved all data collection, storage and organization metrics, as shown in Table 6.11. The introduction of topic-, vehicle- and project-specific databases in an integrated environment has increased the completeness by reducing redundant or non-critical data fields. The introduction of a shared network drive that houses both source documentation as well as the *Data-Engineering* and AVD Sizing synthesis platforms has increased both the *capacity* and user *accessibility* of the total system. Additionally, the *adaptability* of the system has drastically improved (i.e. less time required to adopt new data sets) due to storing all data within a unified environment that provides database batch processing capabilities.

Table 6.11 – Data-Engineering AVD Process Data Collection, Storage & Organization Metrics

Metric	*Control*	*Test*	*Unit*	*Comment*
Completeness	10-50	75-100	%	Introduction of topic-specific variable data fields
Capacity	100	5000	GB	Shared network drives house all communal files
Accessibility	25-100	100	%	Source documentation available across organization
Adaptability	10^8-10^{10}	10^2-10^3	sec / GB	SQL database querying / processing

6.1.4.2 Data Recall

Digitizing existing and new AVD datasets has both decreased the time required to recall data and increased the opportunity to connect relevant data, see Table 6.12. The addition of datasets and source documentation to the *Data-Engineering* platform is still a manual process performed by analysts in response to an underlying forecasting information need, effectively placing a built-in filter for adding topic-relevant meta-data. If data from outside sources is not relevant nor up to the data quality standards set by the analyst, it is never added to the *Data-Engineering* platform and is therefore not produced within internal recall queries. All of these factors have combined to improve the *precision* recall metric (i.e. ratio of recalled data that is relevant).

Table 6.12 – Data Engineering AVD Process Data Recall Metrics

Metric	*Control*	*Test*	*Unit*	*Comment*
Time Cost	10^3-10^6	10^2-10^3	sec / GB	Storage of meta-data and shared hosting of files
Economic Cost	0-10^5	0-10^5	$ / GB	No change in access cost of new data; no access cost for local files, physical or digital
Precision	-	50-100	%	Only relevant documents stored; still primitive search algorithm
Sensitivity	-	-	%	Dependent on project; outside reference search still required

6.1.4.3 Data Analysis & Visualization

Unification of datasets has allowed for data analysis and visualization to be mechanized and even automated to a much larger extent than previously plausible. Data comparison, correlation and regression analysis functions can all occur within the native *Data-Engineering* platform, thereby improving the *multiplicity* metric and removing the requirement to compile project-specific datasheets and perform ad-hoc data analysis procedures. The addition of structured data input, editing and output views has expanded the *degrees of freedom* available for data visualization. Automated export of synthesis input files has reduced the time required to prepare input files (i.e. *interoperability*), as well as reducing potential opportunities for errors in translating data syntax between formats.

Table 6.13 – Data-Engineering AVD Process Data Analysis & Visualization Metrics

Metric	*Control*	*Test*	*Unit*	*Comment*
Multiplicity	0	200	Fields	Current number of vehicle property variables
Degrees of Freedom	10^2	10^3	DoF	Automated user interface forms & deliverable outputs
Interoperability	10^7-10^8	10^6-10^7	sec / GB	Export automation (custom-tailored)

6.1.5 Hypothesis Assessment

In terms of the hypotheses laid out at the beginning of this chapter, the experimental DES prototype applied to the capsule re-entry case study has met and exceeded all expectations.

For Hypothesis #1, the automated implementation of DE capabilities within the forecasting environment has produced the same information results as comparable manual forecasting process, but with 10% of the time resources required. And within the remaining engineering time, lower-level data tasks that are not value-producing have been relegated to automation. As in other engineering fields, automation is a primary enabler to allow the engineer to increase efficiency and spend more time on complex cognitive tasks (e.g. problem-solving and result interpretation). From a purely time-based perspective, as well as from DE metrics derived from data & information science, the implementation of a DES in aerospace forecasting has increased performance, while maintaining or improving the quality of the information product.

For Hypothesis #2, even rudimentary artificial design intelligence features have shown the potential to drastically influence the final information product. The inclusion of the Soyuz capsule design provides an alternative that comprises the two initial design concepts, and has proven more successful than either. This supporting functionality is key to supporting engineer education and ensuring that forecasting analyses occur with a global, encompassing perspective. Individuals and organizations have invested countless resources creating and storing data for further use – it is up to the engineer, with the aid of their forecasting tools, to capitalize on the wealth of experience.

6.2 CONTRIBUTION SUMMARY

The following items have been completed in this chapter that provides a contribution to the dissertation research topic:

- An experimental case study is defined to gauge the delta in performance attained by introduced formal Data-Engineering System into an aerospace forecasting task
- The Data-Engineering System has been executed in concert with the AVD Sizing parametric sizing tool to produce the solution space for a re-entry capsule considering three alternative configurations
- Artificial design intelligence components of the Data-Engineering System have been verified to autonomously select relevant alternative designs and streamline parallel system analysis
- The Data-Engineering System has been shown to reduce the required resources to produce the same decision-making information, and increase the information produced for both primary and secondary forecasting efforts

REFERENCES

[280] Chertok, B., “Rockets and People, Volume 1,” NASA History Series, 2005.

[281] Haney, E., Gonzalez, L., Omoragbon, A., McCall. T., Peng, X., Ricketts, V., Crosley, J. and Chudoba, B., *“Leveraging History in the Context of Project Engineer Education: Project Mercury,”* Proceedings of the 2013 ASEE Gulf-Southwest Annual Conference, The University of Texas at Arlington, Texas, March 21-23, 2013.

[282] McDonnell Aircraft Corporation., “Project Mercury Familiarization Manual: NASA Manned Satellite Capsule”. NASA CR-55226, 1961.

[283] Korando, R., “Mercury Capsule No. 14 Configuration Specification”. McDonnell Aircraft Corporation CR-50068, 1961.

[284] The Bendix Corporation., “Acquisition System Point Arguello”. NASA NAS 1-430,MS-117,VOL. 2, 1961.

[285] Ledford, H., “Actual Trajectory of Mercury-Redstone Flight Test MR-2 (U)”. NASA Marshall Space Flight Center TM X-51215, 1961.

[286] Ledford, H., “Actual Trajectory of Mercury-Redstone Flight Test MR-4 (U)'. NASA, 1961.

[287] Anon., 'Astronaut John H Glenn, Jr., Friendship 7”. NASA Manned Spacecraft Center, 1962.

[288] Gerathewohl, S., “Effects of Weightlessness on Man During U.S. Suborbital and Orbital Flights”. NASA: Ames Research Center TM X-51935, 1965.

[289] Erb, B., Jacobs, S., “Entry Performance of the Mercury Spacecraft Heat Shield”. NASA Manned Spacecraft Center TM X-57097, 1964.

[290] Boyton, J., “First U.S. Manned Six-Pass Orbital Mission (Mercury-Atlas 8, Spacecraft 16)”. NASA Manned Spacecraft Center TN D-4087, 1968.

[291] O’Neal, R., Rabb, L., “Heat-Shield Performance During Atmospheric Entry of Project Mercury Research and Development Vehicle”. NASA TM X-490, 1961.

[292] Jones, F., Smith, F., “Mercury Capsule No. 16 Configuration Specification (Mercury - Atlas No. 8)”. McDonnell Aircraft Corporation CR-52114, 1962.

[293] McDonnell Aircraft Corporation., “Mercury Spacecraft No. 15A Configuration Specification (U) (Mercury-Atlas No. 10)”. NASA CR-55222, 1962.

[294] Grimwood, J., “Project Mercury: A Chronology”. NASA SP-4001, 1963.

[295] Anon., “Project Mercury: Technical Information Summary of Mercury-Atlas Mission No. 5/9 (Capsule No. 9)”. NASA, 1961.

[296] Anon., “Report on Observations of the Mercury Ground Range During Mercury-Atlas (MA-4) Mission”. Bell Telephone Laboratories, 1961.

[297] Anon., “Results of the First United States Manned Orbital Space Flight”. NASA Manned Spacecraft Center, 1962.

[298] Bailey, F., “Review of the Lessons Learned in the Mercury Space Program relative to Spacecraft Design and Operations”. AIAA, 1963.

[299] Boynton, J., “Technical Results of the First Manned Orbital Flight from the United States”. NASA Manned Spacecraft Center, 1962.

[300] Zygielbaum, J., “The First Man In Space”. NASA JPL CR 552458, 1961.

[301] Bertin, J., “Hypersonic Aerothermodynamics”. AIAA Education Series, 1994.

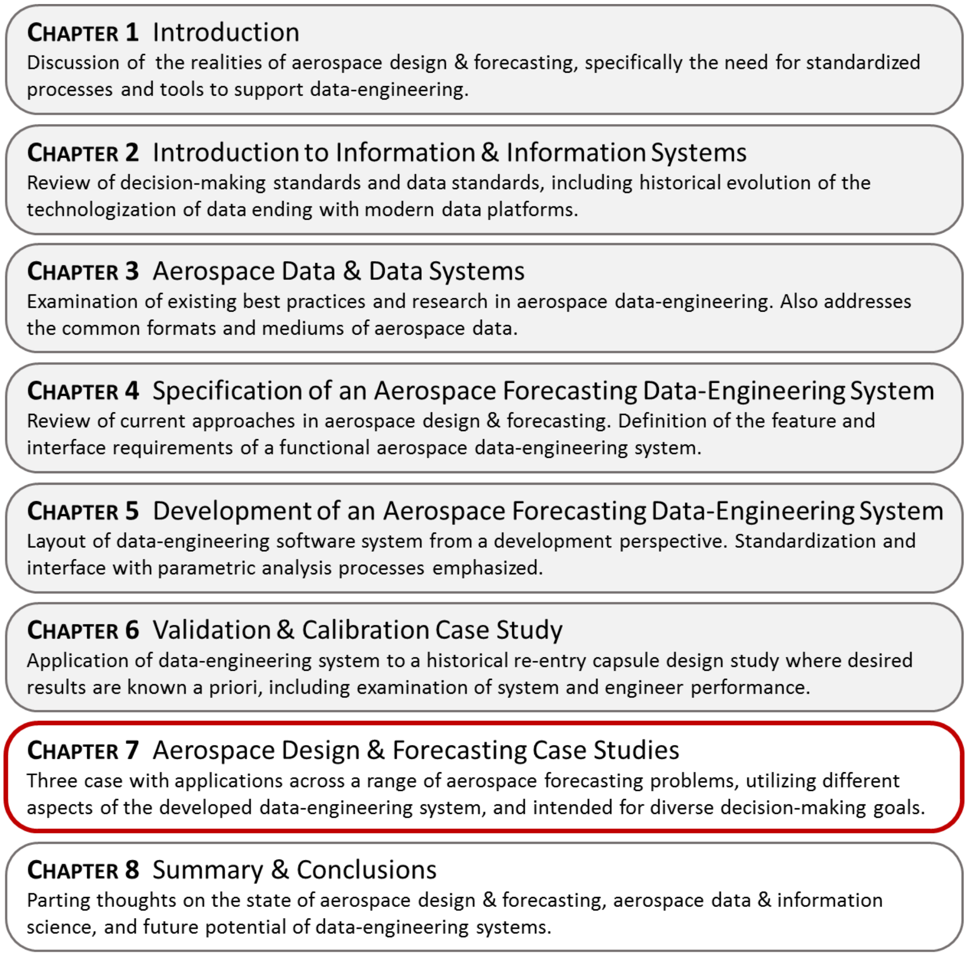
[302] Czysz, P., "Hypersonic Convergence: Volume I," Air Force Research Laboratory, USAF Technical Report AFRL-VA-WP-TR-2004-3114, 2004.

[303] Czysz, P., "Hypersonic Convergence: Volume II," Air Force Research Laboratory, USAF Technical Report AFRL-VA-WP-TR-2004-3115, 2004.

[304] Czysz, P., "Hypersonic Convergence: Volume III," Air Force Research Laboratory, USAF Technical Report AFRL-VA-WP-TR-2004-3116, 2004.Wang, R., and Strong, D., "Beyond Accuracy: What Data Quality Means to Consumers," Journal of Management Information Systems, Vol. 12, No. 4, pp. 5-33, 1996.

[305] Hirschel, E., and Weiland, C., "Selected Aerothermodynamic Design Problems of Hypersonic Flight Vehicles," AIAA, SEL TL 507.P75v.229, 2009.

CHAPTER 7
DATA-DRIVEN AEROSPACE FORECASTING CASE STUDIES



CHAPTER 1 Introduction
Discussion of the realities of aerospace design & forecasting, specifically the need for standardized processes and tools to support data-engineering.

CHAPTER 2 Introduction to Information & Information Systems
Review of decision-making standards and data standards, including historical evolution of the technologization of data ending with modern data platforms.

CHAPTER 3 Aerospace Data & Data Systems
Examination of existing best practices and research in aerospace data-engineering. Also addresses the common formats and mediums of aerospace data.

CHAPTER 4 Specification of an Aerospace Forecasting Data-Engineering System
Review of current approaches in aerospace design & forecasting. Definition of the feature and interface requirements of a functional aerospace data-engineering system.

CHAPTER 5 Development of an Aerospace Forecasting Data-Engineering System
Layout of data-engineering software system from a development perspective. Standardization and interface with parametric analysis processes emphasized.

CHAPTER 6 Validation & Calibration Case Study
Application of data-engineering system to a historical re-entry capsule design study where desired results are known a priori, including examination of system and engineer performance.

CHAPTER 7 Aerospace Design & Forecasting Case Studies
Three case with applications across a range of aerospace forecasting problems, utilizing different aspects of the developed data-engineering system, and intended for diverse decision-making goals.

CHAPTER 8 Summary & Conclusions
Parting thoughts on the state of aerospace design & forecasting, aerospace data & information science, and future potential of data-engineering systems.

Where the previous chapters have established the motivation, theoretical basis, and development of a next-generation *Data-Engineering System*, this chapter will focus on the implementation of this system on three distinct aerospace forecasting case studies. All of these case studies have originated as part of an actual engagement with a decision-making organization and therefore reflect templates to address real forecasting needs.

As introduced in Chapter 1, the production of information is limited to three potential sources: 1) the *data domain* representing known facts, statistics and media, 2) the *knowledge domain* incorporating heuristics, guidelines and lessons learned from previous experience, and 3) the *analysis domain* as the ability to analyze the cause and effect relationship of a phenomena in a logic pattern. Producing information in an organizational setting can include one, two or all of these domains – the approach is dependent on the information requirements provided by the decision-maker and the ability to produce information from these domains.

In addition to providing differential approaches to the decision-making domains in these design forecasting case studies, it is also desired to test the *Data-Engineering System* for a broad range of forecasting decision types: situational assessment, strategic planning and requirements definition activities are all represented. By introducing a variety of information requirements to the system during development, a more robust approach is formed, as well providing applicability to a broader range of design forecasting organizations and decision-makers.

Situational Assessment: Hypersonic Research & Development Database – An executive dashboard and suite of information-graphic deliverables are developed from a self-collected and organized dataset of current hypersonic vehicle R&D projects.

Strategic Planning: High Speed Transport Mission Research – Research of information production and information communication during the mission planning phase of legacy supersonic and hypersonic commercial aircraft for application to competitive analysis of proposed high speed transport concepts.

Requirements Definition: Aerobraking Orbital Transfer Vehicle Sizing – Development of data- and knowledge-driven analysis methods to complement a total system model of a series of manned geostationary orbit servicing architectures featuring aerobraking orbital transfer vehicles.

The case studies are presented in a format that ensures that the entire information production process is framed completely. As specified in the research outline, these case studies are presented as a functional framework for future forecasting efforts to be based. Although the forecasting topics and the means by which information is produced changes for each case study, the overall process is applied in a consistent fashion. This framework process is presented first to orient the reader with the individual steps and their contextual functions.

7.1 DESIGN FORECASTING OUTLINE

Although the topics of aerospace forecasting activities will vary wildly from project to project, the overall flow of the decision-making process should remain constant. In order to standardize this procedure & offer consistency between the case studies, distinct elements have been identified and will be stated explicitly. Figure 7.1 shows the connection and flow-through of these elements in the decision-making process from initiation of the decision-making problem statement through information production on to the selection of available options based on the information provided.

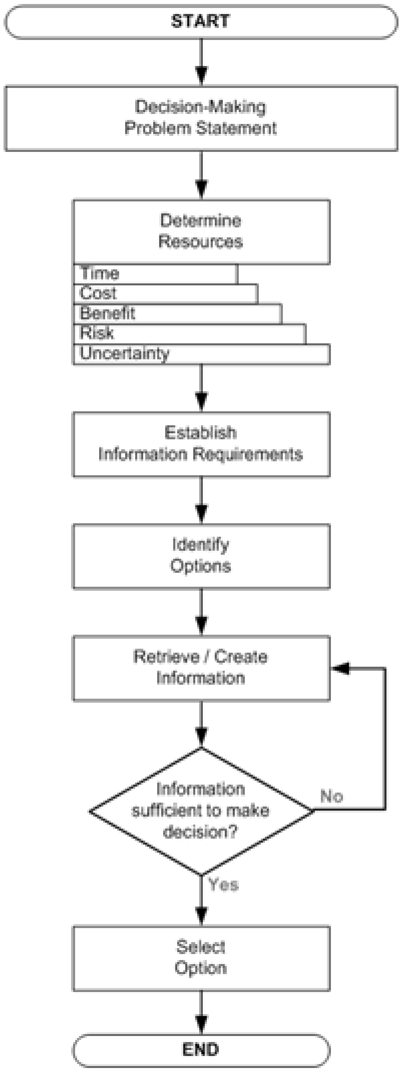


Figure 7.1 – Decision-making process flowchart

7.1.1 Decision-Making Problem Statement

The overarching goal of the decision should be explicitly stated before any further investigation takes place. The decision-maker's interests, organizational position & reasoning should be framed. Specific information required by the decision-maker should be detailed including the delivery medium for conveying that information.

7.1.2 Determine Resources

Information is valuable, and anything with value does not come without a price. The monetary, time & human capital budget should be known beforehand. There is always a negative tradeoff between budget and information that cannot be overcome. The burden lies with the decision-maker to know the potential value and cost of the desired information and allocate resources accordingly.

Resources have been subdivided into: cost, the required investment of time, fiscal and personnel capital; benefit, the positive outcomes that may arise from a decision; risk, the negative outcomes that may arise from a decision; & uncertainty, the portions of the decision where the potential effects are not known and cannot be known definitely.

7.1.3 Identify Options

Options will vary greatly depending on where the decision is along the life-cycle, organizational resources & capabilities, time-frame, and any number of other contributing factors. The range of options may span from binary go/no-go to down-selection of product development alternatives to enterprise-wide pathfinding. If it is possible, specific outcomes should be stated.

7.1.4 Establish Information Requirements

While there is usually a direct correlation between the budget committed and completeness of information, it has been posited that even with an unlimited budget, and therefore perfect information, complex decisions have enough latent uncertainty to warrant a perfect decision unattainable[306]. In some cases, incomplete information that can be produced quickly to gauge the approximate correct course of action is preferable. There is always a balance of exchanging budgeted resources with information.

7.1.5 Retrieve / Create Information

As discussed in Chapter 2, information-production can only come from three potential sources: the data, knowledge, and analysis domains. These domains may be exercised in isolation, in parallel, or integrated together depending on the information requirements & decision-making problem statement of the effort (Figure 7.2). The case studies in the following section represent a range of domain combinations including independent, dual domain, and fully integrated information production – the specific approach has been chosen be

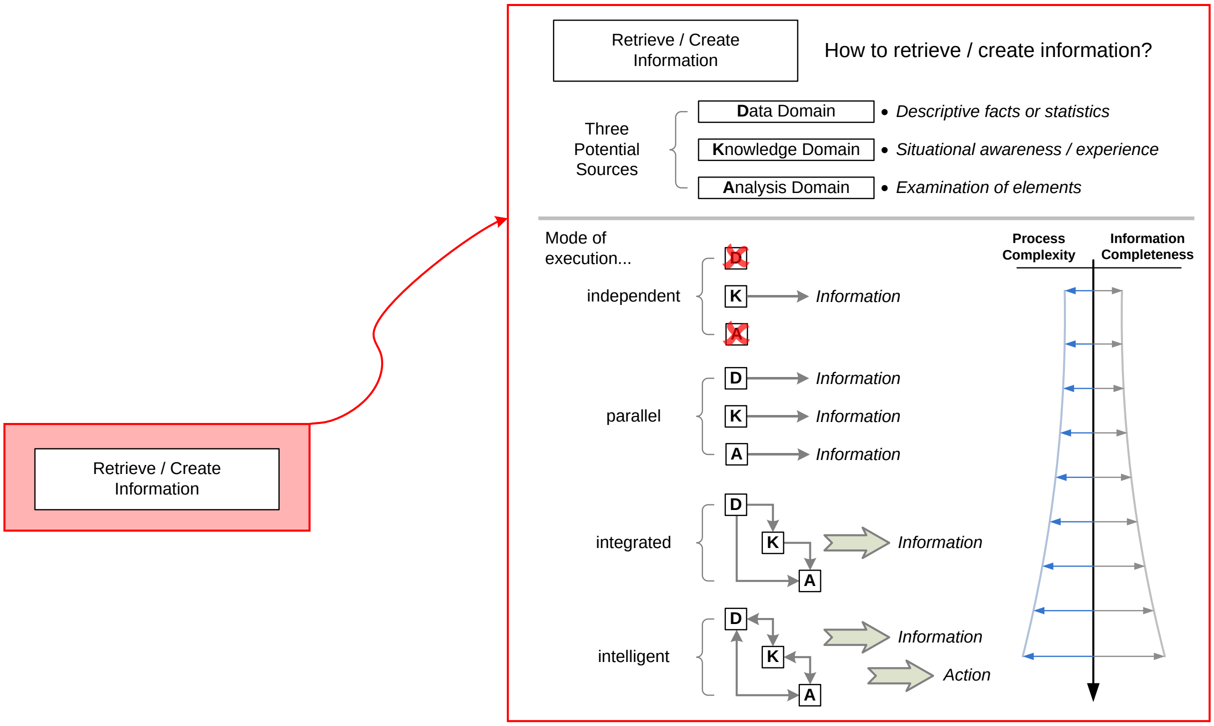


Figure 7.2 – Information production flowchart

Within each domain, the process that leads to production of data / knowledge / analysis to support information production is discussed. In order to illuminate the data-driven nature of the forecasting case studies, the internal process of the data domain is further subdivided into the categories outlined in section Chapter 2 (data collection, organization, storage, recall, visualization, & analysis). Throughout these sub-efforts there is consistent emphasis on what value the current data / knowledge / analysis procedure adds to the final decision-making information.

7.1.6 Sufficient Information Check & Option Selection

The case studies are presented as efforts to create information to enable the decision-maker to make an objective, informed decision. In this definition of stakeholders, the entity creating the information is separate from the entity consuming & applying the information. Therefore, it is necessary that the forecasting (information-production) body present final information in an objective format – the goal is not to guide the decision-maker towards a specific option, but to let the information speak for itself.

7.2 SITUATIONAL ASSESSMENT DATA-ALONE CASE STUDY: HYPERSONIC RESEARCH & DEVELOPMENT DATABASE

Portions of the work presented in this section were completed as part of funded research through the National Institute of Aerospace as requested by the Chief Engineer for Hypersonics at NASA Langley Research Center under contract titled "Collaborative Research Support for Current Investments in High-Speed Technologies."

Deliverables were generated by a collection of engineers at the Aerospace Vehicle Design Laboratory at the University of Texas at Arlington. The author acted as lead System Developer for all data engineering software implementations presented.

Substantial effort was provided by Amit Oza, Amen Omoragbon, Lex Gonzalez and Dr. Bernd Chudoba in the collection of source data and formulation of decision-making deliverables.

Results have been published to The Aeronautical Journal[270] and presented at the American Society for Engineering Education Gulf Southwest Conference[308].

Contributing Individuals: Amit Oza (UTA), Amen Omoragbon (UTA), Lex Gonzalez (UTA), Dr. Bernd Chudoba (UTA), Dr. John Korte (NASA)

Data collection & input, viewed as a straight-forward task left to clerks, librarians & interns by some, suddenly becomes a much more intensive process when data is not well-formatted & single-sourced, but is messy, written in technically-specific terms, and located across several sources, none of which are made readily available. This second situation is representative of the data environment concerning current aerospace research & development (R&D) projects, especially those in the hypersonic mission class (usually taken as Mach 5+). This situation arises from several contributing factors.

The nature of hypersonic missions (high-speed missiles & space access systems) means hypersonic vehicle projects are often classified or organizationally-sensitive. For current projects, the ongoing status results in shifting or unknown design characteristics. National / organizational prestige often plays a large role in hypersonics, especially space vehicle systems, where gross misstatements of time, budget & technical progress can ensure a positive outside perception. As a result, project data & information is communicated (if at all) in press releases, conference proceedings and presentations where technical data is suppressed or ignored.

All of these influences results in a lack of high-quality & technically-filtered data, leaving forecasting decision-makers with a burdensome deficiency of information. Although the resource-intensive nature of high-speed aerospace projects requires objective, long-term strategic planning, an objective situation assessment of the current & projected technical capabilities in the field is missing – correcting these deficiencies is the focus of this case study.

7.2.1 Decision-Making Problem Statement

The decision maker is a chief engineer overseeing hypersonic research & development projects at a national aerospace research organization (NASA) and is tasked with making strategic resource allocation & technology prioritization decisions with long-term, holistic goals. Future opportunities for R&D projects must be identified that: (1) address competitive international efforts, (2) incorporate shared advancement of ancillary projects, & (3) fill prerequisites for improved national enterprise capabilities.

7.2.2 Determine Resources

The decision-maker's organization is pressured by downward budget constraints, but must continue to deal increasing political pressure to produce tangible developments under governmental bureaucracy. The decision-maker does not have dedicated planning personnel, or logistically the time to proceed with such an information task themselves.

Cost

At the program planning level, absolute short-term fiscal & personnel investment cost is minimal. Engineering & managerial work at this level, by definition, does not involve physical testing or development; instead, the organization's investment is limited to the human & time resources dedicated towards planning. Personnel with the expertise to execute such tasks are highly valuable assets though. There will always be a pull for senior engineers & managers to work on the most important project to the organization to which their skills are applicable. Because of this, strategic program planning activities must quickly & efficiently guide these key personnel to the correct information in a short period of time – their opportunity cost to the organization for 'wasted' time is too high to justify allocation on an unwarranted effort.

Benefit

The benefits of correctly identifying the path forward for an entire branch of a national research organization are immense. Advancement of any ideas from study to project to program carries enormous human, time & financial capital investment. However, technology & capability advancement in hypersonics encompasses suborbital tourism, high-speed point-to-point travel, advanced military platforms and sustainable space access. The benefits of receiving backing for a project that enables a breakthrough in any of these high-profile mission classes could truly be historic.

Risk

The nature of this planning decision entails little short-term risk, but has the chance for several longer-term risks. There are risks of stagnation by allocating further resources towards unjustified projects, ceding position to outside agents by not matching competitive capability, and losing organizational funding due to lack of public and political interest. These risk can be lessened by providing the decision-maker with more complete & unbiased information, but there will always been inherent risk in long-term strategic planning.

Uncertainty

The decision-making organization receives all of its funding through the national government, therefore the year-over-year & long-term funding of the organization is uncertain. Likewise, there is also no certainty in the future international geopolitical (i.e. competitive) state. Technical uncertainty lies in proposed & unproven technologies that may enable changes in capability, but require unknown investments to be operationally realized.

7.2.3 Identify Options

A specific project is not the current decision focus, but a series of long-term programmatic decisions. As such, there are no concrete options to identify, but thematic trends that must be explored.

1. Technology Prioritization – choosing which emerging technologies to invest resources and determine the mission capabilities they support
2. Development Methodologies – how to balance project-level risk with enterprise resource investments and level of technology integration
3. Competition Analysis – address adversarial advancements & capabilities before they threaten decision-making organization’s position

7.2.4 *Establish Information Requirements*

The decision-maker requires information about any current or recently active project with R&D goals that would provide capability towards hypersonic air vehicles. Information should be presented to the decision-maker in a systematic format that is able to be immediately distributed without contextual explanation. Personnel both above & below the decision-maker's position should able to assess projects from the formatted deliverables as well. Forecasting assessments should be made at the project, organization, national, & global scales utilizing a central, validated source of data.

7.2.5 *Retrieve / Create Information*

The goal of this forecasting activity is to provide an objective, well-substantiated assessment of the hypersonic vehicle development field. This information activity precedes project or program initiation, before any traditional design activities and therefore vehicle-, mission-, and technology-agnostic. That is, there are no preconceived limits placed on which project concepts should or should not be considered. While this method provides a holistic viewpoint, it also introduces the potential for the 'noise' of projects that are overly ambitious, underfunded, and unpublicized. These outliers provide for challenging data collection, but may still influence the broader hypersonic landscape.

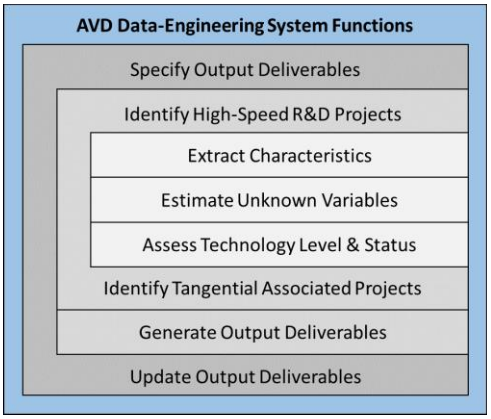


Figure 7.3 – Hypersonic R&D Case Study Methodology Diagram

Before data collection can begin however, the parameters of interest must be chosen. This step requires input from the forecast user (the decision-maker) as well as insight from the forecasting team – identifying the correct data to pull has a direct effect on the quality of resulting information. The availability of factors plays a key role in the definition of required fields. If too many parameters are taken as data, the database will be sparse and comparison between projects will become inconclusive. Conversely, the fewer parameters that are required the less likely it is that the project is fully characterized.

In this case, the decision-maker requires both technical & managerial-level data in order to gain the necessary insight – detailed technical project data to gauge the complexity & scientific contribution (the what), and managerial data to understand the top-level project drivers (the who, where, when, why & for how much). The following gross categories for required data were collaboratively agreed on with the decision-maker before the forecasting research began.

Technical Data

- Performance – mission class, payload, speed, range, endurance
- Vehicle Dimensions – length, span, gross weight
- Mission Characteristics – launch, landing, staging, reusability

Program Data

- Overview – goal, organization, country, sector
- History – status, operational date, funding, milestones
- Reference – point of contact, source documentation

This study does not call for additional knowledge & analysis domain interactions with the established data. While a focused knowledge-based assessment from historical trends, expert elicitations, and legacy documents would identify the mission-vehicle-technology combinations that are the most likely to succeed, it is more important at this stage of research to understand the entirety of the hypersonic field – even if it means considering R&D projects that are exploring suboptimal topics. A parametric analysis of the solution space surrounding missions, vehicles, and technologies is a logical follow-on the projects of interest, but is not considered in this study.

7.2.6 Retrieve / Create Information: Data Domain

The data handling procedure is detailed for the Hypersonic R&D Database follows with emphasis on recall & visual steps.

7.2.6.1 Data Collection

The variables of interest outlined in the previous section are dictated by the data commonly available for hypersonic projects in the R&D phase. This data is communicated to the aerospace community and the public in a number of different methods. The following categories are roughly in the order of their usefulness for this effort.

