DEVELOPMENT OF THE VEHICLE CONFIGURATION COMPENDIUM: A COMPREHENSIVE DATA-INFORMATION-KNOWLEDGE SYSTEM TO AID IN HIGH-SPEED VEHICLE DESIGN

by

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ABSTRACT

DEVELOPMENT OF THE VEHICLE CONFIGURATION COMPENDIUM: A COMPREHENSIVE DATABASE-KNOWLEDGEBASE SYSTEM TO AID IN HYPERSONIC VEHICLE DESIGN

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The conceptual design phase is the most crucial phase in hypersonic vehicle design. Choices made during this phase will have significant impact on the success of the overall project and the feasibility of the end-product. Therefore, it is of utmost importance for the design decision-maker to be adequately informed of past-to-present projects throughout the aerospace community and lessons learned from them. This avoids wasting valuable time and resources for reinventing the wheel. There currently exists no one-stop solution in the aerospace industry to address the issue of lost data, information and knowledge in the field of high-speed vehicle design. The Vehicle Configuration Compendium (VCC) is a self-contained parametric library envisioned by Dr. Chudoba and conceptualized and developed in the AVD (Aerospace Vehicle Design) Laboratory with his guidance to address this need. The VCC combines a comprehensive data, information and knowledgebase system and is currently in the alpha stage of software development.

This compendium, developed to aid in design decision-making and forecasting, features data, information and knowledge collected from hundreds of credible technical sources, which have been selected, digitized, sorted and presented in a user-friendly graphical user interface to parametrically support the education and utilization process of disciplinary analysis engineers, multi-disciplinary designers, and students alike. Earning endorsement and high praise from NASA for its role as a verification companion during the AVD Laboratory NASA-funded research activity regarding hypersonic commercial transportation, the VCC is already proving itself as a much-needed tool in the aerospace industry.

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NOMENCLATURE

Abbreviations

A.C.	Aerodynamic Center
AB	All-Body
ADIR	Absolute Data-Information Richness
AFRL	Air Force Research Laboratory
AI	Artificial Intelligence
AIDRA-DSS	Artificial Intelligence Design and Research Assistant – Decision Support System
AOA	Angle of Attack
AR	Aspect Ratio
AV	Air Vehicle
AVD	Aerospace Vehicle Design
AVDS	Aerospace Vehicle Design Synthesis
BAC	British Aircraft Corporation
BB	Blended Body
C.G.	Center of Gravity
C.P.	Center of Pressure
CD	Conceptual Design
CE	Configuration Evaluation
CFD	Computational Fluid Dynamics
CI	Continuous Integration
CL	Configuration Layout
CMDS	Complex Multidisciplinary System
DARPA	Defense Advanced Research Projects Agency
DB	DataBase
DBMS	Data-Base Management System
DBS	Data-Base System
DD	Detailed Design
DIK	Data-Information-Knowledge
FWC	Flying Wing Configuration
GASL	General Applied Science Labs
GHV	Generic Hypersonic Vehicle
GUI	Graphical User Interface
HOTOL	HOrizontal Take-Off Landing
HUD	Head Up Display
HXLV	Hyper-X Launch Vehicle
HyTECH	Hypersonic TECHnology
ICI	Industrial Capability Index

KB	Knowledge-Base
KBS	Knowledge-Base System
LAPCAT	Long-Term Advanced Propulsion Concepts and Technologies
LCC	Life Cycle Cost
m.a.c.	Mean Aerodynamic Chord
MATLAB	MATrix LABoratory
MBB	Messerschmitt-Bölkow-Blohm
N.P.	Neutral Point
NAA	North American Aviation
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane
OEW	Operating Empty Weight
OFWC	Oblique Flying Wing Configuration
OWC	Oblique Wing Configuration
OWE	Operating Weight Empty
PD	Preliminary Design
PDF	Portable Document Format
PhD	Doctor of Philosophy
Png	Portable Network Graphics
PrADO	Preliminary Aircraft Design and Optimization
PS	Preliminary Sizing
RDIR	Relative Data-Information Richness
S.M.	Static Margin
SDLC	Software Development Life Cycle
SFC	Specific Fuel Consumption
SNECMA	Société nationale d'études et de construction de moteurs d'aviation
SQLite	Structured Query Language
SR	Strategic Reconnaissance
SSTO	Single Stage To Orbit
STL	STereoLithography
TAC	Tail Aft Configuration
TFC	Tail Forward Configuration
TOGW	Take-Off Gross Weight
TPS	Thermal Protection Systems
TSC	Three-Surface Configuration
TSFC	Thrust-Specific Fuel Consumption
TSTO	Two-Stage To Orbit
UTA	University of Texas at Arlington
VCC	Vehicle Configuration Compendium
WB	Wing-Body
WL	Wing Loading
WR	Weight Ratio

Symbols

b	Width
C_D	Coefficient of drag
C_{D_0}	Coefficient of zero lift drag
C_{D_i}	Coefficient of induced drag
C_{f_e}	Coefficient of equivalent skin friction
C_ℓ	Coefficient of rolling moment
C_{ℓ_α}	Variation of coefficient of rolling moment with angle of attack
C_{ℓ_β}	Variation of coefficient of rolling moment with angle of sideslip
C_{ℓ_p}	Variation of coefficient of rolling moment with roll rate
C_L	Coefficient of lift
C_{L_α}	Variation of coefficient of lift with angle of attack
$C_{L_{maneuver}}$	Coefficient of lift for maneuver
$C_{L_{max}}$	Maximum coefficient of lift
C_m	Coefficient of pitching moment
C_{m_α}	Variation of coefficient of pitching moment with angle of attack
C_{m_q}	Variation of coefficient of pitching moment with pitch rate
C_n	Coefficient of yawing moment
C_{n_β}	Variation of coefficient of yawing moment with angle of sideslip
C_{n_r}	Variation of coefficient of yawing moment with yaw rate
C_{sys}	System weight constant
D	Drag force
E	Endurance
E_{TW}	Engine thrust to weight ratio
F	Thrust force
f	Fuel/air ratio

$F/\dot{m}$	Specific thrust
f_{sys}	Fraction of system weights
I_p	Propulsion index
I_{sp}	Specific impulse
I_{str}	Structural index
k	Drag polar constant
K_{crw}	Crew volume coefficient
K_{ve}	Engine volume coefficient
K_{vs}	System volume coefficient
K_{vv}	Void volume coefficient
K_w	Area ratio (S_{wet}/S_{pln})
$\mathcal{L}$	Rolling moment
L	Lift force
L_f	Fuselage side-force
L_{VT}	Vertical tail side-force
L/D	Lift to drag ratio
$\dot{m}$	Mass flow rate
$\dot{m}_0$	Freestream mass flow rate
$\dot{m}_e$	Exit mass flow rate
N	Directional moment
N_{crw}	Number of crew members
N_{power}	Directional moment due to asymmetric power effects
N_{wing}	Directional moment due to wing
q	Dynamic pressure
R	Range
S	Span
S_{pln}	Planform area

S_{ref}	Reference area
S_{wet}	Wetted surface area
T	Thrust
T/W_0	Thrust-to-weight ratio
T_{avail}	Available thrust
T_{max}	Maximum thrust
T_n	Net thrust
T_{req}	Required thrust
V	Velocity
V_{crw}	Volume for cabin space/crew needs
V_0	Freestream velocity
V_e	Exit velocity
$V-n$	Airspeed-load factor
V_{pay}	Payload volume
W_{cprv}	Weight of crew provisions
W_{crw}	Weight of crew
W_{empty}	Empty weight
W_f	Final weight
W_{fixed}	Fixed weight
W_{fuel}	Fuel weight
W_i	Initial weight
W_{pay}	Payload weight
W_{TO}	Takeoff weight
W_{TPS}	TPS weight
$x_{c.p.}$	Position of center of pressure

Greek Letters

α	Angle of attack
β	Sideslip angle
γ	Rate of climb
δ_a	Aileron deflection
δ_e	Elevator deflection
δ_r	Rudder deflection
η_O	Engine overall efficiency
η_P	Engine propulsive efficiency
η_T	Engine thermal efficiency
λ	Taper ratio
Λ	Sweep angle
μ_a	Margin on inert weight
ρ	Density
ρ_{ppl}	Propellant density
τ	Slenderness ratio
$\dot{\psi}$	Turn rate

CHAPTER 1

INTRODUCTION

"We are drowning in information but starved for knowledge" – John Naisbitt, 1984

1.1. Research Motivation and Objectives

Knowledge requires much time and effort to gain, effort to maintain, and intention to pass on to others. However, it takes very little work to lose knowledge in a matter of seconds. This is a fearful tragedy for the world of science and technology, and something that continues to happen in the world of hypersonic vehicles, unfortunately. We often hear of wonderous, innovative projects and concepts developed in the early 1960's when hypersonics as a field was constantly revolutionized, yet very little information and knowledge is available from that era that would allow a modern engineer to either replicate or learn from said projects, as evidenced by some of the projects listed in Figure 1.1 [1].

Case I: Transiting from Air to Space: the North American X-15
by Robert S. Houston, Richard P. Hallion, and
Ronald G. Boston

Case II: Strangled Infant: The Boeing X-20A Dyna-Soar
by Clarence J. Geiger

Case III: The Development of Winged Reentry Vehicles: An Essay from the NACA-NASA Perspective, 1952-1963
by John V. Becker

Case IV: ASSET: Pioneer of Lifting Reentry
by Richard P. Hallion

Case V: Project PRIME: Hypersonic Reentry From Space
by John L. Vitelli, and Richard P. Hallion

Figure 1.1. Hypersonic projects of the past source [1]

For most scientific and technological fields of study, innovation happens by first observing and learning from past mistakes, then improving upon ideas that have already been attempted, or by learning from what has not worked and trying to use that information to save time. This process facilitates progress in the field. However, in the aerospace industry, oftentimes this happens to go by the wayside in the process of innovation, often due to the secretive or proprietary classification of projects. While striving for new technology, engineers often end up repeating the same mistakes again, or taking the risk-free route of sticking to the same old technology that has once proven itself successful. An example of this phenomenon is the British SSTO spaceplane, the HOTOL. The HOTOL was designed as a reusable spaceplane by British Aerospace and Rolls-Royce. However, during development, it was determined that the heavy rear-mounted engine moved the center of mass toward the rear of the vehicle, thereby destabilizing it. This resulted in needing to place the wings and liquid oxygen in the rear as well due to the center of gravity location, while keeping the hydrogen tank and payload bay in the forebody. The configuration as it was had severe stability issues due to the changing center of gravity and center of pressure during ascent. Many design alterations were considered to mitigate this stability issue, all of which resulted in a decrease in payload capability. This ultimately resulted in the cancellation of the project due to the operational disadvantage of the reduced payload volume [2] [3].

There are two issues to consider with the story of HOTOL in relation to knowledge retention. First of all, such a critical design flaw should never have been carried through the project but rather been identified in the early conceptual design phase and mitigated. This would have helped avoid the waste of money and effort on a ‘dead horse’ type project. Second of all, logic dictates that such a disadvantageous configuration would be dropped following the failure of HOTOL. However, a very similar design derived from the HOTOL has continued to undergo development, called the Skylon spaceplane. Skylon is meant to fix the issue of the center of gravity from the HOTOL project by presenting a few changes to the overall design, such as mounting the delta wings as well as the engines toward the center of the vehicle rather than aft. The payload sits in the center of the wings as well. It is yet to be proven that these design changes truly mitigate the issues of HOTOL and will allow Skylon to be successful as an SSTO spaceplane [2]. Another example is the NASP X-30 spaceplane project. This project, although cancelled, remains highly classified and hence it is difficult to obtain data or information concerning the design of this vehicle for both students and professionals alike.

Such instances may stagnate progress and is caused by the failure to pass down valuable knowledge and information over generations. As mentioned before, hypersonic projects are often of secretive nature which means very little is published regarding these projects. What little is published may not be readily accessible to future designers or available in a modernized format, but rather locked away in paper records. Regardless, if only every hypersonic project was properly organized, and the chaos of information appropriately formatted and passed on to the next generation or made easily available, designers would not have to go through the trouble of trying to re-learn what has already been learnt through costly mistakes in the past. This idea has been visualized in Figure 1.2. The *ideal situation* shown in Figure 1.2 must be the goal of this generation of engineers aiming to advance the understanding in this field of study as quickly and efficiently as possible. This would ideally mean that 100% of the knowledge accumulated during a project is passed onto the next generation, or to the next group of project engineers, and thus eliminates the need for redundant research studies. Then the engineers may focus only on the accumulation of newer information whilst it is a pre-requisite that they have to be intimately familiar with legacy studies.

Referring to Figure 1.2, the *non-ideal situation* describes the common tendency in the field of aerospace engineering, where very little of the overall collected knowledge is passed down to the next generation of engineers or designers. Sometimes this inability to pass down knowledge and data may be due to the sensitive nature of the project, as in the case of the X-51 vehicle which was built as a demonstrator partly by the Air Force Research Laboratory and DARPA (Defense Advanced Research Projects Agency) [4]. Other times it is due to an oversight in intentional documentation organization. Unfortunately, this causes the next generation to work hard to reinvent the wheel, to relearn the same information and hopefully come to the same legacy conclusions followed by an advancement of the legacy state-of-the-art. It becomes clear, poor knowledge retention results in overall slowing down of progress in the field considered.

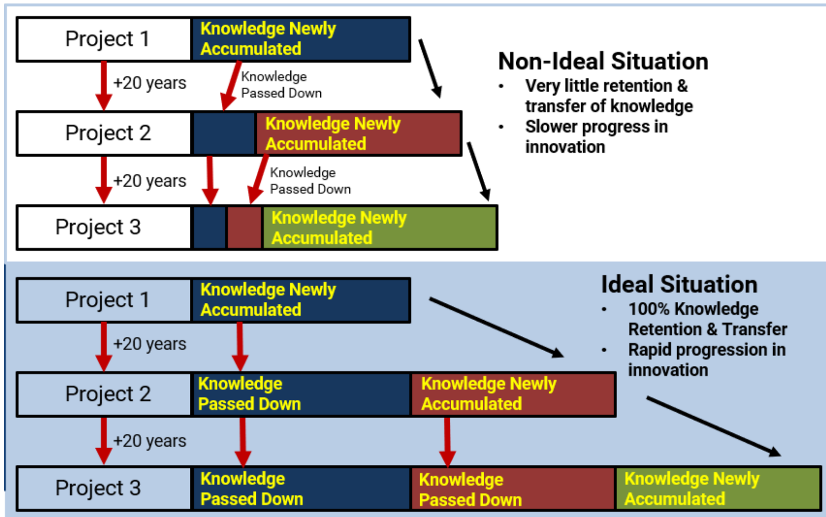

Figure 1.2. Knowledge loss problem in industry visualized

This loss of knowledge between generations recalls the lost library of Alexandria. Founded in Egypt by *Alexander the Great*, this ancient library was said to house over half a million documents from Greece, Egypt, India, Persia, and Assyria. Before being destroyed, this place was a haven of learning, where *"... over 100 scholars lived… full time to perform research, write, lecture or translate and copy documents…"* [5]. A similar digital library in the modern world would bring about faster progress in innovation when applied to the world of aerospace engineering. Therefore, this research effort embarks on the search for an aerospace equivalent that will aid consistent advancements in the field of hypersonics.

1.2. Survey of Current Aerospace Databases

Before implementing a solution to the issue mentioned, it is appropriate to investigate past-to-present currently available options to avoid redundancy in research efforts. For this present research effort, a total of 47 aerospace databases have been surveyed to provide a reference of aerospace related database concepts. This list shown in Table 1.1 is entirely specific to aerospace engineering. Other generalized engineering databases, although considered during the search, are not included as these do not provide an accurate representation of what is available specific to aerospace professionals and students in the public domain. Table 1.1 provides a breakdown of the types of data available in each.

Table 1.1. Aerospace Database Survey Table

Name	Data Formats Available						
	Journals	Abstracts	Text books	Technical Reports	Graphs	Interactive Tools	Spreadsheets
Advanced Technologies & Aerospace Collection	X	X	X	X	-	-	-
AERADE Reports Archive	-	-	-	X	-	-	-
Aerodesign.de	-	-	-	-	X	-	X
Aerospace and High Performance Alloys Database	-	-	-	-	X	-	X
Aerospace Structural Metals Database	-	-	-	-	X	-	X
AeroWeb Database System	-	-	-	-	-	-	X
AIAA ARC	X	X	X	X	-	-	-
Airfleets	-	-	-	-	-	-	X
Agile Novel Overall Aircraft Design Database	-	-	-	-	-	X	-
AHS International – The Vertical Flight Society Publications	X	-	-	X	-	-	-
Aircraft Bluebook	-	-	-	-	-	X	-
Airfoiltools.com	-	-	-	-	-	X	X
Airframes.org	-	-	-	-	-	-	X
Airline Monitor	-	-	-	-	-	-	X
Air University Library Index to Military Periodicals	-	X	X	-	-	-	-
Airliners.net	-	-	-	-	-	-	X
AUVSI Unmanned Systems and Robotics Database	-	-	-	-	-	X	X
AviationDB	-	-	-	-	-	X	-
Aviation Safety Network	-	-	-	-	-	-	X
Aviation Week Intelligence Network	-	-	-	X	-	-	X
Aviatorsdatabase.com							
CAPA Centre for Aviation	-	-	-	X	X	X	X
Cirium	-	-	-	-	X	-	X
Civil Aerospace Medical Institute Publications	-	X	-	X	-	-	-
DTIC Online	-	-	-	X	-	-	-
Encyclopedia of Aerospace Engineering	-	-	-	-	X	-	X
Eurocontrol Aircraft Performance Database	-	-	-	-	X	-	X
Evolution of Flight, 1784-1991	X	X	X	X	-	-	-
FAA	-	-	-	-	-	X	-
ForeFlight	-	-	-	-	-	-	X
ICAO Data+	-	-	-	-	X	X	X
IOP Electronic Journals	X	-	-	-	-	-	-
Jane's All the World's Aircraft	-	-	-	-	X	-	X
Janes.com	-	-	-	-	X	X	X
NASA Technical Reports Server	X	X	-	X	-	-	-
National Technical Reports Library [48]	-	-	-	X	-	-	-
NewSpace Global	-	-	-	X	-	-	X
NTSB Aviation Accident Database & Synposes	-	-	-	X	-	-	X
Opensky	-	-	-	-	-	X	-
Princeton University Aerospace Database	X	X	X	X	-	-	-
RisingUp Aviation	-	-	-	-	-	-	X
Scramble Military Database	-	-	-	-	-	-	X
SKYbrary	-	-	-	-	-	-	X
Space Report Online	-	-	-	X	X	X	X
Stargazer	-	-	-	-	-	-	X
TischLibrary – Aerospace database	X	X	X	X	-	-	-
U.S. Military Aircraft Database	-	-	-	-	-	-	X

As seen from Table 1.1, there are no aerospace databases in existence that accumulate parametric information pertaining to the niche of high-speed vehicle design. The only database that comes close to achieving the interactive data display format envisioned by VCC, is Access Engineering Library, which is a general multidisciplinary engineering database. However, the data showcased is qualitatively not on the same level as VCC, but rather generic in nature. The majority of these databases are simply compilations of publications and journals. While such containers do offer a very typical mode of knowledge retention to some extent, an all-encompassing system of parametric knowledge is missing. As shown in Figure 1.3, a majority of these databases simply house numerical data, most of which was related to performance statistics for passenger aircraft. There is a small percentage of interactive tools, and even then, these are found to be in the form of fillable forms that can be re-filled to view new data. A large percentage (21%) of these databases are actually report servers.

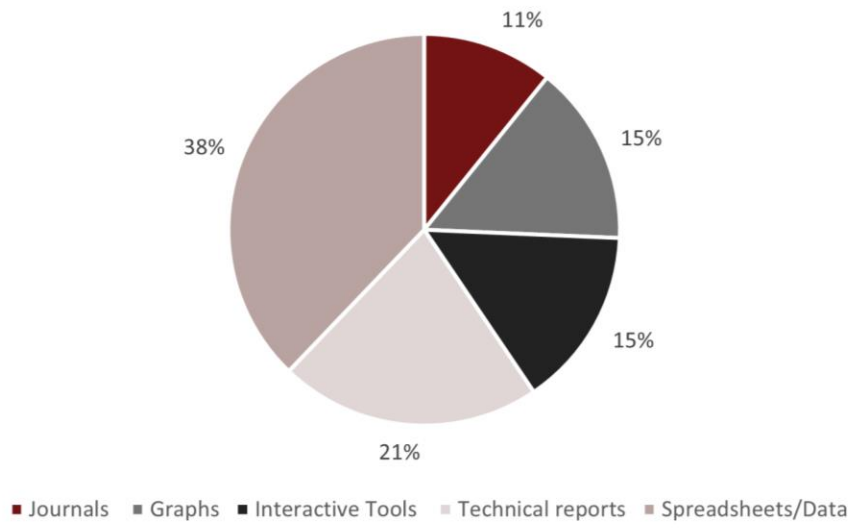

Figure 1.3. Types of data contained in databases surveyed

This research effort is therefore focused on improving towards the concept of the 'ultimate library'. Instead of merely housing resources, the envisioned parametric library adds a crucial step missing from most document-based databases: the selection, categorization and digital availability of parametric design information. Such a library would be a powerhouse of knowledge for a designer and reduces the amount of time a designer must otherwise spend searching for and extracting the needed data from stored documents. This parametric library will also be interactive and feature innovative data visualization and manipulation strategies through a software interface. The need for such an improvement has been aptly stated by AVD Laboratory researcher Eric Haney in his dissertation on data engineering: *"... Though practicing engineers spend the majority of their time identifying, organizing, and transforming data [6], there remains an opportunity to advance research into systematically developing, utilizing and thus formalizing the data & knowledge domains…"* [7]. This research effort describes the undertaking of the AVD laboratory in its quest for pioneering an enduring novel aerospace compendium of data, information and knowledge.

1.3. The Vehicle Configuration Compendium

Imagine the scenario where a designer has immediate access to every piece of design-relevant data, readily available to manipulate and study to directly advance the projects demands. How much more would that availability enhance the overall research experience? This is what the AVD Laboratory envisions with the conceptualization of the Vehicle Configuration Compendium (VCC). The VCC is a collection of vehicle-relevant data, information and knowledge from credible sources. The VCC aims to take legitimate data published and verified for high-speed vehicles, filter through and only capture data that is of importance to the conceptual design process, and to parametrically compile it into a digital compendium in one central software application for ease of access. This will ensure for an aerospace organization when designing a hypersonic vehicle, that they are able to access this vast database and determine what information is available for each type or vehicle configuration contained in VCC. Clearly, the VCC establishes a novel parametric library currently targeting supersonic and hypersonic vehicle design. The following is the disclaimer statement developed regarding the purpose of the VCC:

"In the same vein as that of Jane's and Haynes, the Vehicle Configuration Compendium (VCC) strives to provide the design engineer with impartial, accurate information, that draws on the 18 years of legacy material and experience available to the Aerospace Vehicle Design (AVD) Laboratory. The VCC is committed to the credibility and authenticity of the information stored, not to be influenced by outside entities, but to assist the designer through the ability to verify the accuracy of design tools, rapidly get up to speed on past efforts, and through the ability to compare similar and dissimilar configurations. Through the extraction, digitization, and organization of data gathered from reliable sources, shown in an extensively developed bibliography for each vehicle, the critical design parameters from simulation, experimental and/or flight data are provided at the fingertips for the designer," [8].

In order to develop such digital parametric library, it is necessary to evaluate the logic components minimum required. S.R. Ranganathan, famously known as the father of library science, documentation, and information science in India, visualized a library system as a trinity of readers, books, and staff, as shown in Figure 1.4. According to Ranganathan, *"… the books are the knowledge containers, readers are the knowledge seekers, and staff means the facilitators or providers of various library services to the users, the knowledge seekers. Whenever and wherever this Trinity exists, a library is born…*" [9].

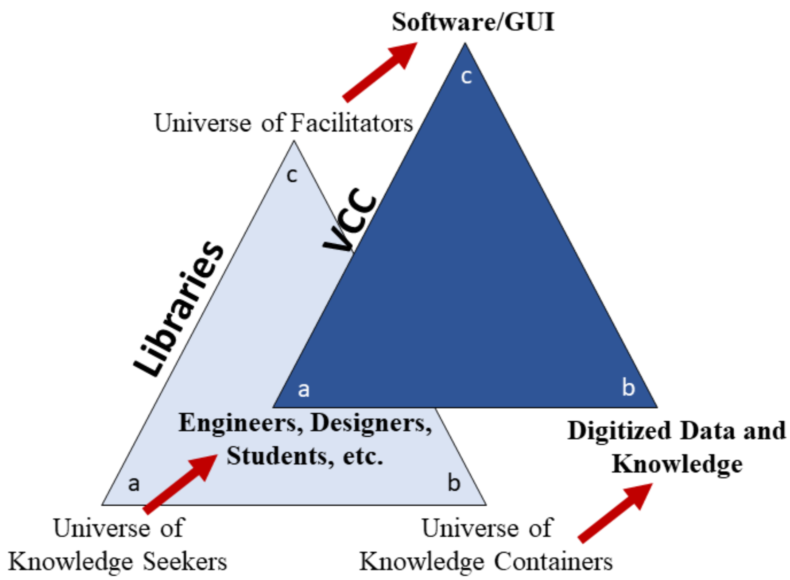

Figure 1.4. Comparing Ranganathan's library trinity to the VCC

As visualized with Figure 1.4, the Vehicle Configuration Compendium (VCC) incorporates this trinity of library components into a digital architecture equivalent, albeit in a novel way. For the VCC software, the(a) *universe of knowledge containers* is the large collection of digitized data, information and compiled knowledge from various sources consolidated in an easily digestible format. The (b) *universe of knowledge seekers* can be anyone, of course, but in this case the niche includes engineers, designers, technology forecasters and students. The (c) *universe of facilitators* is the software GUI itself. It seems the universes of knowledge seekers and knowledge containers have always been represented, but there has been a lack of a *'staffing'* system to connect the two in an efficient way. In a traditional library setting this would be the role of the librarians, helping patrons find the information they need and making recommendations based on the patron need, as well as conducting maintenance and upkeep of the stacks of books. A similar staffing service is needed to connect engineers, designers and students to past project data and knowledge and provide intelligent recommendations. This is where the VCC software comes into play, which is essentially a rich automated 'Library of Alexandria' for the modern times, with the human component only needed for the upkeep of the software.

1.3.1. Project Team

The Vehicle Configuration Compendium project has been initiated by a team of three researchers – the author, Samuel Atchison, and Ramlingam Pillai. The primary involvement of Ramlingam has been during the data collection, digitization and organization process of vehicle disciplinary DIK during the 2020 NASA study mentioned earlier, as well as further research regarding knowledge in the stability and control discipline. During this time, the primary involvement of Samuel has been with the collection and organization of vehicle bibliographies, as well as the development of the vehicle geometry models using OpenVSP, and further development of knowledge in the geometry, aerothermal, and weights and balances disciplines. The author has been involved in the digitization, collection and organization process of DIK, the defining of the VCC specifications, implementation of the software interface, mapping of AVDS-VCC integration, definition of the disciplinary knowledge conversion process, definition of data-information richness schemes, mapping out software development timeline, and development and initiation of software user testing, all resulting in the ultimate alpha release of the VCC software.

1.4. Historical Progression

The concept of developing a data-information-knowledgebase system to aid in design began in the AVD Laboratory with the doctoral research efforts of Dr. Bernd Chudoba, supervising professor for this research work. The foundation was laid in his dissertation, where he describes the ideal conceptual design assistant: *"… Ideally, a combination of a Data-Base System (DBS) containing information on existing designs, and a Knowledge-Based System (KBS) with knowledge about the design process, coupled to analysis packages organized in a multidisciplinary synthesis system, should provide the designer with a great deal of assistance at all stage…"* [10]. Since the early 2000's, the AVD Laboratory has therefore been intentional in the collecting and archiving of conceptual design data, information and knowledge throughout every research effort conducted in the AVD Laboratory. The timeline of historical progression of the VCC concept is demonstrated in Figure 1.5.

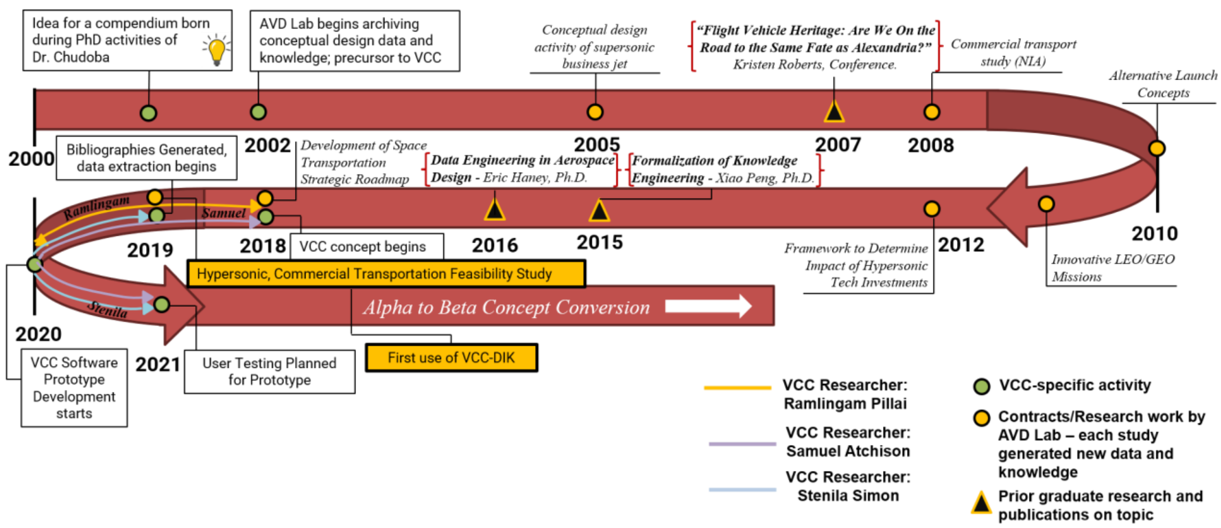

Figure 1.5. Historical timeline leading to development of the Vehicle Configuration Compendium

Dr. Chudoba's dissertation on the development of methods to size vehicle stability and control surfaces included a vast library of collected stability and control derivatives and various parameters for a variety of aircraft configurations and flight scenarios. The level of detail to which this work has been completed, laid the foundation for the future knowledgebase work that would be accomplished with the creation of the Vehicle Configuration Compendium. Regarding this knowledgebase system developed during his work, Chudoba states the following: *"The particular strength of the system manifests, in that it enables the user to advance his/her understanding with respect to the variety of aircraft configurations by identifying aircraft configuration commonalities and peculiarities"* [10]. This is the approach adopted by the VCC as well.

AVD Laboratory member Kristen Roberts further developed the concept in her work, where five distinct classifications to knowledgebase systems were created, each one step ahead of the previous:

- Collection
  - *"Includes a searchable collection of data, information and knowledge; displays to user"* [11]
- Interpretation
  - *"Performs interpretation of collection of data, information, and knowledge"* [11]

- Self-retrieval
    - *“Capable of self-retrieving interpreted knowledge pool”* [11]
- Analysis
    - *“Capable of analyzing the self-retrieved knowledge pool”* [11]
- Feedback into Knowledge Pool
    - *“Capable of feeding-back the analysis into the knowledge pool”* [11]

Dr. Xiao Peng later conducted his doctoral dissertation on the formalization of Knowledge Engineering as an engineering science discipline. His work on an AVD KBS system was also fundamental to bringing the knowledgebase mentality this far in the research environment at the AVD Laboratory. According to Peng, there are three basic knowledge management functions that are crucial to any knowledgebase system: knowledge storage which include activities that happen *“…between humans and the knowledge documentation medium”,* knowledge education which happens *“...between humans, including knowledge transfer”*, and knowledge application which happens *“…between humans and work, including knowledge utilization”* [12].

In terms of the data and information, AVD Laboratory member Eric Haney conducted his doctoral research on data engineering for aerospace forecasting and documented the ideal steps to data processing. According to Haney, data is converted to information using the following size-step process: collection, storage, organization, recall, analysis, and visualization [13].

A couple of years later, the resources collected in the AVD Laboratory thus far have been converted to organized bibliographies in 2018, thereby speeding up the development process of the system via the addition of dedicated researchers to the project, namely Ramlingam Pillai, Samuel Atchison, and the author of this work. The team worked together to collect and digitize data from the massive archive of sources available for a selected list of vehicles (X-43A, X-51, XB-70, SR-71, Sänger-II, Concorde, NASP X-30) since 2019. This is when the AVD Laboratory begins the NASA-funded study on the feasibility of hypersonic commercial transportation. The VCC effort contributed to this study by providing digitized verification data for the vehicle list mentioned before. Providing such support to the NASA study required a very rapid-paced development effort on the VCC, due to the large volume of compiled sources, thereby enabling the completion of the data, information and knowledge collection and digitization process in less than a year. Towards the end of this digitization effort (the end of 2020) begins the software interface development initiated by the author. User testing for the GUI has been conducted in 2021 by the author, with whom the alpha version of VCC is concluded. Future researchers will be continuing this work by further developing the VCC software and fully integrating it with the AVDS synthesis environment, which will be discussed in detail later in the document.

1.5. Advantages of VCC

As envisioned by Dr. Chudoba, the VCC offers a unique combination of design data, information and knowledge from past to present vehicle development efforts. In order to fully appreciate the advantages offered by the VCC, it is important to understand the differences between these three key components of this compendium. This is summarized nicely by Dr. Chudoba: *"Knowledge derives from information as information derives from data"* [8]. Data includes *"… exact numerical descriptions of the object facts…",* information is *"… interpretation of data collections …",* and knowledge is *"… generated from interlinked information, unveiling the nature of the objects, and providing the deepest understanding…"* [10]. Based on the three-step definition provided above, the VCC contains a data-information-base of raw conceptual design data and information, as well as a 'derived' knowledgebase of configuration comparisons for the various aerospace disciplines. These comparisons are generated based on the current number of vehicles processed through the compendium for the initial prototype software. The relationship between this data, information, knowledge and interactions are shown in Figure 1.6.

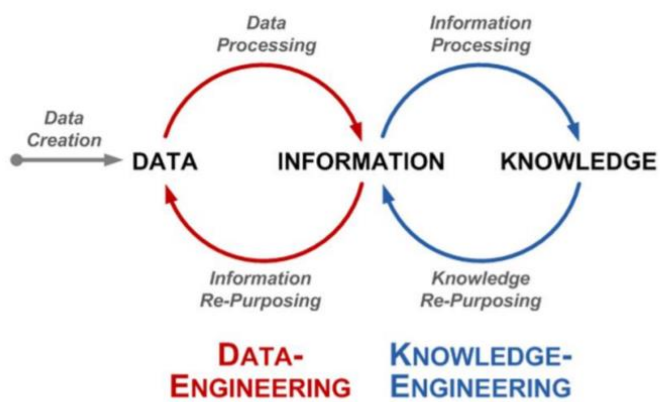

Figure 1.6. Data-Information-Knowledge cycle [13]

What distinguishes VCC as a compendium concept from previous efforts like … is, instead of placing the onus of finding the correct data-information-knowledge on the user, VCC provides a self-contained and self-explanatory compendium for ease of use. Rather than just listing data-information-knowledge (DIK), it presents the DIK in an easily accessible and interactive format. The ease of accessing DIK also means that the VCC implementation is very particular in the kind of vehicle substance that can be found. The current VCC prototype version only focuses on providing data, information and knowledge pertaining to the conceptual design phase of hypersonic vehicles. Overall, the DIK-approach is a novel contribution to aerospace database structuring, where a very focused category is taken into consideration and the database is designed efficiently to cater to that category. Most other databases present an overwhelming number of generalized sources. Table 1.2 highlights the key differences observed between VCC and other databases encountered through the initial review presented with Table 1.2:

Table 1.2. Comparison between VCC and Other Databases – Common Attributes Found

Other Databases	The VCC
Lists raw material in the form of papers and books for a wide variety of subjects.	*Lists data relevant to the niche field of hypersonic vehicle design, hand-picked and sorted.*
Papers and journals need to be searched for – improper searches may mean missed information for the user.	*Data is presented in an organized format readily available to user, no data missed by user error.*
Very old-school format of using database – user reads through sources until they find what they need.	*Very innovative format of using database – user can access the data readily by visual means in the form of plots and tables, along with sources cited.*
Not always user-friendly websites/databases, user must know exactly what to search for.	*Very user-friendly GUI that has been tested and proven easy to navigate after multiple iterations.*
Some websites require logging in with an institution to access data.	*The DIK system designed to help professionals evaluate past vehicles while also educate student audience – versatile functionality.*
No recommendations for means to use the data found; student/professional users may require outside guidance for navigating and utilizing data appropriately.	

1.6. The Importance of Conceptual Design

During the design process of any vehicle, there are many stages to complete before being able to get to the final design of the vehicle. The first and most important stage of that process is the conceptual design (CD) stage. Any mistakes or flaws stemming from this initial design phase must be identified and corrected to avoid wasting time, effort and energy, as well as money once the actual design work has begun. *"…The design of hypersonic vehicles is influenced by tightly coupled interactions between aerodynamics, propulsion, and structures. Therefore, in the conceptual design phases, the identification and mitigation of potential problem areas and disciplinary interrelations are critical…"* [14]. The suggested conceptual design baseline should be correctly defined, entailing major design parameters such as the expected TOGW, basic dimensions, and fuel volume available, before moving on to the preliminary design (PD) followed by the detail design (DD) phase. As aptly stated by one of the previous legacy members of the AVD Laboratory, Gary Coleman: *"… As a rule of thumb, it can be assumed that 80% of the vehicle configuration is determined during the conceptual design phase. Thus, the execution of a well-orchestrated CD phase is vital for future success of the product…"* [15]. Due to the criticality of the CD phase, the VCC methodology and software is compiled with this phase at first in mind. Clearly, for the VCC prototype module, DIK is identified and filtered to be pertinent to the conceptual design of the vehicle. In general, the conceptual design (CD) process involves analysis, integration, iteration, convergence, screening, visualization and assessment of risk as shown in Figure 1.7.

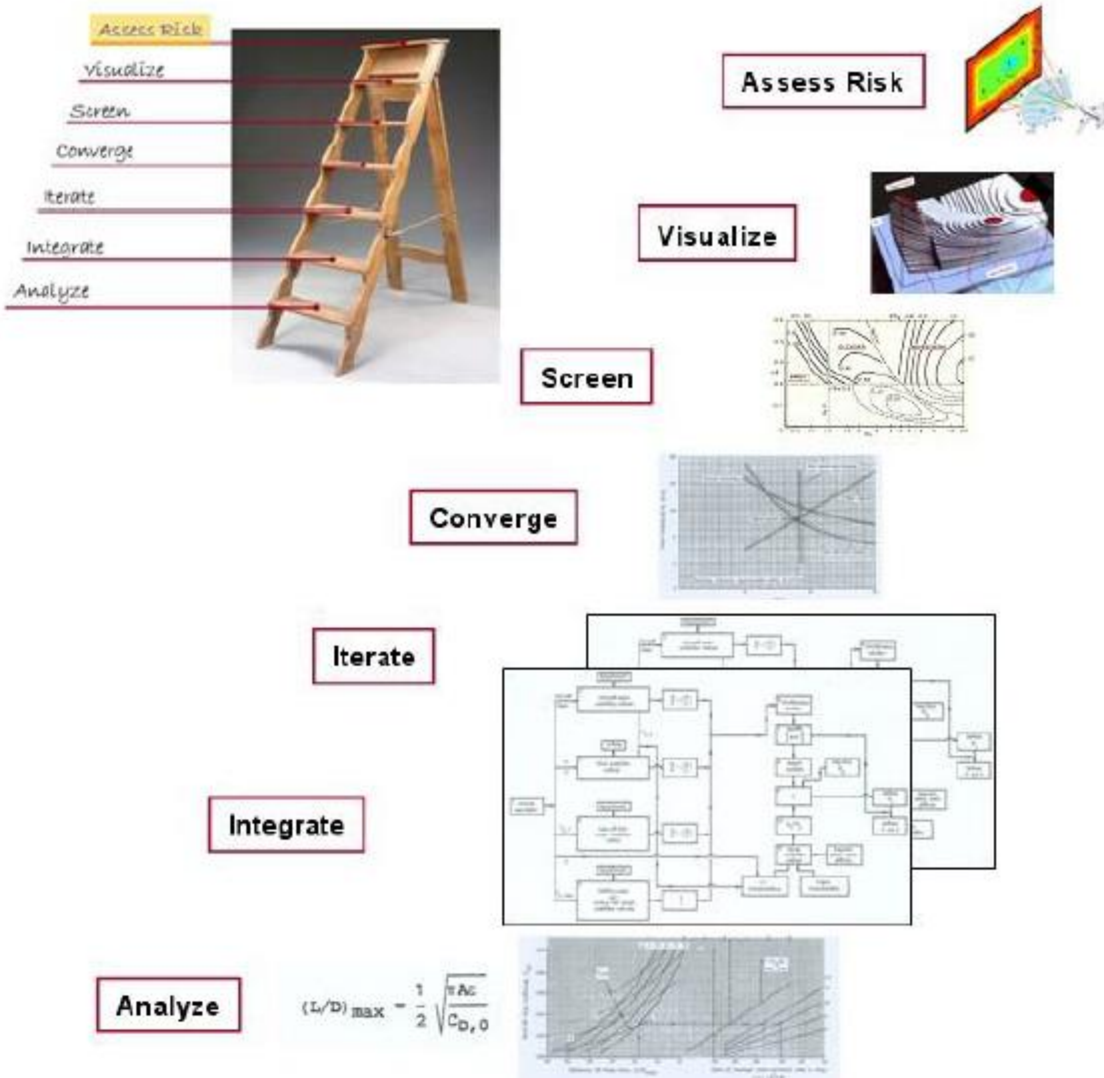

Figure 1.7. The conceptual design ladder with each design step illustrated [16]

1.7. VCC Methodology and Software Specification

In its current and also fully developed form, VCC is and it will be a highly sought-after capability not found elsewhere in the aerospace community. Referring to the survey shown with Table 1.1, there has been a lack of any DIK-system covering the past-to-the-present that allows designers to examine relevant DIK for any aircraft, but of course in particular for the hypersonic vehicle application. The VCC is positioned to become that essential support tool of every hypersonic vehicle design engineer and company that provides the much-needed resource gathering all relevant information in one centralized place. In the future this software could also be released as a smart device application which could then be further updated as more vehicles are added to the database.

The VCC software is planned for release both as a (a) standalone module, as well as (b) an integrated module into the AVDS (Aerospace Vehicle Design Synthesis) system [17], another novel product from the AVD Laboratory.

1.7.1. Standalone Software Specifications

The standalone VCC software stores past-to-present DIK and creates new design knowledge trends and design recommendations, which is the functionality of the *'library staffing system'* mentioned in Section 1.3. The following provides the specification for the standalone VCC module:

- Storage of past-to-present design data and information
    - Digitized disciplinary plots
    - Digitized disciplinary data and information
    - Geometry overviews
    - Performance overviews
    - Reference collections
- Storage of past-to-present design knowledge
    - Configuration breakdowns
    - Configuration trends
- Creating/providing new design knowledge and recommendations
    - Configuration comparisons using knowledgebase trends
    - Lessons learned
    - Design guidelines

1.7.2. Integrated Software Specifications

When integrated into the AVDS system, the VCC will be capable of also aiding in vehicle method verification and filling DIK-gaps for vehicles with relatively low DIK-richness. In this context, the AVDS system is a tool developed in the AVD Laboratory for the synthesis of aerospace vehicles of varying configurations. This system steps through the conceptual design

(CD) and preliminary design (PD) phases, each of which the VCC is able to aid as defined in the specifications below. This prototype VCC software focuses on the CD phase exclusively.

- Aid AVDS during the conceptual design (CD) phase by:
  - Verifying methods library during both, the parametric sizing (PS) stage and configuration evaluation (CE) stage using PS and CE data collected.
  - Providing library of knowledge trends for baseline vehicle ideation for the configuration layout (CL) stage.
- In the future, aid the multi-fidelity implementation of AVDS during the preliminary design (PD) and detailed design (DD) phases by providing verification and forecasting DIK-trends relevant to vehicle design.

Although the current iteration of the VCC focuses on the CD phase, in the future iterations the preliminary design and detailed design relevant data would be added to increase the versatility of the compendium. Having integrated VCC into AVDS provides the desired future projects office or 'cockpit design system' where the design team is able to access VCC while running the AVDS synthesis process for the design of new vehicles, see Figure 1.8.

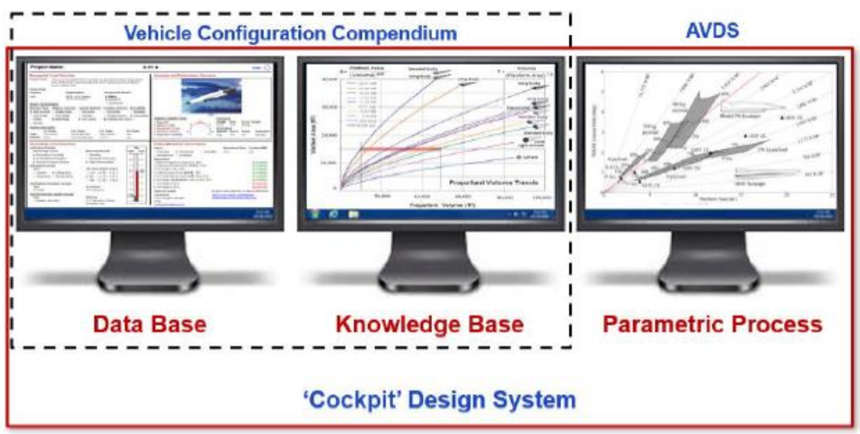

Figure 1.8. Example of future workstation of conceptual design engineer [18]

1.7.3. Future Specifications

In addition to planning for the immediate version of the VCC, the researchers involved in this effort are also interested in mapping out the far future of the software, possibly 10 years ahead. Further advancement in technology would allow this software to truly revolutionize aerospace vehicle design by fulfilling its potential. The following offers a possible specification for the futuristic version of the VCC software:

- Incorporation of AI technology capabilities:
    - Program automatically updates stored data;
    - Program checks for new data or publications regularly using keywords;
    - Kernel programmed to learn from past datasets to fill in gaps;
    - Kernel programmed to update master list of subsonic to hypersonic vehicles using present projects;
    - Digitization process automated.
- Integration of holographic interface (examples shown in Figure 1.9):
    - Enhanced user interface with versatile holographic projection;
    - Software lives in a smart device and is highly portable;
    - User may actively explore the inner workings of vehicles through interactive 3D renderings.

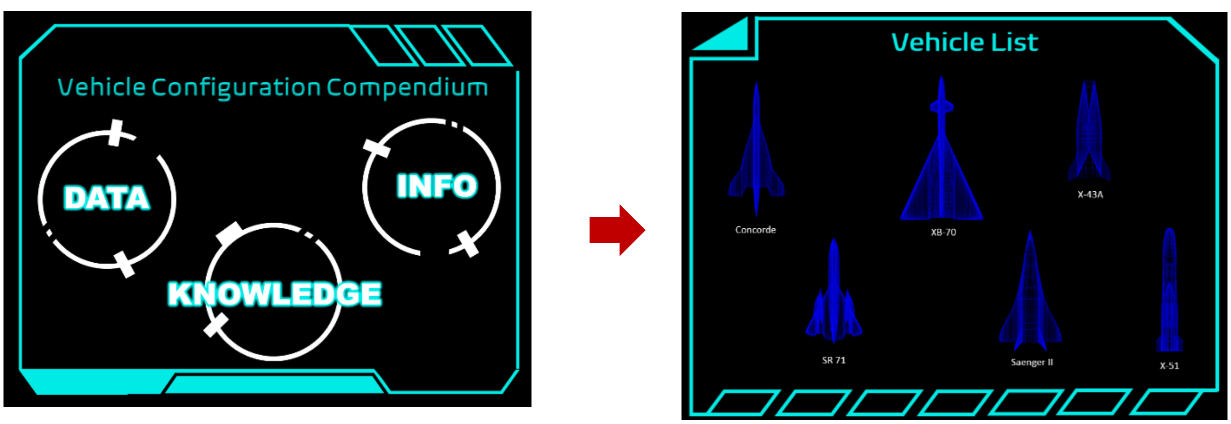

Figure 1.9. The VCC – example visual of possible holographic interface

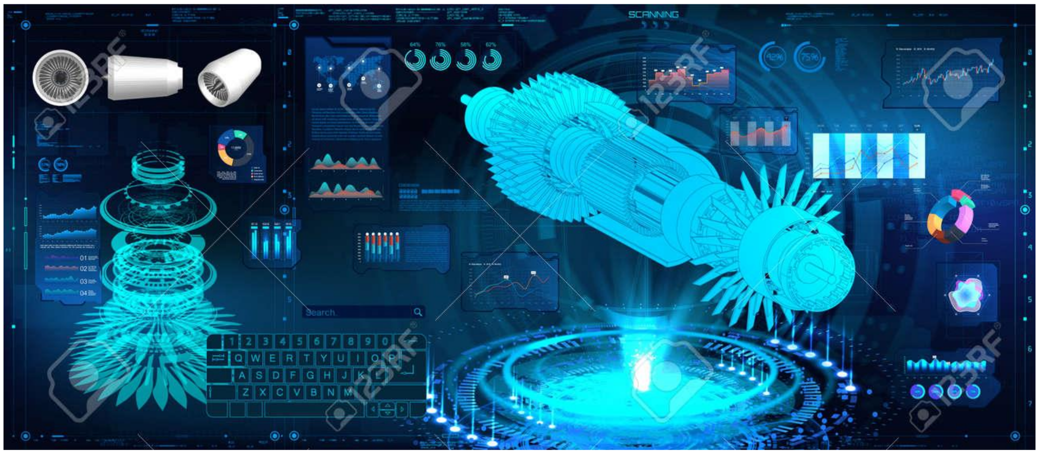

Figure 1.10. Hologram example - jet engine HUD [19]

In summary, VCC could very well evolve into the kind of intelligent support agent seen in sci-fi movies, where the user is able to interact with a holographic version of the software without even the need of a solid screen surface, an example of which is given in Figure 1.10. The holograph could envelope the user and allow for a more immersive experience where they are surrounded with the controls and can interactively change the settings for what type of DIK they would like to access.