- Press releases and non-peer-review articles are predominant when communicating milestones such as securing funding or upcoming flight tests. This is especially true of government-sponsored research projects.
- Hypersonics- & space-focused conferences offer the R&D community an opportunity to share technical and operational breakthroughs. Chief engineers, program managers and senior staff give presentations and submit conference proceedings that often touch on technical details of a project as well as future courses of action.
- White papers and data-sheets give high-level technical specifications and a brief outline of a project.
- Technical journal publications are most prominent with government-sponsored projects, but often focus on detailed phenomena with a technical discipline. The lead time between development, documentation, review & publishing restricts the amount of project data offered of interest for the current effort.
- Official government documents can be found (for most Western countries) that contain project, organization and country-level budgets.

This list of document types represents the sources of data and the previous variable list represents what data to find – what remains is the labor-intensive task of finding the correct documents and extracting the correct data. For the hypersonic R&D database, over 1700 references were initially screened by a team of graduate aerospace engineers. Through several weeks of iteration, documents were filtered on the basis of data clarity & integrity – the credibility of the data sources and the individual article of data was a matter of discretion for the research team. Because of the volume of references collected, an exhaustive list is not provided within this document – Table 7.1 shows examples of the wide array of data collected sources found and later utilized to fill the hypersonic R&D database.

7.2.6.2 Data Storage

During initial filtering, physical documents were filtered with by inclusion of relevant data and earmarking with the project(s) discussed within the document. Digital documents were logged &

saved on a network-shared server for future reference. Upon further research, project characteristic data from this derived source library project is manually entered into the communal Data-Engineering system. The entire team of research analysts has both read and write access to the data-set during the research task.

7.2.6.3 Data Organization

The variables of interest have already been defined within the system – the default scheme is to treat the variables as unbound text fields unless otherwise specified. The qualitative variable fields that demanded restricted choices of inputs were given bounded options in a drop-down ‘combo box’. Project characteristics are linked by a unique project identification number that is assigned when a project is instantiated in the system. The reference source of each piece of data is stored in the same data table to allow for additional research and to promote transparency.

The key to advancing this system away from a static database and towards an adaptive decision support system is the interface with the decision-making users (Figure 7.4). The interfaces must be targeted towards specific questions from specific types of people, as well as enable them to proceed directly from data to information to action.

Table 7.1 – Hypersonic Database Selected Reference List

Title	Project(s)	Reference
Army Eyes Advanced Hypersonic Weapon	AHW	Grossman [309]
Hypersonics in the USA: New Partnerships in the 21st Century	AHW, CSM, HTV-2, X-37B, X-51	Rutledge [310]
Japan's Activities	BOV, CAMUI, Experimental Vehicle, Hayabusa, HYTEX, Pollux, RBCC Technology	Maita [311]
NASA Invests in Private Sector Space Flight with SpaceX, Rocketplane-Kistler	Dragon	NASA [312]
2011 U.S. Commercial Space Transportation Developments and Concepts: Vehicles, Technologies, and Spaceports	CSM, Dragon, Dream Chase, Lynx, RocketPlane XP, Silver Dart, SpaceShipTwo, Super-MOD, X-51A, Xaero	FAA [313]
Current and Near-Term RLV/Hypersonic Vehicle Programs	Expert, FTB-X, Hercules, HTV-3X, HyFly, HyShot, IXV, LEA, Pheonix, SOCRATES, X-37, X-43	Erbland [314]
USA Applied Hypersonics	Facet, HIFiRE, HTV-3X, HyCause, HyFly, HyShot, Hy-V, X-43, X-51A	Jackson [315]
Hypersonic International Flight Research and Experimentation (HIFiRE) - Fundamental Sciences and Technology Development Strategy	HIFiRE	Dolvin [316]
Australia National Report, 2011	HIFiRE, Scramspace	Boyce [317]
France National Report	ATLLAS, LAPCAT, LEA, Expert	Falempin [318]
Lockheed Martin Receives $218 Million for Long Range Anti-Ship Missile (LRASM) Demonstrations	LRASM-B	Vanbebber [319]
Shenlong Space Plane Advances China's Military Space Potential	Shenlong	Fisher [320]
Skylon User's Manual	Skylon	Hempsell [321]
USAF Space Plane Program In Works - Unmanned X-37B To Be Service's Space Test Vehicle	X-37B	Lopez [322]
Air-Breathing Hypersonics Research At Boeing Phantom Works	X-43	Orton [323]
Hypersonic Technologies and Aerospace Plane	FTB-X, HIFiRE, HTV-2, HyFly, LEA, Pollux, Shefex, X-37B, X-51A	Mehta [324]

The unified data-set approach allows the same 'tree-level' data about a single hypersonic project to be repurposed into five different levels (Figure 7.5).

- Product-Evolution Level shows the interaction of projects along program, time, and technology lines.
- Project Level shows the characteristic of an individual hypersonic project.
- Parametric Level shows how a project compares to projects with similar technical characteristics.
- Country Level view aggregates projects that are developed in the same geopolitical area (could also be reframed as all projects from the same organization).
- World Level totals all the efforts of hypersonic R&D.

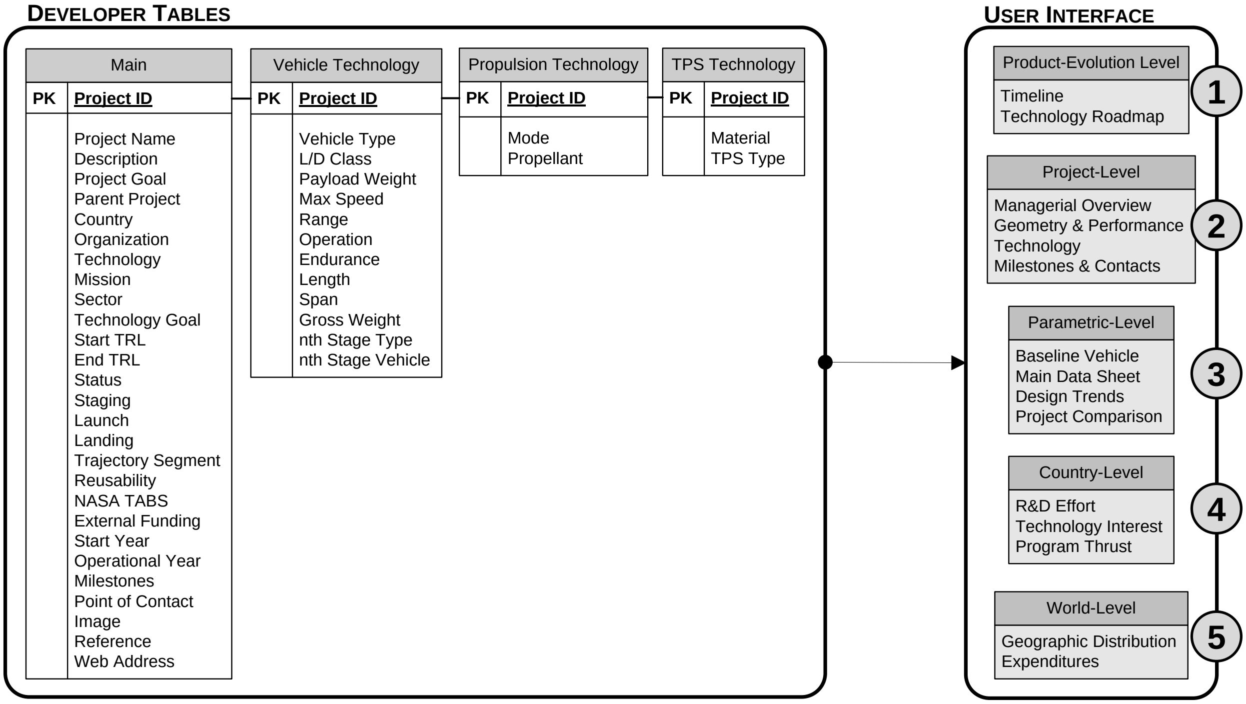


Figure 7.4 – Hypersonic Data-base Schema

7.2.6.4 Data Recall

This method of pulling data towards a pre-made decision-making deliverables is called an (executive) dashboard. Few describes a dashboard as a "*visual display of the most information needed to achieve one or more objectives which fits entirely on a single computer screen so it can be monitored at a glance*" [325]. Dashboards should keep the amount of qualitative data to a minimum, introduce graphic data visualization when possible, and eliminate data that is not necessary to inform the objective decision.

Dashboards for this task are created by with the concept of ‘drill-down’ and ‘zoom-out’. To use the common idiom ‘see the forest for the trees’, levels of data interpretation must be created that allow the user to focus on an individual tree, identify similar trees that share identifying characteristics, evaluate groups of trees that are clustered together, and view the entire forest as a singular entity. The top-level view of the forest is correct only to the extent that the discrete trees are represented correctly.

From this description, the data altitude can be defined as the level / scope of a data view relative to the overall clarity of the dataset.

Five distinct dashboards have been developed that allow the user to access the five discrete data levels specified in the previous section. Under the Data-Engineering paradigm, these dashboard views are the mechanism by which the decision-maker recalls data. Search & filter functions allow the decision maker to select only those projects that pertain to the current decision. Views are digitally linked to allow for back-and-forth exploration of the data. The decision maker is no longer concerned with finding individual pieces of data. They now have the ability to recall pre-digested dashboard views that offer the same pieces of data, but within a larger (and smaller) context at the same time. This represents the functional definition of information production within the Hypersonic DB effort.

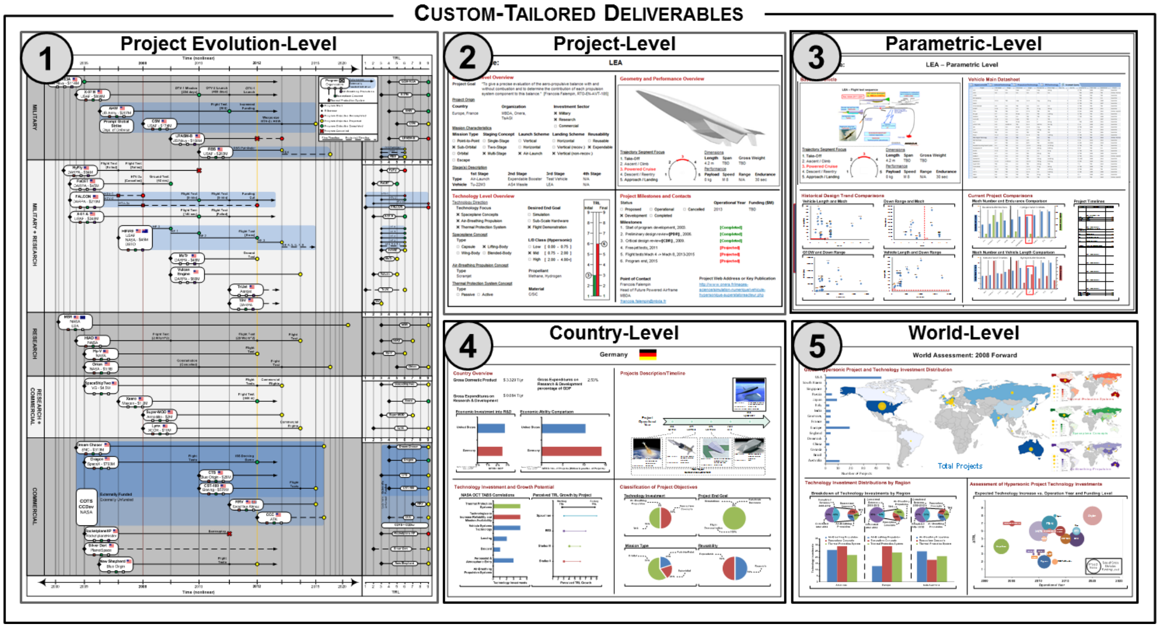
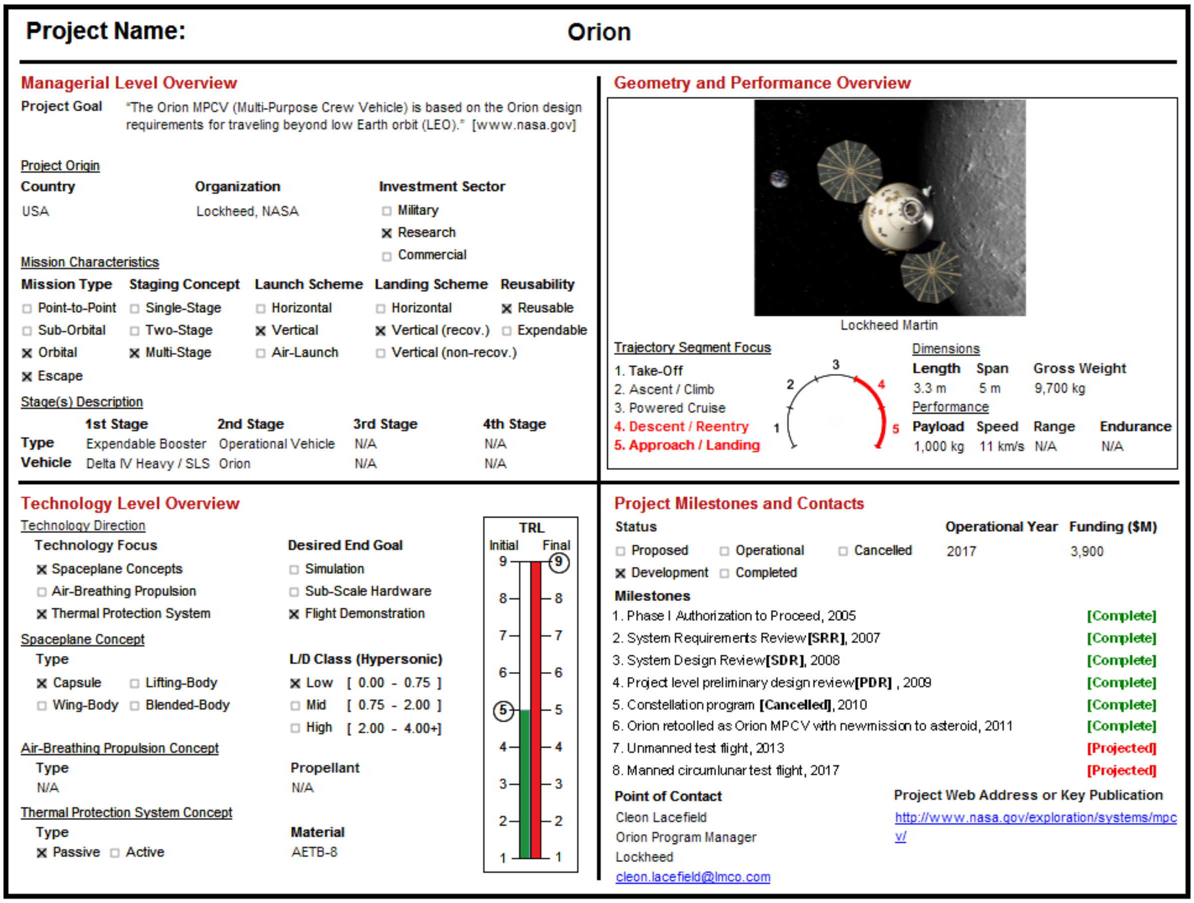


Figure 7.5 – Variable-level Views of the Hypersonic Data-base

7.2.6.5 Data Visualization

Data visualization is intended to illuminate the trends and data points that provide the most impact towards decision making. Each deliverable dashboard should be formatted to elicit the most efficient data to information translation by the decision-maker. Commonality and standardization across the graphic formats must be a point of emphasis throughout the development process.

The project dashboard is designed to communicate an initial managerial assessment of a hypersonic R&D project within a single screen view (Figure 7.6). The dashboard is split into four quadrants that each communicate along a common theme. The upper left provides a qualitative overview, lower left a summary of the technical contributions, upper right quantitative performance characteristics, and lower right the development history of the project and its current status.



Project Name: **Orion**

Managerial Level Overview

Project Goal "The Orion MPCV (Multi-Purpose Crew Vehicle) is based on the Orion design requirements for traveling beyond low Earth orbit (LEO)." [www.nasa.gov]

Project Origin

Country	Organization	Investment Sector
USA	Lockheed, NASA	☐ 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	Expendable Booster	Operational Vehicle	N/A	N/A
Vehicle	Delta IV Heavy / SLS	Orion	N/A	N/A

Geometry and Performance Overview

Lockheed Martin

Trajectory Segment Focus

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

Dimensions

Length	Span	Gross Weight
3.3 m	5 m	9,700 kg

Performance

Payload	Speed	Range	Endurance
1,000 kg	11 km/s	N/A	N/A

Technology Level Overview

Technology Direction

Technology Focus	Desired End Goal
☒ Spaceplane Concepts	☐ Simulation
☐ Air-Breathing Propulsion	☐ Sub-Scale Hardware
☒ Thermal Protection System	☒ Flight Demonstration

Spaceplane Concept

Type		L/D Class (Hypersonic)	
☒ Capsule	☐ Lifting-Body	☒ Low	[0.00 - 0.75]
☐ Wing-Body	☐ Blended-Body	☐ Mid	[0.75 - 2.00]
		☐ High	[2.00 - 4.00+]

Air-Breathing Propulsion Concept

Type	Propellant
N/A	N/A

Thermal Protection System Concept

Type	Material
☒ Passive ☐ Active	AETB-8

Project Milestones and Contacts

Status			Operational Year	Funding ($M)
☐ Proposed	☐ Operational	☐ Cancelled	2017	3,900
☒ Development	☐ Completed			

Milestones

1. Phase I Authorization to Proceed, 2005 [Complete]
2. System Requirements Review **[SRR]**, 2007 [Complete]
3. System Design Review **[SDR]**, 2008 [Complete]
4. Project level preliminary design review **[PDR]** , 2009 [Complete]
5. Constellation program **[Cancelled]**, 2010 [Complete]
6. Orion retoolled as Orion MPCV with newmission to asteroid, 2011 [Complete]
7. Unmanned test flight, 2013 [Projected]
8. Manned circumlunar test flight, 2017 [Projected]

Point of Contact	Project Web Address or Key Publication
Cleon Lacefield Orion Program Manager Lockheed cleon.lacefield@lmco.com	http://www.nasa.gov/exploration/systems/mpcv/

Figure 7.6 – Project-Level View – Orion

Graphical cues have been used to highlight two main project functions.

- The rotary icon highlights the broad segments of trajectory in which the project is contributing R&D (categorized as take-off, climb, cruise, descent, and landing). This roughly translates to the operational capability of the project design.
- The dual bar icon the lower left compares the initial level of technical capability at the start of the program to the technical capability required to complete the goals of the project. The delta split between the two bars represents the technical challenge required two transition through the R&D process.

It is not a coincidence that these two main drivers, operational capability & technical complexity, are the only pieces of data highlighted with graphics – investment cost and return on investment are synonymous with decision making.

The Project-Evolution level data is visualized as a continuous communal timeline that characterizes the top-level features of each project in a condensed icon (Figure 7.8 & Figure 7.7). Projects are subdivided by the role of their primary funding entity; military, research and commercial industry. Each icon contains the project name, funding amount, and country of development – the colored boxes at the bottom edge of each project icon signifies the technology(s) that are being investigated.

The central timeline highlights the major milestones of each project: the line is initiated by the first disclosed start date of the project; strategic events are denoted with points and described in the graphic – completion of all major project goals, as well as project cancellation have been given unique formats to denote their significance; uncertain and defunct timelines are also highlighted.

The secondary scale on the right shows the change in TRL for each project from start to finish. The color of the endpoint corresponds with the development status of the project; yellow – in development, green – operational, red – cancelled. This convention is consistent with the major timeline to the left.

For this research task, the Project-Evolution and Project Level dashboard deliverables have been designed and integrated to function as a single cohesive user interface. When presented to the decision-maker, the project icons on the PE dashboard are digitally linked to the corresponding Project dashboard within the same file – a link back to the PE view from individual projects is also provided. This interactive visualization technique encourages the decision-maker to drill-down and explore related & tangent projects.

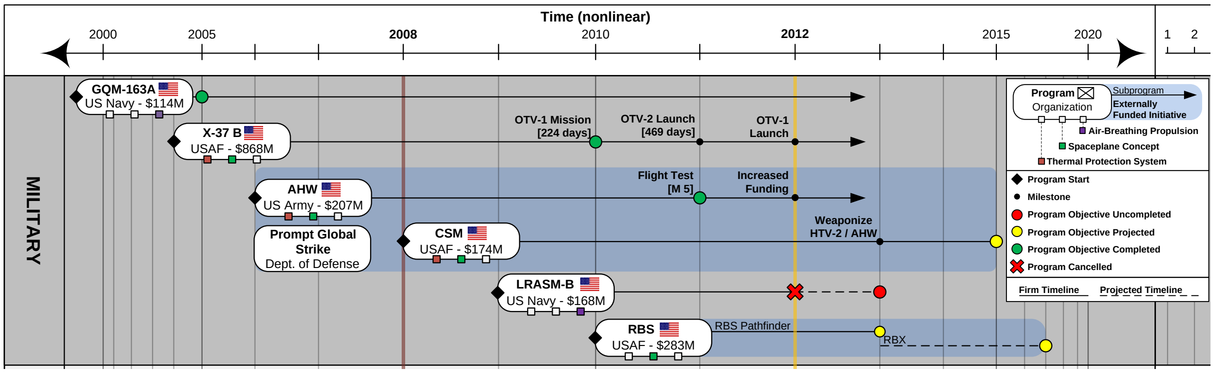


Figure 7.7 – Zoomed View of Project Evolution Level

7.2.6.6 Data Analysis

By aggregating data from different data altitudes, top-level trends about the overall hypersonic R&D landscape can be observed. The trends provide the decision-maker with information on what is changing within the field, what organizations are pushing the changes, and how these changes might affect future capabilities.

Data can be filtered across any combination of variables, and as a consequence the number of trends available to be explored is not bounded. However, the decision-maker is specifically interested in the global status of the United States and its relative position to other technically advanced countries. For these reasons, data analysis is only provided for holistic US hypersonic R&D involvement and adversarial competitors.

Modern Evolution of US Hypersonic Effort

The project status as a function of year has been compiled for all US hypersonic R&D projects that were active between 2008 and 2012 (Figure 7.9). The top portion of the figure shows the number of projects initiated, completed, & cancelled with projected future completions broken out – the bottom portion of the figure aggregates this data to provide the total number of project in development during that year.

As the US recovered from the economic downturn of 2001, several major R&D programs were initiated (X-37B, X-51A, Orion) with the peak number of new projects coming in 2005. However, this increase in R&D effort has not continued after recessionary downturn from 2008 onwards – the number of projects has slowed, with major cancellations in operational programs (Space Shuttle) and proposed concepts (HTV-3X Blackswift). Of all projects successful in the highlighted timeframe of 2008 to 2012, all were at least partially government funded – hypersonic projects still require too much risk & capital investment for the private sector to progress alone.

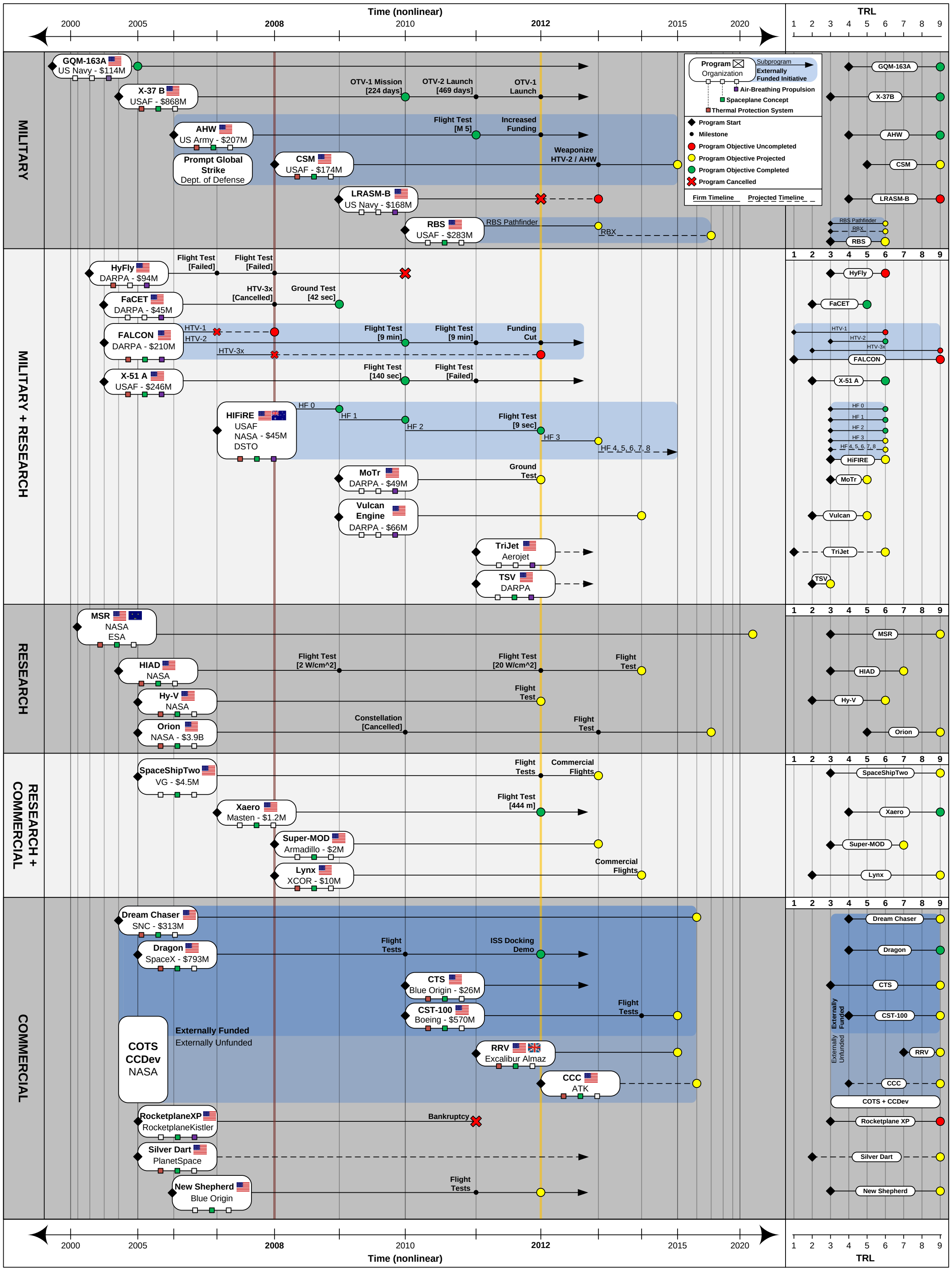


Figure 7.8 – Project Evolution-Level View – Current US Hypersonic R&D

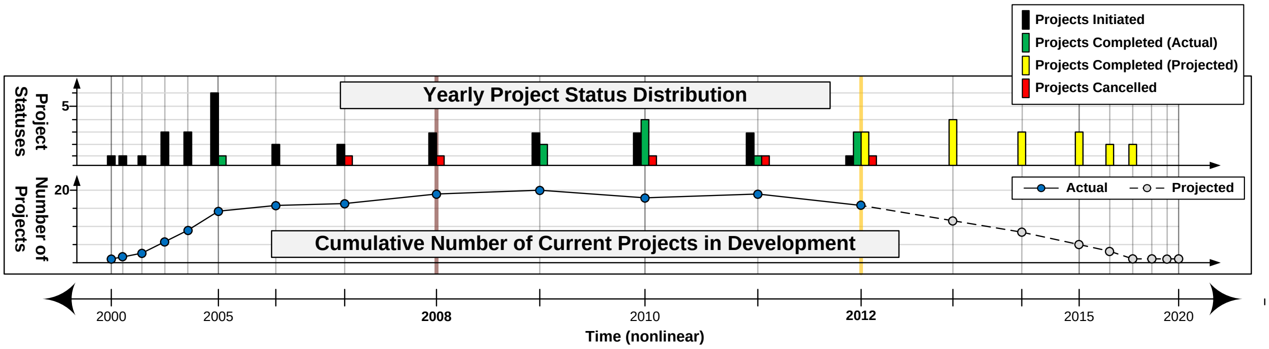


Figure 7.9 – Time Evolution of US Hypersonic R&D Effort

Technical Complexity as an Indicator for Project Success

By aggregating the overall change in TRL for each US project and relating the delta value with the corresponding project status, a correlation between technical complexity and project status is found (Figure 7.10). Cancelled projects tended to be much more complex & ambitious than those projects there were successfully completed within the highlighted timeframe – projects with projected completion past the timeframe had an average technical complexity between the successful & cancelled values.

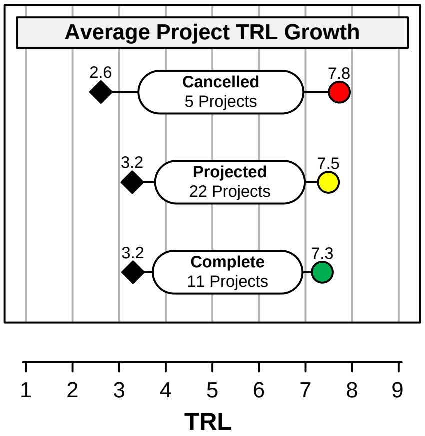


Figure 7.10 – Technical Complexity of Hypersonic R&D Projects by Project Status

This correlation between technical complexity and project status serves as a confirmation of the incremental development paradigm. Programs such as HIFiRE are an example of dividing technical risk amongst a larger number of small, but interrelated R&D efforts. This allows for the individual R&D projects to have reduced time and capital investments, but at a price of lower technical advance per project.

Confirming Unknown Hypersonic Effort with Total R&D Expenditures

By comparing the gross expenditures on R&D (GERD) from reference [326] to the total number of hypersonic R&D projects, country level hypersonic effort can be assessed independently of known projects (Figure 7.11). Due to the strategic & military potential of hypersonic vehicles, hypersonic R&D projects are not always publicly disclosed. Using GERD as a baseline of R&D effort can indicate which countries are likely to have undisclosed hypersonic projects and the magnitude of their concealed effort

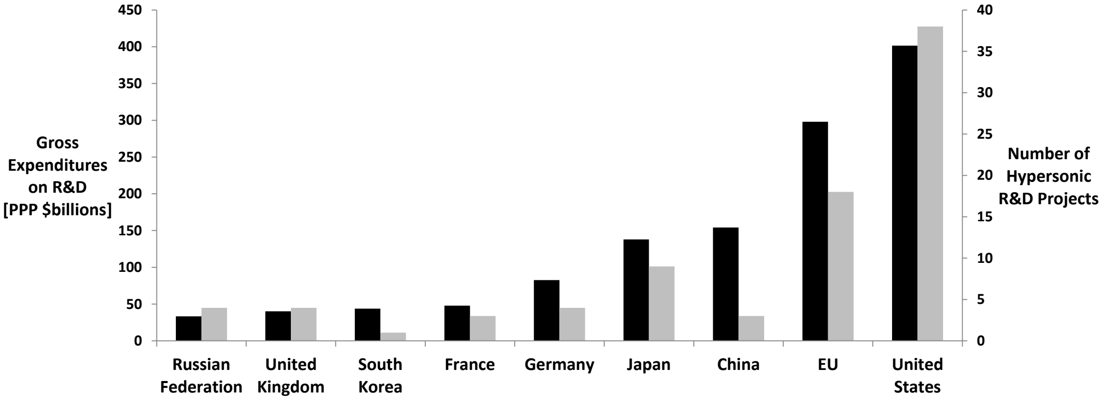


Figure 7.11 – Comparison of Gross Expenditures on R&D and Hypersonic R&D Effort

Of the expected withholders of project data, Russian hypersonic R&D effort is most in line with their country level GERD. Although Russia has significant legacy investments in hypersonics and therefore a residual R&D infrastructure, their current funding levels and hypersonic effort do not reflect progression towards advanced capabilities.

Based on a linear correlation between GERD and hypersonic effort, China's four publically disclosed hypersonic projects at this time of this research task represents roughly one third of the actual hypersonic effort. The number of Chinese hypersonic R&D projects is well below a linear correlation with GERD, which would suggest approximately 15 hypersonic R&D projects.

7.2.7 *Information Summary & Outcome*

The following data-driven tasks have been completed to facilitate information creation:

- Collection, storage, and organization of 53 variables characterizing 118 hypersonic R&D projects (6000+ data points) extracted from press releases, technical reports, conference proceedings, and other publically available sources
- Digital interface of back-end data set with standardized dashboard front-ends

- Graphic visualization of dataset across multiple data altitudes

These steps enabled the following information to be created & communicated the decision-maker:

- A graphically formatted dashboard view of every hypersonic R&D project with data publically available
- An interactive information-graphic timeline displaying the status, characteristics, and relationships of all hypersonic R&D projects based in the United States

These information deliverables created the following conclusions:

- In 2012, the total number of hypersonic R&D projects under development declined for the first time in a decade.
- Of successful US hypersonic R&D projects between 2008 & 2012, all were at least partially government funded.
- The technical complexity of hypersonic R&D projects has an inverse correlation with the success of the project.
- Successful R&D projects are more likely to be incremental in technical complexity.
- Publicly disclosed Russian Federation hypersonic R&D effort is in line with gross expenditures on R&D, and neither are indicative of a country with perceived competitive capabilities.
- Publicly disclosed China hypersonic R&D effort is well below the number expected from gross R&D funding.
- Recent disclosure of the flight test of a hypersonic weapon system[327] exemplifies the probable outcome of Chinese R&D projects only becoming known publicly once they have reached operational status.

7.3 STRATEGIC PLANNING DATA+KNOWLEDGE CASE STUDY: HIGH SPEED TRANSPORT MISSION SELECTION

Portions of the work presented in this section were completed as part of funded research through the NASA Langley Research Student

Scholars Program & the National Institute of Aerospace[328] under contract titled "High Speed Mission Research."

Initial research and discovery was performed solely by the author, under the mentorship of Dr. John J. Korte, as part of a visiting fellowship at NASA Langley Research Center. Additional funded research was performed at the Aerospace Vehicle Design Laboratory at the University of Texas at Arlington, where the author acted as Project Manager and Lead Developer.

Team support in source data collection and analysis formulation was provided by Amit Oza, Amen Omoragbon, Lex Gonzalez, and Dr. Bernd Chudoba in the second phase of this research.

Results have been presented at NASA Langley Research Center.

Contributing Individuals: Amit Oza (UTA), Amen Omoragbon (UTA), Lex Gonzalez (UTA), Dr. Bernd Chudoba (UTA), Dr. John J. Korte (NASA)

Consider the following thought-example: a senior colleague at your organization has decided to retire. They have been with the organization for their entire career, working on a number of projects with their role varying from intern to detailed specialist to manager to executive as time progressed. Your colleague kept notes about each project on which they worked, detailing their individual tasks as well as the top-level organizational progress of the project. The notes describe how (and why) decisions were made from the colleague's position all the way to the top. Now consider after your colleague's last day, the notes, stacked as high as the ceiling, are left in the center of the office for anyone to take & use for their own purposes.

Now the real question: how does one USE these 'notes'? If asked the question, all the colleague's coworkers would probably agree that the notes are valuable – they would not suggest that they be destroyed or discarded as soon as the colleague left the building. But in order to be valuable, something must, by definition, provide value. What is the process to extract value from these notes that directly improves the quality of work of individuals on current projects? Who has time to sit down and read through the notes to find the correct comments about the correct situation that would provide some level of insight? How can results & decisions made with different personnel, toolsets & technical capability for a different period in time be applicable to modern decisions? Is there really anything to learn from the past?

These examples, and the questions posed with it, are very real concerns in aerospace design engineering. Although manned aircraft have only existed for a little over a century, the amount of knowledge obtained (and forgotten) is staggering. It is easy to point to the advances in vehicle technology & analysis methods, and say that the decisions made on past projects do not apply to modern situations & that those legacy decision-making techniques are similarly inferior. Is aerospace vehicle design immune from the Santayana quote, "those who cannot remember the past, are condemned to repeat it"? This argument is pervasive in a number of subfields within the aerospace industry, but there is one vehicle design-mission in particular that is constantly trying (& failing) to reinvent the wheel.

Following the remarkable upward trend of cruise speed in the first half of the 20th century, aerospace organizations sought to extend the technical advances of military aircraft into sustained supersonic commercial flight. The same year the Boeing 707 (which would become the first dominant turbojet-powered airliner) entered production in 1958, separate research committees were formed in the United States & Europe (and shortly thereafter the Soviet Union) to begin research & development towards a supersonic commercial passenger aircraft.

Significant governmental resources went to funding each of these efforts to varying levels of success:

- The US Boeing 2707 was cancelled late in development due to time & cost overruns, and a lack of clear airline interest.
- The European Concorde was successfully developed and operated on a scheduled basis until 2003 despite proving economically & operationally unfeasible in a competitive airline environment.
- The Soviet Tu-144 was successfully developed and operated on a limited basis until 1978 after multiple crashes and uncompetitive economics.

Since this era of development, design engineers have revisited supersonic transport concepts a number of times without any substantial physical development. Due to technical complexity, narrowing operational constraints, and overwhelming financial risk, a mission – vehicle – technology (MVT) combination has not definitely been identified that poses a clear advantageous design concept for supersonic or hypersonic commercial transport – this has not, however, stopped organizations from pursuing technology that support specific concept proposals.

In order to gain public & substantial government (fiscal) support, a MVT combination must be identified that not only satisfies technical requirements, but also competing market, environmental, social, political, and economic requirements. Despite these overwhelming challenges, recent high speed transport R&D has tended to bypass this critical identification phases, instead focusing on detailed technical challenges that may or may not serve a viable MVT combination.

7.3.1 Decision-Making Problem Statement

The decision-makers are program manager- & chief engineer-level personnel with direct input to the hypersonic R&D focus of a national aerospace research organization (NASA). They seek information on how past high speed commercial transport aircraft have identified and justified their mission, vehicle, and technology considerations, as well as how such a process might be applied to future high speed transport efforts to best identify a feasible design direction.

7.3.2 Determine Resources

High speed transport R&D programs have tried and failed spectacularly to bring an aircraft to market in the past. It is doubtful that the public or the US government has the appetite for funding a full-scale development program at any time in the near future. However, the potential gains of such a system remain large enough that individuals and private organizations continue to seek a feasible design, one that will require the planning and early design phases to correctly assess the cost, benefit, risk & uncertainty of the endeavor.

Cost

The immediate costs are minimal – the research task is before design, as well as before strategic planning, and therefore a small number of personnel have been budgeted. The indirect implied costs are large however. The process, if successful, will possibly be used to select the course of action for a R&D program requiring substantial human & fiscal resources.

Benefit

If a high speed transport aircraft is to be successful, it will require not only significant technical advances at the detailed design level, but similar advances in the mission planning phase. But if a high speed transport aircraft is successful to the degree that has been planned in previous early design iterations (replacing long range subsonic aircraft and becoming a substantial portion of the aircraft transportation market), the fiscal & societal benefits are also enormous. Allowing long range travel in less than half the time of the status quo medium was, and is, a revolutionary benefit.

Risk

There is minimal risk in providing no response – if a competitive high speed commercial aircraft exists in the future, the development will be long, costly, and well publicized. The only risk lies with proceeding forward in development with a 'dead horse', a MVT combination that does not meet the necessary technical & non-technical requirements for success. Whether this poor planning choice is due to negligence, misdirection, or inability to properly characterize the holistic system, there is a risk of alienating the funding stakeholders from future high speed aircraft efforts – the public does not have the appetite in the current fiscal environment for back an unsuccessful or unrealized aircraft program.

Uncertainty

The operational requirements of a high speed transport are full of uncertainties – the price & availability of fuel, geopolitical environment, route demand, and environmental constraints are all uncertain inputs that will have a direct effect on the feasibility of a transport system.

7.3.3 Identify Options

At this stage in the design cycle, exactness is both improper and misleading. Therefore options are identified as broad categories of the potential design space: payload capacity is segregated into small & large (roughly divided by business jet-size and all others), and design speed into supersonic & hypersonic (roughly divided by Mach 5). Any mission planning recommendations will point towards a combination of these top-level options.

7.3.4 Establish Information Requirements

Information is being provided at two distinct levels: a process & an implementation of the process that leads to a specification (Figure 7.13).

- Process – Identify a list of key deliverables that have been used in the past to identify & justify the design mission-vehicle-technology of high speed transport aircraft based on their market, environmental, societal, political, economic, and technical considerations
- Implementation – Application of the deliverables identified by the process level to the current high speed transport planning environment in order to specify the most beneficial direction for future research & development.

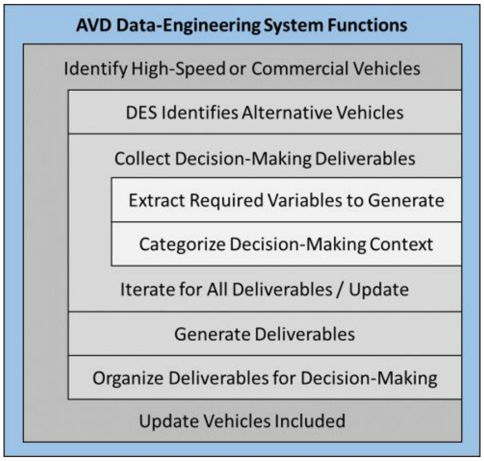


Figure 7.12 – High-Speed Mission Research Methodology Diagram

7.3.5 *Retrieve / Create Information: Data Domain*

Understanding the decision-making process, and specifically, the communication of the decision-making process to stakeholders is a large portion of the current task. One of the key methods of communication in the design & development of any system is the graphical figure – a visual aid that combines qualitative & quantitative data to provide the reader an additional level of information.

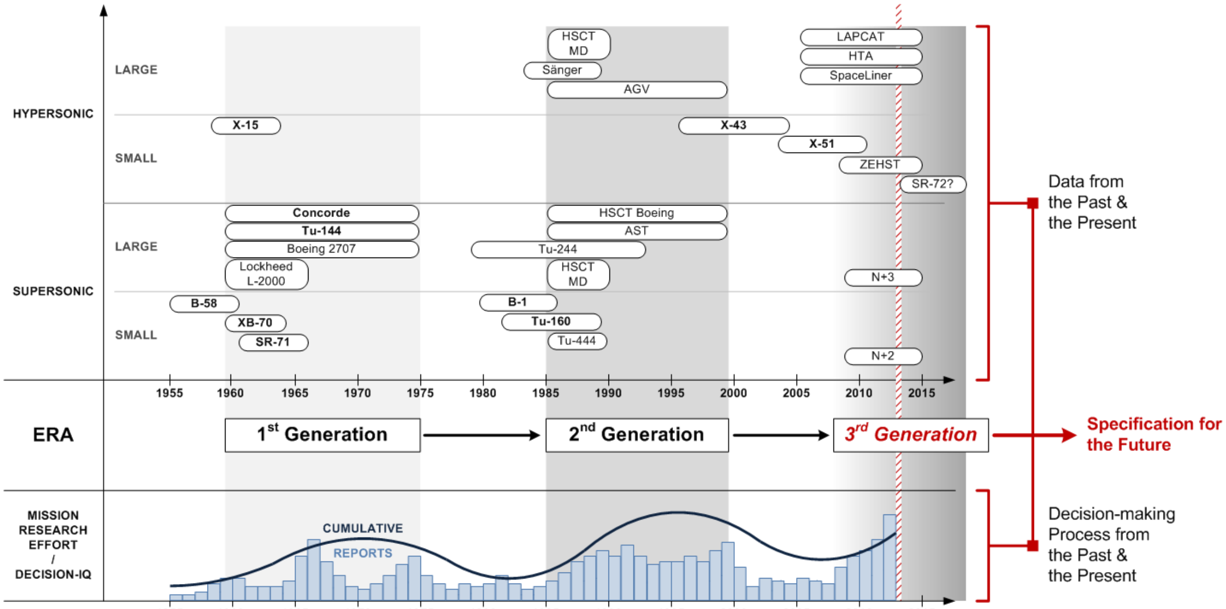


Figure 7.13 – Three Eras of High Speed Transport Research & Development

By this definition, figures (referred to here as deliverables as well) are the de facto end-product of an information production process. They hold the hand-selected variables, visualizations, and verbiage that the information-producing team thought would best communicate the information that they knew and understand about the project. By examining how systems developers have justified projects in the past through deliverables, one can better understand how to communicate justification for future projects with similar demands during the development process.

7.3.5.1 Data Collection

Along the same dual tracks laid out in the Information Requirements section 7.3.4, data points must be collected describing the process (deliverables) and data points must be collected so that the process can be implemented. The process deliverables are often found in the same source documents that contain vehicle & other detailed data (e.g. design reports, market surveys, and historical summaries) – the personnel producing the information are often the best judges of how to communicate the information as well.

Source documentation from the first era of supersonic transport aircraft (Lockheed L-2000, Boeing 2707, Concorde & Tu-144) is either difficult to locate, or is not publicly available (e.g. the final summary report from British Supersonic Transport Advisory Committee, STAC, that justified development of the Concorde is still classified by the British government) – unfortunately, the reasoning behind the design concepts that were actually operational is the least understood. The proceeding generations, including current efforts, however, have significant decision-making data available from a number of different locations.

Contract Reports

Contract reports provide significant insight into both the ‘why’, ‘what’, and ‘how’ of specific design concepts. Although restricted to mostly US efforts, government report servers have made contract reports from high speed transport aircraft development available.

- After the cancellation of the American SST program (Boeing 2707), NASA sponsored independent assessments of the route demand, scheduling, and productivity supersonic plus transport aircraft[329][330].
- The most extensive & well documented studies detailing the full conceptual development are the McDonnell Douglas[331] and Boeing[332][333][334] High Speed Commercial Transport studies overseen by NASA in the late 1980s.

- As part of the most current era, NASA has collaborated with industry & academic organizations to study the technologies required for next-generation supersonic transport concepts in the "N+2"[335] and "N+3"[336][337] research studies.

Conference Proceedings

Conference proceedings from high speed transport-specific symposiums offer insight into government and industry mindsets towards design & concept planning. Although detailed program data is unlikely to be found, summary deliverables are often presented in conference proceedings to clarify & visualize qualitative conclusions. References [338], [339], [340], [341] & [342] all provide high speed transport process data.

Reports (Other)

Reports / memorandum commissioned by industry & governmental agencies are a source of both process & implementation data

- Research council reports offer programmatic motivation & justification for high speed transport, often agnostic of concept specifics – political motivators are often emphasized more in this source type than any other. The National Research Council (NRC) has authored the following references that inform high speed transport planning: [343], [344], [345], [346].
- Population and GDP data needed to recreate route demand deliverables is available from intergovernmental presentation reports (e.g. United Nations Urban Agglomerations[347]) and independent think-tank white papers (e.g. PricewaterhouseCoopers's[349] and McKinsey Global Institute's[350] urban economics forecasts).
- Current & historical fuel prices, including methane, are available online through the US Energy Information Administration[348].
- Major airframers provide market outlooks for traffic and aircraft demand (e.g. Airbus[351], Bombardier[352] & Boeing[353]).

Books

There are a number of books published by individuals on the subject that have provided useful data:

- Due to the highly publicized nature of the high speed transport field, project data and excerpts from internal organization documents can be found in several books detailing historical development projects (e.g., Concorde: [354][355][356]).
- Küchemann's *The Aerodynamic Design of Aircraft*[357] provides a seamless interface between top-level mission-vehicle-technology design and detailed technical analysis – this is a prime source of decision-making justification used in this research task.
- Davies's *Fallacies and Fantasies of Air Transport History*[358] and *Supersonic (Airliner) Non-sense*[359] take a dissenting look at the feasibility of high speed transport in both past & future scenarios from an airline demand professional's point of view – graphic deliverables provide the crux of Davies's thesis.

Data Warehouses

Current & historical airline route demand is available from third-party data providers, but at a substantial cost – publically available cost and route frequency data available through travel search portals is used instead (though these sources require manual data extraction).

Technical Reports

Technical journals were not a significant contributor to design & planning data – they tended to present a disciplinary focus on previously-fixed design concepts.

7.3.5.2 Data Organization

Data has been organized into three main categories within the data support environment: deliverables data, vehicle data, and route demand data. Beneath these functional levels, source documentation data links the original document and saves intra-document location tags.

Deliverables data has been organized into the following descriptive fields (available options are in brackets):

- Scope – the stakeholder / decision-making level to which the deliverable addresses [Project – Country – Global]

- Domain – the decision-making topic(s) addressed by the deliverable [Market – Environmental – Social – Political – Economic – Technical]
- Reference Examples – source documents that use the deliverable (detailed in Section 7.3.5.4)

Vehicle data, used to populate deliverables and develop operational trends, has been processed under the *DE* framework outlined in previous chapters.

Route demand is made up of constituent data sets, most of which will be used for deliverable reconstruction:

- Urban Agglomeration (UA) Data
  - Population – past, current & forecasted population within the UN-defined city parameters
  - Gross Domestic Product – past, current & forecasted GDP within the area
- Country – linked to sub-dataset of countries and corresponding continent
- Location – longitude & latitude of major airport servicing the area
- Route Demand Data
  - City-Pair – combination of UA IDs the route connects
  - Distance – calculated field of great circle distance between the two UAs using latitude (ϕ), longitude (λ), and Earth's radius (R_E) by Equation 1

$$\boldsymbol{D}_{\mathbf{1\leftrightarrow 2}} = \mathbf{cos^{-1}}(\mathbf{sin}(\boldsymbol{\phi}_{\mathbf{1}}) * \mathbf{sin}(\boldsymbol{\phi}_{\mathbf{2}}) + \mathbf{cos}(\boldsymbol{l\phi}_{\mathbf{1}}) * \mathbf{cos}(\boldsymbol{\phi}_{\mathbf{2}}) * \ \mathbf{cos}(\boldsymbol{\lambda}_{\mathbf{2}} - \boldsymbol{\lambda}_{\mathbf{1}})) * \boldsymbol{R}_{\boldsymbol{E}}$$

Equation 2

  - Flight Time – approximate value of flight in hours
  - Demand – average number of available non-stop flights per day
  - Price – approximate ticket value of business class seat (reasoning below)

7.3.5.3 Data Storage

Deliverables have been extracted from their native documents and saved as independent .pdf files – this image location is embedded in the index that specifies where it was found in the original source document (Figure 7.14). Because the deliverable file is stored by reference, the image can be opened from separate data system views as well.

All data variables described in the previous section have been assimilated into a single data support system and linked by common variables (e.g. UA GDP from one source is put in the same data table with UA population from a separate source) – different datasets are not treated separately or in an ad hoc fashion. When visualizing & analyzing data from multiple data sources, ensuring all datasets are in a unified data support system ensures data consistency and promotes data integrity.

7.3.5.4 Data Recall

A data support view is available for each deliverable – the form view contains a description, user notes, decision scope, decision domain, and analysis step of the deliverable. The library of deliverables may be searched, filtered, and sorted by any of these fields. Within each deliverable form, the user can view examples of that deliverable within their respective source document.

7.3.5.5 Data Visualization

Summary views of the deliverables library for each domain have been created to provide a broader view of the available decision-making deliverables. Within each domain-specific library summary view, each deliverable in the library is referenced by decision scope and thumbnail deliverable examples are shown (Figure 7.15).

7.3.5.6 Data Analysis

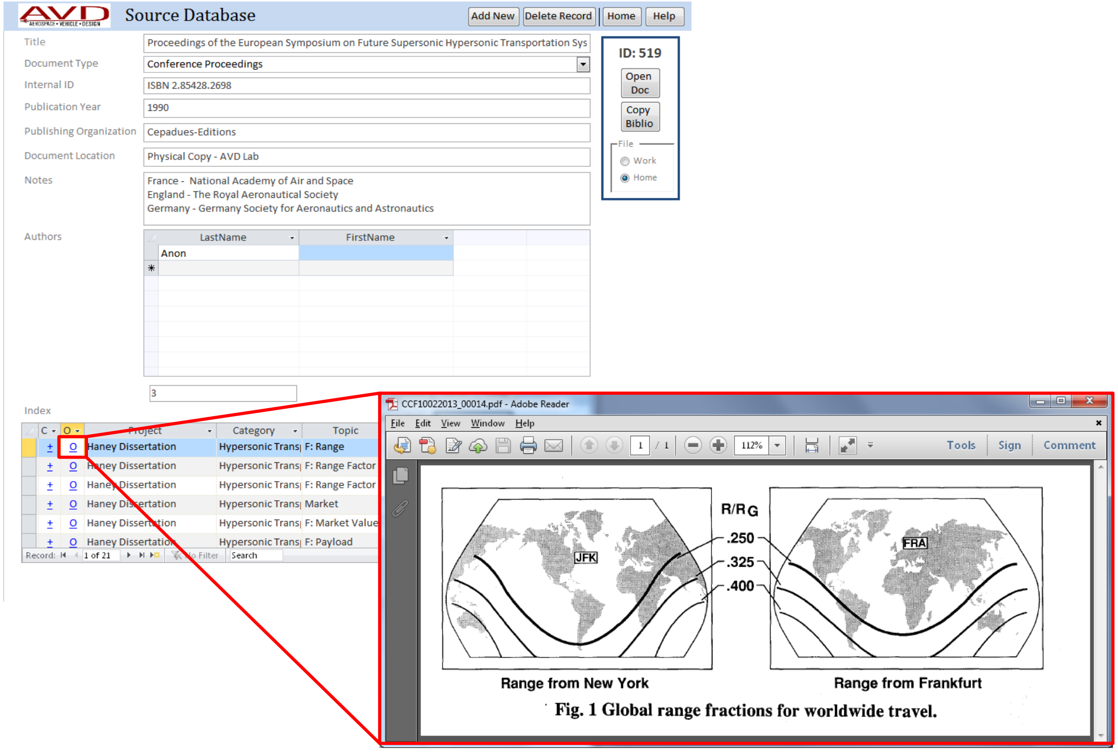
Analysis of the deliverable (process) data and the implementation data comes in the form of recreating deliverables identified as having the largest impact on MVT planning & decision making – the analysis of these deliverable visualizations is covered in Section 7.3.7.

7.3.6 Retrieve / Create Information: Knowledge Domain

After completion of the data domain tasks of information creation, the following items are available to the research team: (1) a library of deliverables that inform high speed transport mission-vehicle-technology selection & decision-making, and (2) a unified dataset of available technical & non-technical data that can be used to populate these deliverables.

The end goal from the knowledge domain is to select deliverables which most influence decision-making under current & future MESPET scenarios, and that have data available to populate them. Although a 'complete information' scenario would call for the recreation of all deliverables within the library, decision-making is never an ideal situation – time, labor and available data are always constraining factors. Additionally, information is not produced uniformly across deliverables

– there are some deliverables that communicate the entire scope of a problem within one view, and some deliverables that only provide information to address a specific slice of the problem.



Title: Proceedings of the European Symposium on Future Supersonic Hypersonic Transportation Sys
Document Type: Conference Proceedings
Internal ID: ISBN 2.85428.2698
Publication Year: 1990
Publishing Organization: Cepadues-Editions
Document Location: Physical Copy - AVD Lab
Notes: France - National Academy of Air and Space
England - The Royal Aeronautical Society
Germany - Germany Society for Aeronautics and Astronautics

ID: 519

File: ○ Work ● Home

Authors

LastName	FirstName
Anon	

3

Index

C	O	Project	Category	Topic
+	O	Haney Dissertation	Hypersonic Trans	F: Range
+	O	Haney Dissertation	Hypersonic Trans	F: Range Factor
+	O	Haney Dissertation	Hypersonic Trans	F: Range Factor
+	O	Haney Dissertation	Hypersonic Trans	Market
+	O	Haney Dissertation	Hypersonic Trans	F: Market Value
+	O	Haney Dissertation	Hypersonic Trans	F: Payload

Record: 1 of 21 No Filter Search

Fig. 1 Global range fractions for worldwide travel.

Figure 7.14 – Embedded Deliverable Image Storage in Data Support System

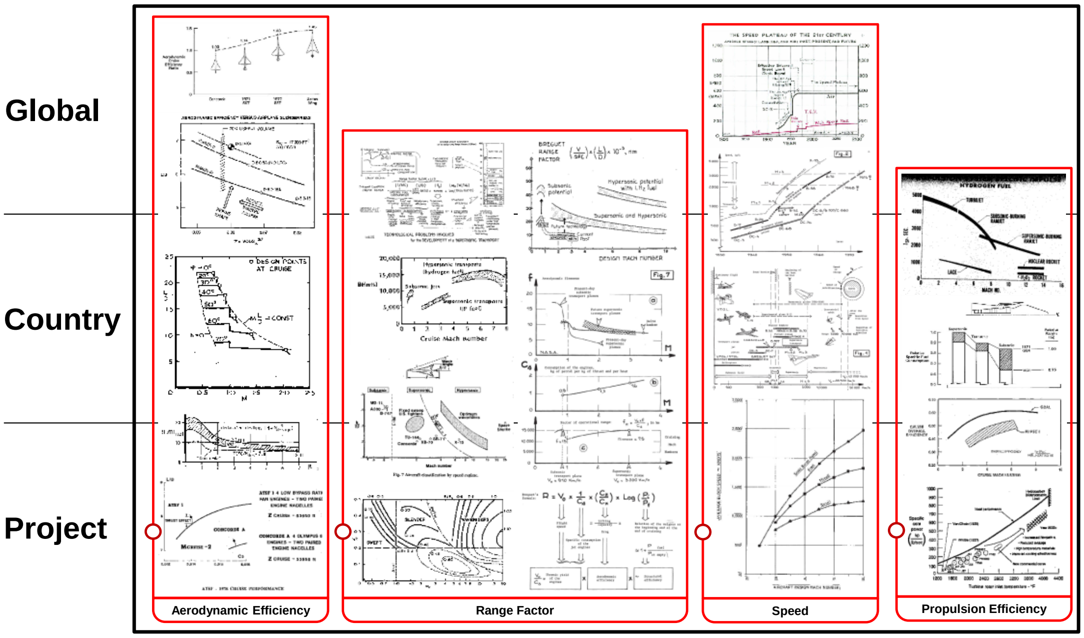


Figure 7.15 – Deliverables Library Summary: Technical Domain

Fortunately, the selection of deliverables is not solely left to the forecasting team – by pulling deliverables from the brightest minds, on the best teams, working on the most relevant historical projects, the current team is directly adding the experience of these individuals to their knowledge domain. Deliverables represent a culmination of knowledge at in instance in time where a group of individuals was completely engrossed in a task.

By using these past deliverables as the basis for future decision-making the forecasting team is indirectly asking individuals that spent substantial portions of their career working on a similar problem, "What information should I produce & how should I communicate this information to the decision-maker?" This is a substantial addition to the knowledge-base of the forecasting team – they cannot expect to study the problem at the level of detail a source individual has, but they can retain the level of understanding necessary to appropriately communicate the problem to the decision-maker.

From this knowledge-based process, three deliverables have been identified that communicate information about more than one domain, have a direct influence on mission planning, and have been utilized in the past to inform decision-making during development.

Operational Capability Evolution

Information Communicated: Compares the specified Payload, Speed and Range specified during the initial design timeframe to the existing Commercial, Military, and Research operational capabilities.

Reason for Inclusion: Understand which configurations & technologies will need to be leveraged for a forecasted operational capability

Required Data: Payload Mass, Speed, Range, Operational Year

Deliverable Source: R.E.G Davies, airline demand forecasting analyst [358]; P. Poisson-Quinton, aerodynamics design engineer Concorde [341][360].

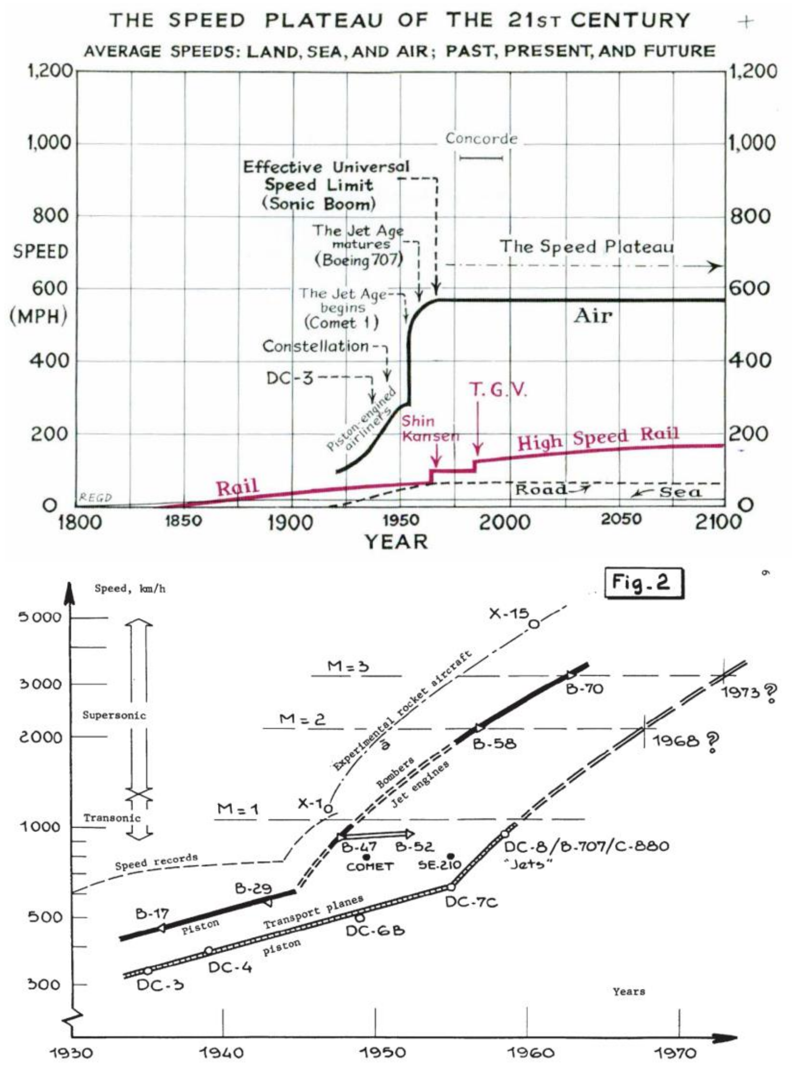


Figure 7.16 – Operational Capability Deliverable Examples (Top from Ref. [358], Bottom from Ref. [360])

Fuel (Operating) Cost

Information Communicated: Provide a proxy for Operating Cost per Passenger with a direct function of Passenger Capacity, Fuel Mass, Fuel Type Selection, and likely range of Fuel Cost.