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CHAPTER 2

CONCEPTUAL DESIGN PROCESS

2.1. Introduction to Aerospace Design

Before discussing the Vehicle Configuration Compendium (VCC) in more depth, it is appropriate to give the reader an overview of the conceptual design (CD) process in the context of the type of data, information and knowledge (DIK) collected. Since the general purpose of the VCC is to support the conceptual design phase, it requires to understand the complexities of this early design initiation phase first. Throughout the design process for any aerospace vehicle, there are successive levels of design evolution that the vehicle is subjected to, each level adding more detail overall refining the vehicle design to perform the assigned mission. Generally speaking, there are three major design phases: conceptual design (CD), preliminary design (PD), and detail design (DD) [1]. Starting with the mission requirements and constraints, each design phase reduces the levels of possible design variations, as illustrated in Figure 2.1 by Heinze [2].

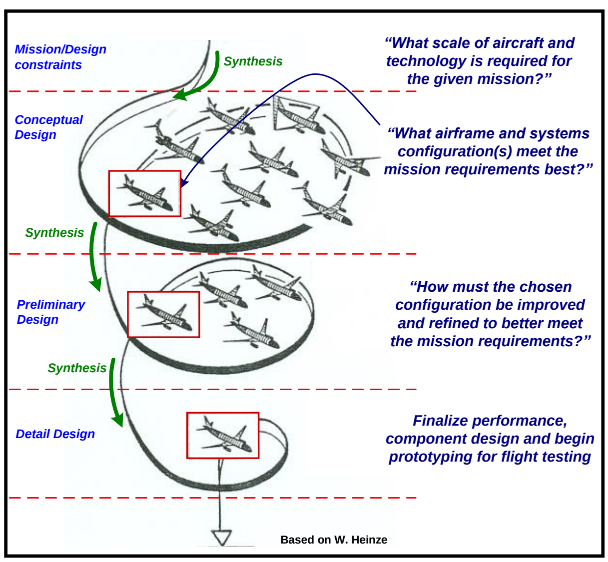

Figure 2.1. Aerospace vehicle design process illustrating design refinement [2]

Conceptual design (CD) is the initial design phase, where the most crucial design decisions are made. This is the phase where basic mission feasibility is determined for a design, and configurational changes are explored accordingly. The number of variables that may affect the overall design is highest during the conceptual design phase, which gives it the highest level of design freedom. Preliminary design (PD) adds more detail to the initial vehicle design configuration chosen and this phase further matures the vehicle design via higher fidelity analysis, wind tunnel testing, etc. During the PD phase, the overall vehicle configuration selection stemming from CD no longer changes, but relatively smaller details of the chosen configuration are varied and refined. The detail design (DD) phase is where the design is locked and engineered towards manufacturing. During this phase, flight hardware is prepared towards the flight-testing campaign. Please note that each distinct design phase, from CD to DD, higher fidelity tools are used based on the needs of the individual design phase [1].

2.2. Conceptual Design

The reason why the conceptual design (CD) phase is so crucial compared to the later design phases is because the decisions made in this phase have the longest lasting impact on the performance and feasibility of the overall vehicle. As Chudoba states, *"… it can be assumed that around 80% of the flight vehicle configuration and mission tandem are determined during the CD phase alone…"* [3]. The CD phase is also a cost-effective phase to make design changes, as *"… the cost of making a design change is small during conceptual design but is extremely large during detail design…"* [1]. The final output of the conceptual design (CD) phase is the vehicle configuration, size, and shape overall, which then undergoes further refinement in the later phases. With conceptual design being such an important phase, the current VCC prototype focuses on this phase of design. Future iterations of VCC may end up including data, information and knowledge that could help in preliminary design and detailed design but first the focus is on fully developing out the compendium to aid in CD. The conceptual design (CD) phase is further subcategorized into the following logic sub-phases:

- Parametric Sizing (PS)
- Configuration Layout (CL)
- Configuration Evaluation (CE)

The iteration process throughout those sub-phases is demonstrated in Figure 2.2. As shown, if the parametric sizing (PS) does not produce feasible design points, the mission requirements may need to be modified for resizing. If the properly sized vehicle is unable to pass the configuration layout (CL) step due to volume issues, then the sizing may need to be modified. If the properly laid out vehicle does not pass the configuration evaluation (CE) phase, then the layout may need to be redone. Finally, once a design point passes every single step in the CD sub-phases, it may be considered a feasible CD-level design alternative to consider. It must be noted that these three subphases of conceptual design are uniquely defined within the AVD Laboratory, although similar activities and implementations exist elsewhere but are not fully formulated. For the current research effort, VCC is supporting the designers through each of these subphases defining the conceptual design.

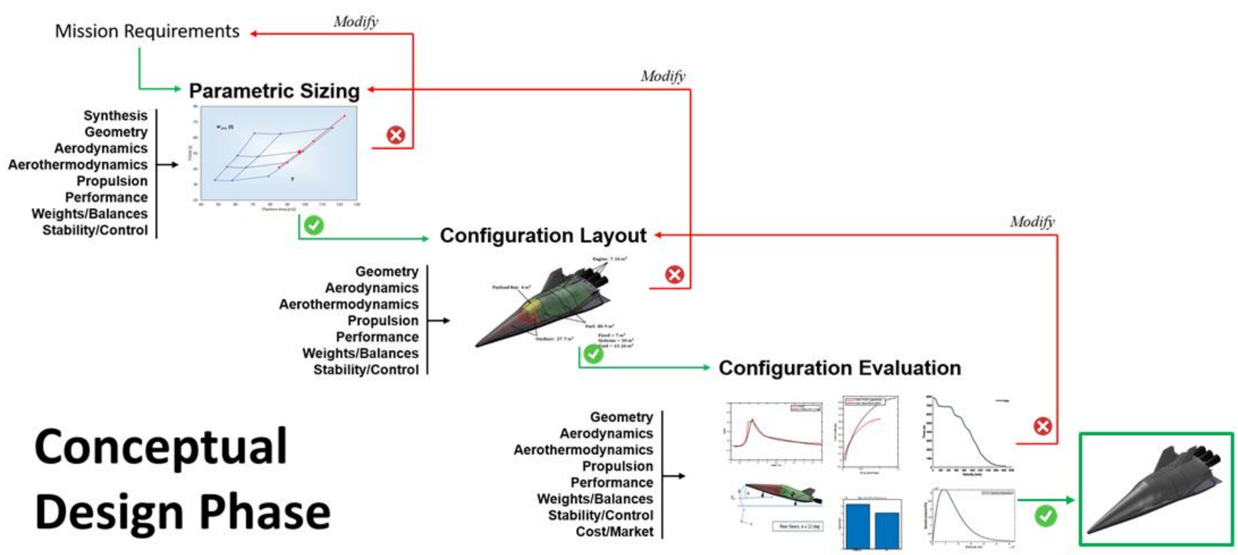

Figure 2.2. Three subphases of the conceptual design process and feedback loops illustrated

These three sequential conceptual design activities, conducted in that order, result in the first feasible design which can then be refined in the later PD and DD design phases. Details of what activities are conducted in each subphase specifically are summarized in the following subsections.

2.2.1. Parametric Sizing

As Coleman states, *"… parametric sizing is the first step in screening the total vehicle in terms of mission, configuration and technology to quickly assess first order design and mission sensitivities…"* [4]. The output of the parametric sizing (PS) step is the initial size information of the vehicle itself. Takeoff gross weight, volume, tau or slenderness ratio, planform area, fuel weight, empty weight, wing loading, engine thrust, engine loading, etc. are determined during this stage for the vehicle [5]. These parameters give context for the overall size and energy of the entire vehicle system. During the parametric sizing step, the following impact attributes affect the overall design: the fixed mission, gross configuration concepts, and disciplinary technology assumptions [4]. Each of these may be traded until a desirable combination is found and sized to satisfy the mission requirements.

According to Coleman, there are six logic process functions that make up the sizing process: (1) operating empty weight (OEW) estimation, (2) trajectory analysis (fuel weight estimation), (3) convergence logic, (4) constraint analysis, (5) sizing logic, and (6) trade studies [4]. Coleman comes to this conclusion after an extensive survey and review of both 'by-hand' and 'computer-based' sizing processes and identifying common traits among them all.

The overall objective of sizing is not to fixate on a specific design configuration. As Chudoba states, *"… The PS phase represents the opportunity for the visionary team to rationally explore inside and outside the box…"* [6]. As such, it is desirable to generate an entire solution space of designs at the end of the sizing activity, rather than focus on one singular design, see Figure 2.3.

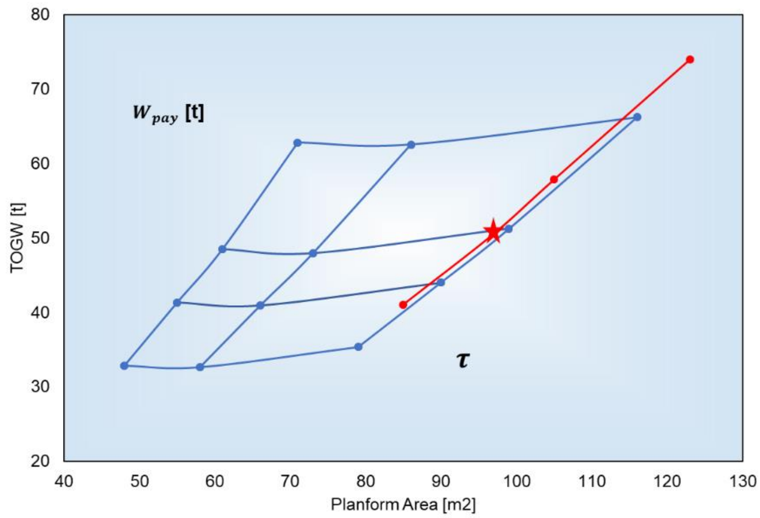

Figure 2.3. Example solution space from previous capstone project [7]

The solution space is a visual of the entirety of feasible vehicle design points visualized in a continuum diagram. A design point is typically a specific combination of takeoff gross weight and any other size factors, and variations in any of the factors creates the next design point. A 'web' can therefore be created to show the range of design parameters that fall within the feasible range from parametric sizing. This web of design points is called a solution space. The solution space may afterward be constrained further during the configuration evaluation (CE) subphase, which will be described in more detail later.

2.2.2. Configuration Layout

Configuration layout (CL) is the subphase where the vehicle layout is determined based on the sized values from the preceding parametric sizing (PS) subphase. During CL, the vehicle configuration choice and component placements are mapped out and the vehicle gains more detail in the design. According to Raymer, configuration layout begins with sketches that show *"… the landing gear, crew station, payload or passenger compartment, propulsion system, fuel tanks, and any unique internal components…"* [8]. These sketches are then refined to add more detail and are used among the engineering team to conduct disciplinary analysis in the configuration evaluation (CE) subphase. Roskam provides a similar breakdown for what needs to be taken into consideration during the configuration layout (CL) phase: cockpit, fuselage, wing and empennage layout, structural arrangement, then landing gear, weapons, and other system layouts [9] [10].

The parametric sizing (PS) and configuration evaluation (CE) subphases are highly multidisciplinary synthesis phases, whereby the creative configuration layout (CL) subphase simply requires the input of each of the disciplines without much actual synthesis involved. Disciplinary inputs in the CL phase are helpful for providing recommendations of the ideal placement of each of the components of the vehicle. Some of the major components that each discipline may make recommendations for are listed in Table 2.1.

Table 2.1. Participation of Disciplines in Configuration Layout

Discipline	**Component Placement in CL Subphase**
Geometry	volume allocation/internal layout
Aerodynamics	placement of wings/lifting surfaces and lift enhancement components, supersonic/hypersonic area ruling, conforming to shock envelope
Aerothermodynamics	TPS material placement
Propulsion	placement of engines and fuel tanks, propulsion/airframe integration
Structures/Weights	systems placement, center of gravity location
Stability and Control	control surface placements

During this CL phase, there may be certain assumptions made in the sizing process (PS) that are found to be not valid, which means *"... the parametric sizing may need to be repeated with corrected assumptions..."* [4]. The other subphases follow a similar iterative process.

The entirety of the conceptual design (CD) process is iterative and reiterative, meaning flaws can be fixed by simply returning to the last design activity and reconducting that activity with new assumptions or modified inputs. This level of flexibility is reduced as the process advances through to the preliminary design (PD) and detailed design (DD) phases due to the high cost or changes associated.

2.2.3. Configuration Evaluation

First the vehicle is sized in the PS subphase, this size is then translated to a layout of the vehicle components throughout the CL subphase, and lastly this vehicle is then passed through a series of disciplinary checks during the configuration evaluation (CE) subphase that determine whether the vehicle meets the specific requirements of each of the disciplines involved. According to Raymer, this evaluation process *"… will almost always tell you that the design you drew doesn't really work…"* [8] and will result in a need to resize the vehicle with varied assumptions.

The following disciplines are typically a part of the configuration evaluation stage:

- Aerodynamics
- Aerothermodynamics
- Propulsion
- Performance
- Stability and Control
- Weights and Balances
- Structures
- Cost and Market

Each of these disciplines has its own analysis that is conducted during this phase. If the vehicle design does not meet the criteria for any one of the disciplines, it is not considered feasible, and parametric sizing must be redone with modified inputs. Mission requirements would be redefined and adjusted since no vehicle of the chosen configuration would be able to meet the basic requirements for the vehicle. The following subsections of the chapter provides a very brief overview of some of the major deliverables of each discipline in terms of evaluating a new design. It must be noted that the parameter calculations presented in this section are the bare minimum and NOT representative of the entirety of the disciplinary analysis procedure. Rather, this simplistic description hopes to convey a general understanding of the analysis procedure. Detailed evaluation criteria are found described in several design texts by authors such as Raymer, Nicolai, and Roskam [1] [8] [11].

2.2.3.1. Aerodynamics

Aerodynamic analysis is typically the first conducted after the configuration layout stage to calculate *"… a refined estimate of the lift and rag to determine baseline takeoff and fuel weights. …"* [1]. Aerodynamic evaluation involves calculating the aerodynamic forces and coefficients acting on the vehicle. Methods for these calculations vary based on whether the vehicle travels through the subsonic, transonic, supersonic, or hypersonic speed regimes.

The main source of lift is the wing, obviously, but there are other components that can enhance the overall amount of lift produced. The lift *"at a given angle of attack can be increased by increasing camber",* which may be done in two ways: active or passive [12]. This may be done by using either trailing-edge devices or leading-edge devices. Typical trailing-edge lift enhancing devices include *"flaps, split flaps, slotted flaps, and Fowler flaps"*, whereas leading-edge devices include *"fixed slot, leading-edge flap, Krueger flap, and plain slats"* [12].

The maximum lift coefficient for the wing is important as this *"will usually determine the wing area"* [8]. The basic equation for lift is given by:

$$L = qSC_L$$

where q is the dynamic pressure, S is the wing reference area, and C_L is the lift coefficient. Similarly drag force is given by:

$$D = qSC_D$$

where q is dynamic pressure, S is the wing reference area, and C_D is the drag coefficient. There are two basic types of drag: parasite drag, or zero-lift drag, and induced drag. Parasite drag is not associated with lift, but rather *"is comprised of all the forces that work to slow an aircraft's movement"* [13]. This may be estimated with the simple equation given below [1].

$$C_{D0} = C_{fe}\frac{S_{wet}}{S_{ref}}$$

Here C_{fe} is the equivalent skin friction coefficient, S_{wet} is the wetted surface area, and S_{ref} is the reference area.

Induced drag, otherwise known as drag due to lift, *"is always present if lift is produced",* [13] and can be expressed by the equation below:

$$C_{di} = kC_l^2$$

Here C_l is the lift coefficient, and k is defined by the following equation:

$$k = \frac{1}{\pi ARe}$$

where AR is the aspect ratio, and e is the wing efficiency factor [12].

It is important to calculate these parameters to figure out what the maximum lift to drag ratio is for the vehicle, whether this supports any cruise/glide mission segments adequately and allows for safe landing, etc. Also knowing the maximum lift coefficient is important because it will *"usually determine the wing area"*, and *"have a great influence upon the cruise drag"*, which affects takeoff weight of the vehicle [8]. These aerodynamic parameters then become inputs for the other disciplines such as performance and stability and control to determine the flying characteristics of the vehicle. This helps the other disciplines conduct their own evaluation of the feasibility of the design.

2.2.3.2. Aerothermodynamics

In terms of the conceptual design of aerospace vehicles, engineers working on this discipline play a crucial role in ensuring the survivability of the vehicle. Especially for hypersonic vehicles which experience higher heating loads during their missions. For example, a space-faring vehicle will encounter incredibly high heating rates during atmospheric re-entry. Hypersonic vehicles that operate within the earth atmosphere may still encounter the heating effects associated with high-speed travel. As Sziroczak mentions, "*the heat generated is proportional to the atmospheric density and to the third power of velocity*" [14]. This means that hypersonic transport vehicles may experience less overall heating during long hypersonic cruise mission segments, whereas launchers experience "*brief but very intense heat loads*" [14]. Outside the realm of hypersonics, even supersonic vehicles experience some amount of heating during flight, although not as intense. For vehicles like the Concorde that remain within the subsonic-to-supersonic flight regime, "*the material used for the vehicle itself will have to be carefully chosen to withstand the increased temperature without compromise in structural integrity*" [15].

The dynamic pressure may be defined as "*the kinetic energy of a flowing fluid per unit volume*" [16]. It may be expressed using the following equation:

$$q = \frac{1}{2}\rho V^2$$

where q is the dynamic pressure, ρ is the density of the fluid, and V is the velocity. For high-speed aerospace vehicles, this density is the density of the fluid medium of air, which may be obtained by utilizing the U.S. Standard Atmosphere Air Properties model [17]. For aircraft design, as Raymer says, *"a maximum q limit is specified in the design requirements and used by the structural designers for stress analysis"* [8].

Thermal protection systems (TPS) are external materials added to a vehicle to reduce the effects of incredibly high heating experienced during the mission. This is more crucial in hypersonic vehicles, as *"materials alone are insufficient to deal with all the heat problems"* [18]. However, materials that are able to withstand incredibly high temperatures may not always be structurally stronger. *"The solution is to combine different schemes of protections, using them in the most effective arrangements"* [18].

The topics discussed are a very brief introduction into the aerothermal analysis, which comprises of more detailed analysis methods and deliverables. References like Anderson's Aerodynamics text will provide the reader with a deeper look at the complexities of both aerodynamic and aerothermodynamic evaluation [19].

2.2.3.3. Propulsion

Propulsion is important in analysis as the discipline that determines if the performance of the engines used in the vehicle during the mission. The propulsion discipline determines if the engines produce enough thrust to carry the vehicle throughout its mission profile, what amount of fuel is necessary, etc. There are various types of propulsion systems, including propellers, gas turbines, ramjets, pulsejets, and rockets, as well as combined cycle systems [1]. The choice of propulsion system obviously has a significant impact on the performance of the vehicle overall.

Thrust is the key parameter in propulsion. Thrust is basically the driving force moving the vehicle, which is *"generate through the reaction of accelerating a mass of gas"* [20]. The very basic equation for thrust is given by:

$$F = \dot{m}_e V_e - \dot{m}_0 V_0$$

Here $\dot{m}$ is the mass flow rate, and V is the velocity, where 'e' and '0' correspond to the exit and inlet of the engine respectively. Calculating thrust helps determine if adequate thrust force is being generated for the completion of the mission. There are different types of thrust, such as installed vs. uninstalled thrust, specific thrust, etc. which will not be discussed in detail in this section but can rather be found in any design or propulsion textbook.

Another important parameter in the propulsion analysis is the calculation of the fuel consumed during the mission. A general equation to describe this is:

$$TSFC = W_f/T_n$$

Here W_f is the fuel weight flow, and T_n is the net thrust [1]. $TSFC$ is *"thrust specific fuel consumption"* and is basically a ratio of the fuel mass flow to the thrust generated. Calculating the fuel consumption of the vehicle over the course of the mission helps to figure out any C.G. shift experienced due to the emptying fuel tanks which is a stability issue. This also helps to calculate the fuel required to complete the mission with a safety margin of excess fuel reserves in case of an emergency scenario.

The parameters discussed in this section barely touch the basics of the propulsion analysis involved in configuration evaluation. Entire engine cycle analysis methods are available in detail in references such as Mattingly's text [21] for an in-depth look at the various methods employed based on the specific engine type.

2.2.3.4. Performance

The performance discipline has the task of determining the mission characteristics and whether the vehicle can meet the requirements based on the operational details of the mission. It combines a variety of outputs from the other disciplines in order to decide the overall performance of the vehicle.

One of the outputs of the performance discipline is the details of the flight path, also called a mission profile or a flight envelope, defined by altitude over range. This is typically defined before the sizing begins in order to constrain the design outcome to operate within these conditions. The flight envelope is determined by *"aircraft limitations such as minimum/maximum dynamic pressure and aerodynamic heating, and operational limits such as sonic boom, noise and air pollution"* [1]. Typically, the flight path of an aircraft involves the takeoff, climb, cruise, gliding and landing phases for horizontal takeoff and horizontal landing. For spaceplanes, this may be varied depending on whether the takeoff is vertical with the assistance of a booster stage or air-launched, etc.

For configuration evaluation, performance discipline checks for the range achieved by the aircraft. The famous Breguet Range equation shown below can be used to calculate the range of the vehicle.

$$R = \frac{V}{C}\frac{L}{D} ln\left(\frac{W_i}{W_f}\right)$$

where V is the flight speed, C is the specific fuel consumption, L/D is the lift to drag ratio, and W_i/W_f describes the initial and final weight of the vehicle [6].

Endurance is also calculated by the performance discipline, given by the following equation:

$$E = \frac{L}{D}\frac{1}{C}ln\left(\frac{W_i}{W_f}\right)$$

Here L/D is the lift to drag ratio, C is fuel consumption, and W_i/W_f is the initial weight compared to the final weight of the vehicle. Calculating endurance gives information about *"the amount of time an aircraft can remain in the air"* [8].

For parts of the flight mission such as gliding flight, thrust is set to zero and the glide ratio is determined to see how far the vehicle may glide before coming to a stop. Glide ratio is simply the ratio between *"horizontal distance traveled and altitude lost"* [8] and is the equivalent of the lift to drag ratio. Therefore, the maximum lift to drag ratio calculated earlier by the aerodynamic discipline is so important.

In addition, the performance discipline typically checks to see if the vehicle is able to carry out any maneuvers that are part of its mission. Some basic requirements that must be met for maneuverability include [22]:

$$C_{L_{maneuver}} < C_{L_{max}}$$

$$T_{reqd} < T_{max}$$

This means that the lift coefficient associated with the maneuver ($C_{L_{maneuver}}$) cannot exceed the maximum lift coefficient ($C_{L_{max}}$), and the thrust required for this maneuver (T_{reqd}) cannot exceed the maximum thrust produced (T_{max}).

For a more detailed look at the performance metrics to analyze a vehicle's ability to conduct its mission, texts from Phillips or Raymer may be utilized [23] [8].

2.2.3.5. Stability and Control

Perhaps the most critical discipline in the configuration evaluation phase, the stability and control discipline determines whether the vehicle is stable and controllable in all flight phases. The safety of the passengers and the entire mission is compromised if the vehicle does not pass the stability and control checks. There are three types of stability for a vehicle: longitudinal, lateral, and directional stability [1]. These three types of stability may be either static or dynamic in nature. Static stability is the inherent tendency of the vehicle to return to equilibrium by itself, while dynamic stability measures the ability of the aircraft to return to equilibrium due to the motion of the unsteady forces and moments eventually [1].

Longitudinal stability is determined by the pitching of the vehicle about the lateral axis, lateral stability is determined by the roll of the vehicle about the longitudinal axis, and directional stability is determined by the yaw of the vehicle about the vertical axis, as seen in Figure 2.4.

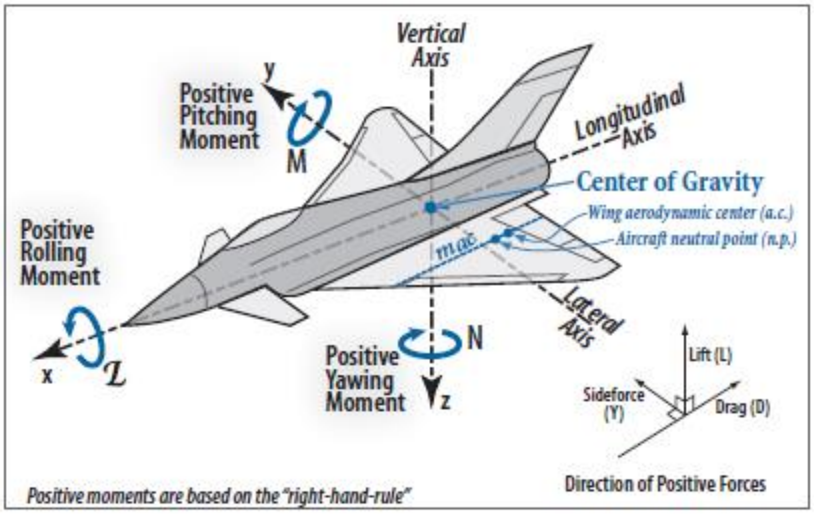

Figure 2.4. Vehicle stability and moment axes [1]

The vehicle is said to be in trim when the total pitching moment about the C.G. equals zero. The location of this center of gravity can be determined by simply dividing the sum of the moments by the sum of the weights of the aircraft [8]. As Nicolai states, the main static stability criterion *"is that its value of C_{M_α} be negative"* [1]. The equations for calculating C_{M_α} vary depending on the configuration of the aircraft.