Reason for Inclusion: Relative cost of transporting payload a given distance is an indicator of commercial feasibility.

Required Data: Number of Passengers, Fuel Mass, Fuel Density, Fuel Cost, Range

Deliverable Source: McDonnell Douglas HSCT Program [331] (Fuel Mass per ASNM); Aerospatiale Advanced Supersonic Transport Program [361]

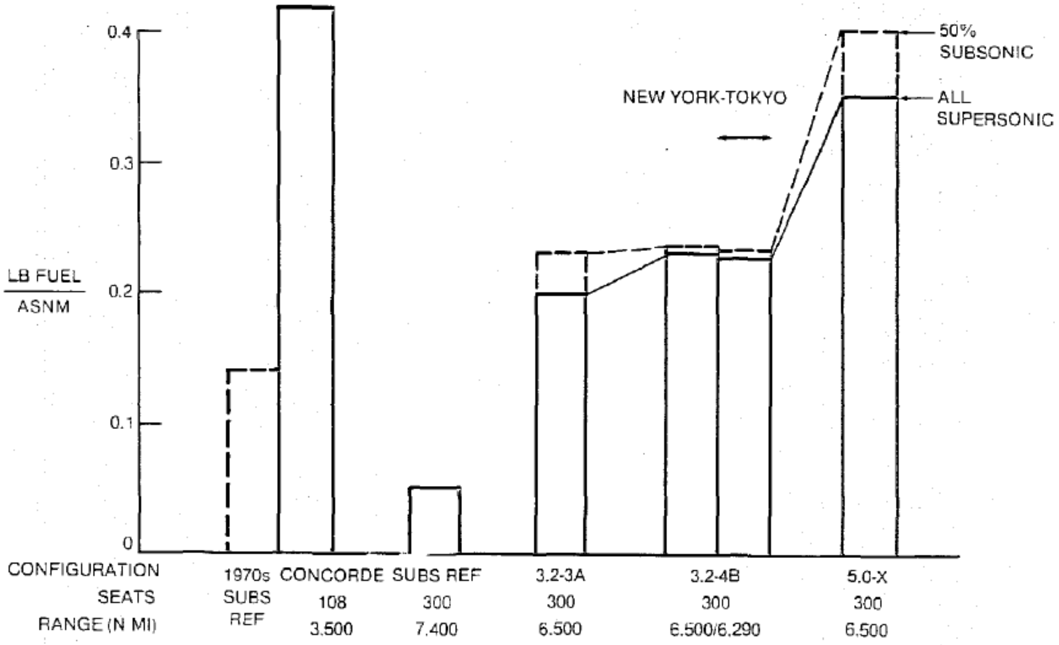
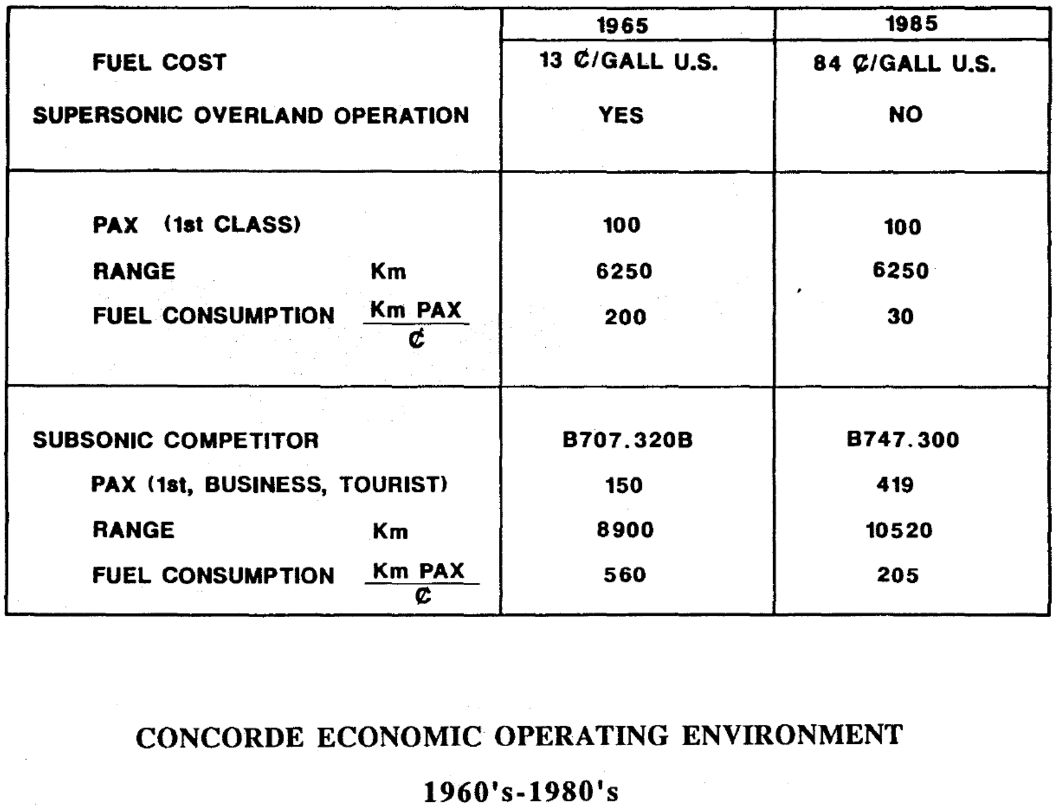


Figure 7.17 – Operating (Fuel) Cost Example[331]



	1965	1985
FUEL COST	13 ¢/GALL U.S.	84 ¢/GALL U.S.
SUPERSONIC OVERLAND OPERATION	YES	NO
PAX (1st CLASS)	100	100
RANGE Km	6250	6250
FUEL CONSUMPTION $\frac{\text{Km PAX}}{¢}$	200	30
SUBSONIC COMPETITOR	B707.320B	B747.300
PAX (1st, BUSINESS, TOURIST)	150	419
RANGE Km	8900	10520
FUEL CONSUMPTION $\frac{\text{Km PAX}}{¢}$	560	205

CONCORDE ECONOMIC OPERATING ENVIRONMENT

1960's-1980's

Figure 7.18 – Operating (Fuel) Cost Example[361]

Latent Route Demand

Information Communicated: Estimates relative range demands by connecting Population distribution and Distance between city-pairs.

Reason for Inclusion: Commercial aircraft provide a transportation function between population centers – follow the people.

Data Required: Urban Agglomeration (UA) Latitude & Longitude, UA Population (forecast), Range

Deliverable Source: D. Kuchemann, aerodynamic design Concorde [357]

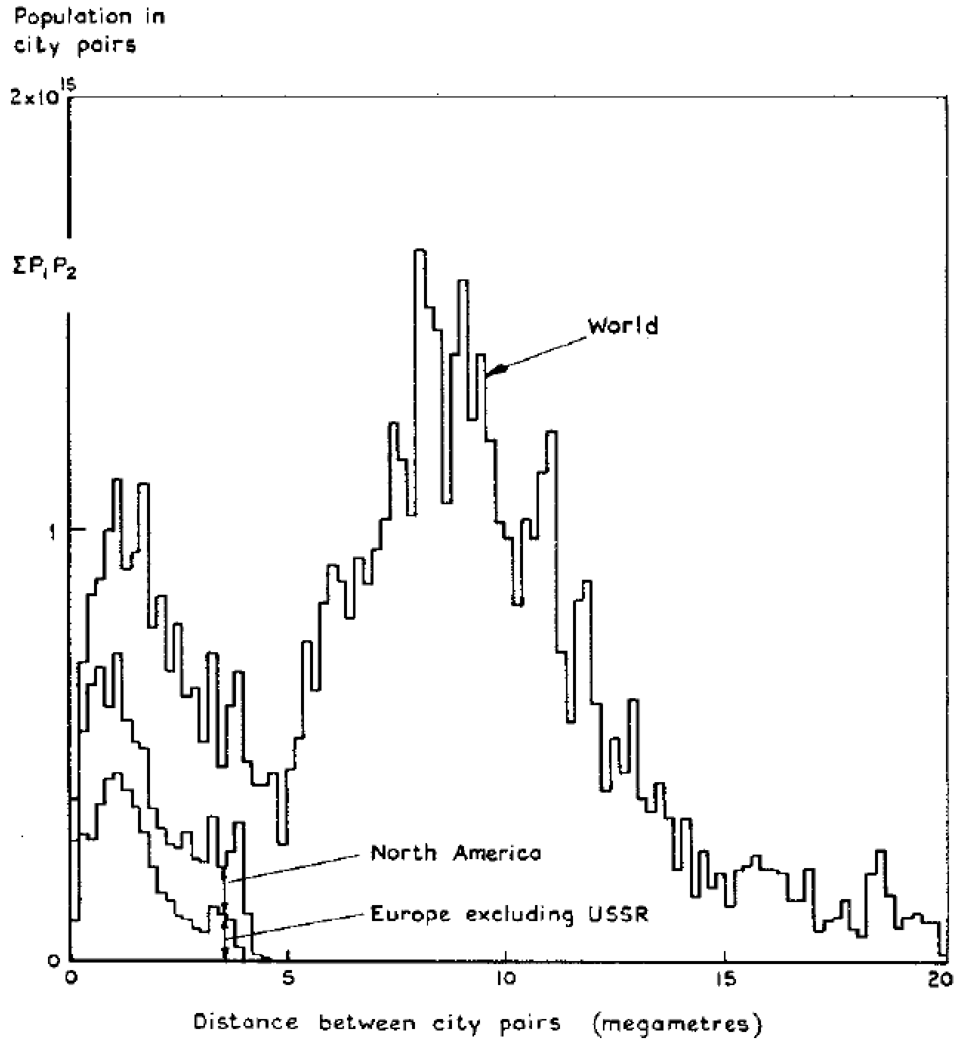


Figure 7.19 – Latent Route Demand: Historical Example (from Reference [357])

7.3.7 *Information Summary & Outcome*

The package of three deliverables identified in the previous knowledge domain section can now be applied to past high speed transport projects to re-engineer the decision-making process, or be applied to current proposed concepts to provide design guidance – both paths have been provided.

For historical application of the deliverables, data from the 1st generation of high speed transport (i.e. Concorde, Boeing 2707, Tu-144) has been used, with the discussion focused around the definition & development decision-making of the Concorde.

Current proposed concepts have been restricted to vetted designs or design of competitive interest: ESA LAPCAT, NASA N+2 & N+3, DLR SpaceLiner, JAXA HTA, and EADS ZEHST.

Past Concepts – 1st Generation High Speed Transport

The Concorde is selected because of its emblematic status of the supersonic transport field. It also stands as the most successful as measured by number of commercial flights. The data used in the following deliverables is in Table 7.2.

Table 7.2 – Concorde Data Required for Deliverables

Variable	Value	Unit	Reference
Range	7250	km	FAA Type Certificate [362]
Propellant Mass	96069	kg	FAA Type Certificate [362]
Payload Mass	13380	kg	BA Website [363]
Cruise Speed	2	M	BA Website [363]
Number of Passengers	100	-	BA Website [363]

Operational Capability Deliverable

Operational capability deliverables (Figure 7.20, Figure 7.21, and Figure 7.22) illustrate the capability of existing military, commercial & research aircraft at the time of the mission definition process – the approximate entry into service year is also denoted.

From the payload capability deliverable (Figure 7.20), it is apparent that the decision-makers chose a design passenger capacity below that of the existing subsonic Boeing 707, and the capability trend was still increasing. The Concorde's 100 passengers was too small to compete in a multi-class market – the decision proceed with a smaller concept restricted operation to business class & first class markets only.

The speed capability deliverable (Figure 7.21) emphasizes that all 1st generation concept were banking on successful crossover of military technology. Mach 2+ cruise speed was a step-change in commercial capability.

In regards to payload capability (shown in Figure 7.22), Concorde is once again below both the existing status quo and the trend line for capability. Taking the military B-52 as the likely trend in range requirements for an international economy, Concorde's design range becomes even more of a detriment.

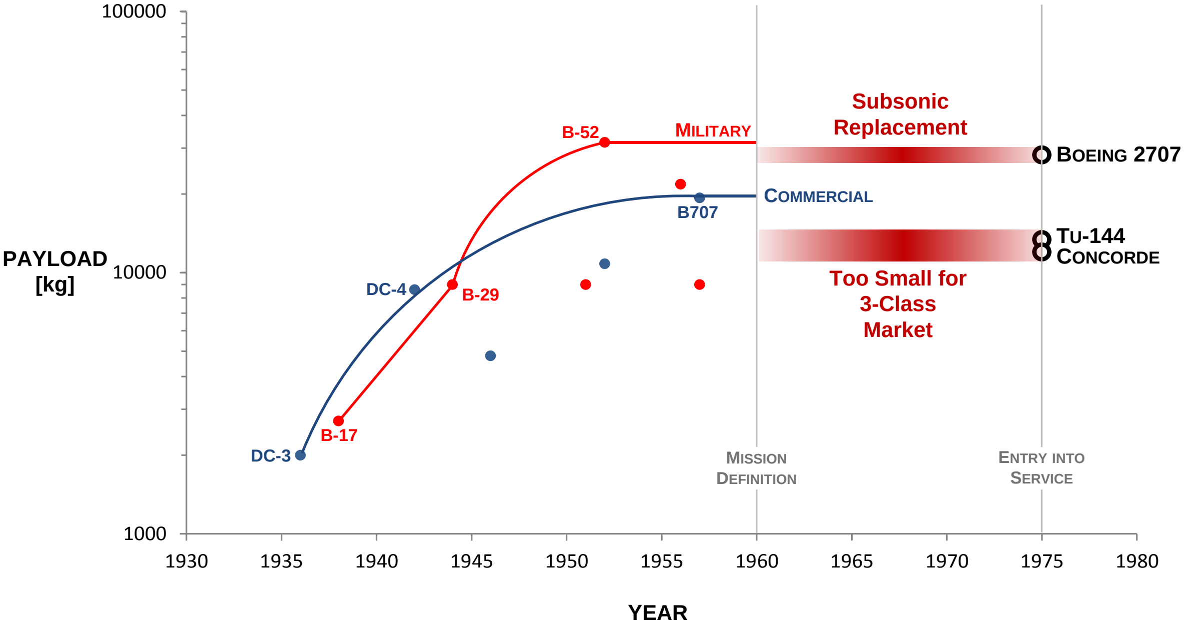


Figure 7.20 – Operational Capability: Payload – 1st Generation

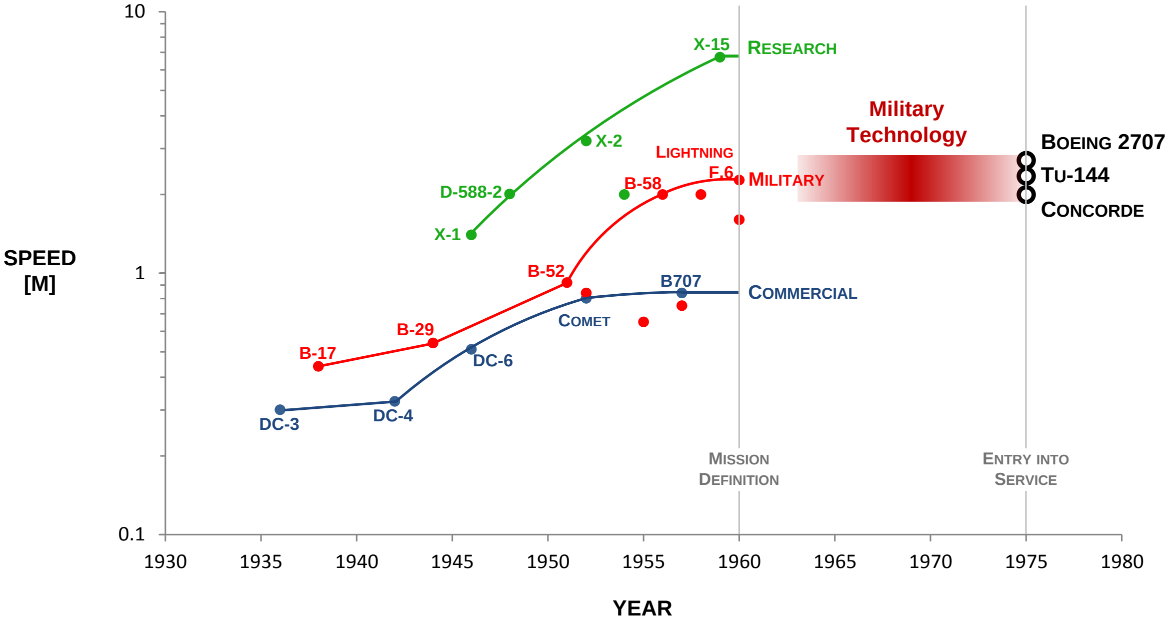


Figure 7.21 – Operational Capability: Speed – 1st Generation

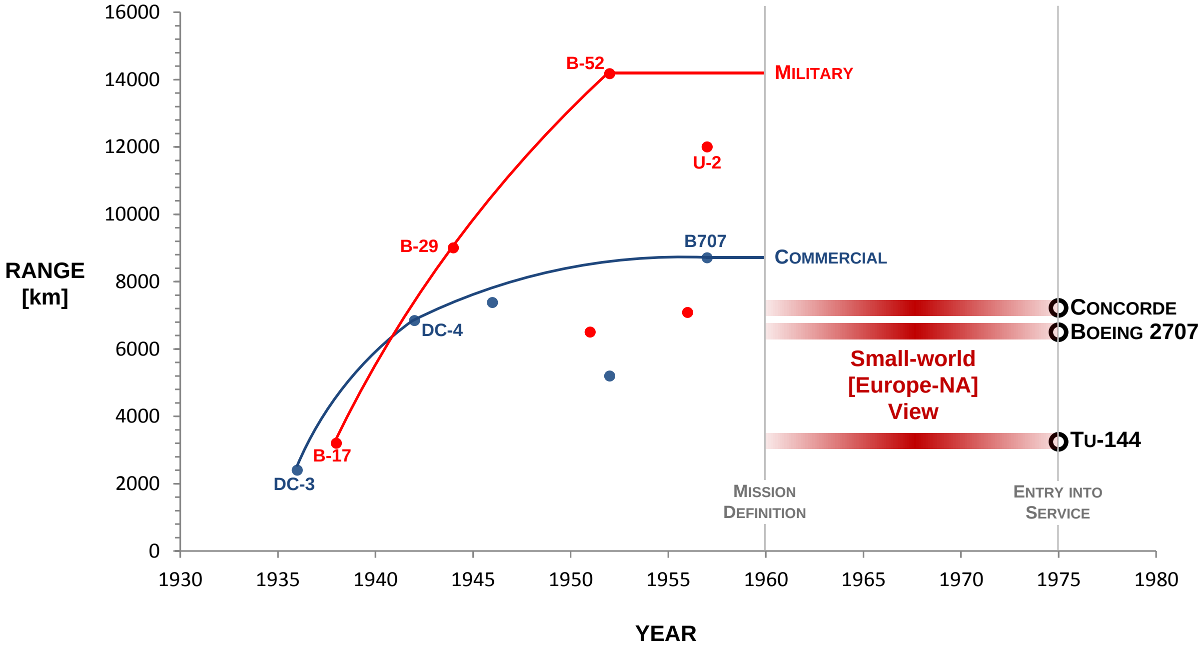


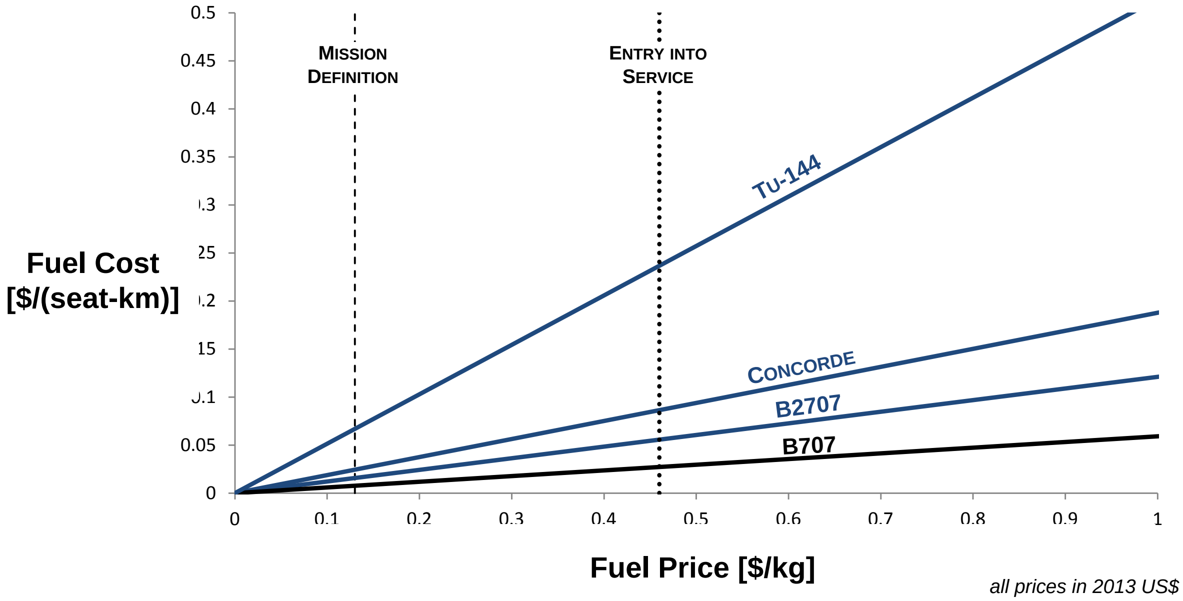
Figure 7.22 – Operational Capability: Range – 1st Generation

Summary (Operational Capability): Concorde chose a design MVT combination that relied on integration of military technology unproven in commercial operations and a capability that failed to address existing or future competitors. Unless the payload, range or both could be increased, the Concorde is not going to compete with the forward trend in subsonic commercial transports on the basis of operational capability.

Operating Fuel Cost Deliverable

The normalized fuel cost deliverables (Figure 7.23) shows the cost for a full tank of jet fuel per available seat per maximum range of the transport aircrafts. At the time of mission definition, fuel cost had been relatively stable a period of decades – back to the 1930s. The larger mass of fuel required for the Concorde design compared to the subsonic competitor means that Concorde's fuel cost is much more susceptible in absolute terms to variances in fuel price.

Summary (Fuel Cost): The drastic rise in fuel price from planning to entry into service date of the Concorde was a low probability event, but the high fuel-low passenger-low range combination increased the sensitivity to an already high risk outcome. In order to keep risks in line with subsonic competitors, some combination of increasing range, increasing payload capacity, or increasing fuel efficiency must occur.



all prices in 2013 US$

Figure 7.23 – Operating Fuel Cost: 1st Generation

Latent Route Demand Deliverable

Potential route demand as estimated by the combined populations of all UAs for a given distance is shown in Figure 7.24. The population distribution is that of the entry into service data, 1975 – UA population data was not found for the mission definition timeframe. It is assumed that the Concorde forecasting team either would have had access to population forecast data. In addition, it is assumed that this discrepancy would only change the magnitude, and not the shape, of the distribution.

Concorde's design range fails to encompass the peak spread of population at roughly 9000 km. Even the subsonic leader of the market failed to adequately address this route demand – the Tokyo–Los Angeles route falls under this range.

Summary (Latent Route Demand): The Concorde range is overextended for a regional transport and under extended for a global transport. By anchoring the design capabilities on the single most popular route (New York–London), the design point is incapable of serving new markets.

Summary (Overall): Given the Operational Capability, Fuel Cost & Latent Route Demand deliverables, a Concorde decision-maker with 1960's data can make the following conclusions:

- The design is too small to compete with current, and especially with future, subsonic commercial transports in a multiple-fair environment
- The design lacks the range to compete with current & future subsonic transports, and is not able to serve high-potential long-range routes

- The design is highly susceptible to upward fluctuations in fuel price compared to subsonic competitors.
- The design is reliant on transfer of technical data & knowledge from research and military sources.

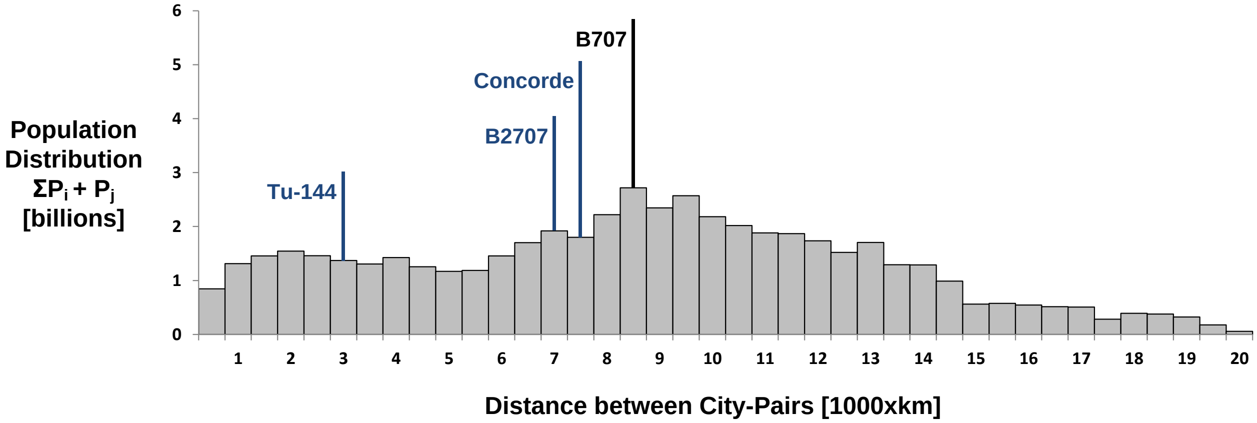


Figure 7.24 – Latent Route Demand: 1st Generation

Current Concepts – 3rd Generation

Identifying which current high speed transport concepts are "competitive" or are legitimate development projects (not publicity stunts, or a jobs-project) is an iterative process that the decision-maker should be involved in. Including all projects in an assessment dilutes the information about projects with a higher chance for success, and therefore demands more attention. Projects are selected based on a combination of: development history of the funding organization, sustained & relevant funding levels, and sufficient documentation of design & development progress.

The N+2 & N+3 Advanced Concept Studies for Supersonic Commercial Transport project is an exploratory research effort sponsored by NASA and performed by a conglomeration of industry & academic partners, headed by Boeing. The two NASA-defined design points for N+2 (two generations in the future) and N+3 (three generations in the future) are the only US concepts considered.

The Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT) II concept is defined by the European Space Agency (ESA) and is considered as a potential competitor due to multi-national support & sustained funding period. There are several preliminary concepts involved in LAPCAT program, however only the A2 concept is considered because of its involvement with Reaction Engines Limited (REL).

The Hypersonic Transport Aircraft (HTA) is a concept funded by the national Japanese Aerospace Exploration Agency (JAXA) and is considered because of the technical expertise of the organization.

Table 7.3 – N+2 Data Required for Deliverables

Variable	Value	Unit	Reference
Range	5926	km	NASA Contract Report [364]
Propellant Mass	33190	kg	NASA Contract Report [364]
Payload Mass	2858	kg	NASA Contract Report [364]
Cruise Speed	1.6	M	NASA Contract Report [364]
Number of Passengers	30	-	NASA Contract Report [364]

Table 7.4 – N+3 Data Required for Deliverables

Variable	Value	Unit	Reference
Range	9130	km	NASA Contract Report [365]
Propellant Mass	60736	kg	NASA Contract Report [365]
Payload Mass	12247	kg	NASA Contract Report [365]
Cruise Speed	1.8	M	NASA Contract Report [365]
Number of Passengers	100	-	NASA Contract Report [365]

Table 7.5 – LAPCAT (A2) II Data Required for Deliverables

Variable	Value	Unit	Reference
Range	18700	km	REL Website [366]
Propellant Mass	198000	kg	REL Website [366]
Payload Mass	30000	kg	REL Website [366]
Cruise Speed	5	M	REL Website [366]
Number of Passengers	300	-	REL Website [366]

Table 7.6 – HTA Data Required for Deliverables

Variable	Value	Unit	Reference
Range	8700	km	JAXA Presentation [367]
Propellant Mass	172000	kg	JAXA Presentation [367]
Payload Mass	10000	kg	JAXA Presentation [367]
Cruise Speed	4.5	M	JAXA Presentation [367]
Number of Passengers	100	-	JAXA Presentation [367]

Table 7.7 – ZEHST Data Required for Deliverables

Variable	Value	Unit	Reference
Range	9500	km	EADS Website [368]
Propellant Mass	91934*	kg	EADS Website [368]
Payload Mass	10000	kg	EADS Website [368]
Cruise Speed	4	M	EADS Website [368]
Number of Passengers	100	-	EADS Website [368]

*approximated from fuel & oxidizer tank volumes

Table 7.8 – SpaceLiner Data Required for Deliverables

Variable	Value	Unit	Reference
Range	17000	km	DLR Technical Paper [369]
Propellant Mass	218500	kg	DLR Technical Paper [370]
Payload Mass	5400	kg	DLR Technical Paper [370]
Cruise Speed	-	-	-
Number of Passengers	50	-	DLR Technical Paper [369]

The Zero Emission Hyper Sonic Transport (ZEHST) is a concept investigated by Airbus (formerly their EADS division). Involvement of a major commercial transport airframer warrants further investigation.

The SpaceLiner vehicle concept under study at DLR, the German Aerospace Center is chosen because of its documented research progress and the technical background of the organization. The SpaceLiner does not have a cruising portion during operation (the vehicle is boosted to suborbital speed and then glides to the destination), and therefore cruise speed does not apply.

Operational Capability Deliverable

The operational capability deliverables for the 3rd generation high speed concepts are shown below (payload - Figure 7.25, speed - Figure 7.26, range - Figure 7.27).

Of the 3rd generation concepts, only the LAPCAT intends to provide multi-class operations – all others are seeking niche markets as first-class-only vehicles, private charter aircraft, business jets, or pseudo space tourism. As a result, the payload capabilities are significantly lower than the subsonic transport status quo.

The 3rd generation concepts have taken a wide range of viewpoints on the design cruise speed to work around the restriction on overland sonic booms.

The NASA N+2 & N+3 design speed has been lowered to a level that overland supersonic flight may be a possibility with advanced configuration optimization techniques. This slower speed also has significant military experience that may allow for technical transfer.

The HTA, LAPCAT, and ZEHST concepts have design point cruise speeds in excess of Mach 4. At this speed, only US research vehicles have successfully flown air-breathing flight vehicles. The necessity to advance technical propulsion capability for these designs to be feasible is a central focus of each project.

The SpaceLiner concept bypasses the limitations on air-breathing propulsion technical capability, instead relying on existing liquid rocket propulsion capability. For this reason the "cruise speed" of the SpaceLiner is approaching orbital speeds. Although a rocket-powered approach introduces uncertainty from a certification and commercial operation prospective, the time savings would be drastic.

The N+2 concept is not seeking international transport markets, instead approaching the domestic business jet market.