For static lateral stability, the rolling moment coefficient C_ℓ is taken into consideration (not to be confused with the aerodynamic lift coefficient). Rolling moment coefficient is given by the equation:

$$C_\ell = \frac{\mathcal{L}}{qS_{ref}b}$$

Here $\mathcal{L}$ is the rolling moment, q is dynamic pressure, S_{ref} is the wing reference area, and b is the aircraft wingspan. The static lateral stability derivative is given in terms of the sideslip angle β as [1]:

$$\frac{dC_\ell}{d\beta} = C_{\ell\beta}$$

For static directional stability, the directional moment coefficient is given by [1]:

$$C_n = \frac{N}{q_\infty S_{ref} b}$$

Here N is the directional moment, given by the equation [1]:

$$N = \ell_f L_f + \ell_{VT} L_{VT} + N_{power} + N_{wing}$$

Here L_f is the fuselage side-force, and N_{power} and N_{wing} are the moments due to the asymmetric power effects and wing respectively. The directional stability derivative is also based on the sideslip angle β, and is given by [1]:

$$\frac{dC_n}{d\beta} = C_{n\beta}$$

To restate what was mentioned earlier, the listed variables and calculations are simply a few major parameters out of many more that are typically involved in the configuration evaluation stage of conceptual design. Stability and control in particular is a discipline with an abundance of variables, the extent of which would be out of the scope of this introductory chapter. A full list of stability and control variables may be found in the knowledge buildup of Dr. Chudoba's dissertation [24].

2.2.3.6. Weights/Balances and Structures

This discipline, as the name suggests, deals with the weight placements of the vehicle, and checks for structural strength of the vehicle. Depending on the complexity of the project, this may be split into a separate weights and balances team and a structures/materials team.

For the weights team, it is very important to calculate the TOGW (takeoff gross weight), which is a very important design parameter because it sizes the vehicle [1]. Nicolai describes the TOGW as comprised of the following:

$$W_{TO} = W_{fuel} + W_{fixed} + W_{empty}$$

Here the fixed weight (W_{fixed}) includes a variety of expendable and non-expendable equipment, empty weight (W_{empty}) includes "structure, propulsion, subsystems, avionics, instruments, and so on", and fuel weight (W_{fuel}) is the total weight of the fuel needed, which can be determined using fuel fraction throughout the entire mission [1].

In contrast to the disciplines listed before, there are no overall equations that typify weights in general, that may be found across various methodologies. Each design group or company may have their own methods for estimating component weights of an aircraft, some of which use statistical data. Raymer presents two basic methods for weight estimation: the first is a crude buildup of component weights based on *"planform areas, wetted areas, and percents of gross weight"* [8]. The second method utilizes statistical equations. Either method may work depending on the specifics of the project and the level of detail to which the this is applied.

2.2.3.8. Cost and Market

The cost and market discipline determines the expenses associated with the vehicle and determines if the vehicle developed is marketable and competitive in industry. This discipline is important for forecasting the survivability and sustainability of a new design.

There are many different methods for calculating cost of a vehicle, and the methods chosen for calculating such could vary depending on the mission specifics. For example, Nicolai and Carichner discuss cost estimation based on life cycle cost (LCC), which includes the following four phases: research, development/test/evaluation, acquisition, and operations/maintenance [1].

On the other hand, Koelle discusses cost as consisting of three major categories in his TRANSCOST methodology [25]: development cost, production cost, and operations cost. Development cost accounts for the cost involved in the development effort for the technologies associated with a vehicle. This is a non-recurring cost and includes *"all activities from detailed design to hardware implementation and verification"* [25]. Production cost is associated with the manufacturing of the vehicle and engine, as well as integration and verification. Operations cost finally deals with the costs associated with the actual operation of the vehicle for its mission and is a recurring cost. The equations associated with these costs vary depending on the reusability of the vehicle and engine, as well as component selection.

For cost estimation, there is no overall strategy for estimation as methods and fidelity levels of these methods vary; nonetheless this discipline is crucial to forecasting the basic economic feasibility of a project.

2.3. Synthesis Processes Available

There are several aircraft synthesis processes available. Some are computer integrated and others are by-hand methods published by those with a good foundational knowledge and understanding of the multidisciplinary process. The AVD Laboratory has spent time and effort surveying these methods to forecast the need for a novel synthesis system, and to develop a multidisciplinary method based on the best-candidate references. Table 2.2 lists these processes found which are a combination of survey results from Chudoba, Coleman, and Omoragbon [26] [4] [27]. The alternating colors shown in the table serve to distinguish between the different decades.

Table 2.2. List of Design Texts To-Date

Text Name	Author	Year	Decade
Birdflight as the Basis of Aviation	Lilienthal, O.	1889	1800's
Aeroplane Design	Barnwell, F.S.	1917	1910's
Airplane Design - Performance	Warner, E.P.	1927	1920's
Airplane Design Manual	Teichmann, F.K.	1939	1930's
Aerospace Vehicle Design, Aircraft Design	Wood, K.D.	1963	1960's
Design for Flying	Thurston, D.B.	1978	1970's
Supersonic and Subsonic, CTOL and VTOL Airplane Design	Corning, G.	1979	
Subsonic Aircraft: Evolution and the Matching of Size to Performance	Loftin, L.K.	1980	1980's
Synthesis of Subsonic Airplane Design	Torenbeek, E.	1982	
The Design of the Aeroplane	Stinton, D.	1983	
Fundamentals of Aircraft Design	Nicolai, L.M.	1984	
Aircraft Design	Heinemann, E.H. et al	1985	
Airplane Design, Parts I-VIII	Roskam, J.	1985	
Design for Air Combat	Whitford, R.	1987	
The Technology of the Modern Transport	Hünecke, K.	1987	
Fundamentals of Flight	Shevell, R.S.	1989	
The Sportplane Builder	Bingelis, T.	1992	1990's
Aircraft Design Handbook - Aircraft Design Aid and Layout Guide	Kirschbaum & Mason	1994	
Introduction to Aircraft Design	Fielding, J.P.	1994	
Systems Engineering for Commercial Aircraft	Jackson, S.	1997	
Modern Combat Aircraft Design	Hünecke, K.	1998	
The Anatomy of the Aeroplane	Stinton, D.	1998	
Fundamentals of Sailplane Design	Thomas, F.	1999	
Civil Jet Aircraft Design	Jenkinson, L.R. et al	1999	
Aircraft Performance and Design	Anderson, J.D.	1999	
Fundamentals of Fighter Design	Whitford, R.	2000	2000's
Aircraft Conceptual Design Synthesis	Howe, D.	2000	
The Elements of Aircraft Preliminary Design	Schaufele, R.D.	2000	
Flight Physics	Torenbeek, E., et al	2002	
Design of Aircraft	Corke, T.C.	2003	
Aircraft Design Projects for Engineering Students	Jenkinson, L.R. et al	2003	
Simplified Aircraft Design for Homebuilders	Raymer, D.P.	2003	
Aircraft Design: A Conceptual Approach	Raymer, D.P.	2006	
Evolution of the Airliner	Whitford, R.	2007	
Lessons Learned in Aircraft Design	Roskam, J.	2007	
Managing Aviation Projects from Concept to Completion	Flouris & Lock	2009	
Fundamentals of Aircraft and Airship Design, Vol.1	Nicolai & Carichner	2010	2010's
Commercial Aircraft Projects	Altfeld, H.H.	2010	
Aircraft Design	Kundu, A.	2010	
Flight Vehicle Synthesis and Systems Engineering	Chudoba, B.	2012	
General Aviation Aircraft Design	Gudmundsson, S.	2013	
Advanced Aircraft Design	Torenbeek, E.	2013	
Aircraft Design: A Systems Engineering Approach	Sadraey, M.H.	2013	
Commercial Airplane Design Principles	Sforza, P.M.	2014	
Manned Spacecraft Design Principles	Sforza, P.M.	2016	
Unmanned Aircraft Design - A Review of Fundamentals	Sadraey, M.H.	2017	
Conceptual Aircraft Design: An Industrial Approach	Kundu, A.K.	2019	
Conceptual Design of Supersonic Commercial Aircraft	Torenbeek, E.	2020	2020's

As seen in Table 2.2, from the 1980's onward, there has been an increasing number of design-specific publications generated each decade. Each author has a somewhat unique approach to aircraft design, while retaining some common elements of design. For example, many texts generally follow the sizing-layout-evaluation logic flow demonstrated in Figure 2.2, although some may phrase this line of thinking differently with differing names for each subphase of conceptual design. Some authors choose to focus on a larger subset of layout processes while spending little time in the parametric sizing realm, or vice-versa, etc. Such methods and other computer implementations were surveyed by Chudoba when determining the specification for the design system developed within the AVD Laboratory, which will be described in more detail in Chapter 3.

2.3.1. Hypersonic Convergence

Hypersonic convergence is a conceptual design process for hypersonic vehicles that is utilized in this context for a basic understanding of a convergence-based design process, which the texts mentioned in the previous chapter do not address explicitly. The sizing process of the AVDS system (detailed in Chapter 3) with which the VCC will eventually become fully integrated, has been developed based on the general convergence logic employed by Dr. Paul Czysz in his Hypersonic Convergence method [28]. Hence it is of use to the reader to gain some insight into the hypersonic convergence method through a review of an implementation of such a convergence-based logic, which will provide much-needed context for the next chapter discussing AVDS. The chart shown in Figure 2.5 shows the derived sizing, layout, and evaluation process in a flowchart schematic.

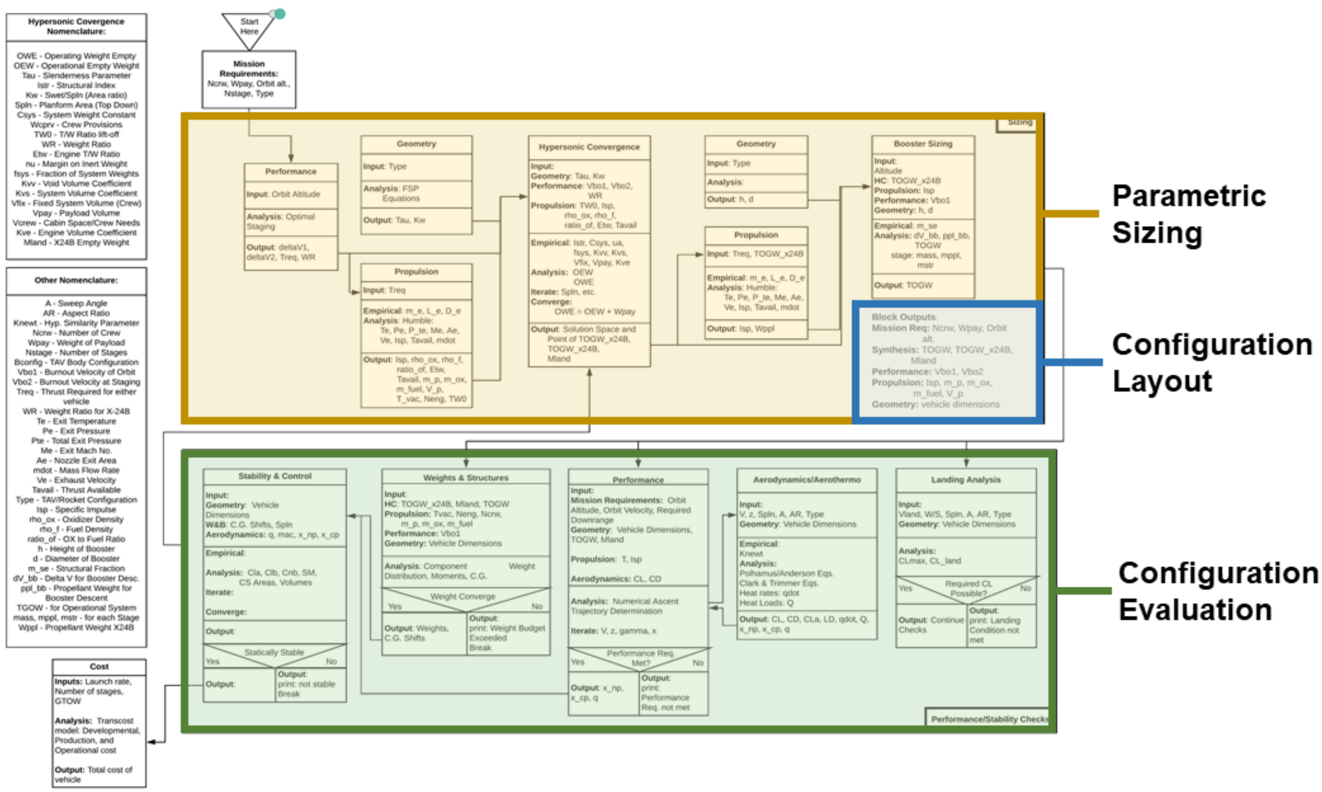

Figure 2.5. Hypersonic convergence process mapped

This chart is derived from a previous two-stage-to-orbit system sizing project conducted by the author for her undergraduate capstone design project [29]. The sizing process, as seen in Figure 2.5, starts off with the determination of the mission requirements such as the weight of the payload, the orbital altitude to achieve, number of stages for the vehicle, the number of crew members for a manned mission, etc. Then this information is fed into the performance discipline that calculates the delta V required to meet these mission requirements, as well as the thrust required and the weight ratio desired. This is then output to the propulsion team which uses the required thrust to calculate the propulsion outputs needed for the hypersonic convergence logic. The geometry team calculates the tau or slenderness ratio that feeds into the convergence logic as well. The equations shown below describe the convergence criteria:

$$OWE = OEW + W_{pay} + W_{crew}$$

Here W_{pay} is the payload weight, W_{crew} is the crew weight, and OWE is the volume budget and OEW is the weight budget, described by the equations given below:

$$OEW = \frac{I_{str} K_W S_{pln} + C_{sys} + W_{cprv} + T/W_0 \cdot \frac{WR}{E_{TW}} \left(W_{pay} + W_{crw} \right)}{\frac{1}{1+\mu_a} - f_{sys} - T/W_0 \cdot \frac{WR}{E_{TW}}}$$

Table 2.3. Variables in Weight Budget Equation [30]

Variable	Nomenclature
I_{str}	Structural Index
K_W	Area Ratio (Swet/Spln)
S_{pln}	Planform area (top down)
C_{sys}	System weight constant
W_{cprv}	Crew provisions
T/W_0	Thrust to weight ratio (lift-off)
WR	Weight Ratio
E_{TW}	Engine T/W Ratio
W_{pay}	Weight of payload
W_{crw}	Weight of crew
μ_a	Margin on inert weight
f_{sys}	Fraction of systems weights

$$OWE = \frac{\tau . S_{pln}^{1.5} (1 - k_{vv} - k_{vs})(V_{crw} - k_{crw}) . N_{crw} - V_{pay}}{\frac{WR - 1}{\rho_{ppl}} + k_{ve} . T/W_0 . WR}$$

Table 2.4. Variables in Volume Budget Equation [30]

Variable	Nomenclature
τ	Slenderness parameter
S_{pln}	Planform area (top down)
k_{vv}	Void Volume Coefficient
k_{vs}	System volume coefficient

V_{crw}	Cabin space/crew needs
k_{crw}	Crew volume coefficient
N_{crw}	Number of crew members
V_{pay}	Payload volume
WR	Weigh ratio
ρ_{ppl}	Propellant density
k_{ve}	Engine volume coefficient
T/W_0	Thrust to weight ratio

As seen from the equations above as well as the tables detailing the inputs for convergence, the basic sizing and convergence logic is highly multidisciplinary in nature.

The output from hypersonic convergence is a solution space that provides an array of design points. The example shown in Figure 2.6 visualizes a solution space, as demonstrated within the Hypersonic Convergence methodology:

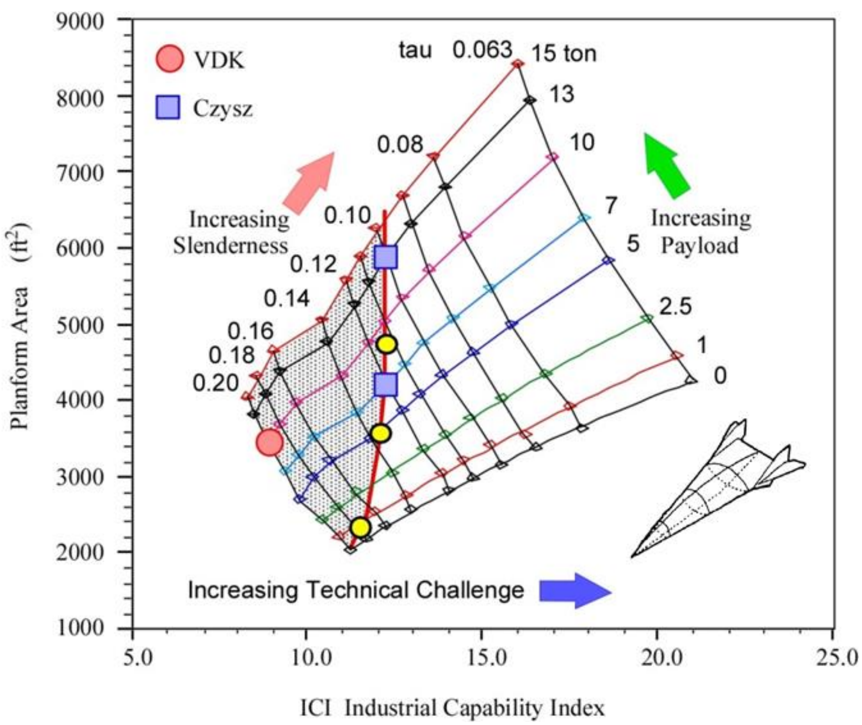

Figure 2.6. Solution space constrained by ICI [30]

A solution space may have any number of major design variables identified on the axes, but the typical parameters shown are planform area, slenderness ratio, payload weight, takeoff gross weight, and range. From this continuum graph of design points, one or several baseline design vehicles are chosen to advance further to the configuration layout (CL) phase where the geometry, weights and balances disciplines interact to detail the layout of the vehicle components.

The sized vehicle with the defined layout is then advanced to the configuration evaluation (CE) subphase of conceptual design. During configuration evaluation (CE), as shown in Figure 2.5, analysis is conducted for each discipline to determine if the vehicle meets disciplinary requirements for the mission. Landing analysis is conducted to determine if the vehicle meets the lift requirements to make a smooth landing. The aerodynamic team conducts other analysis to calculate the lift and drag coefficients, aerodynamic center calculation, and dynamic pressure experienced by the vehicle. The performance/trajectory discipline calculates the trajectory of the vehicle, the weights team determined whether the weight converges, or the weight budget exceeds what is allowed by the volume of the vehicle. The stability and control team determines whether the vehicle is stable and controllable in all phases of flight, and the cost team calculates the recurring and non-recurring cost associated with the vehicle.

All this analysis then determines whether the vehicle can perform the mission. Further design points from the solution space may be explored to check whether there is a more efficient design available and feasible with potentially increased performance capabilities.

It must be emphasized that the process described here is a generic conceptual design cycle, and not necessarily reflective of the exact process followed by the AVDS system. AVDS follows the convergence logic employed by hypersonic convergence; however, within each subphase of conceptual design, AVDS system completes disciplinary analysis of varying levels of fidelity. There is a very basic level of disciplinary analysis that AVDS employs in the parametric sizing subphase, with very low-fidelity methods. With the completion of configuration layout and configuration evaluation, the fidelity level of the disciplinary analysis employed is increased. Configuration evaluation is conducted using the highest fidelity methods available to AVDS, which will be discussed in detail in the following chapter.

2.4. Application of a DIB-KB System in Design

With the design advantages offered within the conceptual design (CD) phase, it is imperative to spend more time and effort within this phase than is typical before moving onto the more detailed design iterations. This will ensure the passing on of an efficient design point before spending more money and resources on it. What could support this is a database-knowledgebase system, as Chudoba states:

"… Ideally, a combination of a Data-Base System (DBS) containing information on existing designs, and a Knowledge-Based System (KBS) with knowledge about the design process, coupled to analysis packages organized in a multidisciplinary synthesis system, should provide the designer with a great deal of assistance at all stages…" [24].

The level of convenience offered by such a system would be outstanding. For example, the designer might want to compare the lifting capabilities of a variety of configurations before choosing one. Also, the designer may want to verify that a particular method chosen works by comparing C.G. shift tendencies of a vehicle. Having an all-encompassing database and knowledgebase at their fingertips would enable the designer to move forward at a quicker pace rather than spending valuable time searching for such data. This would become a reference manual of sorts for the designer. This need was made clear during the capstone senior design project that the author was involved in. The amount of time and effort spent searching for the relevant data, information and knowledge that could help with verification and for making design decisions was immense. Comparatively, the time left to implement the design process was rather lacking. Knowledge was so scarce that the team often questioned whether it was worth spending effort and time developing knowledgebase diagrams to begin with, because of the time constraint of the project. A DIK system like the VCC, at that point in time, would have helped accelerate the pace at which the project was completed. It is then clear that, if a simple student project had such an obvious need for a design companion, the need in industrial design settings would be much greater.

Currently there is a gap in the world of aerospace design for such a singular library of design data, information, and knowledge to be *"… readily available for design-decision making …"* [24]. This is the gap that the VCC seeks to fill. Working in tandem with the AVDS system, the connection between VCC and AVDS will be detailed in the next chapter.

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CHAPTER 3

AEROSPACE VEHICLE DESIGN SYNTHESIS (AVDS)

3.1. Introduction to AVDS

The AVDS (Aerospace Vehicle Design Synthesis) methodology and software is the design environment software which the VCC is intended to support. It is therefore important to contextualize the integration of the two systems by detailing the inner workings of the AVDS software as well as the history of its development. As such, further sections in this chapter aim to provide this context as well as identify the ideal integration points between VCC and AVDS. AVDS is a generic Class V synthesis system framework [1], meaning that it is configuration-independent and built to generically handle a wide range of aerospace vehicle applications. This is in stark contrast to other currently available class IV synthesis systems which are typically focusing on singular configurations or concepts. A survey of such currently available systems was conducted by Dr. Chudoba [2] and shown in Table 3.1.