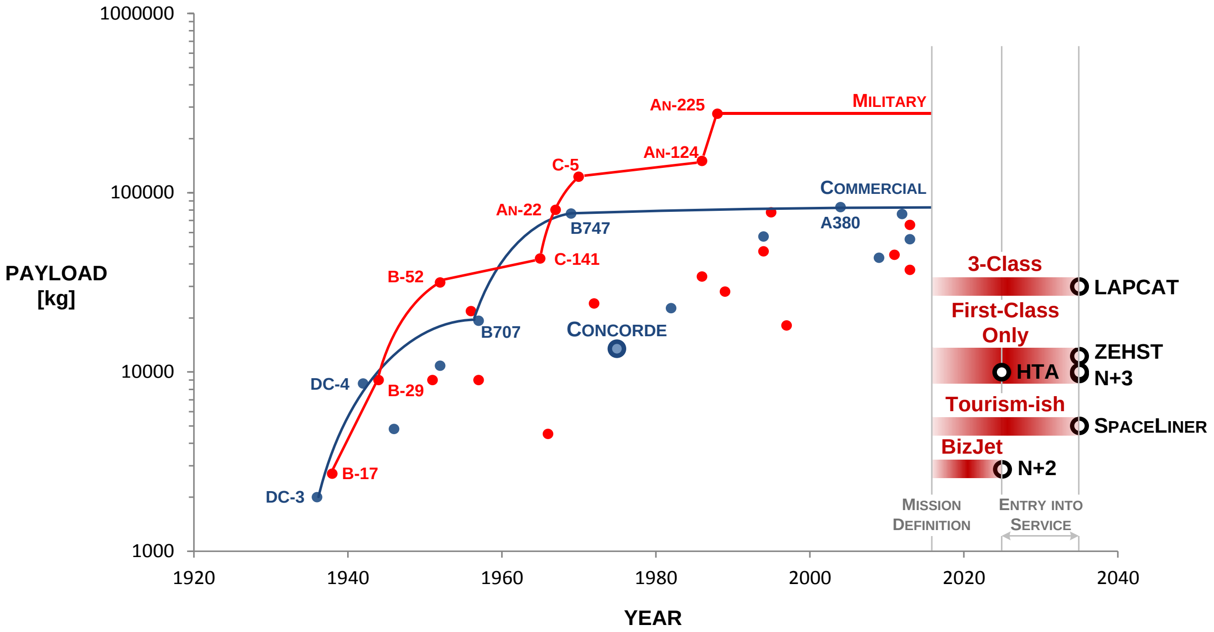


Figure 7.25 - Operational Capability: Payload – 3rd Generation

The N+3, ZEHST, and HTA concepts have a design range focused on Pacific Rim operations. Although they offer more operational flexibility than the previous Concorde design range, the current generation of subsonic transports still offers a substantial capability improvement.

The LAPCAT & SpaceLiner concepts are seeking to connect any two points on Earth with anti-podal range. Current subsonic transports are approaching such a capability, but no current concept has reached the plateau.

Summary (Operational Capability):

The NASA N+2 & N+3 design concepts have size & speed commonality with military vehicles and may have technical transfer opportunities. N+2's combination of payload & design range limits the design to niche markets of single-class commercial and large domestic business class. The growth N+3 concept still does not have the payload or range to be competitive in a multi-class operational setting.

The ESA LAPCAT A2 concept has both the largest payload capacity and the longest design range of any high speed concept, as well as a design speed that is not substantiated with flight-proven technology requiring substantial technical advances. This highly-aggressive design point may still not be able to compete against subsonic transports in the ultra-long-range market.

The JAXA HTA & Airbus ZEHST concepts do not have supporting flight capability for their design speeds and are therefore reliant on technology advances during development. The range is limiting to perceived high-status routes (Tokyo-LA) and the design payload is in an awkward operational position between private and public operation for a long-range transport aircraft.

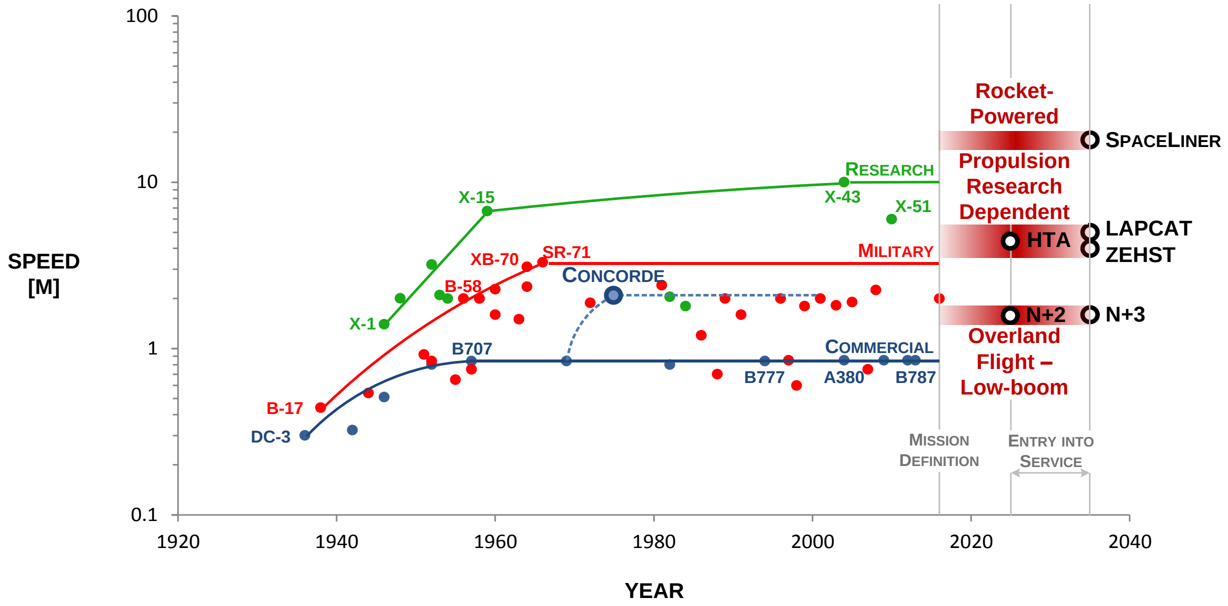


Figure 7.26 – Operational Capability: Speed – 3rd Generation

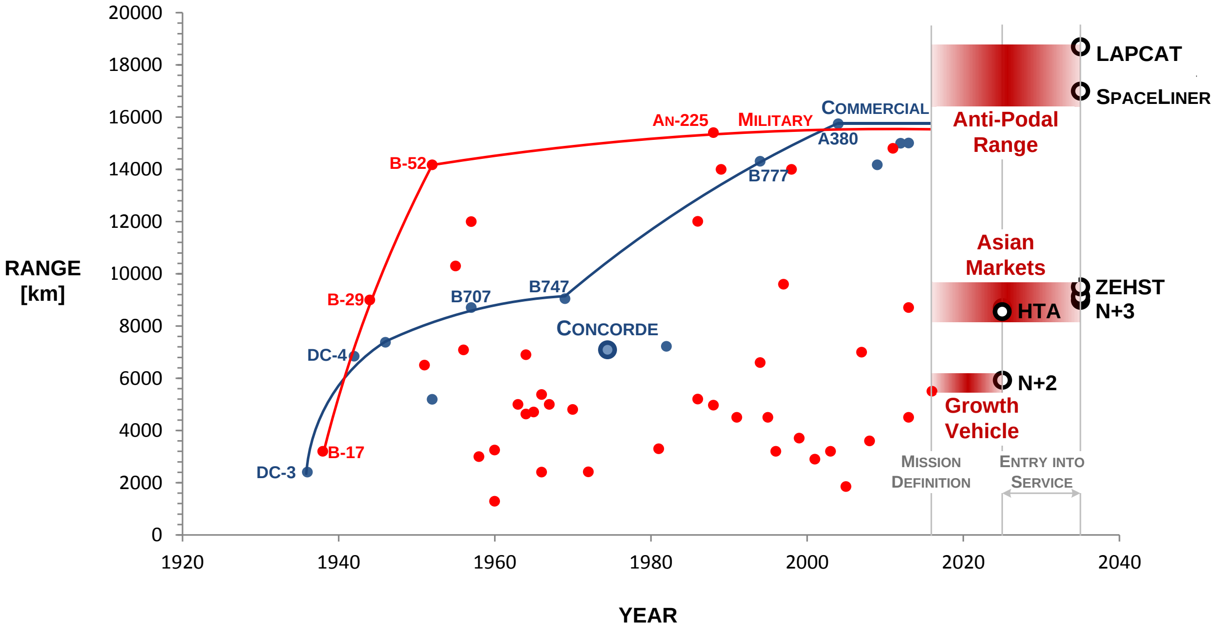


Figure 7.27 – Operational Capability: Range – 3rd Generation

The DLR SpaceLiner concept, although faster than any other 3rd generation, does not rely on technical advances. In addition, its operational concept as a novelty / tourism vehicle may allow its limited payload capability to suffice.

Operating Fuel Cost Deliverable

The fuel cost deliverable of the 3rd generation concepts is divided by their choice of fuel: the NASA N+2 & N+3 use traditional kerosene, while all other concepts utilize hydrogen as their fuel source (Figure 7.28). Hydrogen not only introduces different design considerations (hydrogen is much less dense, and therefore requires more volume than kerosene) and operational procedures (liquid hydrogen must be kept at cryogenic temperatures), but the current fuel cost of hydrogen is quadruple that of kerosene.

The fuel costs shown below are the approximate present values – they represent the planning environment during the mission definition process of the current concepts. However, these concepts have development lead times of 20 to 25 years and therefore the fuel price during operations will be different from the current price. Forecasting fuel price is inherently uncertain though.

Kerosene fuel prices mirror the price of crude oil – a commodity that is substantially affected by geopolitical (unstable) influences. As a consequence, the current EIA forecast for 2030 fuel prices range from 72% to 172% with a reference value of 120% of 2014 fuel prices (all prices are converted to 2013 $US for comparison) [371]. This forecast distribution only reiterates that petroleum fuel price is a relative unknown and should only influence the designer to reduce their dependence on advantageous pricing for product success.

Today, hydrogen is most often produced from natural gas – meaning the $4/kg price of fuel shown is a direct function of the natural gas price and the cost of chemical production process. While the production costs will have a downward pressure if economies of scale are reached, natural gas prices are forecast to increase at a rate higher than kerosene due to its absolute cost benefit and use as an industrial fuel. A dramatic leftward shift in hydrogen fuel prices would need to come from a revolutionarily cost-effective process of hydrogen production.

Summary (Operating Fuel Cost):

The NASA-sponsored N+2 design point is an order of magnitude more expensive to operate than the best-in-class subsonic transport. Even offered as a business jet, the cost for a full tank of fuel at current kerosene prices is $33,000 – upward fuel price movements in the future would only worsen the operating conditions of the N+2 concept.

While the N+3 concept is less expensive to operate than its baseline N+2 counterpart, the relative operating costs are still roughly three times as high as the subsonic baseline. The commercial viability of such a vehicle that will enter service into a social & political environment that is increasingly energy-conscious is suspect – the N+3 has roughly the same normalized fuel costs as the first generation Boeing 707, designed in the 1950s.

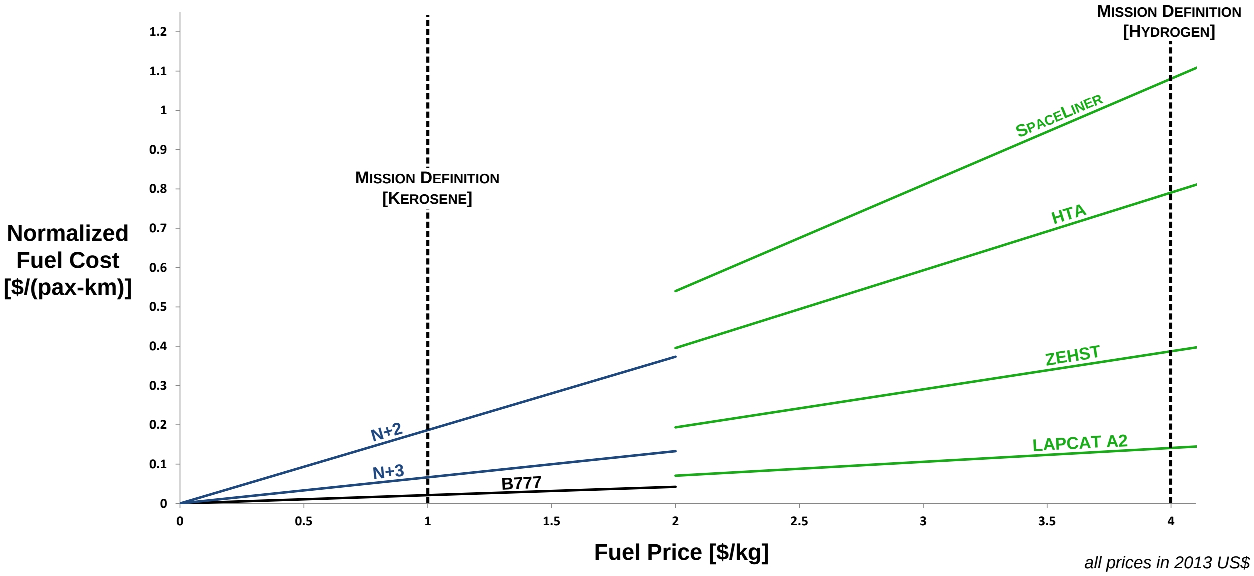


Figure 7.28 – Operating Fuel Cost Deliverable: 3rd Generation

The hydrogen-based concepts (SpaceLiner, HTA, ZEHST, and LAPCAT A2) all suffer on a fuel cost basis due to their reliance on a much more expensive fuel. Even if hydrogen prices were reduced to $1/kg (a fourfold decrease and in-line with current kerosene prices), SpaceLiner, HTA & ZEHST would still be more expensive to operate than the subsonic baseline, but would be in the same proximity as the current generation kerosene high speed concepts.

In contrast, the LAPCAT A2 concept claims a normalized fuel cost trend that, while not competitive at current fuel prices, would be in direct fuel cost competition with subsonic kerosene transports if the price decrease were assumed.

Although no designs from the current generation have explored the topic, a fuel choice of liquid natural gas may prove beneficial from a normalized cost perspective. The current fuel price of $.40/kg offers a lower entry point than kerosene and may be somewhat insulated from geopolitical factors due to domestic U.S. production.

Latent Route Demand

The latent route demand deliverable (Figure 7.29) shows the population distribution both at the current mission definition phase, but also forecasted population distribution at the projected entry into service data for the 3rd generation high speed transport concepts. Although the general trend of the distribution does not change between the two dates, the growth rate of city-pairs under 1000km, as well as over 15,000 km, noticeably trail the average growth rate.

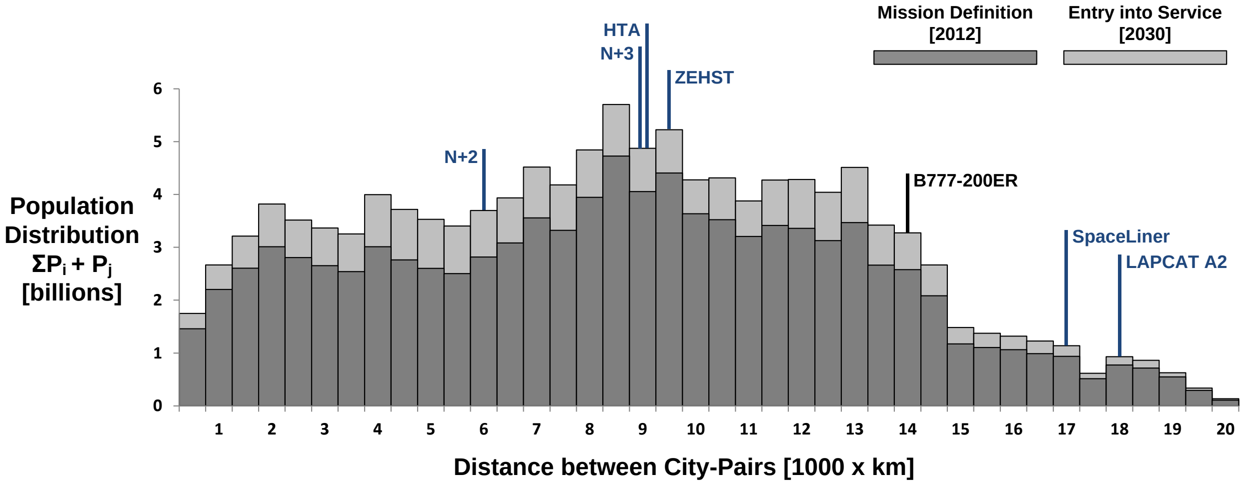


Figure 7.29 – Latent Route Demand: 3rd Generation

Summary (Latent Route Demand):

The N+2 design range is located past an inflection point in population distribution and is therefore poorly positioned on both fronts: it is has excess capability for domestic routes and inferior capability for long-range international routes. If the N+2 seeks to serve the overland domestic business jet market as the first stage in a growth concept, the design range should be lowered to allow for greater design & technology flexibility.

N+3, HTA & ZEHST share a similar design range that just barely captures the peak population distribution around 9,000 km. However, there are significant markets not accounted for in the relatively high plateau from 9,000 to 14,000 km that the subsonic baseline (Boeing 777-200ER) can potentially serve. Additionally, the ZEHST & HTA concepts will not be permitted to operate supersonically overland – there is currently very little range margin to adjust for overwater routing built into their assumptions that will very limit their potential markets.

SpaceLiner & LAPCAT designs have removed range constraints by opting for anti-podal range (i.e. they can reach any destination from any point of departure on Earth). However, there is only a small population distribution to be captured after 15,000 km and the excessive technical requirements for the additional range may be a net detriment to the design concept.

Summary (Overall):

The following conclusions are segmented for each 3rd generation high speed transport concept.

NASA N+2

- The design speed is able to take advantage of technical propulsion and airframe knowledge from the military field.
- The design combination is prohibitively expensive to operate commercially, and is oversized in range and payload capacity for a domestic business jet.

NASA N+3

- The design speed is able to take advantage of technical propulsion and airframe knowledge from the military field.
- Commercial operations under an all-first-class system are economically borderline and heavily dependent on level or negative momentum in petroleum fuel prices.
- The available range underserves potential international growth routes.

LAPCAT A2

- Technical development not leveraged from existing flight vehicles is required to reach the design operational speed.
- Operational costs are competitive with subsonic transports only in a scenario where hydrogen productions costs are drastically reduced.
- Anti-podal range does not gain enough additional markets over a 15,000 km range to warrant the technical risk.

JAXA HTA & Airbus ZEHST

- Technical development not leveraged from existing flight vehicles is required to reach the design operational speed.
- Hydrogen prices make the design concepts economically unfeasible near current prices – hydrogen costs would need to be below that of kerosene to approach a competitive operating cost.
- Although the concepts serve current high-profile long-range routes, emerging market routes are underserved by the operational ranges.

DLR SpaceLiner

- Operating costs are unrealistic for commercial operations near current hydrogen fuel cost levels – however, operating under a "tourism" concept may bypass this limitation.
- The anti-podal design range is unnecessary for commercial transportation, but the lack of air-breathing propulsion does not add substantial technical risk because of the added range.

7.4 REQUIREMENTS DEFINITION DATA+KNOWLEDGE+ANALYSIS CASE STUDY: AEROBRAKING ORBITAL TRANSFER VEHICLE SIZING

Portions of the work presented in this section were completed as part of funded research through the National Institute of Aerospace under contract title "Innovative Manned Missions to LEO and GEO."

Research was completed at the Aerospace Vehicle Design Laboratory at the University of Texas at Arlington – additional teams collaborated

at NASA, the Aerospace Corporation, and DARPA, but did not directly contribute to the results below.

The author acted as primary source of data collection and parametric modeling development for aerobraking vehicle concepts. Dr. Gary Coleman acted as Chief Engineer, along with substantial efforts provided by Amit Oza, Lex Gonzalez, and Dr. Bernd Chudoba.

Results have been published in a NASA special publication – Reference [269] and submitted for publishing to The Aeronautical Journal – Reference [373].

Contributing Individuals: Dr. Gary Coleman (UTA), Amit Oza (UTA), Lex Gonzalez (UTA), Dr. Bernd Chudoba (UTA), Jeffrey Cerro (NASA), Jeffrey Bowles (NASA), David Glass (NASA), Paul Czysz (Hypertech Concepts)

Theodore von Karman's famous quote postulates that "…engineers create the world that never was" – where once there was a gap in human capability, the engineer is to find a solution that fills it. Engineers tasked with designing these artifacts are asked to use whatever data and knowledge they can obtain to create something new. Sometimes the something new is really something new, something no person or organization has ever attempted before. But often times, the progress of humanity looks much more like the edge of a saw than a clean knife blade. Often times, we can find evidence of people and organizations that have tried (& failed) to bridge this same gap in capability, and it is the engineer's duty to understand what they did right, what they did wrong, and how their progress can be used as a stepping stone to successful design.

Repairing / servicing an orbital satellite is one such capability. The nominal operational life-cycle of a satellite includes a design lifetime – a length of time after which the satellite will no longer be functional or valuable or both. This can be due to parts having a high probability of failure by this point, diminishing technical value, or a set mission duration. If a system or subsystem fails before the end of its design lifetime or if propellant required for station-keeping has been depleted, there is currently no physical capability to engage the satellite. The exceptions have been the Space Shuttle which had limited capability to perform these tasks in low earth orbits (LEO), notably repairing the Hubble Space Telescope, before it was retired [374] and, the X-37B which may currently be capable but whose missions are currently classified [322].

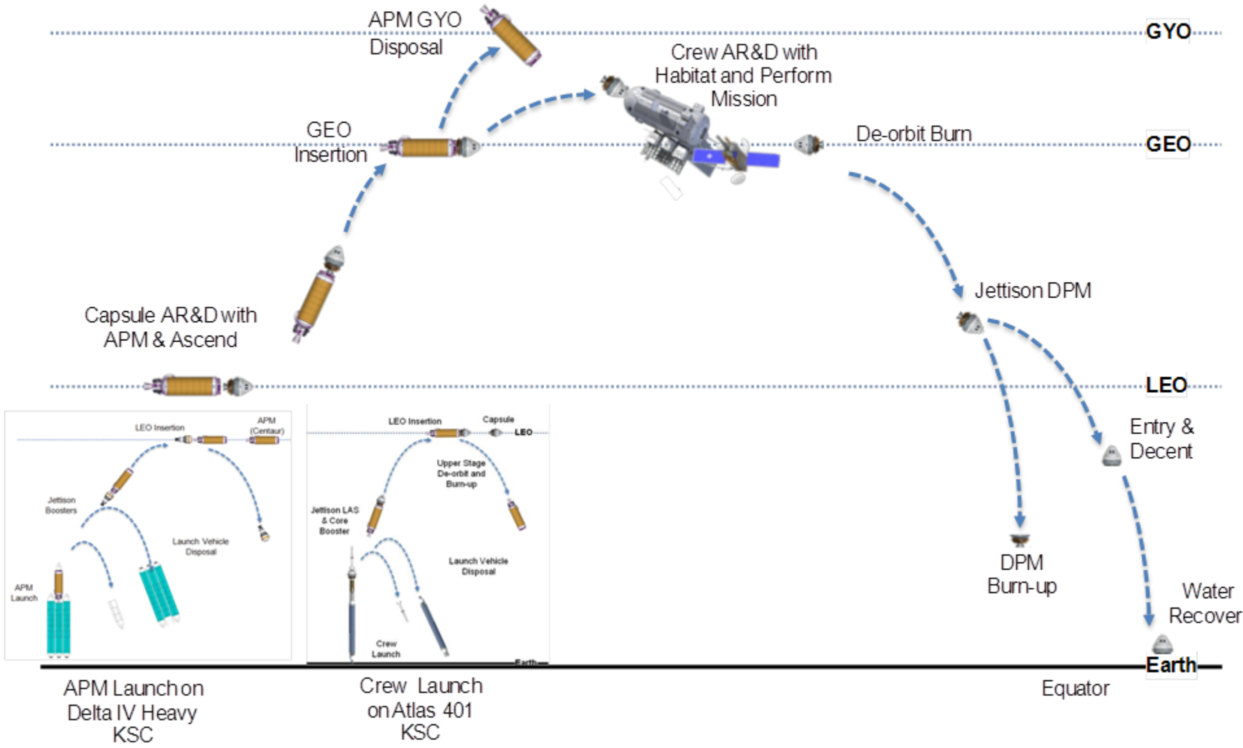


Figure 7.30 – ConOp 1: Direction GEO insertion and return (image from [269])

In response to the growing number of aging high-value satellites in geostationary orbit (GEO) and the lack in capability to service them, the U.S. Defense Advanced Research Projects Agency (DARPA) initiated a research study with NASA to explore potential system configurations and technologies that would enable manned satellite servicing missions. The study seeks near-term solutions and therefore considers only existing or one-off launch systems. Additional vehicle systems requiring technology development will be judged by their quantifiable delta improvement over the nominal system as well as their potential for tangent mission classes.

The baseline concept of operations ConOp 1 (Figure 7.30) uses an expendable launch system and an expendable ascent propulsion module (APM) to place a reentry capsule in GEO where the crew can service the satellite. The capsule then returns to Earth after a deorbit burn from an expendable descent propulsion module (DPM).

The experimental ConOp 2 initially places the crew in LEO where they are then staged in a crew transfer vehicle towards the satellite at GEO. After the servicing mission has been completed, the crew module then performs an orbit transfer (requiring deorbit & re-circularization burns) to reduce to a LEO altitude where the crew docks with the reentry capsule and returns to Earth.

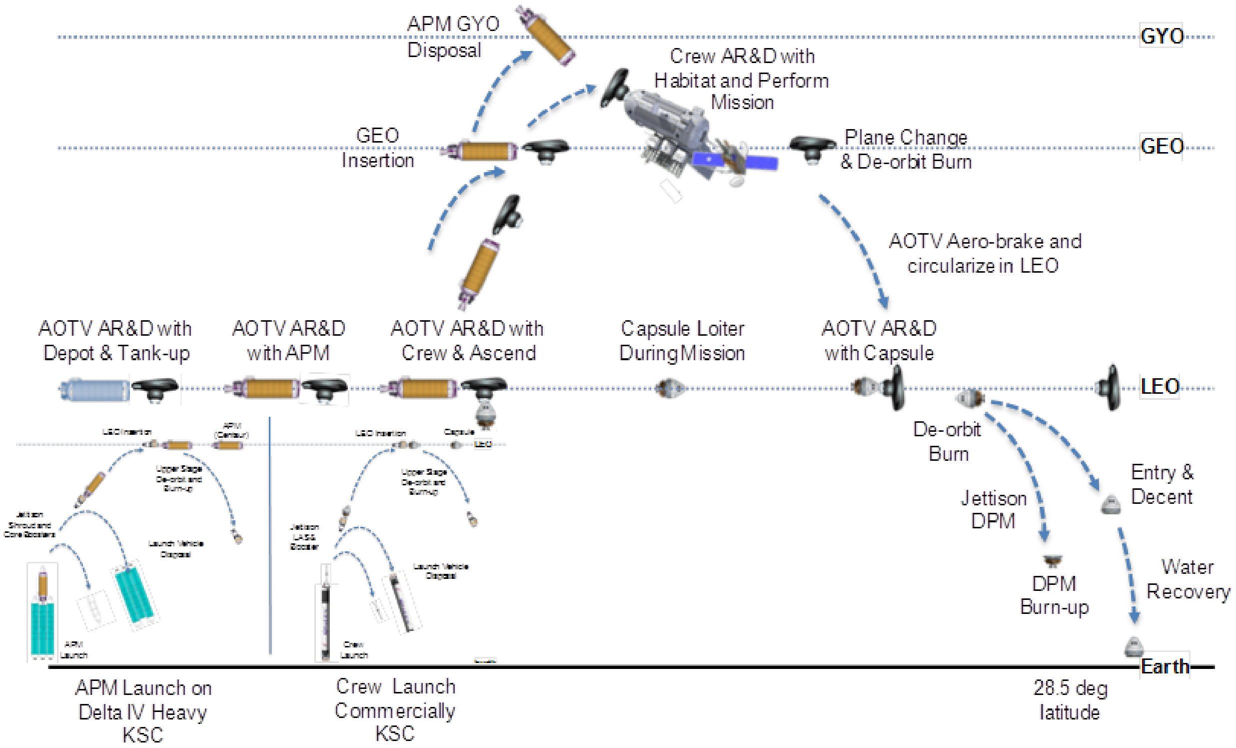


Figure 7.31 – ConOp 2: LEO insertion, orbital transfer to/from GEO, LEO return[269]

In addition to a pure-propulsive DPM for ConOp 2, the study was particularly interested in the feasibility of a standalone structure known as an aerobrake that would allow for aerodynamic drag through the upper atmosphere to replace the re-circularization burn. The aerobrake configuration reduces the propellant requirements from the baseline and has the potential to be reusable. A similar aerobrake is also considered with the APM.

7.4.1 Decision-Making Problem Statement

A collaboration of national research organizations seeks to identify the near-term possibilities for manned servicing of satellites in geostationary orbit. The interrelationships between technologies, vehicle configurations, and operational concepts should be quantified. The feasibility for an aerobraking orbital transfer vehicle (AOTV) within the mission class is to be judged in a total systems context against baseline direct insertion and all-propulsive operational concepts.

7.4.2 Determine Resources

Cost

To initiate a feasibility study of MGS, a multi-organization design team has been formed with members from NASA, DARPA, the Aerospace Corporation, and academia. In addition to vehicle element sizing, crew operations, launch integration, logistics, and crew health & safety have all been addressed by different personnel.

Benefit

The immediate benefit of a function servicing architecture is the saved cost of prolonged satellite operations. For high-value systems including the cost of additional development and launch, the potential for monetary benefit is immense. In the long-term, development of aerobraking capability opens the potential for innovative mission models beyond GEO – this is driving secondary influence for NASA stakeholders in particular.

Risk

While there is no immediate program risk introduced at this stage of research – there are long-term cost & schedule risks if technologies / system configurations are oversold.

Uncertainty

The quantity of GEO satellite servicing missions, as well as the required capabilities from a servicing architecture, is uncertain. The operational feasibility of an AOTV has not been proven and therefore also introduces uncertainty.

7.4.3 Identify Options

The decision-maker is seeking the answer to two main questions from the study: (1) Is servicing of GEO satellites possible in the near-term? and (2) If yes, which configurations shows the greatest potential? It is then up to decision-maker to push the selected configuration for further study / program initiation based on their judgement of available resources and potential capability benefit.

Aerobraking performance is gauged by the hypersonic lift-to-drag ratio (L/D), an aerodynamic characteristic determined by the vehicle's geometry. As the L/D of a vehicle increases, so does its ability to maneuver while in the atmosphere – this increasing the margin for safe reentry, as well as offering the potential to perform plane change maneuvers.

In actuality, values of hypersonic L/D can vary continuously from zero towards five by gradually increasing slenderness but in order to aide future down-select decisions, only three discrete AOTV configurations are considered (Figure 7.32). The (1) symmetric, (2) raked cone, and (3) ellipsled AOTV configurations were selected early in the research effort because they represent geometric configurations that have sufficient historical data and have the potential for reusability with current thermal protection system (TPS) material technology.