Table 3.1. Aircraft and Aerospace Vehicle Class IV Synthesis Systems

AAA	Advanced Airplane Analysis	DARcorporation
ACDC	Aircraft Configuration Design Code	Boeing Defense and Space Group
ACDS	Parametric Preliminary Design System for Aircraft and Spacecraft Configuration	Northwestern Polytechnical University
ACES	Aircraft Configuration Expert System	Aeritalia
ACSYNT	AirCraft SYNThesis	NASA
ADAM	-	McDonnell Douglas
ADAS	Aircraft Design and Analysis System	Delft University of Technology
ADROIT	Aircraft Design by Regulation Of Independent Tasks	Cranfield University
ADST	Adaptable Design Synthesis Tool	General Dynamics/Fort Worth Division
AIDA	Artificial Intelligence Supported Design of Aircraft	Delft University of Technology
AircraftDesign	-	University of Osaka Prefecture
APFEL	-	IABG
AProg	Auslegungs Programm	Dornier Luftfahrt
ASAP	Aircraft Synthesis and Analysis Program	Vought Aeronautics Company
ASCENT	-	Lockheed Martin Skunk Works
ASSET	Advanced Systems Synthesis and Evaluation Technique	Lockheed California Company
AVID	Aerospace Vehicle Interactive Design	N.C. State University, NASA LaRC
AVSYN	-	Ryan Teledyne
BEAM	-	Boeing
CAAD	Computer-Aided Aircraft Design	SkyTech
CAAD	Computer-Aided Aircraft Design	Lockheed-Georgia Company
CACTUS	-	Israel Aircraft Industries
CADE	Computer Aided Design and Evaluation	McDonnel Douglas Corporation
CAP	Configuration Analysis Program	North American Rockwell (B-1 Division)
CAPDA	Computer Aided Preliminary Design of Aircraft	Technical University Berlin
CAPS	Computer Aided Project Studies	BAC Military Aircraft Devision
CASP	Combat Aircraft Synthesis Program	Northrop Corporation
CASTOR	Computer Aircraft Synthesis and Trajectory Optimization Routine	Loughborough University
CDS	Configuration Development System	Rockwell International

CISE	-	Grumman Aerospace Corporation
COMBAT	-	Cranfield University
CONSIZ	CONfiguration SIZing	NASA Langley Research Center
CPDS	Computerized Preliminary Design System	The Boeing Company
DesignSheet	-	Rockwell International
DRAPO	Definition et Realisation d' Avions Par Ordinateur	Avions Marcel Dassault/Breguet Aviation
DSP	Decision Support Problem	University of Houston
EASIE	Environment for Application Software Integration and Execution	NASA Langley Research Center
ESCAPE	-	BAC (Commercial Aircraft Devision)
ESP	Engineer's Scratch Pad	Lockheed Advanced Development Co.
FASTPASS	Flexibly Analysis for Synthesis, Trajectory, and Performance for Advanced Space Systems	Lockheed Martin Astronautics
FLOPS	FLight OPtimization System	NASA Langley Research Center
FPDB & AS	Future Projects Data Banks & Application Systems	Airbus Industrie
FPDS	Future Projects Design System	Hawker Siddeley Aviation Ltd
FVE	Flugzeug VorEntwurf	Stemme GmbH & Co. KG
GASP	General Aviation Synthesis Program	NASA Ames Research Center
GPAD	Graphics Program for Aircraft Design	Lockheed-Georgia Company
HASA	Hypersonic Aerospace Sizing Analysis	NASA Lewis Research Center
HESCOMP	HElicopter Sizing and Performance COMputer Program	Boeing Vertol Company
HiSAIR/Pathfinder	High Speed Airframe Integration Research	Lockheed Engineering and Sciences Co.
Holist	-	-
ICAD	Interactive Computerized Aircraft Design	USAF-ASD
ICADS	Interactive Computerized Aircraft Design System	Delft University of Technology
IDAS	Integrated Design and Analysis System	Rockwell International Corporation
IDEAS	Integrated DEsign Analysis System	Grumman Aerospace Corporation
IKADE	Intelligent Knowledge Assisted Design Environment	Cranfield University
IMAGE	Intelligent Multi-Disciplinary Aircraft Generation Environment	Georgia Tech
IPAD	Integrated Programs for Aerospace-Vehicle Design	NASA Langley Research Center
MacAirplane	-	Notre Dame University
MIDAS	Multi-Disciplinary Integrated Design Analysis & Sizing	DaimlerChrysler Military
MIDAS	Multi-Disciplinary Integration of Deutsche Airbus Specialists	DaimlerChrysler Aerospace Airbus
MVA	Multi-Variate Analysis	RAE (BAC)
MVO	MultiVariate Optimisation	RAE Farnborough
ODIN	Optimal Design INtegration System	NASA Langley Research Center
OPDOT	Optimal Preliminary Design of Transports	NASA Langley Research Center
Paper Airplane	-	MIT
PASS	Program for Aircraft Synthesis Studies	Stanford University
PIANO	Project Interactive ANalysis and Optimisation	Lissys Limited
POP	Parametrisches Optimierungs-Programm	Daimler-Benz Aerospace Airbus
PrADO	Preliminary Aircraft Design and Optimisation	Technical University Braunschweig
PreSST	Preliminary SuperSonic Transport Synthesis and Optimisation	DRA UK
PROFET	-	IABG
RCD	Rapid Conceptual Design	Lockheed Martin Skunk Works
RDS	-	Conceptual Research Corporation
Rubber Airplane	-	MIT
SENSxx	-	DaimlerChrysler Aerospace Airbus
SSP1	System Synthesis Program	University of Maryland
SSSP	Space Shuttle Synthesis Program	General Dynamics Corporation
SYNAC	SYNthesis of AirCraft	General Dynamics
TASOP	Transport Aircraft Synthesis and Optimisation Program	BAe (Commercial Aircraft) LTD
TRANSYN	TRANsport SYNthesis	NASA Ames Research Center
TRANSYS	TRANsportation SYStem	DLR (Aerospace Research)
VDEP	Vehicle Design Evaluation Program	NASA Langley Research Center
Vehicles	-	Aerospace Corporation
VizCraft	-	Virginia Tech
WIPAR	Waverider Interactive Parameter Adjustment Routine	DLR Braunschweig
X-Pert	-	Delft University of Technology
-	Dialog System for Preliminary Design	TsAGI
-	Hypersonic Aircraft Conceptual Design Methodology	Turin Polytechnic
-	Design Methodology for Low-Speed High Altitude UAV's	Cranfield University (Altman)
-	Preliminary Design of Civil Transport Aircraft	ONERA
-	Numerical Synthesis Methodology for Combat Aircraft	Cranfield University (Siegers)
-	Synthesis Model for Supersonic Aircraft	Stanford University (Van der Velden)
-	Spreadsheet Analysis Program	Loughborough University

Most of these Class IV approaches are not generic in nature, whereas AVDS is a multi-fidelity and multi-vehicle capable design synthesis forecasting implementation. Of most importance to note is that the AVDS system overall engages in the development of generic synthesis codes based on design choices made by a designer, making it a unique system in comparison to any other currently existing synthesis program.

AVDS progresses a design through the conceptual design and preliminary design phases. It employs a vast library of references, data, information, knowledge, variables, methods, processes and deliverables for any desired configuration. The primary objective of the AVDS system is to support decision-makers (program managers), the integrators (chief engineers), and the technologists (specialists) by providing a consistent approach to composing and delivering multi-disciplinary design synthesis codes and results. This allows for consistent and rapid comparisons of a wide range of potential design configurations once robust disciplinary methods have been selected for the synthesis code build. The strength of this synthesis implementation lies in how the system integrates, *"… the disciplinary analysis environments and their methods libraries into a total system convergence logic process. …"* [3].

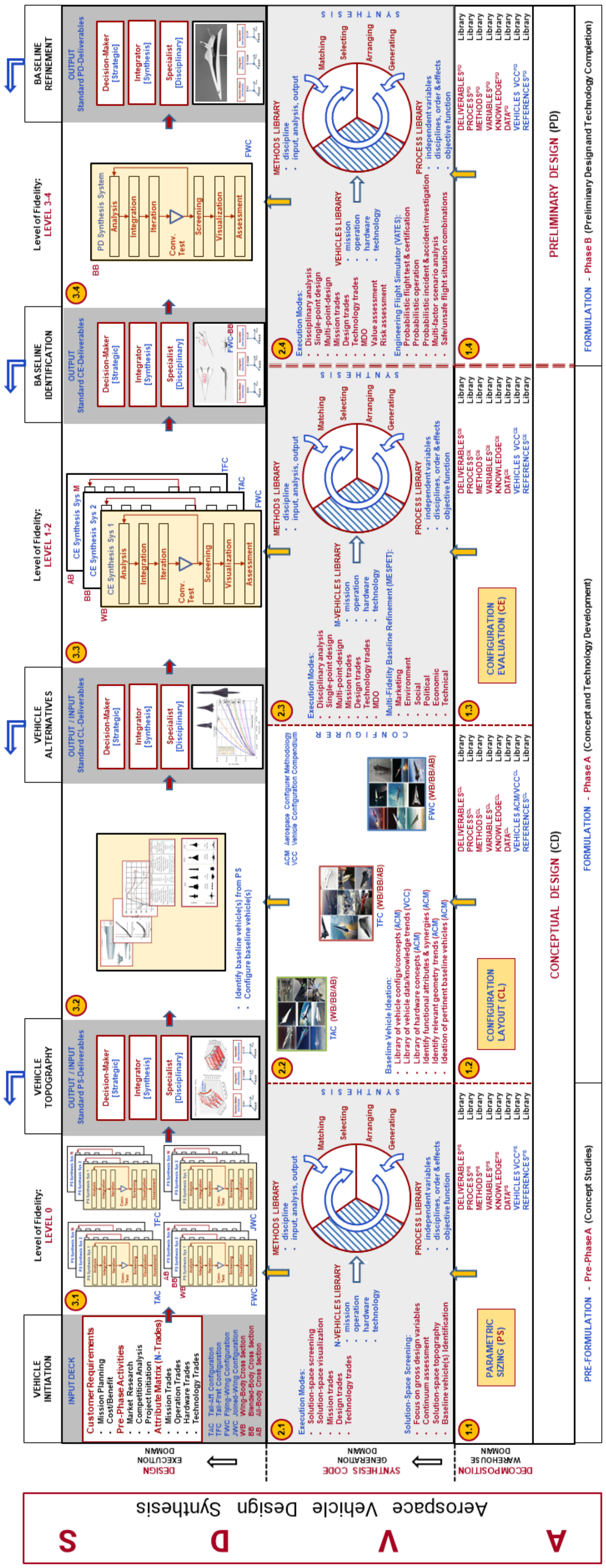

Figure 3.1. AVDS methodology and process diagram [3]

The purpose of developing a synthesis system is to bridge the apparent gap observed between the conceptual design (CD) phase of aerospace vehicles when compared to the wealth of development effort and detail that goes into the preliminary design (PD) and detailed design (DD) phases and supporting tools. As Chudoba states, most current computer-aided design methods use *"… statistical data when available, without necessarily questioning and balancing the physical rationale of the solution. …"* [4]. This rationale is almost entirely addressed during the conceptual design (CD) phase, which is why the AVD Laboratory focuses on further development and evolution of the AVDS best-practice system seeking to revolutionize the world of aerospace design and forecasting. The process chart for the architecture of the AVDS system is shown in Figure 3.1.

3.1.1. History of AVDS

The AVDS system as it currently stands was iterated multiple times before finalizing the current, refined Python version. Dr. Chudoba, supervisor for this research effort and director of the AVD Laboratory, used his previous experience from industry future projects office environments to lay the foundation for the conceptualization of the AVDS system. Three major contributors to its development included AeroMech, PrADO, and Hypersonic Convergence by Professor Paul Czysz [4]. Working on projects together with these systems and individuals influenced the defining characteristics of the system developed later and enabled for the evolution of the AVDS system into the current capabilities it possesses.

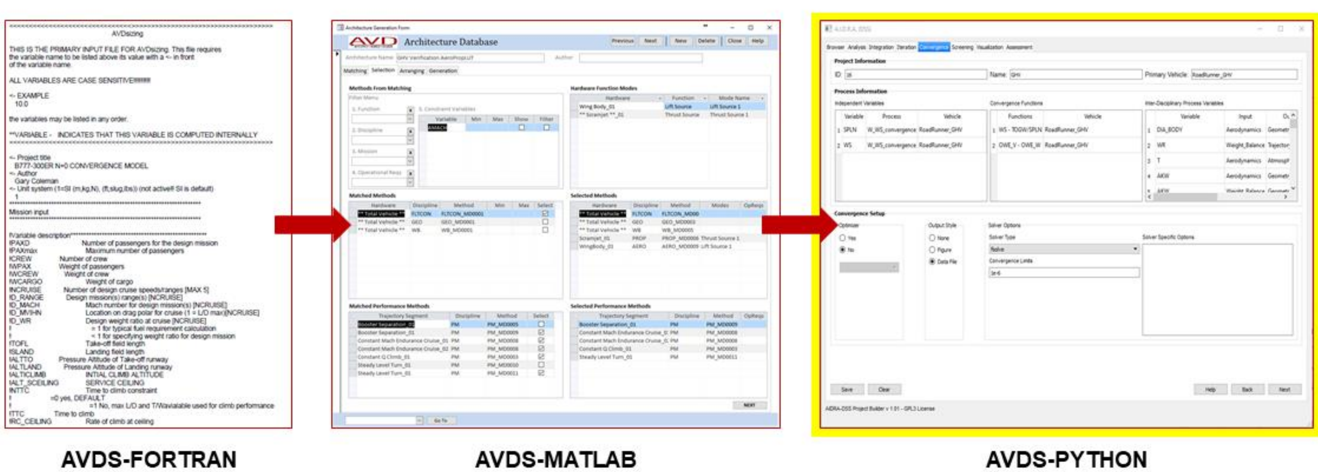

Figure 3.2. Evolution of AVDS system through various programming languages [5] [6] [7]

As shown in Figure 3.2, the history of the AVDS system may be considered as made up of three distinct eras: the FORTRAN era, MATLAB era, and current Python era.

3.1.1.1. AVDS FORTRAN

The very first software implementation of the AVDS sizing methodology has been accomplished with FORTRAN. AVD Laboratory researcher Gary Coleman primarily worked on developing this system during his doctoral research [5]. This system establishes the initial design toolbox, consisting of a design process library, a disciplinary methods library, and a disciplinary deliverables library, as shown in Figure 3.3 [5].

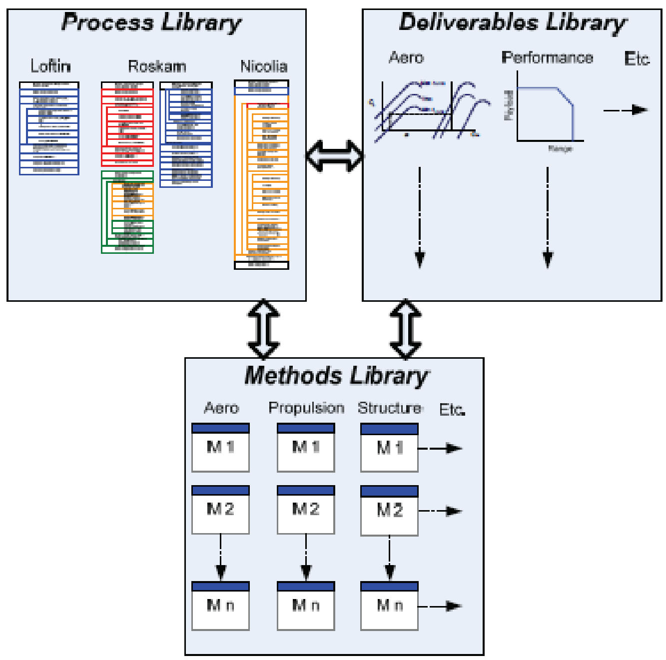

Figure 3.3. Design toolbox [5]

After a thorough literature review of the available parametric sizing methods – both 'by hand' and 'computer-integrated' – the AVDS sizing logic was developed as shown in Figure 3.4. This logic has been based on Hypersonic Convergence by Paul Czysz [8] which employs the convergence of the weight budget and volume budget as a means of generating a solution space of feasible designs (described in Chapter 3). As Coleman states, this is in contrast to the typical sizing processes seen where only weight is converged and "… *volume is checked as an inequality constraint* …" [5].

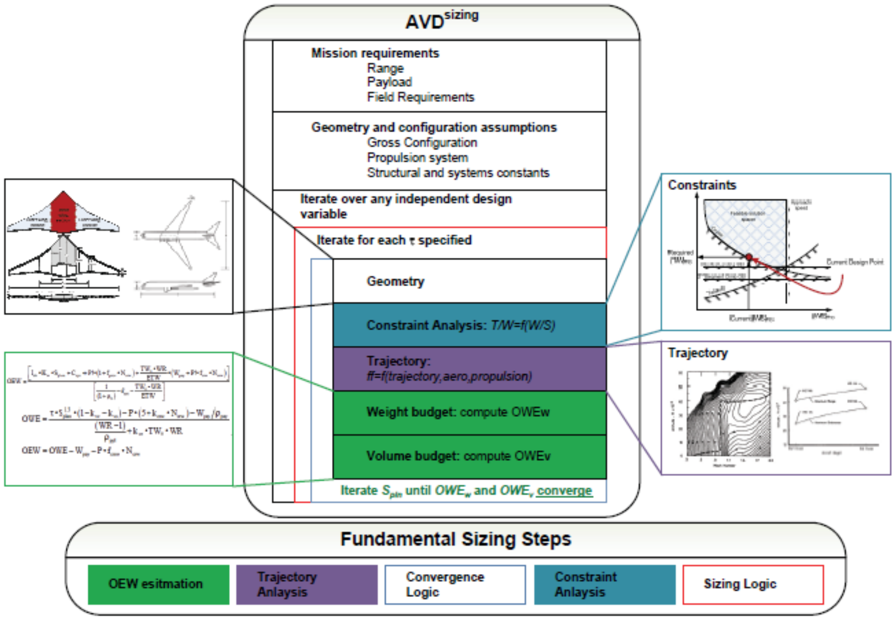

Figure 3.4. Fundamental AVD sizing logic [5]

This FORTRAN-implemented AVD sizing system used an input file to carry out the calculations. The method has been verified with the sizing of the B777-300ER, the Learjet 24, Sänger-II, and LAPCAT vehicles [9].

3.1.1.2. AVDS MATLAB

The MATLAB era of the AVDS system has been spearheaded by former AVD Lab researcher Lex Gonzalez as part of his dissertation work, with supporting work from Amen Omoragbon, and Amit Oza [6] [10] [11]. Gonzalez, Omoragbon and Oza worked together on an initial decomposition of the components that defined the *"CMDS",* or "*Complex Multidisciplinary System*". The purpose of such a decomposition study was to develop a methodology for the composition of a multidisciplinary system, the techniques of which are then applied to the synthesis of aircraft. This process yielded the following blocks that make up an aircraft synthesis system: product, analysis process, and disciplinary methods, as shown in the breakdown in Figure 3.5 [6].

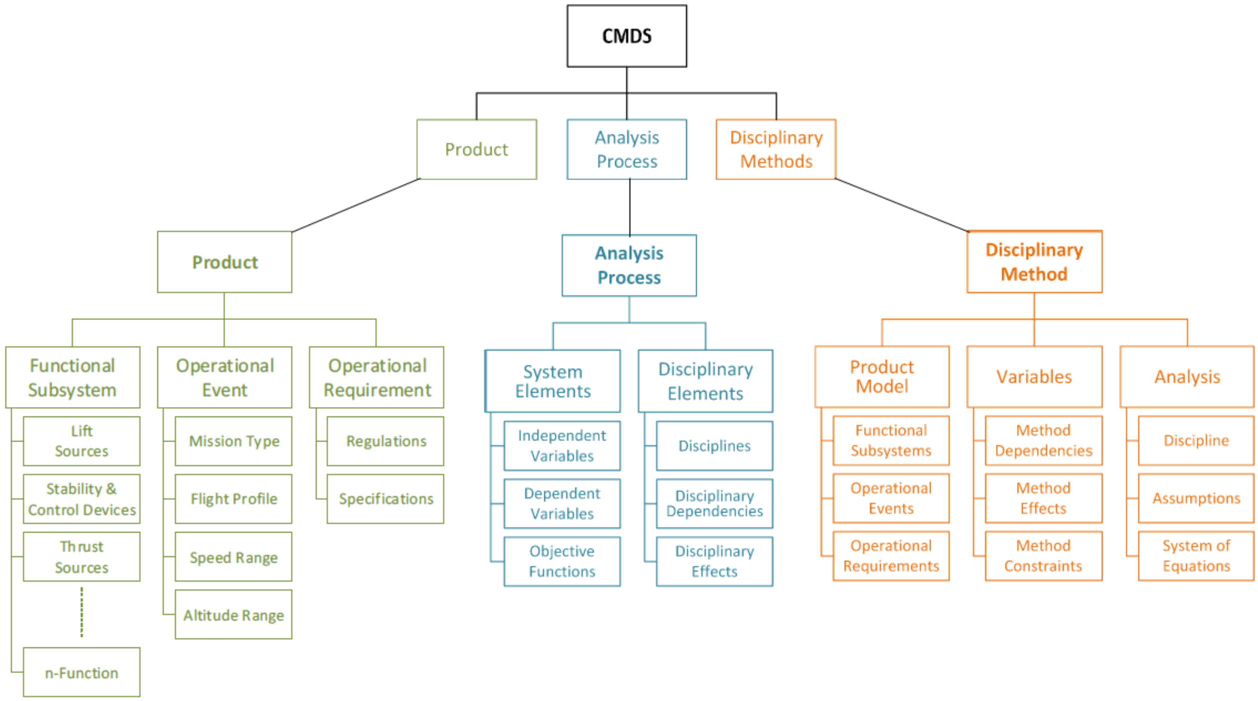

Figure 3.5. Lex Gonzalez - breakdown of synthesis systems [6]

Gonzalez then worked on the composition of these components back into a synthesis system, with the AVD-DBMS (Aerospace Vehicle Design - Database Management System) as an integrated component of the synthesis method. AVD-DBMS has been a sort of precursor to the VCC-DIK (Vehicle Configuration Compendium – Data-Information-Knowledge) system, allowing the user to interact with and query stored data. The DBMS helped the user to define a process, architecture, vehicles and methods to generate a generic sizing code with AVDS tailored to the design problem at hand [3].

The decomposition process implemented by Gonzalez results in an understanding of the crucial components of a complex multidisciplinary system, which are shown in Figure 3.5. The CMDS described by Gonzalez contains the following four steps: matching, selecting, arranging, and generation. Matching is the phase where all disciplinary methods are queried, and it returns "… *all disciplinary methods that are applicable to the problem requirements* …" [6]. The selecting phase is where the user reviews the methods returned and selects the appropriate ones for the CMDS to integrate into a tailored vehicle synthesis code. Arranging is then the step where an integration blueprint is generated for the AVD-DBMS based on an assessment of, "… *the combination of Product, Analysis Process and Selected Disciplinary Methods* …" [6]. Finally, the generation phase creates an analysis architecture (the logical structure and organization for analysis) based on the previous blueprints. This concept is then coded up using a combination of Microsoft Access, Microsoft Visual Basic with Applications for the GUI, SQL for the database, and MATLAB for the analysis script. AVDS-MATLAB was verified using the GHV, X-20, and X-51A vehicles [6][12]

3.1.1.3. AVDS Python

The current AVDS system is Python-based, and it is under development to be capable of the full conceptual design cycle shown in Figure 3.1, with the preliminary design and detail design phases planned for the future. Several AVD Lab researchers have been involved in the development of the Python-era AVDS system, notable of which is work by Thomas McCall on what he called the "*AIDRA-DSS*" (Artificial Intelligence Design and Research Assistant Decision Support System) [7]. AIDRA-DSS has been the first iteration of the AVDS-Python architecture, which has evolved into its current implementation. For detailed information on AIDRA-DSS, see the PhD dissertation by McCall [7]. The architecture of the system McCall developed is demonstrated in Figure 3.6.

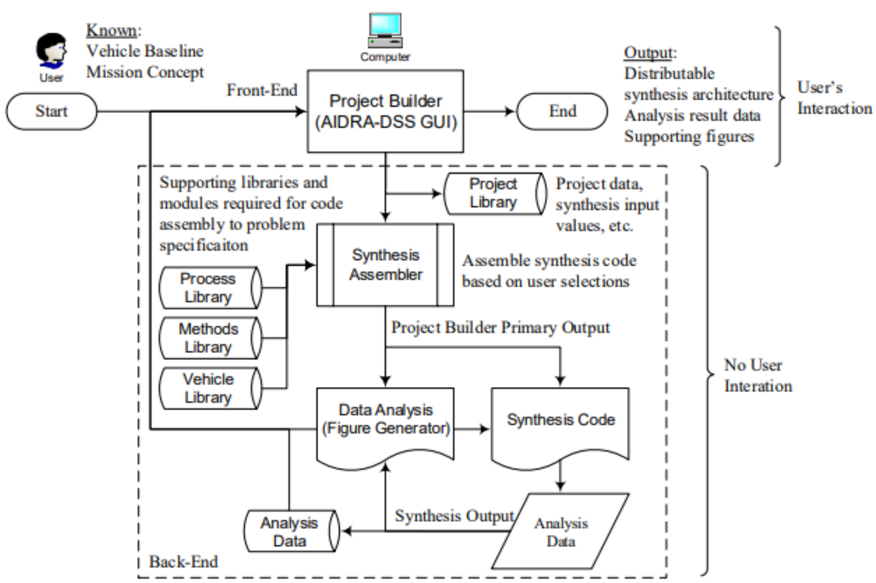

Figure 3.6. AVDS Python architecture [7]

This software utilizes Python QT for the GUI as well as SQLite for the back-end database files. The front-end consists of the following subsystems: "*… the Project Builder, Variable Library, Reference Library, Methods Library, Vehicle Library, and Process Library …*" [7].

Each of these front-end subsystems has a corresponding back-end database file, with an additional synthesis assembler file.

The Python-era AVDS system has been verified using the X-51A, X-43, XB-70, SR-71, Concorde, Sänger II, and Orient Express as part of the NASA-funded study on hypersonic commercial transportation conducted by AVD Laboratory in 2020 [4]. This study along with verification activities has been conducted in tandem with the development of the VCC, which is detailed later in the document.

3.2. AVDS Tool Development and Design Execution Domain

The AVDS system as it currently stands has three main domains of function: the warehouse domain, the generation domain, and the execution domain, each of which are described briefly in the further sub-sections. The VCC is able to aid the AVDS system by direct integration into one or more of these domains.

3.2.1. Decomposition: Warehouse Domain

The warehouse domain of AVDS, shown in Figure 3.7, houses several different reference libraries that feed into the design system. The VCC described in this present research effort fits into this warehouse domain as an all-encompassing DIK system with past-to-present vehicle data, information and knowledge. The overall purpose of this domain is to provide relevant vehicle attribute entries for hypersonic vehicles for both *synthesis code generation* and *to enable an informed design execution* [4]. The warehouse domain consists of extensive information-rich libraries, and hence it may be comparable to the backbone of the AVDS system.