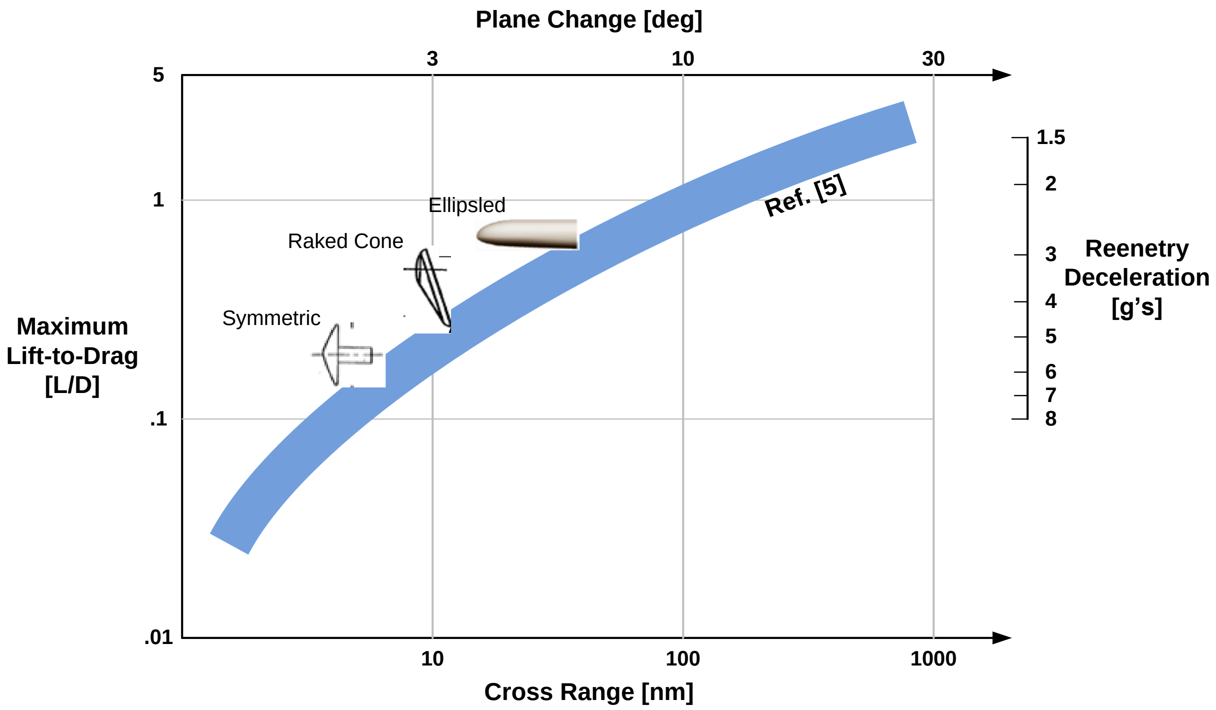


Figure 7.32 – AOTV Concepts Considered with Relative Aerobraking Performance (modified from [390])

7.4.4 Establish Information Requirements

Evaluation of discrete system configurations over a range of missions requires a parametric analysis and solution space visualization. For each configuration and mission combination, a common toolbox must quantify the figure of merit (FoM) as a function of one or more design variables with operational constraints overlaid. The current task arrives at systems-level FoM by modeling the disciplinary interactions of the entire system with the aide of data-based and knowledge-based design techniques.

7.4.5 Retrieve / Create Information: Data Domain

Parametric systems analysis requires decomposing each vehicle element of each configuration into a series of interrelated disciplinary performances. The synthesis of disciplinary analyses into a singular model of the system requires choosing a collection of analysis methods with two traits: the methods must (1) simulate the performance of the vehicle element in a relevant operational environment and (2) be represented by a set of parameters that are either calculated in other disciplinary methods or specified as a design input.

This requirement to match the level of analysis detail with the amount of data known about the current vehicle system is a key distinction. It ensures that the proper tools are used at the proper point in the design life-cycle. For instance, using a high-fidelity computational fluid dynamics (CFD) for aerodynamic analysis requires a three dimensional geometric representation of the vehicle along with the flight conditions for each point in the trajectory. But specifying a detailed moldline assumes that specifics of the vehicle configuration are known *a priori* – an assumption that is self-limiting and over-constraining for early design considerations, such as the current task.

In cases where the configuration has been well-explored previously, empirical and semi-empirical methods may already exist that parametrically estimate the characteristics & performance over some operational window. These methods often exist in engineering literature, contract reports, and technical journals as a means to summarize a subset of data into a format that is useful to the broader community by describing parameter interactions in an integrated systems context. Using such a method assumes that the new design is bounded by roughly the same operating environment and shares commonality with the underlying data points.

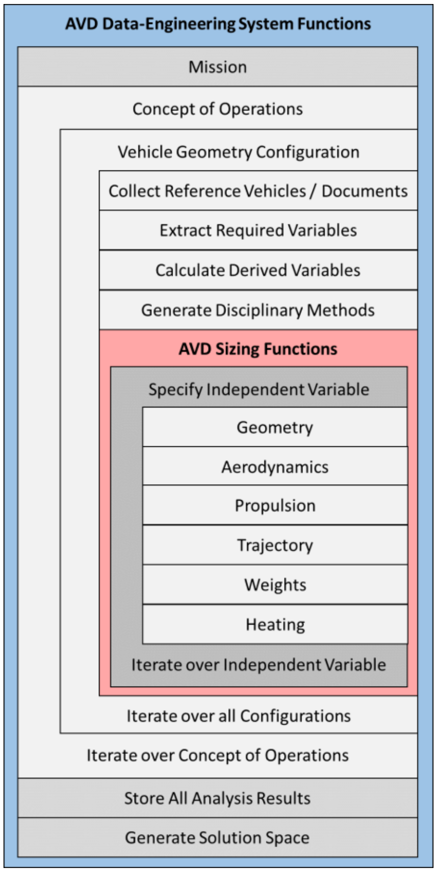


Figure 7.33 – Orbital Transfer Vehicle Sizing Methodology Diagram

For the MDA framework proposed (section 7.4.7), parametric models are used to describe the geometry, weight, aerodynamics, and heating characteristics of a range of aerobrake configurations. By using parametric modelling instead of analytical methods, the complexity of the inputs can be greatly reduced while still representing the system interactions correctly. Historical vehicle data that was created with high-fidelity methods, teams of engineers, and much longer design times can be leveraged.

The aerobraking orbital transfer vehicles in the current satellite servicing task are able to capitalize on previous conceptual & preliminary R&D (discussed in the following section) to establish disciplinary methods that can integrated into the systems analysis environment. While some disciplines can be represented by existing parametric analysis models, others require establishing a new method from historical data. The process of finding, validating and implementing data into a usable format for systems analysis is the focus of the following sections.

7.4.5.1 Data Collection

The technically-focused nature of the required data is mirrored in the potential data sources. Detailed operational and design characteristics for AOTV concepts is only found in a few places.

First, there are technical reports authored by government and academic sources – these documents generally deal with analysis of a fixed configuration along a narrow band of analysis.

There are also a few books that have been discussed the topic of AOTVs – aerodynamics and aerodynamic heating (aeroheating) are often the main focus.

However, the primary source for data pertaining to AOTVs is contract reports submitted to the U.S. government. Once declassified and cleared for public viewing, historical projects funded by NASA, DoD, Air Force, or any other office is made available on government-hosted report servers. Although AOTVs have not been heavily researched in the past, there are a few select programs that carried on a thorough R&D assessment of the possible configurations.

Space Tug

NASA Marshall Space Flight Center contracted Boeing in the early 1970s to study the potential feasibility of a ‘space tug’ – an in-space vehicle that would transport cargo, satellites, and supplies to & from LEO-GEO. The space tug was to be unmanned, launched from the (in development) Space Shuttle payload bay, operate at zero degree angle of attack, and be fully self-sufficient once in orbit (i.e. no assembly required).

The majority of the contract effort was with a reusable all-propulsive configuration, but a side-effort involved research of an aerobraking kit that could be retrofit on the baseline vehicle. However, because the system was designed to be unmanned, the time to lower orbit was not a critical parameter and therefore the aerobraking space tug design was allowed to pass through the atmosphere multiple times. The system required much less drag from the aerobrake as a byproduct.

Unfortunately, the operational geometry constraints of the Shuttle payload bay and the technology constraints of high-temperature materials at the time limited the highest performance configuration, a symmetric heatshield deployed from the front of the vehicle, to a two-pass aerobrake mission. Additionally, this configuration resulted in a negative payload capability in order to maintain the heating levels specified by the design team. For these reasons, data was collected for the Space Tug but was not used for any further system modelling (Figure 7.34).

	Data Categories Covered				Data Useful for Analysis
	Geometry	Aerodynamics	Heating	Weights	
Space Tug	🟩	🟩	🟩	🟩	⬜

Figure 7.34 – Space Tug Data Summary

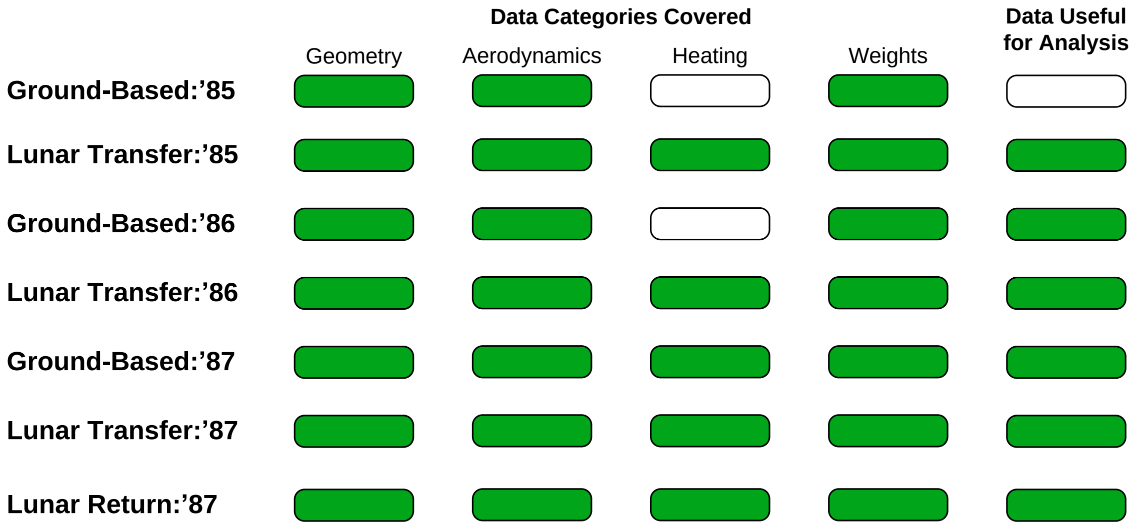
References: [375][376]

NASA Orbital Transfer Vehicle (OTV)

In the mid-to-late 1980s NASA Marshall Space Flight Center provided funding to Martin Marietta & Boeing to perform preliminary research & design of a family of AOTV concepts. NASA defined a suite of missions that would benefit from the added capability of a transfer vehicle in addition to the existing capabilities: GEO payload delivery, unmanned GEO satellite servicing, manned GEO satellite servicing, and lunar transport. Both contractors used commonality where available to address multiple missions with a single vehicle element.

The contracts progressed from conceptual studies through technology & configuration down-select towards preliminary component / subsystem design. In order to capture the trends behind the development of AOTVs, these overlapping configuration results are considered as separate vehicles. Only those configurations with incomplete or suspect data were not included for consideration during analysis.

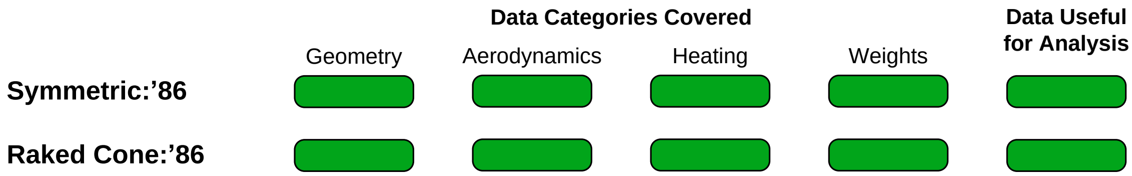
Martin Marietta design configurations (Figure 7.35) were restricted to symmetric deployable designs after initial studies ruled out raked cone and ellipsled configurations. Initially two designs were shown in contract reports: a ground-based AOTV that would transfer from-to the Space Shuttle during GEO servicing missions, and a space-based AOTV that would be permanently stationed in orbit between GEO servicing & lunar transfer missions. Later studies added a mission to perform a lunar landing and return crew, requiring the design of an additional AOTV concept.



	Data Categories Covered				Data Useful for Analysis
	Geometry	Aerodynamics	Heating	Weights	
Ground-Based:’85	🟩	🟩	⬜	🟩	⬜
Lunar Transfer:’85	🟩	🟩	🟩	🟩	🟩
Ground-Based:’86	🟩	🟩	⬜	🟩	🟩
Lunar Transfer:’86	🟩	🟩	🟩	🟩	🟩
Ground-Based:’87	🟩	🟩	🟩	🟩	🟩
Lunar Transfer:’87	🟩	🟩	🟩	🟩	🟩
Lunar Return:’87	🟩	🟩	🟩	🟩	🟩

Figure 7.35 – Martin Marietta OTV Data Summary

Boeing chose to advance two design configurations during their research: a symmetric AOTV and a raked cone AOTV, both sized for space-based GEO-to-LEO use. Because the full volume of contract report documents are not available through the government report servers, only a limited number of configurations can be used for further analysis.



	Data Categories Covered				Data Useful for Analysis
	Geometry	Aerodynamics	Heating	Weights	
Symmetric:’86	🟩	🟩	🟩	🟩	🟩
Raked Cone:’86	🟩	🟩	🟩	🟩	🟩

Figure 7.36 – Boeing OTV Data Summary

This occurrence, known documents that are impossible to find, is common when collecting data from industry projects, especially for older reports. Government classified status, lack of digitization, and the limitations of the search portals are all barriers to finding a hard-to-find document. In such cases, matching the exact title string or contract number through a global internet search can sometimes provide better results than a technical report server.

References (Martin Marietta): [377][378][379][380][381][382][383]
References (Boeing): [384][385]

NASA Aeroassist Flight Experiment (AFE)

During the same period of time, NASA funded its own internal study of a raked cone AOTV configuration. The goal was to create a functional prototype AOTV that could demonstrate aerobraking maneuvers and validate the raked cone configuration during a real flight environment. Compared to the level of engineering detail presented in the previous contract reports, the AFE source documents are sparse and bring into question the validity of the data.

	Data Categories Covered				Data Useful for Analysis
	Geometry	Aerodynamics	Heating	Weights	
AFE	🟩	🟩	🟩	🟩	🟩

Figure 7.37 – AFE Data Summary

References: [386]

NASA Space Transfer Vehicle (STV)

As a follow-on the OTV program, NASA funded Boeing and Martin Marietta to further study the design of AOTVs for high-priority missions – emphasis was placed on lunar & Mars exploration missions. Systems engineering, operational details, costing, and programmatic scheduling are much more heavily detailed in the STV studies as opposed to the OTV studies. Therefore, the number of data points offered is much less, but the validity of the data points is very high.

Boeing designs focused on symmetric aerobrake designs for the lunar missions and raked cone design for the Mars missions (Figure 7.38). The design also changed from a deployable fabric construction to a rigid structure that would need to be assembled in orbit – it is not clear at this point if this difference will affect weight analysis.

	Data Categories Covered				Data Useful for Analysis
	Geometry	Aerodynamics	Heating	Weights	
Lunar Transfer:'91	🟩	🟩	🟩	🟩	🟩
Mars Transfer:'91	🟩	🟩	🟩	🟩	🟩
Mars Return:'91	🟩	🟩	🟩	🟩	🟩

Figure 7.38 – Boeing STV Data Summary

The Martin Marietta design team followed the same paradigm: rigid construction, symmetric aerobrake configurations – sufficient documentation was not given, however, on the design configuration for the Mars exploration mission (Figure 7.39).

	Data Categories Covered				Data Useful for Analysis
	Geometry	Aerodynamics	Heating	Weights	
Lunar Transfer:’91	🟩	🟩	🟩	🟩	🟩
Mars Transfer:’91	🟩	🟩	🟩	🟩	⬜

Figure 7.39 – Martin Marietta STV Data Summary

References (Martin Marietta): [387][388][389]
References (Boeing): [390][391][392][393]

NASA Ellipsled

NASA started a series of investigations into more slender, higher-performing aerobrake configurations in 2004. Designed for use aerocapture at Neptune and later Mars, the designs (referred to as ellipsleds) allow for larger control authority when braking in the atmosphere. This is a distinct advantage over lower L/D design configurations in atmospheric environments with variable or uncertain thermodynamic properties.

The design of ellipsleds at NASA takes a generic spherical capped cylinder as its initial shape and then applies a geometric optimizer on top of a coupled analysis process for a constant mission. This framework is known as the Co-optimization of Blunt-body Re-entry Analysis (COBRA). In order to capture the design trends of the system, data from multiple vehicle configurations designed under the COBRA framework have been collected (Figure 7.40).

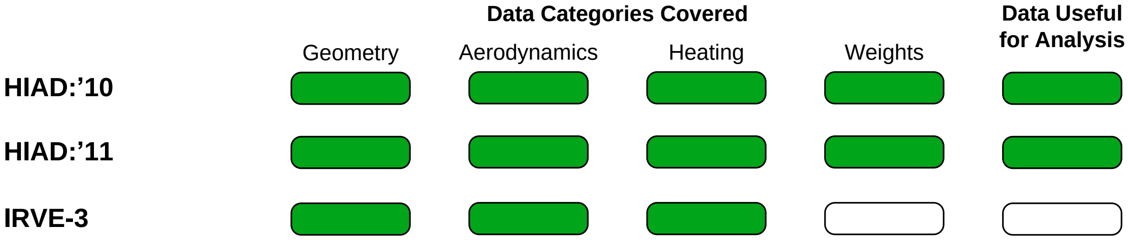
	Data Categories Covered				Data Useful for Analysis
	Geometry	Aerodynamics	Heating	Weights	
Neptune Capture	🟩	🟩	🟩	🟩	🟩
COBRA:Baseline	🟩	🟩	🟩	🟩	🟩
COBRA:14888	🟩	🟩	🟩	🟩	🟩
COBRA:8459	🟩	🟩	🟩	🟩	🟩
COBRA:14297	🟩	🟩	🟩	🟩	🟩

Figure 7.40 – NASA Ellipsled Data Summary

References: [394][395][396][397]

NASA Hypersonic Inflatable Aerodynamic Decelerator (HIAD)

NASA has continued to push for aerobraking as technology, especially in support of Mars exploration missions. The HIAD program is using incremental technology demonstration test flights known as Inflatable Reentry Vehicle Experiments (IRVE) to expand operational aerobraking capability. Because the IRVE test articles have not been designed with an operational payload in mind, their data has been disregarded for future analysis. Only those HIAD configurations designed for operational scenarios have sufficient data commonality and completeness to be considered.



	Data Categories Covered				Data Useful for Analysis
	Geometry	Aerodynamics	Heating	Weights	
HIAD:'10	🟩	🟩	🟩	🟩	🟩
HIAD:'11	🟩	🟩	🟩	🟩	🟩
IRVE-3	🟩	🟩	🟩	⬜	⬜

Figure 7.41 – NASA HIAD Data Summary

References: [397][398][399][400][401]

7.4.5.2 Data Organization

For this combined data-knowledge-analysis forecasting study, data must be organized in a manner which allows the flow of data directly from the source documents into the analysis domain (and onto creating decision-making information). This requires data at several levels to be stored within the same environment:

- Source Library – stores meta-data about documents, including tagged indices describing the location and description of data taken from the document
- Variable Library – list of standardized variables to be used in the analysis domain; includes the discipline and common units of the variable
- Vehicle Library – stores the characteristics of the vehicle configuration; data must be a variable already defined in the Variable Library and referenced to an index within the Source Library
- Methods Library – stores the available disciplinary methods within the analysis domain; source of the method, if not original, is linked to an index within the Source Library; data-based methods pull data points directly from the Vehicle Library

This data organization scheme ensures that opportunities for mistranslation of data are minimized. At any point in the data stream, the original document can be opened electronically for further investigation.

7.4.5.3 Data Storage

All libraries are stored within a single back-end database. The entire forecasting team has simultaneous access to read & write through a shared network. This allows for the data collection phase to proceed much more rapidly than with individual-user systems and reduces the amount of duplicated effort.

7.4.5.4 Data Recall

At each higher level of data, there is a digital link to data library beneath it (i.e. each vehicle characteristic in the Vehicle Library has a highlighted field that links directly to the source document). By mechanizing the most common drill-down situations, the need to search for specific records is effectively reduced. A search function is also available that can be tuned to return results for a specified library.

For analysis methods defined by project data, the links have been made parametrically. That is, parameters of the method are determined by pre-set variables from a pre-defined class of vehicles (i.e. a method parameter can be a function of the structural weight of all symmetric deployable AOTVs). As new vehicle data is added that fulfills the criteria, the method automatically updates. This ensures that the method needs to only be correctly set up once – there is no need for updates to a list of projects included.

7.4.5.5 Data Visualization

Data is visualized for each library with a graphically-formatted database front-end. To promote parametric data analysis (detailed in the next section), adaptable scatter plot functionality is used. The dependent & independent axes as well as the subset of vehicles desired for visualization are specified by the user. Because source data is not required for decision-making purposes, no visualizations have been developed for references, methods, or individual vehicles.

7.4.5.6 Data Analysis

The primary pull for data in this case study has been to create parametric weight models for AOTVs that can be implemented within the multi-disciplinary analysis domain. The data collection through visualization steps have created standardized data sets which may now be analyzed to form trend fits that capture the relationship between vehicle characteristics and the operational environment / mission. From the previous list of disciplines requiring additional analysis methods:

- Geometry – vehicle configurations are described by a combination of normalized shapes identified as representative of their class (symmetric, raked cone, ellipsled); project data is used to establish any coefficients
- Aerodynamics – lift & drag coefficients as a function of attitude & Mach number are taken directly from source documents
- Heating – an existing semi-empirical method was found in [402] and has been previously validated with AOTVs (described in Section 7.4.6)
- Weights – normalized aerobrake weight (weight per unit area) equations are needed as a function of some operational variable for each class; vehicle data forms the basis for the trends

Of these, only the parametric weight model requires further data analysis. The difficulty lies in finding a set of variables that are available in the data set, correlate, and have physical significance / causation between the variables.

The weight estimation process of an AOTV can be seen as, roughly, the same as the sizing of the heat shield and structure of a standard re-entry vehicle. The type of TPS material required for the heat shield is determined by the maximum heating rate during reentry – if the heat shield is considered as one material, this sets the mass per unit volume. The thickness of the heat shield is determined by the total heat load absorbed by the vehicle during reentry – along with material density, this sets the required areal weight of the heat shield. The structure is sized to accommodate the aerodynamic loads during reentry.

Therefore, it can be hypothesized that to first-order the weight of the aerobrake is determined by the heating and aerodynamic loads which is determined by the trajectory and geometric shape of the aerobrake. By grouping classes of vehicles together to eliminate variances in (normalized) geometry, the trajectory is the only remaining driver. And the parameter that has the most direct effect on the reentry trajectory of a vehicle is the ballistic coefficient. As ballistic coefficient increases, the vehicle loses the ability to decelerate and vice versa.

So in order to proceed with data analysis, values for both ballistic coefficient and the normalized aerobrake weight (referred to as unit weight) are needed. The ballistic coefficient is reported as data in some instances, or can be calculated from the reentry weight, drag coefficient during reentry, and the reference area. The aerobrake unit weight is calculated as the aerobrake weight divided by the wetted area.

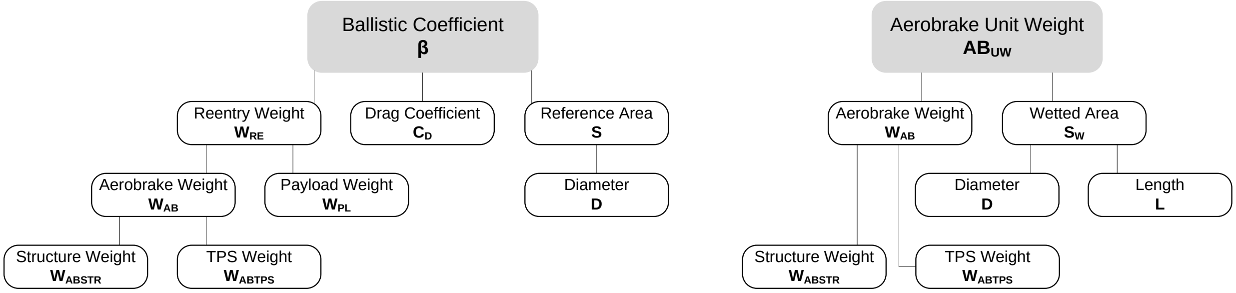


Figure 7.42 – Aerobrake Data Analysis: Variable Flow

Each vehicle class has its own separate parametric weight model for sizing analysis (Figure 7.43 – Figure 7.45). The analytic correlation function must satisfy the requirements of positive unit weight at ballistic coefficient equal to zero, and a positive slope as ballistic coefficient goes towards infinity.

After testing the hypothesis by verifying that the unit weight and ballistic coefficient correlate along an analytic function, the parametric weight method can be implemented within the systems analysis framework. As the vehicle scales up and down in size to accommodate the design & operational constraints, the unit weight of the aerobrake is determined by the ballistic coefficient of that configuration iteration.

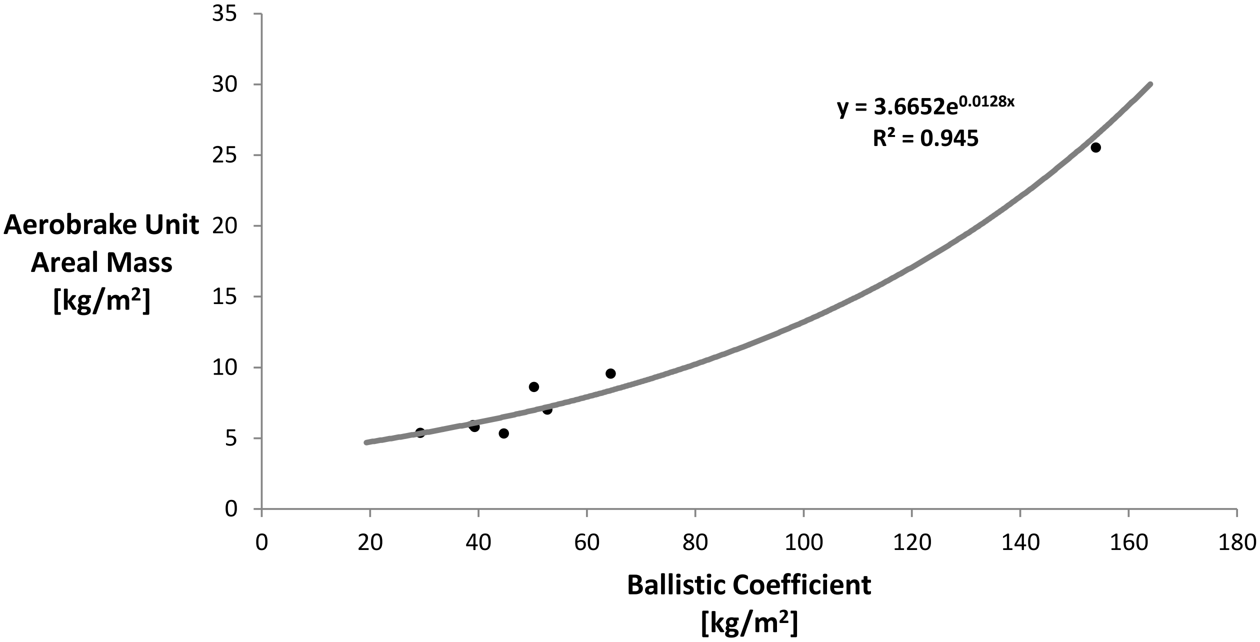


Figure 7.43 – Parametric Weight Analysis of Symmetric Deployable Aerobrakes

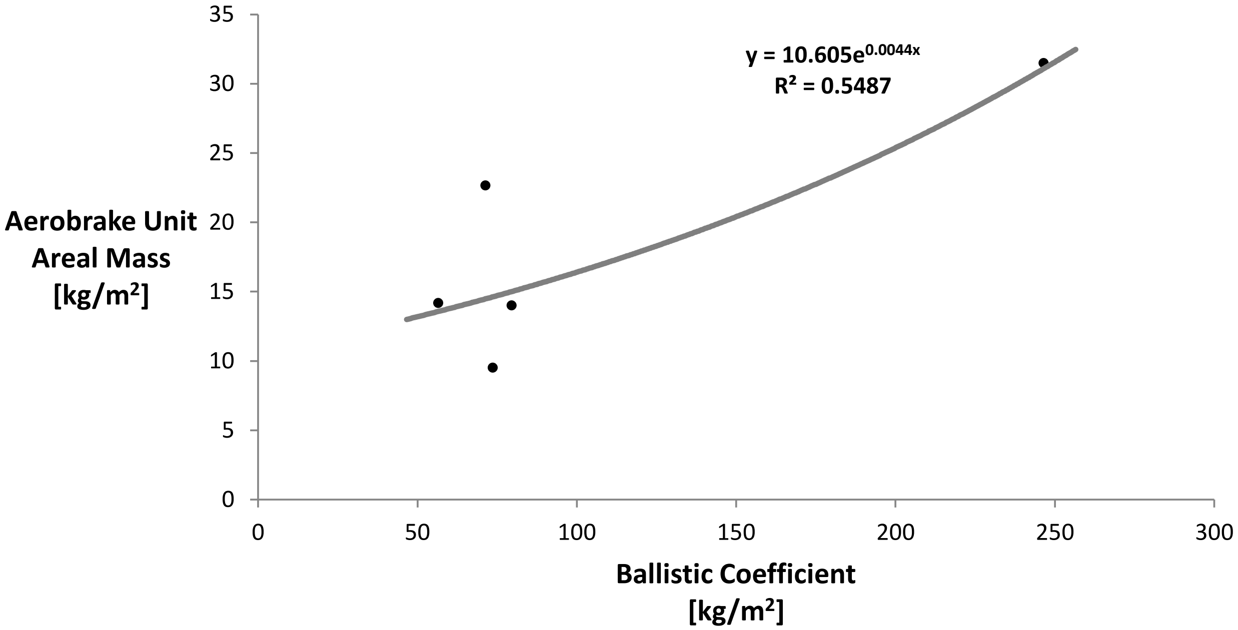


Figure 7.44 – Parametric Weight Analysis of Rigid Raked Cone Aerobrakes

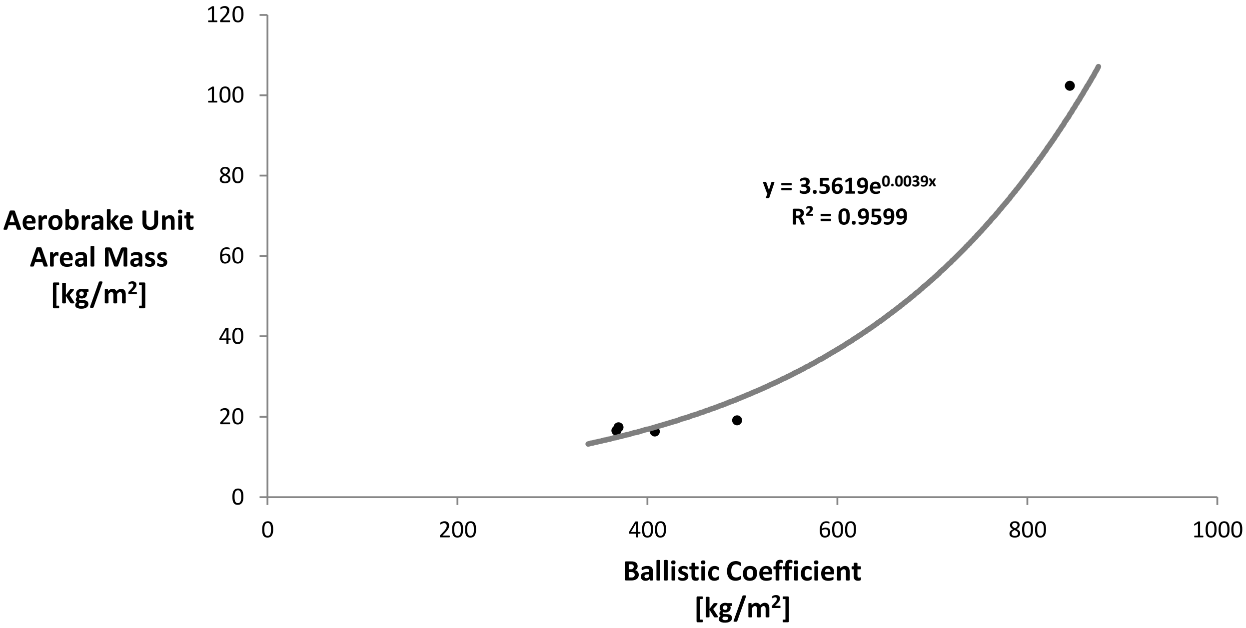


Figure 7.45 – Parametric Weight Analysis of Ellipsled Aerobrakes

7.4.6 Retrieve / Create Information: Knowledge Domain

In addition to data-driven information, sizing analysis of aerobrake vehicles requires additional knowledge-based input. Specifically, there is a need for a heuristics that approximate the two driving heating considerations of aerobraking vehicles – impingement of flow on the afterbody payload and peak nose heating.

During reentry, the hypersonic flow around the edge of the aerobrake forms an entropy-swallowing boundary layer that carries high enthalpy gas away from the heat shield. This flow is complex to model analytically, but is critical to the overall geometry of the aerobrake payload. If the payload is too long this flow impinges on the stack and can cause thermal failure unless additional TPS is added to the payload. Conversely, if the stack is shorter than required by the impingement angle of the wake flow, the aerobrake can be a smaller diameter and still protect the required payload.

The effect of heating on the weight of the vehicle is already captured in the parametric weight methods, but as a functional check of the actual peak heating rate at the nose an empirical heuristic is used. If the heating rate predicted by the heuristic is higher than the maximum value for current reusable TPS materials, the aerobrake size can be increased to increase nose radius and decrease ballistic coefficient. The relation was formed specifically for use in sizing of AOTVs to estimate heating rate with low-order variables available during conceptual design (Equation 1 from reference [403]).

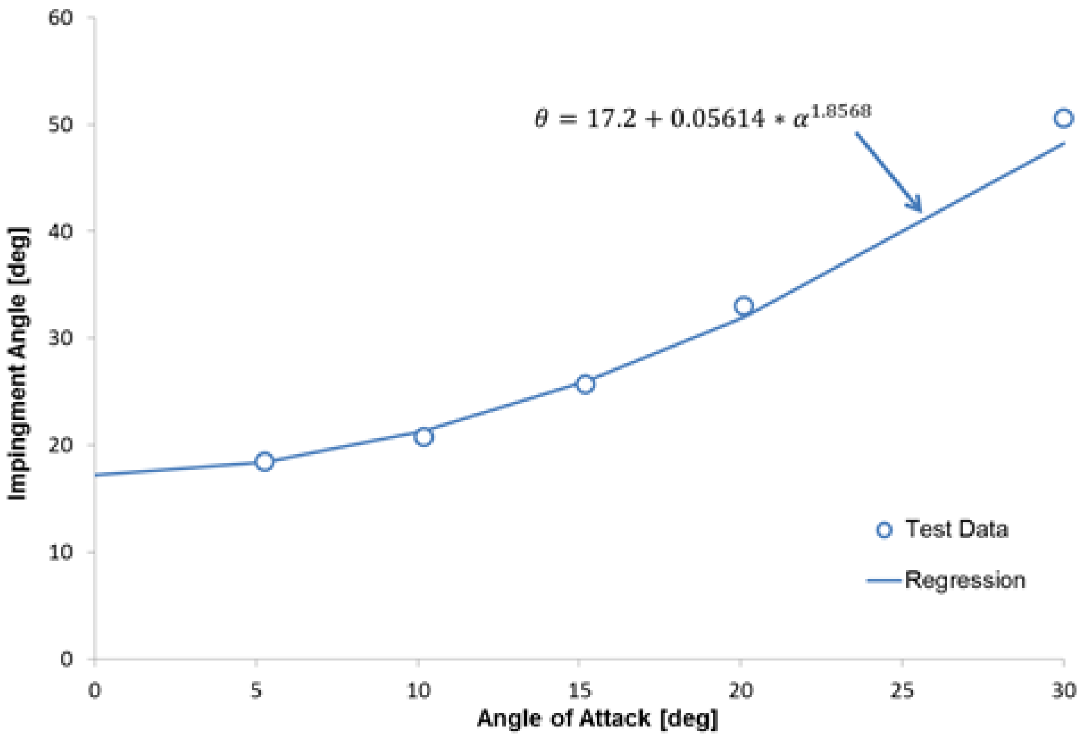


Figure 7.46 – Wake Impingement Flow for Open Aerobrake Configurations (figure from [373], data from [378])

$$\dot{q}_{MAX}\sqrt{R_N} = 7.3(\beta)^{.467}\left(\frac{L}{D}\right)^{-.242} \qquad \left[\frac{W\sqrt{m}}{cm^2}\right] \qquad \textbf{Equation 3}$$

7.4.7 Retrieve / Create Information: Analysis Domain

The systems analysis of satellite servicing architectures (including AOTVs) is carried out within the AVD Sizing conceptual design environment [404]. The aerospace sizing software platform has been developed since 2008 through a broad range of design efforts including general aviation aircraft, business jets, commercial aircraft, supersonic transport, and hypersonic demonstrators. It has been designed to adapt to new vehicle configurations in a generic manner with minimal changes to the overall framework. Disciplinary modules are stored and linked by reference instead of being hard-coded or interconnected to streamline the sizing of a specific vehicle configuration. While the disciplinary modules changes with each sizing project, the outer loop of the software environment that handles input / output variables, method integration, and system convergence stays constant

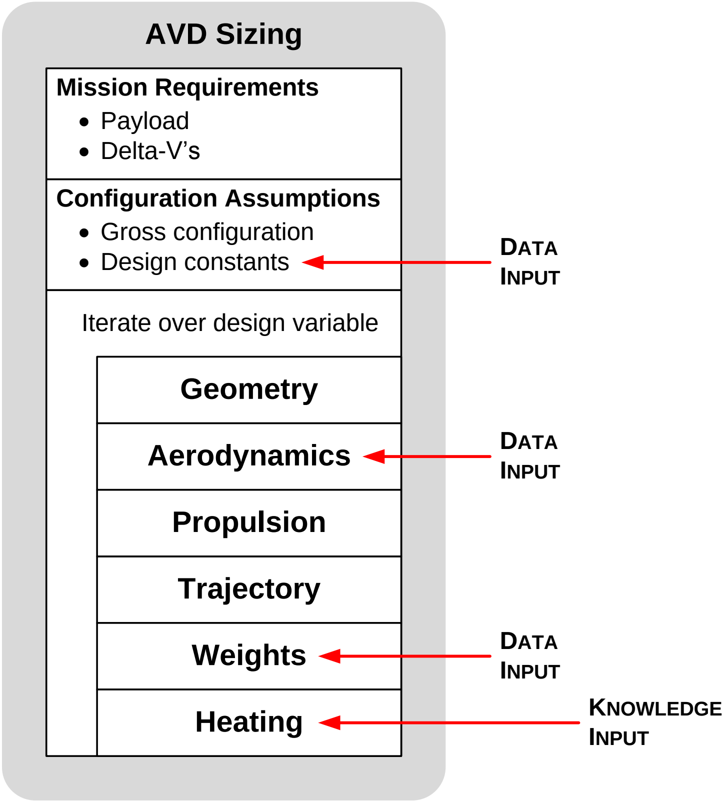


Figure 7.47 – Parametric Systems Analysis Framework for AOTV Sizing

Although AVD Sizing has been used previously assess the feasibility of hypersonic vehicle configurations, the MGS architecture has unique traits that require additional support. New disciplinary analysis methods for geometry, aerodynamics, component weights, and heating are required to model the characteristics of the system correctly (Figure 7.47). As detailed in the previous sections, these new methods are formed from a combination of historical AOTV project data and associated knowledge. The sizing software proceeds linearly from the global input file through each discipline with a specified independent design variable until each discipline has been addressed. The independent variable is then recalculated with the updated characteristics of the configuration – the process is then iterated over until the independent variable value reaches convergence between iterations.

The output of the vehicle sizing process is a converged vehicle configuration under the given design assumptions & operational constraints specified by the design team. By varying the design inputs, the configuration will be re-converged within the same framework and output. Analyzing the entire system architecture across the range of concept of operation within a standardized platform creates a true apples-to-apples comparison – alternative designs can be judged consistently based on numerical values of their performance & characteristics.

7.4.8 Information Summary & Outcome

The initial information requirements at the beginning of the task (Section 7.4.4) specified that figure of merit solution spaces provided to the decision-maker as a function of AOTV concept. The primary FoM has been identified as the gross mass of the vehicle – this value has implications on the available payload of the system as well as the launch capability required. With the assumption that all configurations considered are technically and operationally feasible within the development period, the gross mass shall be taken as the driving decision-making parameter.

The expendable ascent module ConOp (Table 7.9 & Figure 7.48) provides the gross geometry & mass characteristics of an AOTV aerobraking from GTO to LEO with a common payload & mission. The reduction in gross mass from the propulsive baseline comes almost exclusively from the reduction of propellant required for the second re-circularization burn of the transfer from servicing to low Earth parking orbit.

As a sub-trade to this ConOp, it was proposed to investigate a raked cone with asymmetric diameters to attempt to comply with operational packing constraints of the assumed launch vehicle. This concept, along with the ellipsled AOTV, converged to design points that exceed the limits for current reusable TPS technology and are included only for completeness.

Table 7.9 – Mass Summary of Reusable Orbital Transfer Vehicle Concepts: Expendable APM ConOp

CTV	Deployable kg	Raked Cone kg	Raked Cone (min diameter), kg	Ellipsled, kg	POTV kg
Dry Mass	3296	3880	4268	4367	3475
Propellant	3560	4100	4462	4553	12402
Reentry Mass	4101	4724	5140	5192	-
Gross Mass	7391	8515	9265	9454	16412
			Excessive Peak Heating No Convergence with TPS Analysis		

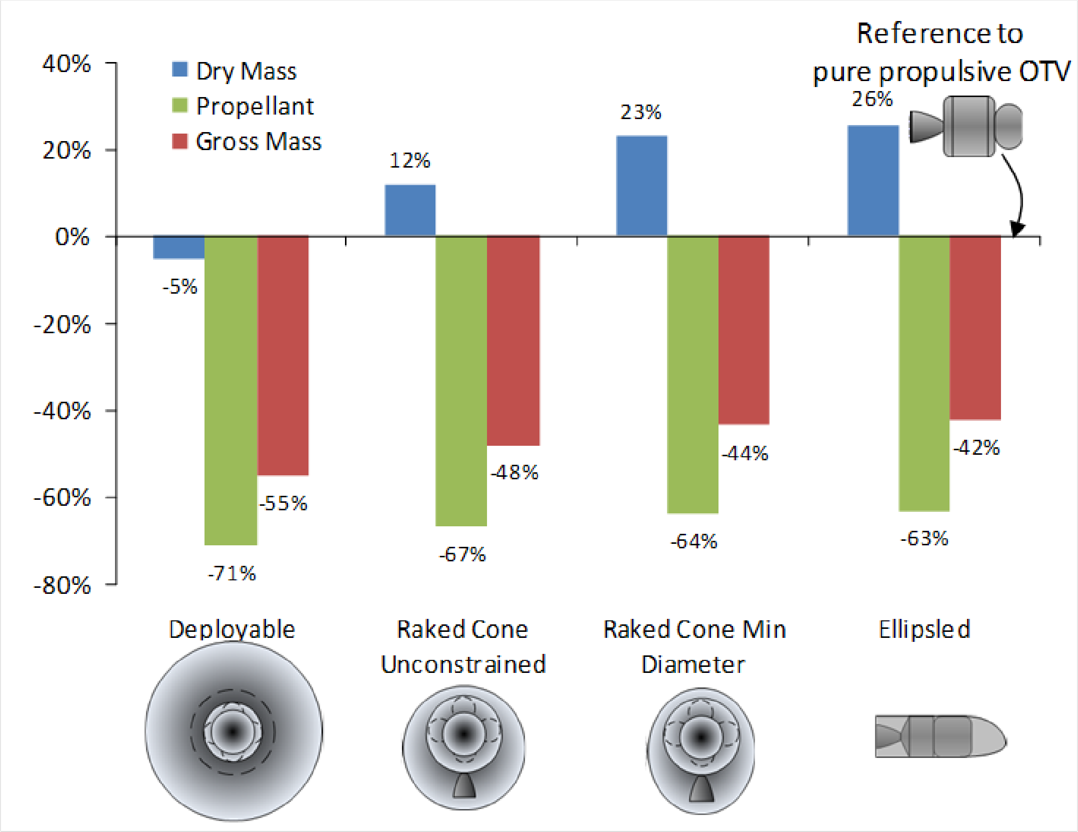


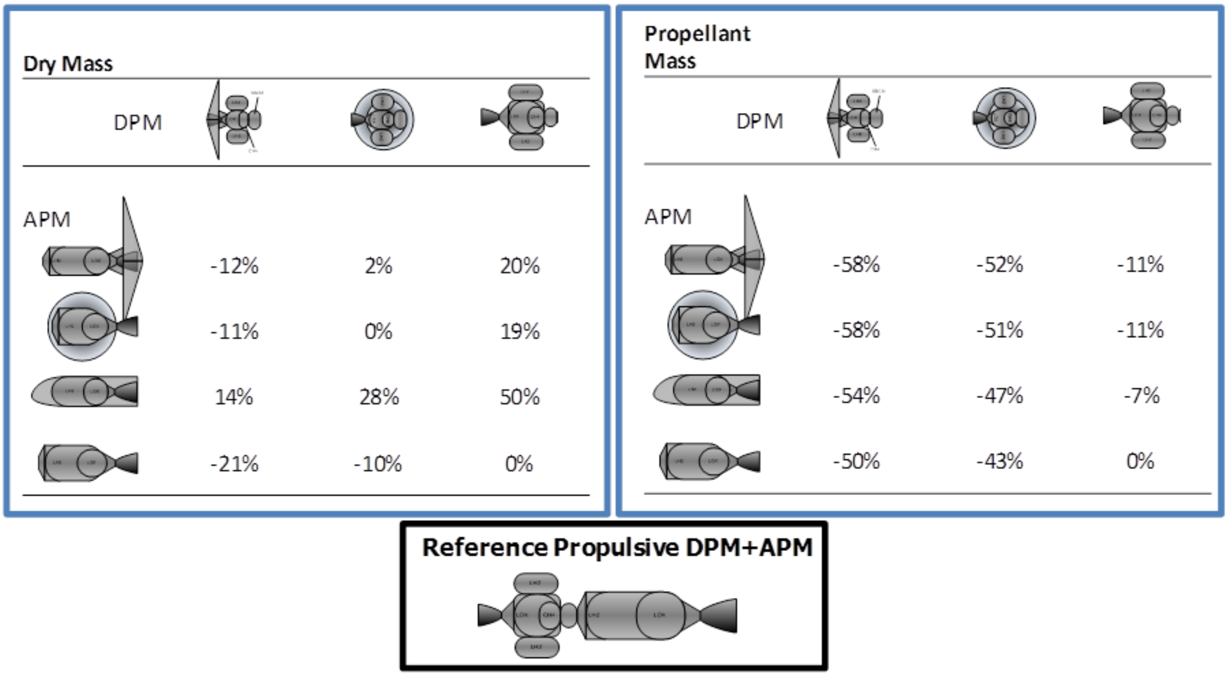
Figure 7.48 – Summary of AOTV Concepts for Expendable Ascent Module ConOp [373]

The reusable ascent module ConOp (Table 7.10 & Figure 7.49) adds an additional vehicle element to the first ConOp – instead of the ascent transfer vehicle being discarded after propelling the crew & payload from LEO towards GEO, the element is deorbited and repositioned at LEO for reuse on a future mission. This reusable vehicle has again been represented by an all-propulsive baseline with AOTV perturbations. This architecture adds significant mass to all concept combinations over the expendable ConOp, but offers the (unquantified) potential for reusability and reduced life-cycle resource needs.

By staging two AOTVs within the same concept architecture, the reduction in propellant mass has a chance to compound over the baseline. However, the reusable ascent AOTVs must also increase in size to shield the fuel tanks and propulsion systems. Because of this interaction, the configuration of the descent module remains the primary driver for mass reduction.

In both experimental concepts of operation, AOTVs provide a significant mass advantage over an all-propulsive baseline system. The capability to aerodynamically brake when lowering the orbit from GTO to LEO decreases the required propellant mass by eliminating the re-circularization burn. Although the aerobrake system adds dry mass over the baseline, the net effect is an overall decrease in gross weight (or an increase in potential payload weight).

Whether an expendable all-propulsive APM or a reusable AOTV APM is considered, both the deployable symmetric aerobrake & raked cone aerobrake are identified as the feasible configurations for further investigation based on the gross mass FoM and operational constraints considered. The ellipsled configuration offers a lower mass benefit, violates reusable TPS limits, and does not provide a substantial operational benefit under the current design reentry conditions.



Dry Mass

DPM			
APM			
	-12%	2%	20%
	-11%	0%	19%
	14%	28%	50%
	-21%	-10%	0%

Propellant Mass

DPM			
APM			
	-58%	-52%	-11%
	-58%	-51%	-11%
	-54%	-47%	-7%
	-50%	-43%	0%

Reference Propulsive DPM+APM

Figure 7.49 – Summary of AOTV Concepts for Reusable Ascent Propulsion Module ConOp [373]

Table 7.10 – Mass Summary of Reusable Orbital Transfer Vehicle Concepts: Reusable Ascent Module ConOp

	Deployable Lifting Break APM			*Raked Cone APM*		
Function	Deployable DPM, kg	Raked Cone DPM, kg	Propulsive DPM, kg	Deployable DPM, kg	Raked Cone DPM, kg	Propulsive DPM, kg
Dry Weight	5084	5697	8528	5206	5571	8337
Propellant	15376	17704	28931	15477	17818	29101
Reentry Mass	5526	6201	9332	5656	6348	9550
Gross Mass	35185	40522	66266	35408	40510	66245

	Ellipsled APM			*Propulsive APM*		
Function	Deployable DPM, kg	Raked Cone DPM, kg	Propulsive DPM, kg	Deployable DPM, kg	Raked Cone DPM, kg	Propulsive DPM, kg
Dry Mass	7949	8674	11847	3996	4400	6233
Propellant	17698	20117	31623	19943	22670	35685
Reentry Mass	8513	9306	12795	-	-	-
Gross Mass	40372	45913	72277	38664	44191	70725

Overall, this study has facilitated data-driven & knowledge-driven forecasting in the following tasks.

- Source documentation pertaining to a specific operational class of aerospace vehicles has been detailed.
- Variables of interest have been selected based on availability within the data and the information requirements of the decision-maker.
- A parametric AOTV weight model has been created from historical data points.
- Heuristic aero-thermodynamic heating approximations have been identified.
- Data-based & knowledge-based methods have been integrated into an existing vehicle analysis domain.
- Multi-disciplinary vehicle analysis has been performed to quantify the systems-level sensitivity to changes in vehicle configuration

7.5 CONTRIBUTION SUMMARY

The following topics presented in this chapter have been novel contributions to the overall research.

- A functional framework of the decision-making process with the logic steps required for information production of aerospace systems forecasting tasks has reviewed; all steps have been addressed in a linear fashion through all subsequent case studies.
- Guided step-by-step process of executing aerospace design & forecasting projects for real aerospace problems with real aerospace decision-makers; a variety of vehicle systems classes, information outputs and decision-making goals have been addressed.
- An exhaustive dataset of hypersonic research & development projects has been gathered from disparate sources and unified in a standardized format.
- Data visualizations formatted to direct decision-making have been directly linked to back-end datasets.
- A common datasets has been created to merge long-range, transport, supersonic and hypersonic aircraft data.
- Deliverables have been identified as a primary carrier of design knowledge in historical documentation.
- Application of standardized set of deliverables has characterized an entire segment of aerospace vehicles based on publicly-available data alone.
- The process of identifying driving parameters and condensing data to a format useful in a systems analysis context has been detailed.
- Aerobraking orbital transfer vehicle data has been assimilated into a common vehicle database, from which correlated size & weight trends have been directly fed into vehicle conceptual design / sizing analysis.

REFERENCES

[306] Oostenbrink, J., Maiween, J., Oppe, M., and Rutten-van Molken, M., “Expected Value of Perfect Information: An Empirical Example of Reducing Decision Uncertainty by Conduction Additional Research,” The Journal of the International Society for Pharmacoeconomic and Outcomes Research, 2008.

[307] Chudoba, B., Haney, E., Gonzalez, L., Omoragbon, A., and Oza, A., “Strategic Forecasting in Uncertain Environments: Hypersonic Cruise Vehicle Research and Development Case Study,” Royal Aeronautical Society Aeronautical Journal, Vol. 119, No. 1211, 2015.

[308] Haney, E., Gonzalez, L., Omoragbon, A., Oza, A., and Chudoba, B., “Integrated Engineering Database: A 21st Century Decision Aid,” America Society for Engineering Education Gulf Southwest Conference Proceedings, 2013.

[309] Grossman, E., "Army Eyes Advanced Hypersonic Weapon," InsideDefense.com, 2007. URL: http://www.military.com/features/0,15240,121633,00.html [2012]

[310] Rutledge, W., OUSD (AT&L)/PSA/Strategic Warfare, “Hypersonics in the USA: New Partnerships in the 21st Century” at the 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2011.

[311] Maita, M., Japan Aerospace Exploration Agency-JAXA, "Japan's Activities," 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference, Bremen, Germany, 2010.

[312] "NASA Invests in Private Sector Space Flight with SpaceX, Rocketplane-Kistler," URL: http://www.nasa.gov/exploration/news/COTS_selection.html [2006]

[313] "2011 U.S. Commercial Space Transportation Developments and Concepts: Vehicles, Technologies, and Spaceports," Federal Aviation Administration, January 2011.

[314] Erbland, P. J., “Current and Near-Term RLV/Hypersonic Vehicle Programs,” RTO AVT Lecture Series: “Critical Technologies for Hypersonic Vehicle Development”, von Kármán Institute, Rhode-St-Genèse, Belgium, 2004. URL: http://ftp.rta.nato.int/public//PubFullText/RTO/EN/RTO-ENAVT-116///EN-AVT-116-02.pdf [2012]

[315] Jackson, T., "USA Applied Hypersonics," 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference, Bremen, Germany, 2010.

[316] Dolvin, D, "Hypersonic International Flight Research and Experimentation (HIFiRE) - Fundamental Sciences and Technology Developement Strategy," 15th AIAA International Space Planes and Hypersonic Systems and Technologies AIAA 2008-2581, Dayton, OH, 2008.

[317] Boyce, R., “Australia National Report, 2011,” 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2011.

[318] Falempin,F., "France National Report," 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference, Bremen, Germany, 2010

[319] Vanbebber, C., "Lockheed Martin Receives $218 Million for Long Range Anti-Ship Missile (LRASM) Demonstrations," LockheedMartin.com, 2011, URL: http://www.lockheedmartin.com/news/press_releases/2011/MFC_012011_LM_Receives218_Million.html [2012]

[320] Fisher, R. Jr., "Shenlong Space Plane Advances China's Military Space Potential," Strategycenter.net, 2007. URL: http://www.strategycenter.net/research/pubID.174/pub_detail.asp [2012]

[321] Hempsell, M., Longstaff, R., Bond, A., "Skylon User's Manual," Reaction Engines Ltd., SKY-REL-MA-0001, Revision 1.1, 2010.

[322] Lopez, T., "USAF Space Plane Program In Works - Unmanned X-37B To Be Service's Space Test Vehicle," Aero-News.net, 2006. URL: http://www.aero-news.net/index.cfm?do=main.textpost&id=2d21f489-57c3-4bb1-b65d-ea2564deba49 [2012]

[323] Orton, G., "Air-Breathing Hypersonics Research at Boeing Phantom Works," 11th AIAA/AAAF International Space Planes and Hypersonic Systems and Technologies AIAA 2002-5251, 2002.

[324] Mehta, U., "Hypersonic technologies and aerospace plane," Aerospace America, pp. 72, December 2010.

[325] Few, S., “Information Dashboard Design: The Effective Visual Communication of Data,” O’Reilly Media, 2006.

[326] “Science and Engineering Indicators 2012,” National Science Foundation, 2012. URL: http://www.nsf.gov/statistics/seind12/c0/c0s1.html [2012]

[327] Gertz, B., “China Conducts First Test of New Ultra-High Speed Missile Vehicle,” The Washington Free Beacon, 2014.

[328] Haney, E. and Korte, J., “High-Speed Commercial Transport R&D: Competition and Market Survey,” NASA Langley Aerospace Research Student Scholars Program, 2013.

[329] Feir, J., "Evaluation of Routing and Scheduling Considerations for Possible Future Commercial Hypersonic Transport Aircraft," NASA, NASA CR-132632, 1975.

[330] Bond, E., Carroll, E., and Flume, R., "Study of the Impact of Cruise Speed on Scheduling and Productivity of Commercial Transport Aircraft," NASA, NASA CR-145189, 1977.

[331] Graf, D., "Study of High-Speed Civil Transports," NASA Langley Research Center, NASA CR-4235, 1989.

[332] Boeing, "High-Speed Civil Transport Study," NASA Langley Research Center, CR-4233, 1989.

[333] Lee, W., Roll, R., Bateman, R., Higman, T., and Henderson, S., "High-Speed Civil Transport Study Commercial Value Analysis," NASA Langley Research Center, NAS1-18377, 1989.

[334] Boeing, "High-Speed Civil Transport Study: Summary," NASA Langley Research Center, NASA CR-4234, 1989.

[335] Welge, H., and et. al, "N+2 Supersonic Concept Development and Systems Integration," NASA Langley Research Center, NASA CR-2010-216842, 2010.

[336] Morgenstern, J., Norstrud, N., Stelmack, M., and Skoch, C., "Final Report for the Advanced Concept Studies for Supersonic Commercial Transports Entering Service in the 2030 to 2035 Period, N+3 Supersonic Program," NASA, NASA CR-2010-216796, 2010.

[337] Welge, R., and et al, "N+3 Advanced Concept Studies for Supersonic Commercial Transport Aircraft Entering Service in the 2030-2035 Period," NASA, NASA CR-2011-217084, 2011.

[338] Henshaw, J., "Supersonic Engineering," John Wiley & Sons, Inc., ASIN B001P9J5BK, 1962.

[339] Loomis, J., "High Speed Commercial Flight: The Coming Era," Batelle Memorial Institute, ISBN 0-935470-37-9, 1987.

[340] Loomis, J., "High Speed Commercial Flight: From Inquiry to Action," Batelle Memorial Institute, ISBN 0-935470-49-2, 1988.

[341] "Proceedings of the European Symposium on Future Supersonic Hypersonic Transportation Systems," Cepadues-Editions, ISBN 2.85428.2698, 1990.

[342] Maita, M., "Proceedings of the International Workship on Spaceplace/RLV Technology Demonstrators," Workshop Organizing Committee of Japan, 1997.

[343] National Research Council, "Hypersonic Technology for Military Application," Committee on Hypersonic Technology for Military Application, ISBN 0-309-04229-1, 1990.

[344] National Research Council, "U.S. Supersonic Commercial Aircraft: Assessing NASA's High Speed Research Program," National Academy of Sciences, ISBN 0-309-05878-3, 1997.

[345] National Research Council, "Maintaining U.S. Leadership in Aeronautics: Breakthrough Technologies to Meet Future Air and Space Transportations Needs and Goals," National Academy of Sciences, ISBN 0-309-06226-8, 1998.

[346] National Research Council, "Evaluation of the National Aerospace Initiative," National Academy of Sciences, ISBN 0-309-53107-1, 2004.

[347] "Urban Agglomerations 2007," United Nations, 2007.

[348] “Petroleum & Other Liquids,” U.S. Energy Information Administration, 2015.
URL: http://www.eia.gov/petroleum/data.cfm#summary

[349] "Which are the largest city economics in the world and how might this change by 2025?," PricewaterhouseCoopers, 2008.

[350] Dobbs, R., Smit, S., Jaana, R., Manyika, J., Roxburgh, C., and Restrepo, A., "Urban World: Mapping the economic power of cities," McKinsey Global Institute, 2011.

[351] Leahy, J., "Airbus Global Market Forecast 2010," Airbus, 2010.

[352] "Business Aircraft Market Forecast 2013-2032," Bombardier, 2013.

[353] "Current Market Outlook: 2011-2030," Boeing, 2011.

[354] Owens, K., "Concorde: New Shape in the Sky," Jane's Publishing Company Limited, ISBN 0867206306, 1982.

[355] Turnill, R., "Celebrating Concorde," Ian Allan Publishing, ISBN 0711022968, 1994.

[356] Owen, K., "Concorde: Story of a Supersonic Pioneer," The Science Museum, ISBN 1-900747-21-1, 2001.

[357] Kuchemann, D., "The Aerodynamic Design of Aircraft," Pergamon Press, TL 570.K75 1978, 1978.

[358] Davies, R., "Fallacies and Fantasies of Air Transport History," Paladwr Press, ISBN 0-9626483-5-3, 1994.

[359] Davies, R., “Supersonic (Airliner) Non-Sense : A Case Study in Applied Market Research,” Paladwr Press, 1998.

[360] Poisson-Quinton, P., "Future Possibilities of the Supersonic Transport Plane," NASA, TT F-8321, 1963.

[361] Carlier, P., Debelmas, C., Pilon, J., and Velot-Lerou, A., "Preliminary Project On Commercial Supersonic Transport Plane," Aerospatiale, 1992.

[362] "Type Certificate Data Sheet No. A45EU," Department of Transportation Federal Aviation Administration, No. A45EU, 1979.

[363] “Celebrating Concorde,” British Airways, 2014. URL: http://www.britishairways.com/en-gb/information/about-ba/history-and-heritage/celebrating-concorde

[364] Welge, H., and et. al, "N+2 Supersonic Concept Development and Systems Integration," NASA Langley Research Center, NASA CR-2010-216842, 2010.

[365] Welge, R., and et al, "N+3 Advanced Concept Studies for Supersonic Commercial Transport Aircraft Entering Service in the 2030-2035 Period," NASA, NASA CR-2011-217084, 2011.