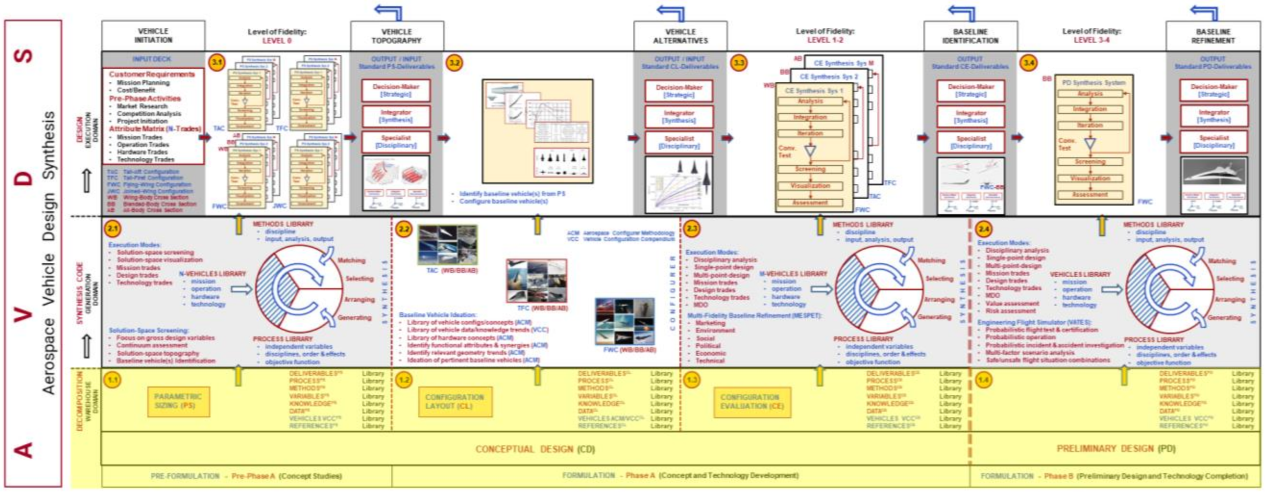

Figure 3.7. AVDS process – decomposition warehouse domain [4]

Described below are the individual libraries which make up the AVDS warehouse domain:

- Reference Library

  The reference library contains sources of past-to-present hypersonic projects that have been collected since before the conception of the AVD Laboratory, by Director Dr. Chudoba. A variety of sources, both physical and digital, have been compiled since the early 1990s, that are rich in design information, methods, and processes which define the foundation of the AVDS system. This reference material stems from sources like public domain literature, DOD & company internal sources, research institutes, and witness and expert interviews. This collection of reference material has been utilized to generate the bibliographies for the VCC effort, which is detailed below [4].

- Vehicle Configuration Compendium

  The research topic presented by the author, the VCC, is a conceptual design (CD) data-information-knowledge (DIK) compendium that houses conceptual design-relevant data, information, and knowledge for selected high-speed vehicles. A total of seven high-speed vehicles have been compiled in the VCC currently; the sum of all bibliographies for these vehicles is 1300 sources. The vehicles contained in the current VCC include the X-51, X-43A, SR-71, XB-70, Concorde, Sänger-II, and NASP X-30. Although currently in the prototype phase, the data contained within the VCC has been utilized for verification purposes along with the AVDS system as part of the NASA study mentioned earlier, proving the power of such a compilation. The VCC research team consisting of the author along with Samuel Atchison and Ramlingam Pillai has been providing the digitized data and information for the AVD Laboratory research team for such verification activities. The results from this verification study are provided in the upcoming chapters in greater detail.

- Data/Information Library

The data/information library is simply a further categorization of the data already contained within the VCC, based on disciplinary categories, with the source material appropriately referenced.

- Knowledge Library

The knowledge library houses the knowledge gained during past design projects that often is not passed down effectively. As Dr. Chudoba states, *"knowledge represents a mixture of experiences, values, contextual information, and expert insight"* [4] which is incredibly valuable to use in new design initiatives. After all, such valuable knowledge is built up over time and with years of experience, and hence takes more time to build up from scratch but is rather better utilized by learning from others who have already made the time and money investment.

- Variables Library

The purpose of the variable library is to store all of the input, analysis, and output variables that are required for each disciplinary method code. It also provides additional information for each variable such as definition of the variable, the English and SI units of the variable, whether it is a global/local variable, whether it is independent/dependent, etc. When selecting or developing a disciplinary method in AVDS, input and output variables are assigned to that method by using the available variables defined in the variable library. These variable assignments are used during the stitching process where the synthesis codes are built from individual disciplinary method codes [4].

- Methods Library

The methods library consists of various disciplinary methods for estimating aerodynamics, propulsion, performance, weights and balances, etc. This helps the designer choose from the available options, the methods that best fit their design and sizing needs. Each method is broken down into the details of the assumptions and applicability which helps the user make an intelligent decision. There may be disciplinary methods found and documented during the VCC activity that are also stored in this library [4]. The VCC supports the selection of methods by providing verification data for the listed methods, or the VCC could also provide error percentages for each of the methods listed based on previous verification attempts. This would help the designer choose the methods best suited for the design needs of the project.

- Process Library

The process library is a collection of hands-on and computational conceptual design approaches. This library provides the key elements of each process in a tabulated format for easy comparison and helps in the implementation of the best practice design process. Most of the processes collected are specific to certain vehicle configurations or component technologies, which means these configurational assumptions may be utilized for faster process execution. Any processes collected along with the VCC activity may be added here as well [4].

- Deliverables Library

The deliverables library collects relevant disciplinary DIK and their presentation visualizations that assemble the standardized deliverables library for each subphase of the conceptual design process. This library is updated with the identification of pertinent deliverables observed as meaningful to the designer. The VCC exposure is permanently updating the deliverables library. If the VCC exposure identifies certain disciplinary or multi-disciplinary deliverables that tend to be utilized by the professional community, then this sub-deliverable is added to the library to possibly enable meaningful consistent comparisons [4].

3.2.2. Synthesis Code: Generation Domain

In this domain, visualized in Figure 3.8, the system generates *tailor-made synthesis systems* based on the needs of the problem to be solved [4]. This domain utilizes the decomposition and subsequent composition process described by Gonzalez in his dissertation [6]. The four sequential steps involved are the following: *"… (1) matching, (2) selecting, (3) arranging, and (4) generating. …"* [4]. This results in the generation of a series of parametric sizing-level synthesis codes that are then available for run-time execution at the execution domain to address the problem at hand.

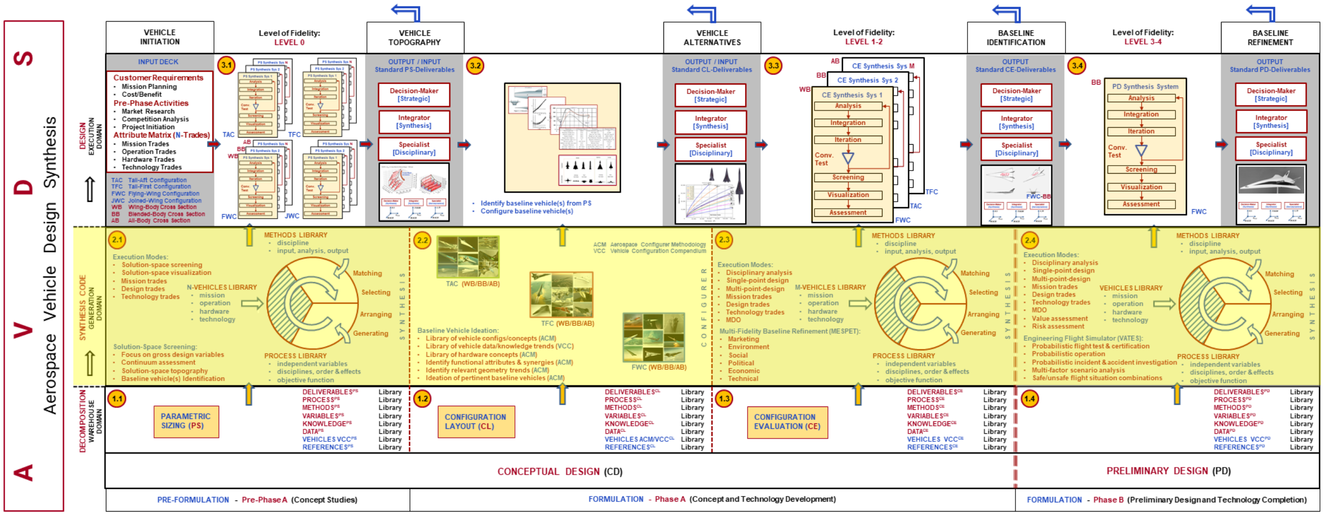

Figure 3.8. AVDS process - synthesis code generation domain [4]

As Chudoba states, the overall goal for the synthesis code generation domain is to *"tailor-make synthesis systems"* for aerospace vehicle conceptual design as well as preliminary design [4]. There is no 'one-size-fits-all" synthesis method that works for every single aerospace vehicle configuration, which is why currently available synthesis systems are found to be tailored to a singular vehicle configuration at a time. The AVDS is unique in its approach of formulating generic synthesis methodology through the modeling of multiple synthesis codes to accurately compare several different similar or dissimilar vehicle concepts or configurations.

3.2.3. Design: Execution Domain

The final step is the execution domain where the generated synthesis system(s) are executed, as shown in Figure 3.9. This execution results in PS-deliverables that address the decision-maker, integrator, and specialist.

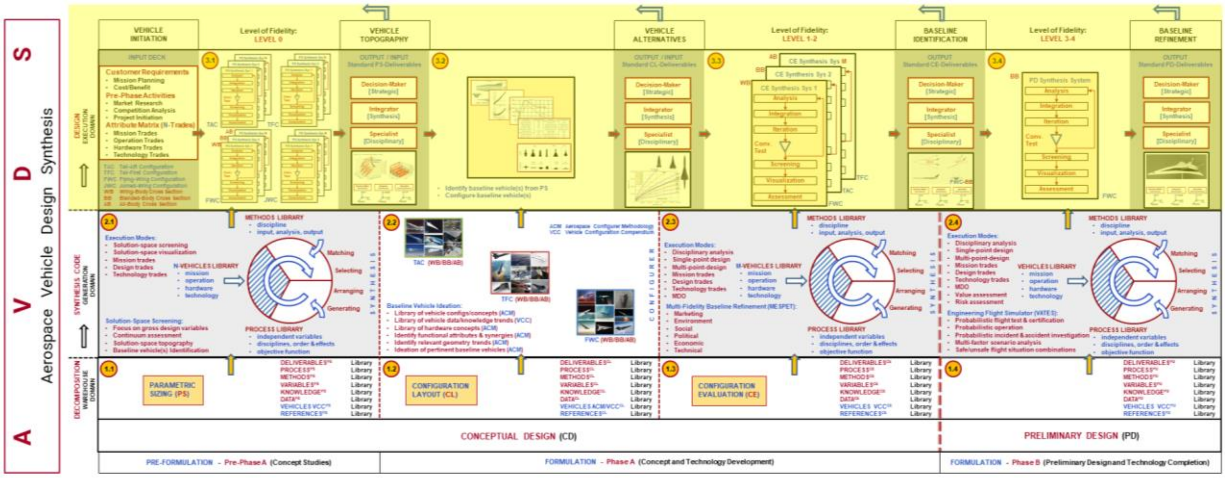

Figure 3.9. AVDS process - design execution domain [4]

Chudoba describes the primary deliverable from this domain as *"… the continuum solution-space topographies …"* that support the identification of any alternative designs. During the execution of the conceptual design process, all three sub-phases described in Chapter 2 are engaged. After the parametric sizing (PS) synthesis process that defines feasible alternative design solutions to consider, the configuration layout (CL) phase is employed to *"… formulate vehicle alternatives with the boundary conditions dictated by parametric sizing. …"* [4]. After this, the configuration evaluation (CE) sub-phase conducts a more refined or higher-fidelity synthesis assessment of the defined baseline designs to *"… independently re-confirm feasibility. …"* [4].

During the CL phase, the VCC engages for verification purposes. The synthesis process employed is verified by comparing CL synthesis results with the actual size values identified by the VCC compendium. The VCC may also assist with benchmark comparisons between a newly sized vehicle concept versus past-to-present existing or projected vehicles of a similar configuration or speed regimes.

The development history and architecture details presented in this sub-chapter communicates that the AVDS system is a novel synthesis implementation, in that it custom-develops new synthesis codes to address the design problem posed. It is also clear that there are multiple critical layers in the AVDS methodology where the VCC module serves as an integrated module. The specifications for the standalone and integrated VCC system are provided in the following chapter.

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CHAPTER 4

VEHICLE CONFIGURATION COMPENDIUM SPECIFICATION

4.1. Standalone Software

The Vehicle Configuration Compendium (VCC) is initially developed as a standalone prototype software, with the intent to integrate into the AVDS system in the near future. The prototype standalone software operates with its own GUI for the time being. This standalone software is currently developed as the alpha prototype of the VCC system, and the following specifications of this version are presented with the following subsection.

4.1.1. Storage of Past-to-Present Design Data

The Vehicle Configuration Compendium (VCC) must store past-to-present conceptual design related data. These attributes would include any numerical DIK available for any of the eight CD-relevant design disciplines (aerodynamics, aerothermodynamics, propulsion, geometry, synthesis, stability and control, performance/trajectory, and weights/balances). Such numerical attributes are typically available in tabulated format within the source material. Pieces of data such as mission characteristics, vehicle configuration or geometry parameters, lift/drag values, etc. are examples of data tables or data values that must be identified and stored.

Design data collected and presented in the compendium would end up functioning as lookup tables for the designer, providing concise design-pertinent data in a quickly navigable format with column and row identifiers.

The data being collected must be ‘past to present’ since the compendium aims to collect both old and new knowledge as the industry evolves in understanding. This will allow the VCC to become an all-encompassing high-speed vehicle compendium that evolves and grows with the industry, similar to Jane’s All the World Aircraft [1]. Jane’s publication, which began in 1989, continues to produce aircraft volumes every single year, thereby documenting vehicles as the industry continues to work on new designs.

4.1.2. Storage of Past-to-Present Information

Information is the interpretation of data. This would mean any graphical figures found that represent raw data in a visual format is considered information. This information is important since it is easier to digest and understand than looking at numbers in a table. For example, looking at a mission profile with the altitude plotted against speed or range would give more context regarding the vehicles flight path than reading these numbers from a table. As such, the VCC needs also to house past-to-present vehicle information collected from the sources listed earlier.

Collecting design information helps the designer and forecaster by providing data in a visual, easy-to-digest format. By providing these information plots which are categorized by discipline, the VCC must fulfil the need for a reference manual to guide the designer during the design activity, with each disciplinary category functioning like a separate chapter of a reference book.

4.1.3. Storage of Past-to-Present Knowledge

If information is the visual interpretation of numerical data, then knowledge is the organization of this information in an intelligent format to allow the designer to come to a conclusion about a vehicle design. Knowledge plots have to include any trends or regressions that compare a variety of vehicle configurations based on chosen parameters of interest.

28% of the design parameters identified relevant are in the form of knowledge plots, which is less than half the amount of information plots identified. Of these, a majority of plots are disciplinary knowledge plots comparing the effects of varying specific disciplinary parameters, rather than comparing entire vehicle configurations or vehicle types. However, this does not limit the ability of the researchers involved to generate knowledge using the tools available, which leads to the next and most important specification of the compendium.

4.1.4. Generation of New Design Knowledge and Recommendations

The most powerful requirement for the standalone VCC is its ability to generate new knowledge trends and regressions using the data and information collected for the various vehicles. This data is, after all, being stored in a local database and easily recalled. For the prototype version, the knowledge generation ability has to be hard coded into the system due to the time constraint associated with processing a large volume of data, information and knowledge. In future iterations the system has to evolve to be capable of generating and storing knowledge of its own according to user input. This knowledge generated has to be retrieved to support the designer to make decisions on configurational design changes that may benefit the project.

The knowledge plots generated have to be annotated for easy referencing for the designer (annotations provide guide to the user). Design recommendations have to be generated alongside the knowledge plots based on the individual configurations the designer is considering. For example, if a user chooses to compare between the tail-aft and tail-forward configurations, the VCC has to be able to recommend one or the other alternative based on the type of performance the user is trying to obtain.

4.1.5. Provide Reference Library

The VCC collection process has to result in the accumulation and digital storage of hundreds of reliable design sources in the form of PDF documents. The VCC is required to provide a reference list of these sources for each of the vehicles to the user, in addition to providing citations at the bottom of each of the disciplinary plots displayed. This supports the user to rapidly locate the reference of origin for each element of DIK to be showcased in VCC, if the document may be of interest.

4.1.6. Data-Information-Knowledge Richness

The VCC must provide a means of quantifying the wealth or richness of attributes available for each of the vehicles collected in the compendium in the form of DIK-R (Data-Information-Knowledge Richness). The DIK-R is a factor to be utilized when choosing to add a qualified vehicle for the VCC software in the first place. Such a richness scale has to provide the user of VCC with an idea of the availability of design-relevant attributes, broken down by disciplines, vehicle types, and individual vehicles. This combined with the reference library helps the user gain insight into the ease or difficulty of obtaining conceptual design-related parameters for certain vehicle-types, as this may vary depending on the timeline or nature of the project and its subsequent success or failure.

4.1.7. Graphical User Interface

The graphical user interface of VCC must provide the users with an interactive, easy way of viewing the data, information and knowledge contained within the compendium. The GUI must employ a user-friendly landscape to allow for maximum efficiency. The user interface must be easily navigable and provide quick performance overviews, vehicle bibliographies, data and information graphics, as well as annotated knowledge graphics.

The compendium must store and make available through the GUI, the entirety of the data set collected from the bibliographies of each of the vehicles. The data must be stored in an SQLite database, and during the packaging of the standalone software, this must be packaged together with other integrated elements of the software to generate an executable file. This local SQLite database will also enable integration with the database file used by the AVDS system for easy recall of the numerical data values. Details of AVDS-VCC integration are provided in the next section.

4.2. Integrated System with AVDS

In addition to the standalone software, the VCC has to be integrated into the AVDS system as described in Chapter 3, which is the overall purpose for which the VCC is conceptualized. The AVDS system steps through the conceptual design (CD) and preliminary design (PD) phases, each of which depend on the VCC to aid as defined in the specifications below. This prototype VCC software must focus on the CD phase exclusively. Together this combination of a synthesis methodology and VCC-organized DIK system will totally revolutionize the way in which conceptual design has been conducted to date. It is required that the VCC provides an immense amount of design freedom (through the generic synthesis system) while not overwhelming the designer but providing adequate guidance (through recommendations curated by the VCC-DIK module). The designer must be able to obtain all the available knowledge and understanding needed at their fingertips before making design decisions. In short, VCC is tasked to provide a strategic advantage to its users in comparison to designers without access to such a synthesis-DIK system.

The fully integrated design module (AVDS+VCC) will have the following specifications:

4.2.1. Vehicle Decomposition – Verification

The VCC, when integrated with the AVDS system, is required to be a powerful verification tool. Currently, the compendium is required to store past-to-present project DIK for seven chosen high-speed vehicles that are useful to any designer for reference. The designer may choose to verify either the disciplinary analysis method employed for AVDS (PS), or the disciplinary analysis methods chosen for AVDS (CE) using this compendium. It is required that verification be conducted by implementing the method of choice to either PS or CE for the seven vehicles minimum stored in VCC, using the stored compendium DIK to check for accuracy of the analysis method.

Future iterations of the AVDS-VCC have to be able to provide quick error margin analyses based on the users input values to make this verification process easier for the designer. Such a system has to automatically check the sizing results by consulting the database library of the VCC stored in SQLite to produce these error margins.

4.2.2. Vehicle Decomposition – Reverse Engineering

One functionality of the AVDS system must be the utilization for the purpose of reverse engineering a vehicle from an initial set of known parameters. Reverse engineering a vehicle means starting with a given vehicle and using synthesis and analysis methods to extract the disciplinary relations and parameters from what is already known, which is the difference compared to sizing and verifying a vehicle. This concept is demonstrated in Figure 4.1. For the integrated AVDS-VCC system, it is required to have a capability where a vehicle can be reverse engineered that has been stored in the VCC compendium. The VCC must provide any data or information that supports the designer to extract the required elements of DIK for such a vehicle. If, however, the user is reverse engineering a vehicle that is outside the library of collected vehicles in the VCC, then the VCC must support the usage of data from similar vehicles within the compendium to be used as a first estimate of the parameters that are needed to execute the reverse engineering process.

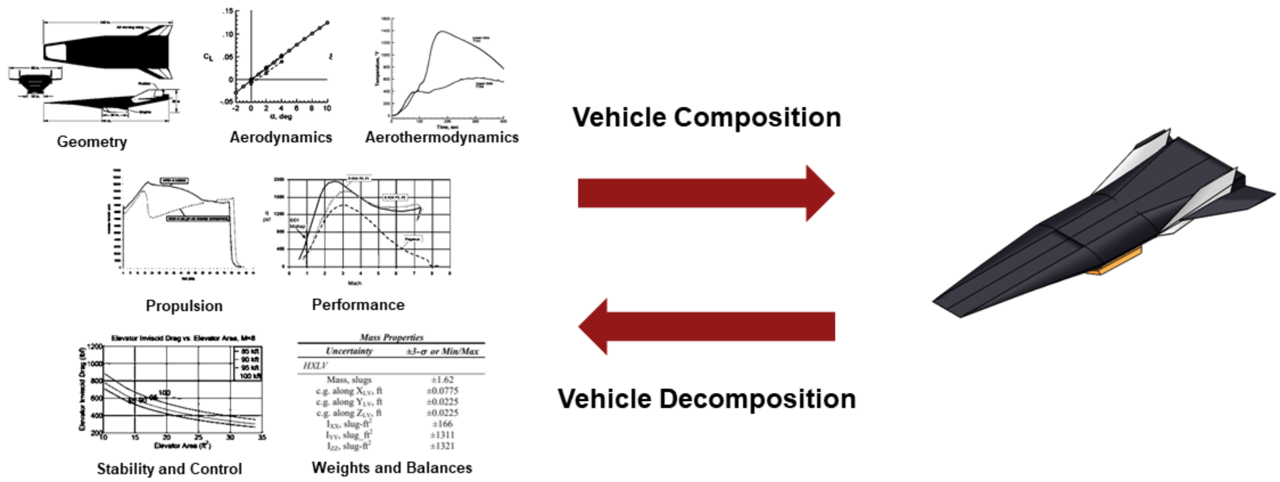

Figure 4.1. The difference between vehicle composition and decomposition

4.2.3. Single-Point Vehicle Sizing with Knowledgebase

The knowledgebase described as part of the standalone version of the VCC is required to aid in the ideation process supporting designers using the AVDS system to size a new vehicle. The AVDS system provides the designer with a vast array of design choices before finalizing the configuration of the vehicle. Just from the specification of the mission itself, as shown in Figure 4.2, the designer is given the option of choosing from over a million different unique design combinations. Deciding on a concept to implement is greatly assisted with the usage of the knowledge trends generated by the VCC. Knowledge trends compare the strengths and weaknesses of choosing a particular propulsion concept or a geometry concept, or a particular configuration. VCC is tasked to help the designer make these decisions wisely rather than being forced into a time-consuming trial-error iteration loop.

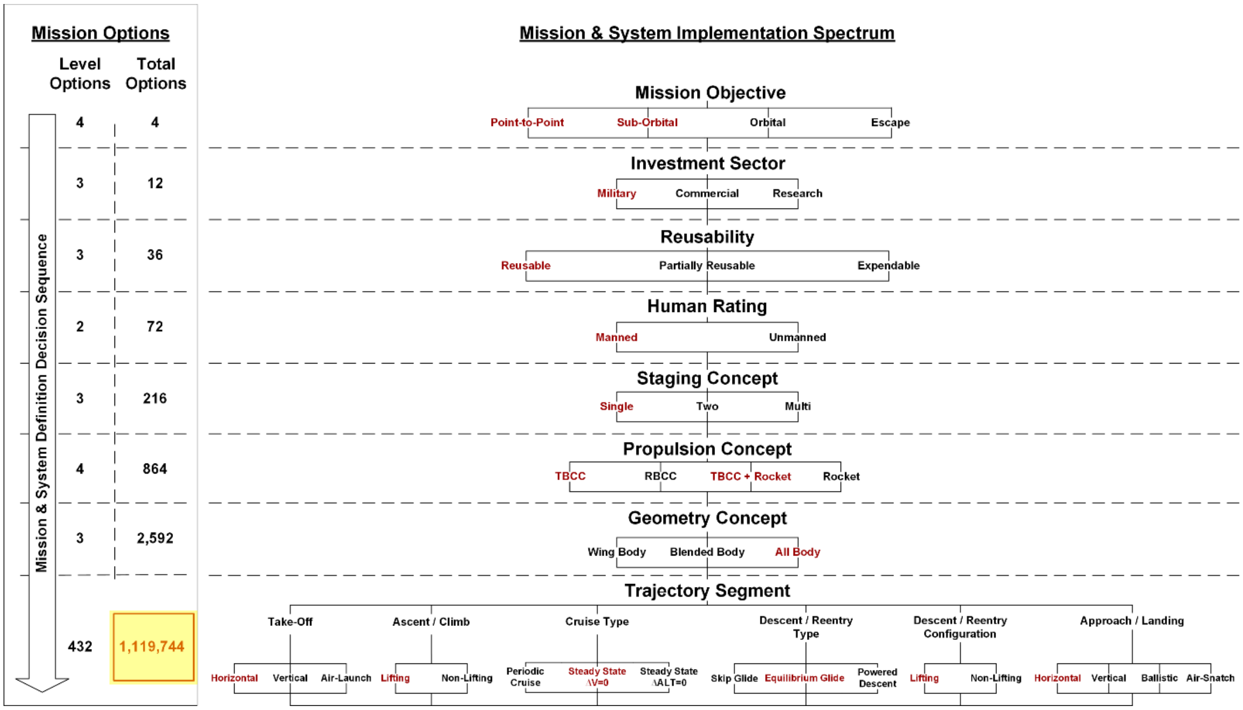

Figure 4.2. Scope of mission and system concepts considered - AVDS [2]

After the selection of the mission specifics, the user is tasked with specifying the value of certain independent design variables. Sizing cannot begin without an array of engineering assumptions for the input deck of AVDS. For numerical parameters, the AVDS utilizes a stitcher code which analyzes the unknown parameters and determines the order in which to implement each of the disciplinary methods. However, there are certain parameters for which the stitcher code is unable to find dependencies since these design parameters must be specified by the user and they are independent of any interdisciplinary relationships. This is where the knowledge plots stemming from VCC are used.

For the AVDS user, having access to plots that compare and contrast the effects of choosing certain design parameters, or ranges of values, is helpful to determine the inputs required for the AVDS system. A knowledge plot is tasked to for example identify a common mission range to expect from a particular configuration-propulsion system combination. This way, the VCC should provide the much-needed design assistance during the stage where design variable assumptions are being made.

4.2.4. Multi-Point Design Study – Trades

If AVDS is used to conduct a design study where multiple design trades are being compared at once, VCC is tasked to help with the identification of intelligent trades to conduct. For example, if the user would like to vary the design choices made for a particular configuration, but needs recommendations of useful component or design trades, the VCC is to be consulted. Ideally, future versions of VCC are tasked to accommodate hundreds of high-speed vehicles as a complete archive. This VCC compendium must then be able to provide a list of trade studies that have been conducted in the past for certain vehicle configurations. In addition, VCC should also provide results from those trade studies to help the designer understand what type of performance was affected by a certain trade. For example, if a particular trade study resulted in a vehicle with higher speed but less fuel efficiency, or if a particular trade improved the vehicle's aerodynamic performance, etc.

4.2.5. Enhancing Libraries

It has already been established that the VCC is a self-contained parametric library. As such, data, information, knowledge, methods, and processes have been collected from external references by surveying all relevant sources listed for each of the seven vehicles mentioned earlier. This bibliography is provided in Appendix A for each of the vehicles compiled within the prototype VCC. As mentioned in the previous chapter, the AVDS system also has its own libraries that feed into the process (the warehouse domain). The methods and processes collected for the VCC have to be integrated into the methods and processes libraries of the AVDS system to enhance and expand them.

VCC is also capable to provide method recommendations to users of the AVDS system. During the disciplinary method selection, in order to help the user who may be overwhelmed by the vast number of choices, the VCC is tasked to be integrated as a pop-up side-panel in AVDS with a recommended list of methods based on the user's choice of configuration. In the future, this may also be accompanied by a percentage of error for each of the methods based on method verification results.

4.2.6. Post-Sizing: Benchmark Comparisons

In addition to aiding before and during the design process, the VCC is tasked to support the user make smart comparisons at the end of a design activity. If the VCC has vehicles in its library that are similar in configuration to the newly sized vehicle, then comparing the new design against these vehicles would be useful to understand the effects of changing particular design elements of that configuration. This would also be useful as a final ‘sanity check’, where the user may want to determine if the final design makes sense – if certain parameters like the ratio of TOGW to thrust available or propellant mass to payload mass fall within a reasonable range compared to other vehicles of this type. Even if there are no similar vehicles in the VCC, it would still be useful to compare or verify the new vehicle against others to understand the advantages and disadvantages of configurational tradeoffs.

4.2.7. Integrating AVDS Back to VCC

The AVDS system is also tasked to dynamically contribute back to the VCC by expanding the existing VCC library. This can be seen as a sort of ‘symbiotic’ relationship between the two systems. Commonly used in biology, the term ‘symbiotic’ refers to the interdependent relationship between two organisms. In this case, the VCC is providing AVDS with collected past-to-present project data, information, and knowledge, and in return, the AVDS feeds newly generated data, information and knowledge back to the VCC to plug in any missing pieces and try to complete the compendium. Any newly designed vehicles by AVDS can be added to the VCC catalogue, complete with the disciplinary information generated from the evaluation process of AVDS-CD. Any missing disciplinary information for vehicles already existing in VCC may be filled in by the reverse-engineering process of AVDS. As such, the AVDS-VCC integrated system becomes a unique system that could someday soon be automated. Automation of the aforementioned processes would allow the system to evolve and learn on its own, which is a reasonable goal for the developing age of artificial intelligence.

REFERENCES

[1] Jackson, P., Peacock, L., Bushell, S., Willis, D., and Winchester, J., *Jane's all the worlds aircraft: Development and production*, Coulsdon: IHS Markit, 2018.

[2] Chudoba, B., Maynard, I.W., Patel, H.R., Connerly, C.N., Atchison, S.C. and Van Ausdoll, A.S., "Hypersonic, Commercial Transportation Feasibility Study – Paving the Way to Revolutionary Aircraft Shapes and Propulsion," NASA-CR-2021-017755, Hypersonic Technology Project (HTP), NASA Langley Research Center, NASA, 06 July 2021 [Available only with approval of the following issuing office: NASA Langley Research Center, System and Analysis Concepts Directorate, Hypersonic Technology Project, Hampton, Virginia].

CHAPTER 5

METHODOLOGY AND PROCESSES

5.1 Vehicle Configuration Compendium Development Process: Overview

In order to outline the specific methodology followed for the development of the Vehicle Configuration Compendium (VCC), a process visual has been used to plan out the development steps, see Figure 5.1. The purpose of this chart is to provide a breakdown of the specific steps taken toward the completion of a project, from start to finish, similar to the function of a flowchart. Developing a well-planned process diagram at the beginning of a project provides a schedulable task breakdown for the remaining timeline. The Nassi-Schneiderman diagram format has been selected to develop the process flowchart towards structured programming, as shown in Figure 5.1 [1].

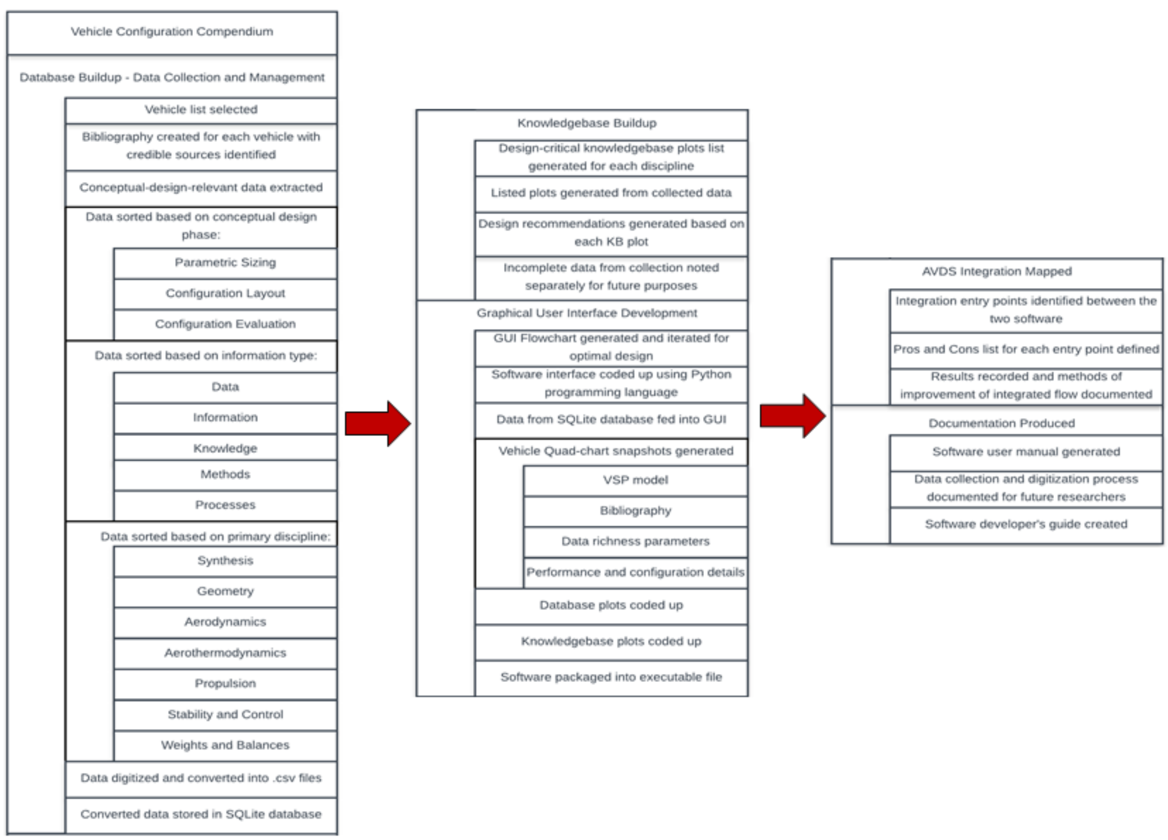

Figure 5.1. Detailed VCC development process diagram

The initial stage of the VCC development process is the creation of the database. The compendium is a combination of a data, information and knowledge compilation that generates useful information for the designer to help forecast optimal design decisions, as shown in Figure 5.2. The data-information-base houses all the raw digitized data and information plots generated from this data, organized by discipline, vehicle, configuration and cross-section.

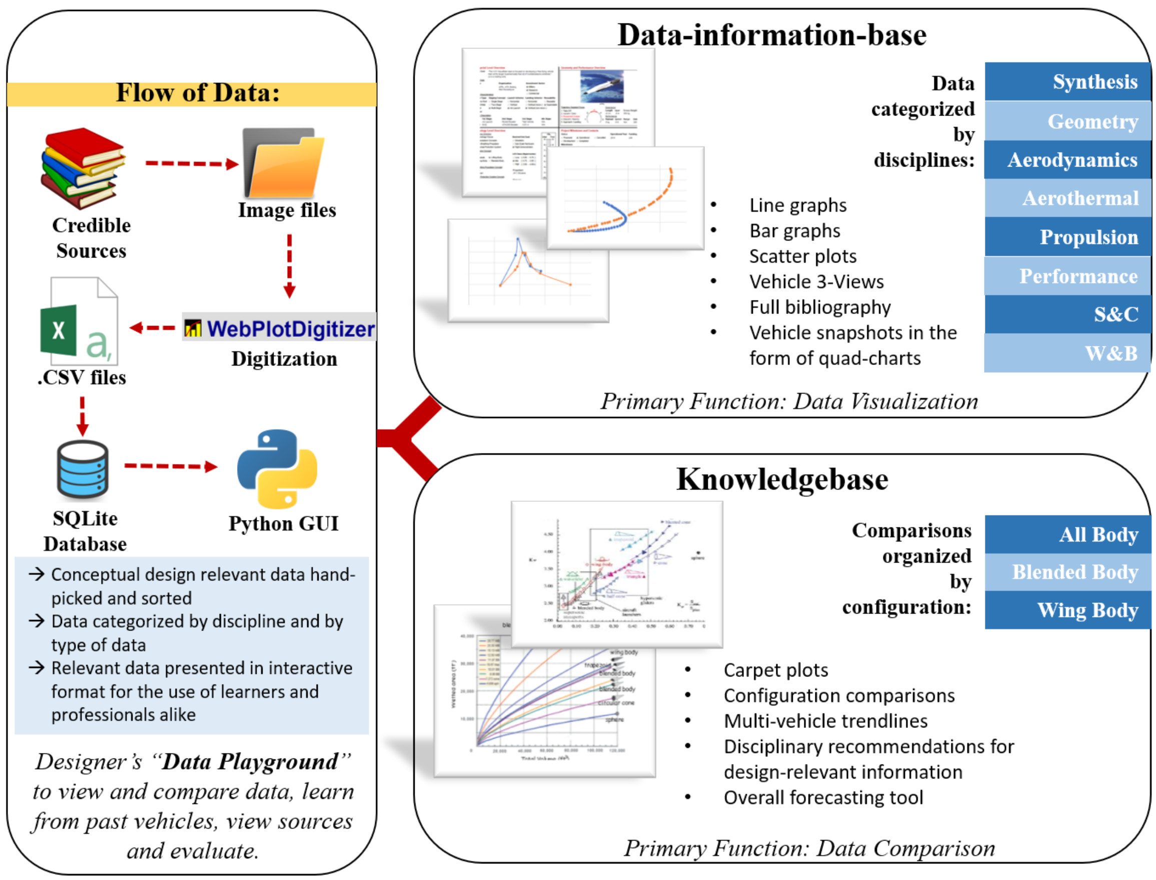

Figure 5.2. Structure of the Vehicle Configuration Compendium

Once a thoroughly organized data-information-base (DIB) is developed as detailed in the following section, this paves the way for the build-up of the knowledgebase which provides intelligent knowledge trends using the collected data, information and knowledge. Ideally the VCC system should be programmed to identify relevant pieces of data from the database and generate knowledge trends automatically. However, since this compendium is still in prototype development phase, the automatic knowledge-generation function has been postponed for later integration. For the prototype software, the knowledge trend generation is rather facilitated by the developer manually.

After the database and knowledgebase development comes the implementation of this system in a user-friendly software interface (GUI). The graphical user interface streamlines how the collected data is presented to the end user and is meant to increase the accessibility of the compendium for individuals who may be unfamiliar with the compilation strategy used for VCC. The compendium interface is developed using Python's Tkinter standard GUI toolkit due to its versatility of use across different operating platforms [2].

Once the standalone user interface is finalized for the VCC, plans for integration with the AVDS system are made for the reference of future researchers, and any information pertinent to the software developer is documented thoroughly to encourage further iteration of the software and integrated system in the future. This is part of the final step of the research process, the finalization of thorough documentation. In addition to producing documents relevant to the developer, a software user guide is also generated for front-end users of the compendium.

5.2 Data-Information-Base Buildup

To begin the development of the data-information-base, the data must be collected, categorized, and digitized for ease of storage. As shown in Figure 5.3, the first step is the generation of thorough vehicle bibliographies for each of the seven vehicles processed in the VCC prototype: X-51, X-43A, SR-71, XB-70, Concorde, Sänger-II, and NASP X-30. Each source collected in the bibliography is checked to ensure the credibility of the information available in these sources. The collected data is subjected to a specific categorization and digitization process outlined in Figure 5.3. This includes searching, collecting, storing, categorizing, and digitizing relevant data. It must be noted that these steps are followed very precisely with a high level of attention to detail to ensure the highest level of accuracy in the provision of design-relevant parameters to users of the VCC. This is also compounded by the fact that the collection process of DIK for this compendium has played a crucial role in the 2020 NASA study conducted by the AVD Laboratory, which will be discussed in a later chapter [3]. Hence it has been of utmost importance to the VCC research team to perform due diligence in the collection, digitization, and storage process of VCC-DIK.

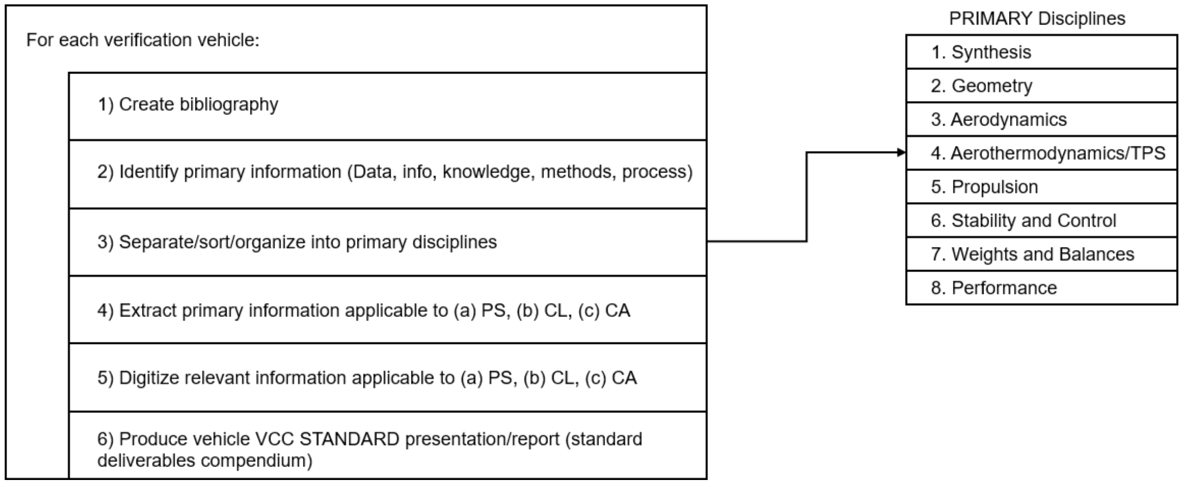

Figure 5.3. VCC Data collection process

The bibliographies for the first step of the process are generated from the archived references of legacy material stored within the AVD Laboratory, as well as any additional material found published on these vehicles. The bibliography lists generated for each vehicle include published academic papers, journals, textbooks, flight test reports, technical reports, technical presentations, magazine articles, flight manuals, accident reports, transcribed interviews, company briefings, technical memorandums, and other miscellaneous legitimate publications on the given vehicles. A total of 1300 sources have been collected for the purpose of the initial VCC prototype. These sources are then compiled and stored in a shared reference management library "Zotero" in PDF format. The physical sources are scanned as digital documents and added to this same library.

5.2.1. Data Organization Process

The data collected is organized in two different ways for proper cross-referencing. First and foremost, the collected parameters are categorized based on the type of information offered, namely, the following: data, information, knowledge, methods, and processes, each of which is defined below:

5.2.1.1. Data

Data is defined as *"... factual information such as measurements or statistics used as a basis for reasoning, discussion, or calculation"* [4]. In terms of aerospace engineering, data would be typically found tabulated for storage or plotted for visualization.

5.2.1.2. Information

"... Data reaches a more complex level and becomes information by integrating them to a context" [5]. In searching for information, this research effort seeks to collect contextual information for the conceptual design process of vehicles, to allow a better understanding of the data collected.

5.2.1.3. Knowledge

Knowledge found for the vehicles because of the culmination of data and information to produce an interlinked understanding of the best direction to proceed with the design. According to Chudoba, "*… Knowledge represents a mixture of experience, values, and contextual information, and expert insight that provides a setting for evaluating and incorporating new experiences and information"* [6]. Plots and other figures containing continuum guidelines with multiple configurations of vehicles presented is collected and categorized as knowledge found.

5.2.1.4. Methods

In addition to the three primary categorizations mentioned prior, any methods found for the various disciplines is also stored and categorized. This may include disciplinary analysis methods, or, in the case of synthesis, overall sizing methods described in detail in the sources.

5.2.1.5. Process

If any of the vehicles on the list contain the conceptual design process and disciplinary integration process description, this is also collected, although only very few instances of this have been found. This would give insight into the steps undertaken by various past design teams to finalize a vehicle design. As mentioned in the earlier chapters, Dr. Chudoba has conducted an evaluation of available synthesis systems in general [7], as these provide insight into the design process undertaken by various research groups and vehicle design companies. This mentality has continued to be applied during the VCC compilation process, as the research team has made the effort to document any occurrences of such process details in the sources collected for each vehicle.

In addition to these categories, the collected parameters are also organized according to the eight aerospace disciplines that play a crucial role in conceptual design for any vehicle, which is inherently a multidisciplinary activity. The disciplinary categories include the following: Synthesis, geometry, aerodynamics, aerothermodynamics, propulsion, performance, weights/balances, and stability/control. Some of these disciplines were discussed earlier in the conceptual design chapter when detailing their role in configuration evaluation. In this section, each of the eight disciplines are explored in terms of the type of design parameters and attributes required for conceptual design.

5.2.1.6. Synthesis

Synthesis is the *"primary integration capability that is the key to close (converge) the design through iteration*" [8]. As such, synthesis brings together the inputs from the rest of the disciplines mentioned to achieve a converged design point. Parameters of interest include:

Table 5.1. Parameters of Interest for Conceptual Design: Synthesis

	PS			**CL**			**CE**		
Categories	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*
Mission Definition	-	Max altitude	M	-	-	-	-	-	-
	-	Max speed	m/s	-	-	-	-	-	-
	-	Max range	M	-	-	-	-	-	-
	-	Payload capacity	Kg	-	-	-	-	-	-
	-	Flight Envelope limits	-	-	-	-	-	-	-
Configuration	-	-	-	-	Component placements	-	-	-	-
	-	-	-	-	Component dimensions	-	-	-	-

5.2.1.7. Geometry

The geometry discipline deals with the entire vehicle geometry and its components, configurational characteristics, and cross section, etc. The configuration layout process is mostly handled by this discipline. The geometry discipline produces dimensions using the final sized design point, but also provides some initial inputs prior to the sizing process. Parameters of interest are categorized in Table 5.2.

Table 5.2. Parameters of Interest for Conceptual Design: Geometry

	PS			CL			CE		
Categories	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*
Fuselage	L	Length	m	-	-	-	-	-	-
	W	Width	m	-	-	-	-	-	-
	τ	Slenderness ratio	-	-	-	-	-	-	-
Wings	S_{pln}	Planform area	m^2	s	Wing span	m	-	-	-
	-	-	-	AR	Aspect ratio	-	-	-	-
	-	-	-	Λ	Sweep angle	deg	-	-	-
	-	-	-	λ	Taper ratio	-	-	-	-
	-	-	-	$m.a.c.$	Mean aerodynamic chord	$\%\ chord$	-	-	-
Vertical Control Surfaces	-	-	-	S_{pln}	Planform area	m^2	-	-	-
	-	-	-	s	Span	m	-	-	-
Horizontal Control Surfaces	-	-	-	S_{pln}	Planform area	m^2	-	-	-
	-	-	-	s	Span	m	-	-	-
Propulsion System	-	-	-	L	Length	m	-	-	-

5.2.1.8. Aerodynamics

This discipline deals with the aerodynamic phenomena, coefficients, and derivatives that are crucial to understanding the interaction between the vehicle and its fluid medium during flight, at a basic level. Aerodynamic coefficients and forces are important inputs for performance and stability and control disciplines to evaluate the vehicle. The most important part of the aerodynamic analysis is dealing with the lifting surfaces of a vehicle. In addition to the wings, there are other lifting surfaces a vehicle may have, including the canard, lifting body planform area instead of wings, or horizontal tailplane, and lift enhancing components such as flaps or slats. A vehicle may have any combination of these which is part of what defines different configurations.

There is a variety of methods that may be employed to conduct aerodynamic analysis, ranging in levels of fidelity from simple first order numerical derivations to high fidelity CFD calculations. The different elements of interest as well as the parameters associated with them are listed in Table 5.3.

Table 5.3. Parameters of Interest for Conceptual Design: Aerodynamics

	PS			CL			CE		
Categories	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*
Forces	L	Lift force	N	-	-	-	L	Lift force	N
	D	Drag force	N	-	-	-	D	Drag force	N
	L/D	Lift-drag ratio	-	-	-	-	L/D	Lift-drag ratio	-
Coefficients	C_L	Lift Coefficient	-	$C_{l_{max}}$	Maximum lift coefficient	-	C_L	Lift Coefficient	-
	C_D	Drag Coefficient	-	-	-	-	C_D	Drag Coefficient	-
	-	-	-	-	-	-	C_{D_i}	Induced Drag Coefficient	-
	-	-	-	-	-	-	C_{L_α}	Variation of lift coefficient with AOA	-
	-	-	-	-	-	-	C_{m_α}	Variation of pitching moment coefficient with AOA	-
	-	-	-	-	-	-	C_{D_0}	Zero lift drag coefficient	-
Components	-	-	-	-	Wing Area	m^2	-	-	-
	-	-	-	-	Flap area	m^2	-	-	-
	-	-	-	-	Slat area	m^2	-	-	-
	-	-	-	-	Canard area	m^2	-	-	-
	-	-	-	-	Horizontal tailplane area	m^2	-	-	-
	-	-	-	-	Fuselage area ruling	m^2	-	-	-
	-	-	-	$x_{c.p.}$	Center of pressure location	$\%\ chord$	-	-	-
	-	-	-	$A.C.$	Aerodynamic Center	$\%\ chord$	-	-	-

5.2.1.9. Aerothermodynamics/TPS

The aerothermodynamics discipline is of particular interest for hypersonic vehicles which experience higher heating at increasing speeds. *"… Thermal problems much greater than those in present supersonic vehicles will be found at these hypersonic speeds. …"* [9]. The heating loads experienced by the vehicle introduces the need for the careful selection of thermal protection systems (TPS) materials, as *"… the most fruitful structural approach for hypersonic vehicles will be based on external insulation. …"* [9]. Parameters of interest are listed in Table 5.4.