[366] "Reaction Engines Limited: LAPCAT A2," Reaction Engines Ltd, 2013.
URL: www.reactionengines.co.uk/lapcat.html

[367] Maita, M., "Japan's Activities: National Report 2012," 18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2012.

[368] "EADS Global Website - ZEHST Concept," EADS, 2013.

[369] Sippel, M., Schwanekamp, T., Bauer, C., Garbers, N., van Foreest, A., Tengzelius, U., and Lentsch, A., "Technical Maturation of the SpaceLiner Concept," 18th AIAA/3AF International Space Planes and Hypersonics Systems and Technologies Conference, AIAA 2012-5850, 2012.

[370] Kopp, A., Garbers, N., Jarlas, R., and Rabia, H., "Parametric Structural Analysis for the SpaceLiner," AIAA, AIAA 2012-5944, 2012.

[371] “Annual Energy Outlook 2014 Early Release Overview,” U.S. Energy Information Administration, 2014.

[372] Chudoba, B. Coleman, G., Oza, A., Gonzalez, L., Haney, E., Ricketts, V. and Czysz, P., “Manned GEO Servicing (MGS) Crew Return Vehicle Sizing,” Final Contract Report, National Institute of Aerospace (NIA), NASA LaRC and DARPA, Section in Final Report “Manned Geosynchronous Earth Orbit (GEO) Servicing (MGS) Joint NASA/DARPA Study,” NASA SP-2012-598, MGS Study Team, NASA Headquarters and DARPA Tactical Technology Office, Washington, DC, 27 April 2011.

[373] Coleman, G., Gonzalez, L., Haney, E., Oza, A., Ricketts, V., and Chudoba, B., “Conceptual Architecture Planning for Manned GEO Satellite Servicing,” The Royal Aeronautical Society Aeronautical Journal, [PENDING].

[374] “Space Shuttle Mission Information,” NASA, 2015.
URL: http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/index.html

[375] Corso, C., and Eyer, C., "Space Tug Aerobraking Study: Volume 1, Executive Summary Volume," Boeing, NASA CR-123641, 1972.

[376] Corso, C., and Eyer, C., "Space Tug Aerobraking Study: Volume 2, Technical," Boeing, NASA-CR-124057, 1972.

[377] Dickman, G., "Orbital transfer vehicle concept definition and system analysis study, 1985. Volume 2: OTV concept definition and evaluation. Book 2: OTV concept definition," Martin Marietta Corporation, NASA-CR-183543, 1985.

[378] Dickman, G., “Orbital transfer vehicle concept definition and systems analysis study, 1986. Volume 1-A: Executive summary supplement,” Martin Marietta, NASA-CR-183549, 1986.

[379] Kofal, A., "Orbital transfer vehicle concept definition and system analysis study, 1986. Volume 9: Study extension results," Martin Marietta Corporation, NASA-CR-183549, 1987.

[380] Willcockson, B., "Orbital transfer vehicle: Concept definition and system analysis study," NASA Marshall Space Flight Center, NASA ID 19880012676, 1987.

[381] Kofal, A., "Orbital transfer vehicle concept definition and system analysis study. Volume 2: OTV concept definition and evaluation. Book 1: Mission and system requirements," Martin Marietta Corporation, NASA-CR-179321, 1987.

[382] Willcockson, W., "Orbital transfer vehicle concept definition and system analysis study. Volume 10: Aerocapture for manned Mars," Martin Marietta Corporation, NASA-CR-183550, 1988.

[383] Willcockson, W., "Orbital transfer vehicle concept definition and systems analysis study. Volume 11: Study extension 2 results," Martin Marietta Corporation, NASA-CR-183552, 1988.

[384] "Orbital Transfer Vehicle Concept Definition and Systems Analysis Study: Final Report - Phase I Volume II, Configuration and Subsystem Trade Studies 1986," Boeing, NASA CR-183685, 1986.

[385] "Orbital Transfer Vehicle Concept Definition and Systems Analysis Study: Final Report - Phase I Volume III, System and Program Trades 1986," Boeing, NASA CR-183687, 1986.

[386] Scott, C., Roberts, B., Nagy, K., and Taylor, P., "Design Study of an Integrated Aerobraking Orbital Transfer Vehicle," NASA, NASA TM-58264, 1985.

[387] Pattison, W., and Hodge, J., "Space transfer vehicle concepts and requirements. Volume 1: Executive summary," Martin Marietta, NASA-CR-184488, 1991.

[388] Pattison, W., and Hodge, J., "Space transfer vehicle concepts and requirements. Volume 2, book 1," Martin Marietta, NASA-CR-184489, 1991.

[389] Pattison, W., and Hodge, J., "Space transfer vehicle concepts and requirements. Volume 2, book 2: Appendix," Martin Marietta, NASA-CR-184490, 1991.

[390] Weber, G., Vinopal, T., and Goo, S., "Space transfer vehicle concepts and requirements study. Volume 1: Executive summary," Boeing, NASA-CR-192524, 1991.

[391] Weber, G., Vinopal, T., and Goo, S., "Space transfer vehicle concepts and requirements study. Volume 2, book 1: STV concept definition and evaluation," Boeing, NASA-CR-192525, 1991.

[392] Woodcock, G., "Space transfer concepts and analysis for exploration missions. Implementation plan and element description document (draft final). Volume 2: Cryo/aerobrake vehicle," Boeing, NASA-CR-192490, 1991.

[393] Cannon, J., Vinopal, T., Andrews, D., Richards, B., Weber, G., Paddock, G., Maricich, P., Bouton, B., Hagen, J., and Kolesar, R., "Space transfer vehicle concepts and requirements study, phase 2," Boeing, NASA-CR-192430, 1992.

[394] Dyke, E., and Hrinda, G., "Structural Design for Neptune Aerocapture Mission," AIAA Atmospheric Flight Mechanics Conference and Exhibit, AIAA 2004-5179, 2004.

[395] Lockwood, M., and et al, "Aerocapture Systems Analysis for a Neptune Mission," NASA Langley Research Center, NASA TM-2006-241300, 2006.

[396] Garcia, J., Brown, J., Kinney, D., Bowles, J., Huynh, L., Jiang, X., Lau, E., and Dupzyk, I., "Co-Optimization of Mid Lift to Drag Vehicle Concepts for Mars Atmospheric Entry," 10th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, AIAA 2010-5052, 2010.

[397] Dwyer Cianciolo, A., Davis, J., Komar, D., Munk, M., Samareh, J., Williams-Byrd, J., and Zang, T., "Entry, Descent and Landing Systems Analysis Study: Phase 1 Report," NASA Langley Research Center, NASA-TM-2010-216720, 2010.

[398] Litton, D., Bose, D., Cheatwod, F., Hughes, S., Wright, H., Lindell, M., Derry, S., and Olds, A., "Inflatable Re-entry Vehicle Experiment (IRVE-4) Overview," 21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, 2011.

[399] Samareh, J., and Komar, D., "Parametric Mass Modeling for Mars Entry, Descent and Landing System Analysis Study," 49th AIAA Aerospace Sciences Meeting, AIAA-2011-1038, 2011.

[400] Dwyer Cinciolo, A., Zang, T., Sostaric, R., and McGuire, K., "Overview of the NASA Entry, Descent and Landing Systems Analysis Exploration Feed-Forward Study," 8th International Planetary Probe Workshop, 2011.

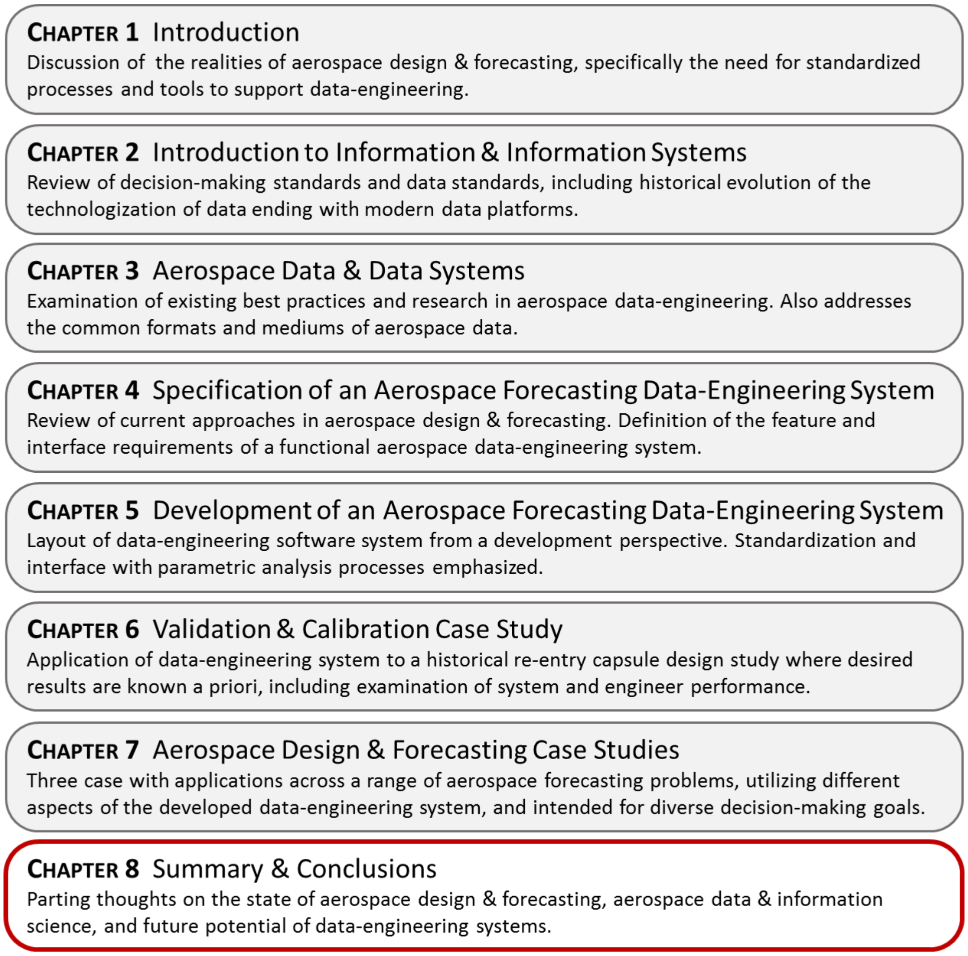
[401] Bose, D., Winski, R., Shidner, J., Zumwalt, C., Johnston, C., Komar, D., Cheatwood, F., and Hughes, S., "The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Mission Applications Study," 22nd AIAA Aerodynamic Decelerator Systems Technology Conference, 2013.

[402] Hirschel, E., and Weiland, C., "Selected Aerothermodynamic Design Problems of Hypersonic Flight Vehicles," AIAA, SEL TL 507.P75v.229, 2009.

[403] Scott, C. D., Roberts, B. B., Nagy, K., Taylor, P., Gamble, J. D., Ceremeli, C. J., Knoll, K. R., Li, C. P., and Reid, R. C., "Design Study of an Integrated Aerobraking Orbital Transfer Vehicle," NASA TM-58264, 1985.

[404] Coleman, G., "Aircraft Conceptual Design - an Adaptable Parametric Sizing Methodology," University of Texas at Arlington, 2010.

CHAPTER 8
SUMMARY & CONCLUSIONS



CHAPTER 1 Introduction
Discussion of the realities of aerospace design & forecasting, specifically the need for standardized processes and tools to support data-engineering.

CHAPTER 2 Introduction to Information & Information Systems
Review of decision-making standards and data standards, including historical evolution of the technologization of data ending with modern data platforms.

CHAPTER 3 Aerospace Data & Data Systems
Examination of existing best practices and research in aerospace data-engineering. Also addresses the common formats and mediums of aerospace data.

CHAPTER 4 Specification of an Aerospace Forecasting Data-Engineering System
Review of current approaches in aerospace design & forecasting. Definition of the feature and interface requirements of a functional aerospace data-engineering system.

CHAPTER 5 Development of an Aerospace Forecasting Data-Engineering System
Layout of data-engineering software system from a development perspective. Standardization and interface with parametric analysis processes emphasized.

CHAPTER 6 Validation & Calibration Case Study
Application of data-engineering system to a historical re-entry capsule design study where desired results are known a priori, including examination of system and engineer performance.

CHAPTER 7 Aerospace Design & Forecasting Case Studies
Three case with applications across a range of aerospace forecasting problems, utilizing different aspects of the developed data-engineering system, and intended for diverse decision-making goals.

CHAPTER 8 Summary & Conclusions
Parting thoughts on the state of aerospace design & forecasting, aerospace data & information science, and future potential of data-engineering systems.

The purpose of this dissertation has been to formally define *Data-Engineering* as a discipline, and subsequently to identify its application to an aerospace design & forecasting environment. To the first point, data has been assessed from a holistic perspective including historical treatment of data, current data software platforms and research in data & information science to arrive at a working definition of *Data-Engineering* principles. And to the second point, a prototype platform has been built, tested within the rigors of real decision-making requirements, and shown to positively influence the ability to produce design & forecasting information.

The initial hypothesis that a formalized *Data-Engineering System* could improve the quality of design forecasting information, and at the same time reduce resource overhead has been proven under a controlled experiment. Such a system is a living, breathing entity that should constantly adapt to new forecasting efforts, but the return on investment with even the prototype system has been substantial.

8.1 SUMMARY OF CONTRIBUTIONS

Research contributions are best measured against the criteria set forth in the research hypothesis, specification & development requirements. The primary hypothesis was that implementing *Data-Engineering* standards into design & forecasting processes would increase the productivity, efficiency & consistency of the organization. This hypothesis has been confirmed through one validation case study and three applied case studies across a range of aerospace information requirements and forecasting topics. By standardizing *Data-Engineering,* tasks industry and academically-recognized forecasting information has been produced with small engineering teams under constrained timelines. Within the AVD aerospace design and forecasting setting, the following uniquely novel contributions have been made throughout the current research:

- Source documentation has been standardized and stored communally as a shared resource.
- An exhaustive hypersonic research & development vehicle database has been generated and stored for tangential uses.
- Information deliverables have been identified and catalogued for the first time.
- Parametric vehicle analysis interfaces have been streamlined and automated.
- Time to generate alternative design analyses has been reduced by an order of magnitude.

The contribution, then, of the current research effort has been to influence design & forecasting organizations towards implementing *Data-Engineering* standards and formal *Data-Engineering Systems*, where possible. Adjusted to large-scale aerospace design & forecasting organizations, the potential efficiency & productivity gains from the implementation of *Data-Engineering Systems* is substantial. In this context, it is beneficial to summarize the total research effort removed from the prototype software environment and elevated towards universal goals.

Transparency

- The flow of data from creation to initial discovery to incorporation within an information task should be documented and made available.

- All information-production tasks should be made available to the entire forecasting organization.
- Program-specific knowledge should have an immediate outlet for recording.
- Data processes should encourage the flow of experience from senior engineers into formalized systems.

Universality

- Data processes should be agnostic of the size and scope of required data sets.
- Previous organizational efforts should be made available for reference and as a starting point for future efforts.
- Interface standards should be agnostic of the outbound data use – i.e. data analysis, modelling, or visualization.
- Interfaces between software environments should be codified and standardized.

Adaptability

- Data processes should be adaptable across decision-making domains, analysis approaches, and vehicle systems.
- Data sets should be available and query-able across project and disciplinary domains.

Productivity

- Repetitive, non-cognitive data tasks should be automated.
- Data processes should prompt forecasting tasks to consider alternative analysis and / or design approaches, if relevant data items are available to support.

8.2 CLOSING REMARKS ON AEROSPACE DATA-ENGINEERING

Data-driven decision-making is not going away. Decisions involving substantial investments of time, fiscal and human capital must come to the table with data in hand. The era of the all-knowing chief engineer, program manager or executive justifying design & requirements decisions based on “gut-feel” and intuition is coming to quick and ceremonious close. In the evolving data-centric landscape, the microscope will not only be on the technical & operational solution provided by the traditional engineering discipline, but on the underlying decisions that drove the engineering solution. It is not enough to provide assumptions, rules of thumb and engineering common sense –

transparent justification through supporting data will be required all the way from source to implementation.

If data is the language of decision-making, where does that leave the engineering discipline? In current curricula, data is treated as an afterthought, an intermediate medium that must be dealt with in order to get to the "real" problems. This is a dangerous and self-destructive mindset. Decisions will be made at the data-driven level, divorced from the technical minutiae of traditional engineering technical disciplines – by refusing to learn the language, engineers are excusing themselves from the table where the big decision are made. These same decisions will frame the technical solution space later in the design cycle, whether they are there to contribute to the conversation or not. And they should be.

Aerospace vehicle systems are only growing more complex and more disciplinarily integrated – expecting managerial personnel without a scientific or engineering background to fully grasp the interdisciplinary effects of their decisions is a doubtful prospect. It is critical that an engineering mindset be introduced to these decisions at the earliest & highest levels possible. This requires an expansion of what an engineer is and what an engineer is (and is not) capable. The question, then, is if engineering will be confined to its self-contained analytical silo or will it widen its view towards the holistic research, development and operational realities? If the latter is preferred, the inclusion of *Data-Engineering* in education, mindset and tool proficiency will be a mandatory requirement into the foreseeable future.

From an organizational perspective, billions are spent every year creating information and billions more spent recording and cataloguing data – but to what end? A warehouse full of data, by itself, is of little practical use to the practicing engineer. It must be made real, tangible and relevant to the problems they see directly in front of them. Historical project data should be the greatest possible educator for an engineer, but it must come in a manner more pre-digested than a several hundred page report – the number of projects and the amount of data available to the engineer is increasing exponentially, while the time available for research and absorption is shrinking. Consumption of data must become more efficient in our engineering processes or, collectively, we are resigning ourselves to re-inventing the proverbial wheel. The physics of flight are not changing – air & space vehicles designed yesterday obey the same laws as today's systems and tomorrow's concepts. Let us put ourselves in the best possible position, then, to have a collective memory spanning the successes – and failures – while designing the aerospace vehicles of the future.

Appendix A
Data-Engineering System – AVD Sizing Interface

Data-Engineering System Input File Generation VBA Code

```
    Dim db As DAO.Database
    Dim rs, rst As DAO.Recordset
    Dim strSQL As String
    Dim i
    Dim DisciplineID As Integer

'FILE CREATION
    Dim FileNumber As Integer
    FileNumber = FreeFile
    Open Me.InputFileName For Output As #FileNumber
    Close #FileNumber
    Open Me.InputFileName For Output Access Write As #FileNumber

'WRITE
    Print #FileNumber, "function [input]=" & Me.AnalysisName & "()"
    Print #FileNumber, "%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>"
    Print #FileNumber, "%                   AVDsizing"
    Print #FileNumber, "%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>"
    Print #FileNumber, "%"
    Print #FileNumber, "% ***********************************************************************"
    Print #FileNumber, "% Problem Description"
    Print #FileNumber, "% ***********************************************************************"
    Print #FileNumber, "%"

'HEADING
    Print #FileNumber, "%Variable description****************************************************"
    Print #FileNumber, "%Project_title      " & Me.AnalysisName
    Print #FileNumber, "%Author             " & Me.Author
    Print #FileNumber, "%Unit system        Not active, SI default"
    Print #FileNumber, "%File Creation Date " & Now()
    Print #FileNumber, "%% *"

'CONSTANTS
    Print #FileNumber, "%************************************************************************"
    Print #FileNumber, "% Global Variables"
    Print #FileNumber, "%************************************************************************"
    Print #FileNumber, "  DTR=pi/180;"
    Print #FileNumber, "  API=pi;"
    Print #FileNumber, "  G0=9.81;"
    Print #FileNumber, "  sigma = 5.670373e-8; %Stefan-Boltzmann constant, W/m^2 K^-4 "
    Print #FileNumber, "  RE = 6378*1000;"
    Print #FileNumber, "  MU = 398600*1000^3;"
    Print #FileNumber, "%% *"

'AERODYNAMICS
    DisciplineID = 4
    MethodSelection2 DisciplineID, FileNumber
    VariableSelection2 DisciplineID, FileNumber

Print #FileNumber, "%% *"

'PROPULSION
    DisciplineID = 5
    MethodSelection2 DisciplineID, FileNumber
    VariableSelection2 DisciplineID, FileNumber

Print #FileNumber, "%% *"

'GEOMETRY
    DisciplineID = 2
    MethodSelection DisciplineID, FileNumber
    VariableSelection DisciplineID, FileNumber

Print #FileNumber, "%% *"
```

```
'WEIGHT & BALANCE
    DisciplineID = 3
    MethodSelection DisciplineID, FileNumber
    VariableSelection DisciplineID, FileNumber

Print #FileNumber, "%% *"

'PERFORMANCE MATCHING
    DisciplineID = 6
    MethodSelection DisciplineID, FileNumber
    VariableSelection DisciplineID, FileNumber

Print #FileNumber, "%% *"

'HEATING
    DisciplineID = 7
    MethodSelection DisciplineID, FileNumber
    VariableSelection DisciplineID, FileNumber

Print #FileNumber, "%% *"

'CONVERGENCE
    DisciplineID = 8
    MethodSelection DisciplineID, FileNumber
    VariableSelection DisciplineID, FileNumber

Print #FileNumber, "%% *"

'DESIGN
    DisciplineID = 13
    MethodSelection DisciplineID, FileNumber
    VariableSelection DisciplineID, FileNumber

Print #FileNumber, "%% *"

    Print #FileNumber, "AnalysisID = " & Me.AnalysisID & ";"
    Print #FileNumber, "ResultFile = '" & Me.ResultFileName & "';"
    Print #FileNumber, "%% *"
    Print #FileNumber, "  input=v2struct;"
    Print #FileNumber, "end"
    Close #FileNumber

    MsgBox "Done!"
```

AVD Sizing Input File (Example)

```
function [input]=MercuryTest()
%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
%                   AVDsizing
%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
%
% ************************************************************************
% Problem Description
% ************************************************************************
%
%Variable description*****************************************************
%Project_title      MercuryTest
%Author             Eric
%Unit system        Not active, SI default
%File Creation Date 3/22/2016 10:31:33 PM
%% *
%*************************************************************************
% Global Variables
%*************************************************************************
  DTR=pi/180;
  API=pi;
  G0=9.81;
  sigma = 5.670373e-8; %Stefan-Boltzmann constant, W/m^2 K^-4
  RE = 6378*1000;
  MU = 398600*1000^3;
%% *
%*************************************************************************
```

```
% AERODYNAMICS input
%*************************************************************************
  AERO_SWITCH = [];
%Method Selection ********************************************************
% AERO_MD19 - empirical capsule aerodynamics
%*************************************************************************
  AERO_M={'AERO_MD19'};
%Variable description*****************************************************
% []        no variables required, []
%*************************************************************************
%% *
%% *
%*************************************************************************
% PROPULSION input
%*************************************************************************
  PROP_SWITCH=[];
%Method Selection ********************************************************
%*************************************************************************
  PROP_M={};
%Variable description*****************************************************
%% *
%% *
%*************************************************************************
% GEOMETRY input
%*************************************************************************
%Method Selection ********************************************************
% GEOMETRY_MD9 - generic capsule geometry
%*************************************************************************
  GEO_M={'GEOMETRY_MD9'};
%Variable description*****************************************************
% DT                capsule top diameter, m
% HT                capsule top height, m
% ALLE              sidewall angle, deg
% RN_DC             nose radius to diameter ratio, []
%*************************************************************************
  DT = [.8128];
  HT = [1.2];
  ALLE = [20];
  RN_DC = [2.032/1.8923];
%% *
%*************************************************************************
% WEIGHT AND BALANCE input
%*************************************************************************
%Method Selection ********************************************************
% WB_MD17_Mercury - semi-empirical weight/volume
%*************************************************************************
  WB_M={'WB_MD17_Mercury'};
%Variable description*****************************************************
% VUN               unmanned system volume, m^3
% FUEL_DEN              FUEL DENSITY, kg/m^3
% NAISTR_MODE               structural index mode [1-input,2-solved], []
% AISTR             structural industry capability factor, kg/m^2
% FPRV              fixed provisions per passenger, kg
% VENG_TJ               TURBOJET VOLUME, m^3
% AMUA              inert weight margin, []
% FSYS              fixed systems weight, kg
% CUN               unmanned systems weight, kg
% VUN               unmanned system volume, m^3
% FMND              crew systems weight per crew, kg
% AKVV              void volume coefficient, []
% AKVS              system volume coefficient, []
% FCRW              fixed crew specific volume, m^3/person
% VPCRW             crew provisions specific volume, m^3/person
% AKCRW             crew member specific volume, m^3/person
% V_PAX             passenger specific volume, m^3/person
% EBAND             structural index margin, []
% RHO_CARGO             cargo density, kg/m^3
% OX_DEN                OXIDIZER DENSITY, kg/m^3
% CREW              number of crew, []
% WPAX              weight per passenger, kg/pax
% WCREW             weight per crew, kg/crw
% WCARGO                cargo weight, kg
% SPLN              Planform Area, m^2
```

```
% AKSYS             systems weight correlation factor, []
% AMSYS             systems volume-weight correlation factor, []
% ETW_TJ                Engine Thrust-to-Weight Ratio (Turbojet), []
% ETW_SC                Engine Thrust-to-Weight Ratio (SC), []
% AKVE_TJ               Engine Volume Coefficient (Turbojet), []
% AKVE_SC               Engine Volume Coefficient (Scramjet), []
% NFUEL             Number of Fuel Types, []
% ANENG             Number of Engines, []
% NTHR_AC               Fixed Rocket Engine Toggle (1 = Yes), []
% THRUST_VAC                Vacuum Thrust (Req. for Rocket method only), N
% PAX               number of passengers, []
% TW_TJ_V               Thrust to Weight (Turbojet), []
% TW_SC_V               Thrust to Weight (Scramjet), []
% TW_RJ_V               Thrust to Weight (Ramjet), []
% FF_V              Fuel Fraction (vector), []
% WR_V              Weight Ratio (vector), []
% DFF_V             Delta Fuel Fraction (vector), []
%*************************************************************************
  VUN = [154.253];
  FUEL_DEN = [1.0];
  NAISTR_MODE = [1];
  AISTR = [(265.5+144.3)/(9.76+2.98)-2.5];
  FPRV = [8.89];
  VENG_TJ = [0];
  AMUA = [.046];
  FSYS = [(444-(154.253 + 54.844))/1215.77];
  CUN = [154.253];
  VUN = [0];
  FMND = [54.844];
  AKVV = [.544/3.2];
  AKVS = [.8371/3.2];
  FCRW = [0];
  VPCRW = [3];
  AKCRW = [0];
  V_PAX = [1.7];
  EBAND = [.06];
  RHO_CARGO = [92.0/1.7];
  OX_DEN = [0];
  CREW = [1];
  WPAX = [102];
  WCREW = [85];
  WCARGO = [0];
  SPLN = [1285/2.8];
  AKSYS = [2.0];
  AMSYS = [.5];
  ETW_TJ = [16];
  ETW_SC = [1];
  AKVE_TJ = [0];
  AKVE_SC = [0];
  NFUEL = [1];
  ANENG = [3];
  NTHR_AC = [0];
  THRUST_VAC = [0];
  PAX = [0];
  TW_TJ_V = [2.9];
  TW_SC_V = [0];
  TW_RJ_V = [0];
  FF_V = [.977];
  WR_V = [1];
  DFF_V = [1];
%% *
%*************************************************************************
% PERFORMANCE MATCHING input
%*************************************************************************
%Method Selection ********************************************************
% PM_MD15 - time-integrated range/altitude
%*************************************************************************
  PM_M={'PM_MD15'};
%Variable description*****************************************************
% q_MAX             maximum dynamic pressure, Pa
% g_MAX             maximum loading, g
% RANGE_START               starting range, m
% TIME_START                starting time, sec
```

```
% ASTEP_TIME                time-step for integration, sec
% D_ORBIT               design orbital altitude, m
% ALT_P_AIM             goal altitude for deorbit burn, m
% GAMMA_START               starting flight path angle, deg
% ALT_PARA              parachute opening altitude, m
% ALT_DROUGE                drogue parachute opening altitude, m
% R_PITCH               retro-rocket firing angle, deg
% R_THRUST              retro-rocket thrust, N
% R_TIME                retro-rocket firing length, sec
% R_INTERVAL                retro-rocket time between firing, sec
% N_RETRO               number of retro-rocket, []
% ALT_LAND              landing altitude, m
% R_INTERVAL                retro-rocket time between firing, sec
% CDS1_DROUGE               Drag Coefficient of Drouge Chute, []
% CDS2_DROUGE               Drag Coefficienct of Drouge Chute after Opening, []
% TF1_DROUGE                Time Interval for Drouge Chute Deployment, sec
% TF2_DROUGE                Time Interval for Drouge Chute Deployment, sec
%*************************************************************************
  q_MAX = [28057.8318*1.5];
  g_MAX = [11];
  RANGE_START = [0];
  TIME_START = [33*60];
  ASTEP_TIME = [50];
  D_ORBIT = [161124];
  ALT_P_AIM = [-175*1000];
  GAMMA_START = [-0];
  ALT_PARA = [10600*.3048];
  ALT_DROUGE = [2100*.3048];
  R_PITCH = [-34];
  R_THRUST = [1070*4.444];
  R_TIME = [5];
  R_INTERVAL = [5];
  N_RETRO = [0];
  ALT_LAND = [1];
  R_INTERVAL = [5];
  CDS1_DROUGE = [5.02];
  CDS2_DROUGE = [11.61];
  TF1_DROUGE = [2];
  TF2_DROUGE = [6];
%% *
%*************************************************************************
% HEATING input
%*************************************************************************
%Method Selection *******************************************************
% HEAT_MD1 - empirical spherical reentry heating
%*************************************************************************
  HEAT_M={'HEAT_MD1'};
%Variable description****************************************************
% EMM               emissivity, []
%*************************************************************************
  EMM = [.9];
%% *
%*************************************************************************
% CONVERGENCE input
%*************************************************************************
%Method Selection *******************************************************
% CONV_HC - HC methodology
%*************************************************************************
  CONV_M={'CONV_HC'};
%Variable description****************************************************
% WS_IN             wing loading (initial guess), kg/m^2
% SPLN_IN               planform area (initial guess), m^2
%*************************************************************************
  WS_IN = [2.8];
  SPLN_IN = [1285/2.8];
%% *
%*************************************************************************
% AVD Sizing Control
%*************************************************************************
%Set X-Vector Variable for FZERO solver **********************************
% X_NAMES           String values for X-Vector
% X0            Numerical values for X-Vector
%*************************************************************************
```

```
  X_NAMES={'WS','SPLN'};
  X0=[WS_IN;SPLN_IN];
%% *
%*************************************************************************
% DESIGN input
%*************************************************************************
%Method Selection ********************************************************
% DESIGN_MD2 - convergent design sweep
%*************************************************************************
  DESIGN_M={'DESIGN_MD2'};
%Variable description*****************************************************
% MV_NAMES              Variables to be traded, []
% MV_init               Initial value of traded variables, []
% MV_SS             Variable step sizes, []
% MV_NS             Number of steps, []
%*************************************************************************
  MV_NAMES = {'VPCRW'};
  MV_init = [.5];
  MV_SS = [.5];
  MV_NS = [10];
%% *
AnalysisID = 1;
ResultFile = 'C:\Users\ehaney\Dropbox\Dissertation\MATLAB\MercuryResults.csv';
%% *
  input=v2struct;
end
```