Table 5.4. Parameters of Interest for Conceptual Design: Aerothermodynamics

	PS			CL			CE		
Categories	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*
Thermal Protection Systems	T	Temperature	K	Tmax	Temperature limits of material	K	T0	Stagnation temperature	K
	-			WTPS	TPS Weight	kg			
	-			Component Tmax	Maximum temperatures experience by vehicle components	K			
Airframe Material	T	Temperature	K	Tmax	Temperature limits of material	K	T0	Stagnation temperature	K
				Component Tmax	Maximum temperatures experience by vehicle components	K			

5.2.1.10. Propulsion

The propulsion discipline plays a crucial role in the inputs for the preliminary sizing of the vehicle. As Bowcutt mentions in his paper on hypersonic vehicle design, "… *One of the greatest challenges to hypersonic flight is having a propulsion system that can efficiently accelerate vehicles from rest to hypersonic speed and then cruise at hypersonic speed. …*" [10]. There are several types of propulsion systems available currently, including rockets, ramjets, scramjets, turbojets with and without afterburners, etc. The analysis methods used for an engine differs depending on the type of engine in the first place. There are two types of engine parametric cycle analysis that may be conducted, according to Mattingly: ideal cycle analysis, and real engine analysis.

Ideal cycle analysis makes the assumption that the compression and expansion processes in the inlet, compressor, fan, turbine, and nozzle are isentropic (reversible and adiabatic), combustion is constant-pressure, air behaves as a perfect gas, and that engine exhaust nozzles expand the gas to ambient pressure [11]. As such, ideal cycle analysis is based on idealizations which may not be accurate to real performance scenarios. In contrast, real engine analysis uses realistic assumptions for each engine component.

Once a method is selected based on the engine type and analysis type, then the parameters of interest may be extracted from the analysis of specific components of an engine. The different components of an engine include but are not limited to the following listed in Table 5.5:

Table 5.5. Parameters of Interest for Conceptual Design: Propulsion

	PS			CL			CE		
Categories	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*
Components	-	-	-	-	Engine length	m	-	-	-
	-	-	-	-	Nozzle area	m^2	-	-	-
	-	-	-	-	Inlet area	m^2	-	-	-
Fuel	W_{ppl}	Propellant weight	kg	-	-	-	$TSFC$	Thrust-Specific Fuel Consumption	$(kg/hr)/$
	-	-	-	-	-	-	f	Fuel/air ratio	-
	-	-	-	-	-	-	$\dot{m}$	Mass flow rate	kg/s
Overall	T_{req}	Thrust required	N	-	-	-	η_o	Engine overall efficiency	%
	TR	Thrust ratio	-	-	-	-	η_T	Engine thermal efficiency	%
	-	-	-	-	-	-	η_P	Engine propulsive efficiency	%
	-	-	-	-	-	-	I_{SP}	Specific impulse	sec
	-	-	-	-	-	-	$F/\dot{m}_0$	Specific thrust	$N/(kg/s$

5.2.1.11. Stability and Control

The stability and control discipline is highly prevalent in the configuration evaluation (CE) stage of conceptual design, when determining whether a generated design point satisfies the flight requirements for safety. As Chudoba aptly states in his dissertation, *"…in all cases, the aim is to ensure that the vehicle is safe to fly and that it has desirable flying qualities"* [6]. During the conceptual design process, the safety evaluation conducted as part of this stability and control analysis often results in reiterating the design point with the newly learned information to either select another design point or to generate a new solution space if this is necessary.

There are three major categories of stability: longitudinal, lateral, and directional. These could be static or dynamic. The different parameters of interest may be derived from each of these categories and are listed in Table 5.6.

Table 5.6. Parameters of Interest for Conceptual Design: Stability and Control

	PS			CL			CE		
Categories	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*
Longitudinal	$S.M.$	Static Margin	m	C_m	Pitching moment coefficient	-	C_{m_α}	Variation of Cm coefficient with respect to AOA	-
	-	-	-	δ_e	Elevator deflection angle	deg	C_{m_q}	Variation of Cm with respect to pitch rate	-
	-	-	-	-	Elevator Area	m^2	-	-	-
Lateral	-	-	-	C_l	Rolling moment coefficient	-	C_{l_β}	Variation of Cl with respect to sideslip angle	-
	-	-	-	δ_a	Aileron deflection angle	deg	C_{l_p}	Variation of Cl with respect to roll rate	-
	-	-	-	-	Aileron area	m^2	-	-	-
Directional	-	-	-	C_n	Yawing moment coefficient	-	C_{n_β}	Variation of Cn with respect to sideslip angle	-
	-	-	-	δ_r	Rudder deflection angle	deg	C_{n_r}	Variation of Cn with respect to yaw rate	-
	-	-	-	-	Rudder area	m^2	-	-	

5.2.1.12. Weights and Balances

Another important discipline that works closely with the Stability and Control and sizing disciplines as well as geometry is weights and balances (W&B). This discipline operates in all three conceptual design phases. It determines the distribution of masses along the airframe. Parameters of interest are listed in Table 5.7.

Table 5.7. Parameters of Interest for Conceptual Design: Weights and Balances

	PS			CL			CE		
Categories	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*
Dry Mass	-	Empty weight	Kg	-	Component weights	Kg	-	-	-
Wet Mass	-	Fuel mass	kg	-	-	-	-	-	-
Overall	TOGW	Takeoff Gross Weight	Kg	C.G.	Center of gravity	M	-	-	-
	WR	Weight Ratio	-	-	-	-	-	-	-

5.2.1.13. Performance and trajectory

The performance and trajectory discipline are crucial to the parametric sizing (PS) and configuration evaluation (CE) phases, as it defines the initial mission requirements that the vehicle must meet. During the CE phase, this discipline produces updated mission profiles and analyzes the performance characteristics of the newly sized vehicle design point. Phillips defines this process: "… *In the design process, certain performance parameters, for example minimum airspeed and maximum range, are specified as engineering design requirements, and the design parameters and operating conditions necessary to meet these requirements must be determined.* ..." [12].

Unlike the breakdown of the other disciplines mentioned, with performance and trajectory, the breakdown of parameters is associated with the different portions of a vehicle's mission profile. Since the performance and trajectory discipline uses various disciplinary parameters to evaluate whether the vehicle can perform its mission, there is no specific hardware associated with this discipline alone. The "hardware" is rather a combination of other disciplinary hardware and the way they contribute to the vehicle performance during a mission. The various phases of a typical mission profile include but are not limited to:

- Takeoff
- Climb/Ascent
- Cruise
- Payload delivery
- Maneuvers
- Approach/Descent
- Landing

For each of these mission segments, the aerodynamic and propulsive performance of the vehicle may be evaluated. The parameters of interest for each of these phases are listed in Table 5.8.

Table 5.8. Parameters of Interest for Conceptual Design: Performance/Trajectory

	PS			**CL**			**CE**		
Categories	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*	*Variable*	*Parameter*	*Units*
Takeoff	T_{req}	Thrust required	N	-	-	-	T_{max}	Maximum thrust	N
	$TOGW$	Takeoff Gross Weight	kg	-	-	-	V_{TO}	Takeoff speed	m/s
Climb/ Ascent	-	-	-	-	-	-	γ	Rate of climb	deg
	-	-	-	-	-	-	$TSFC$	Thrust specific fuel consumption	$(kg/hr)/N$
Cruise	R	Range	m	-	-	-	E	Endurance	min

	-	-	-	-	-	-	η_0	Engine overall efficiency	
	-	-	-	-	-	-	$(L/D)_{max}$	Maximum lift-to-drag ratio	-
	-	-	-	-	-	-	$\dot{\psi}$	Turn rate	deg/s
Maneuvers	-	-	-	-	-	-	$TSFC$	Thrust specific fuel consumption	$(kg/hr)/N$
	-	-	-	-	-	-		Minimum thrust to weight ratio	-
	-	-	-	-	-	-	WL	Wing Loading	kg/m^2
	-	-	-	-	-	-	$C_{l_{max}}$	Maximum lift coefficient	-
	-	-	-	-	-	-	T_{req}	Thrust required	N
Descent	-	-	-	-	-	-	S	Distance covered	m
	-	-	-	-	-	-	-	Descent angle	deg
Approach/ Landing	-	-	-	-	-	-	$C_{l_{max}}$	Maximum lift coefficient	-
	-	-	-	-	-	-	R	Range	m

For each vehicle being processed through this data compilation process, a separate datasheet is filled out as one of the first steps. This datasheet organizes the data and information retrieved into columns and rows that make it easy for any reader to quickly identify all the data available for either one particular discipline throughout all the sources or for one particular source through all the disciplines. Figure 5.4 shows a blank template of this organization structure:

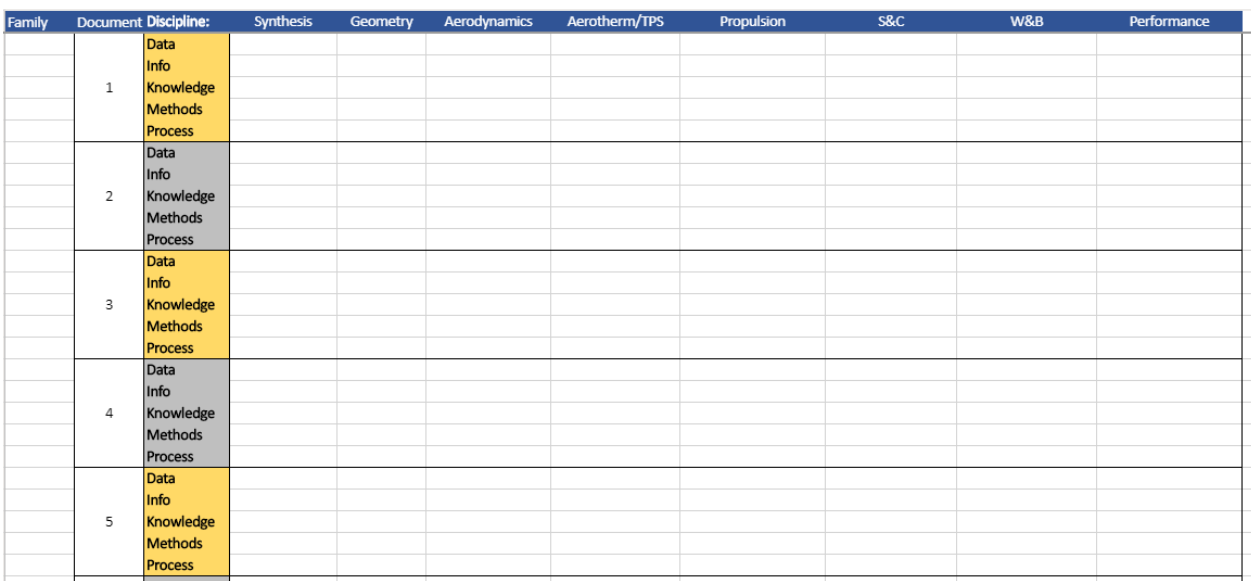

Figure 5.4. Blank template of datasheet used for VCC-DIK organization

The numbers to the left side represent the source number in the bibliography for each vehicle. The bibliography is typically listed at the bottom of the datasheet for easy reference. As seen in Figure 5.4, the datasheet allows for easily viewing what pieces of data, information, knowledge, methods, and processes are available from each source for each discipline listed.

5.2.2. Digitization Process

Each of the plots and tables collected are digitally extracted using the built-in snipping tool on Windows and stored locally as .png files before digitization. Each snipped piece of data, information or knowledge plot is stored locally with file names that represent the source of origin as well as the page number. This allows for ease of retrieval and organization.

Digitization is the process in which images are converted into a processible digital format. In this research activity digitization refers to the conversion of plots and data tables on paper or a digital document into numerical datasets. The tables are digitized directly by manual data entry, but the plots are digitized using a specific software called *WebPlotDigitizer* [13]. This web-based software allows the user to specify the axes and then identify the plot lines by color and specify the distance between data points as needed by preference for precision levels. Several digitizers have been initially considered before deciding upon WebPlotDigitizer, as shown in Table 5.9. WebPlotDigitizer has been chosen because it is free to use, requires no download as it is available on the web, and due to the ease of using the interface compared to the other digitizers.

Table 5.9. List of Digitization Tools Surveyed

Digitizer	Cost	Import File Format	Data Format
DCS Digitiser	$423	.jpg/.jpeg/.png	.csv
Unscan it	$423	.jpg/.jpeg/.png	.csv
Dagra	$49.95	.jpg/.jpeg/.png	.csv
DigitizeIt	$49	.jpg/.jpeg/.png	.csv
Xy Extract Graph	$45	.jpg/.jpeg/.png	.csv
Data Thief	$25	.jpg/.jpeg/.png	.csv
Engauge	Free	.jpg/.jpeg/.png	.csv
G3data	Free	.jpg/.jpeg/.png	.csv
Get Data	Free	.jpg/.jpeg/.png	.csv
Graph Click	Free	.jpg/.jpeg/.png	.csv
Im2graph	Free	.jpg/.jpeg/.png	.csv
Graph Data Extractor	Free	.jpg/.jpeg/.png	.csv

Image J plugin	Free	.jpg/.jpeg/.png	.csv
MATLAB grabit	Free	.jpg/.jpeg/.png	.csv
PlotDigitiser	Free	.jpg/.jpeg/.png	.csv
WebPlotDigitiser	Free	.jpg/.jpeg/.png	.csv

The digitization process using the WebPlotDigitizer app is detailed in Figure 5.5 for the example of a temperature plot collected for Sänger II [14].

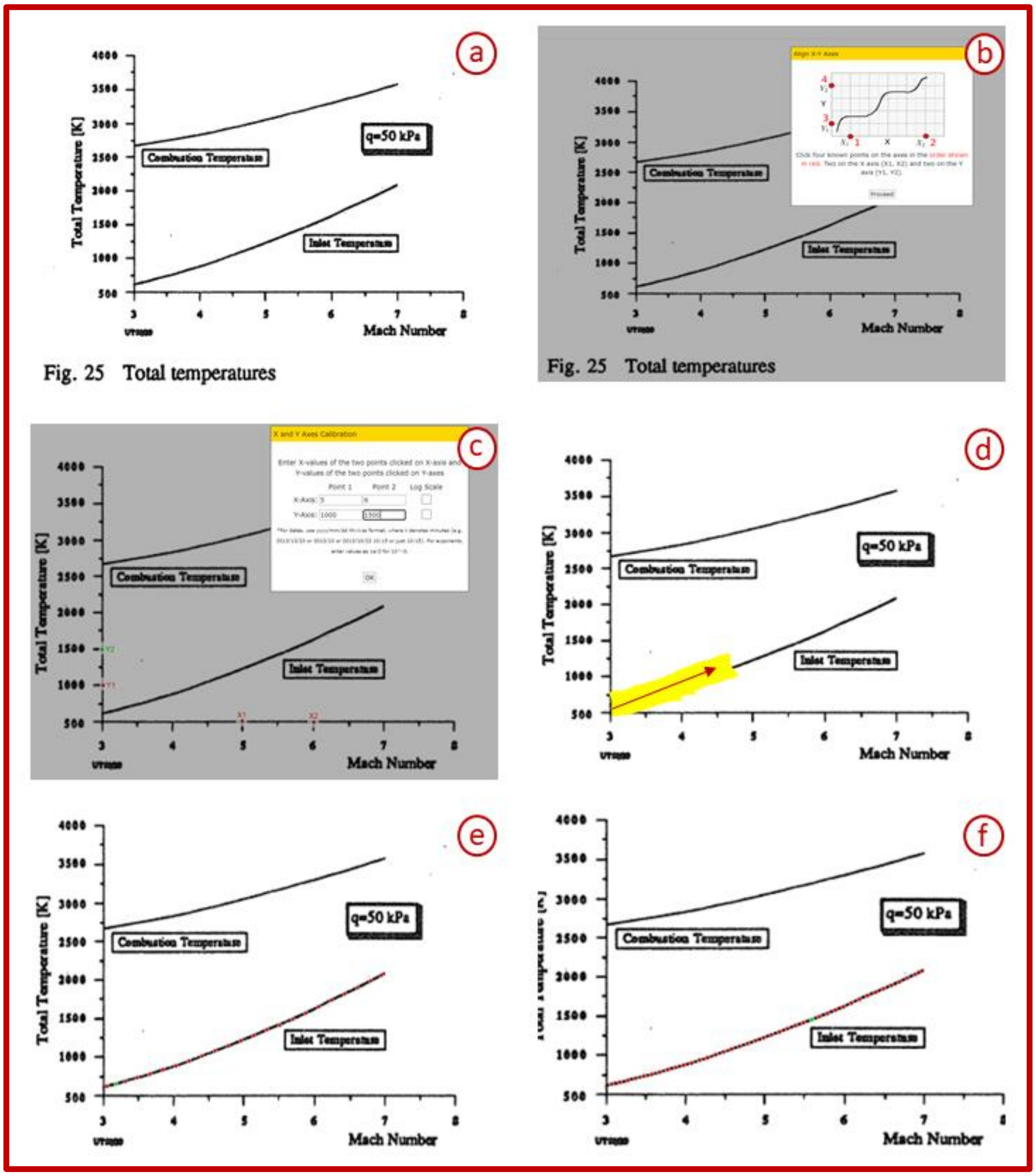

Figure 5.5. Digitization process of a sample plot demonstrated

The plot shown in Figure 5.5 contains data for total temperature vs. Mach number for the inlet and combustor of the Sänger II vehicle. Once the researcher confirms the relevance of this data for the conceptual design phase, it is advancing to the digitization process. Before digitizing, the overall datasheet shown in Figure 5.4 is updated by adding this plot under the 'Aerothermodynamics' section into the *Data* category, similar to the sample shown in Figure 5.6. The table entry is to be as descriptive as possible to facilitate future retrieval. Note that the overall datasheet also allows for entering the data specific to the sources listed under the collected bibliographies. These sources are listed under the *Document #* column in the table, with the full citation.

Document #	Discipline:	Synthesis	Geometry	Aerodynamics	Aerotherm/TPS	Propulsion
"Design Sensitivities of Airbreathing Hypersonic Vehicles,"	Knowledge					
	Methods	CADEHYP design				
	Process					
[161] Staufenbiel, R. "Horizontal Aerospace Transport Systems,"	Data	-	Vehicle length, wing span	-	Total temperature vs. Mach number	Burnout mass vs. velocity Specific impulse vs. Mach number
	Info	-	-	-	-	-
	Knowledge	-	-	-	-	-
	Methods	-	-	-	-	-
	Process	-	-	-	-	-
[162] Steinebach, D., Kuhl, W., and Gallus, H. "Design Aspects of the Propulsion System for Aerospace Planes,"	Data	-	-	-	-	-
	Info	-	-	-	-	-
	Knowledge	-	-	-	-	-
	Methods	-	-	-	-	-

Figure 5.6. Overall datasheet with sample entry

For easy retrieval of the plots at a later stage, comments are added to each entry in the table with the page number within the specified source where the plot is located. After this step the digitization process is facilitated using WebPlotDigitizer.

When WebPlotDigitizer is accessed, the initial landing page points to a file upload option. The image is uploaded to the site, which loads the plot on the interface. The app then allows the user to align axes so the data is accurately extracted from the image, as shown in Figure 5.5b.

Any two points on each axis are selected and the values entered [Figure 5.5c] which calibrates the software to understand the scale of the x- and y-axes and extrapolate the distance between any other two points in either direction.

After the initial setup, the manual digitization may be conducted in a couple of different ways depending on the specifications and complexity of the plot. If, for example, the plot has very few data points as shown for the example in Figure 5.7, the software may be run in *'manual extraction'"* mode where the user manually marks (by clicking) the datapoints using the *'add* *point'* software feature. At this point, minor adjustments may be made to center each point on the actual data point.

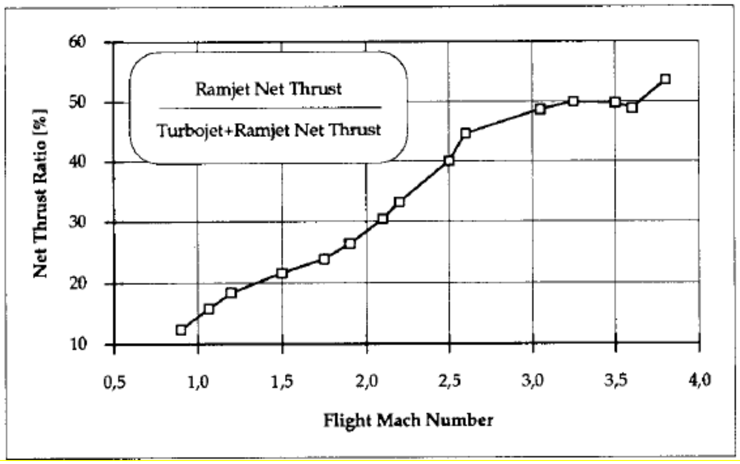

Figure 5.7. Engine thrust ratio plot - Sänger II [11]

In the case of the plot shown in Figure 5.5, the plot is a curve with no distinguishable datapoints, so the entire line may be considered as made up of infinite number of datapoints and it is up to the user to select how many data points to extract. In this case, the digitizer may be operated in *'automatic mode'*, using the color scheme. The menu shown in Figure 5.8 shows the options available for automatic digitization. The pen tool may be used for drawing directly following the plot line, or the box tool may be used to select the entire area surrounding the plot line if it is easily distinguishable from other plot lines in the same image. For the most part during the VCC digitization process, the pen tool has been utilized for its versatility.

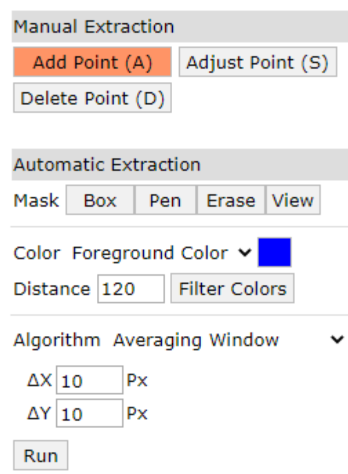

Figure 5.8. WebPlotDigitizer menu

Once the pen tool is used to select the plot line to digitize as shown in Figure 5.5d, the correct color option is selected for 'foreground color' in the menu, which in this case would be black. Then the digitization is run, which provides the result shown in Figure 5.5e.

Note that the resulting set of datapoints in Figure 5.5e is due to the algorithm averaging option chosen in the menu. The values for Δx and Δy have been selected to be 10 pixels each, which is the distance along the respective axes between any two datapoints. If a higher number of datapoints is desired, the averaging rate may be increased by decreasing the pixel distance between individual datapoints. For the VCC datasets, the averaging has been set to be 5 pixels for most of the plots except for ones with clearly distinguishable datapoints as in Figure 5.7. The result from using 5-pixel distancing is shown in the example in Figure 5.5f.

For plots with multiple trendlines of data plotted together, the initial digitized dataset can be stored under a specific name, and then a new dataset can be added to then digitize the second trendline. In this example shown, the first digitized dataset would be the "initial temperature" line; "*combustion temperature*" can then be stored under a different name within the same .csv file that would be downloaded for this plot. Once the data is digitized, the data is then downloaded as a .csv file and added to the respective datasheet for each discipline. The .csv file is difficult to work from which is why the data is then transferred by copying onto a central excel sheet located in a shared Microsoft Teams folder. Later on, this data is then transferred to an SQLite database using the SQLite Studio software [15].

5.3 Knowledgebase Buildup

The knowledgebase serves the greater purpose of using the data collected to generate useful trends and inform the designers, forecasters, or students using the VCC. Each of the involved disciplines will eventually contain a full knowledgebase created from the currently processed vehicles list. Therefore, the continuation of work on the compendium is crucial to the relevance of the software. Adding more vehicles of varying configurations to the compendium will allow comprehensive cross-comparisons between different types of vehicles. This will significantly expand the options available for the designer's consideration.

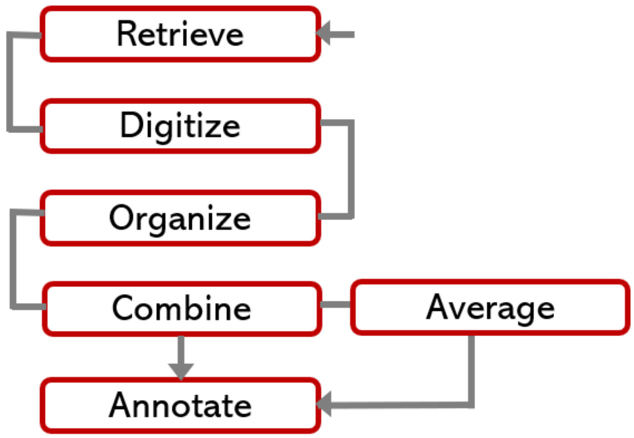

Figure 5.9. Information to knowledge conversion process

The knowledgebase buildup process is demonstrated in Figure 5.9. The six steps to building a well-informing knowledge graphic include the following:

- Retrieve

  This step includes retrieving relevant information plots from various sources
- Digitize

  Once the needed information plots are retrieved, they are digitized following the procedure discussed in the information section prior
- Organize

  Once the information plots have been digitized to retrieve the raw data from them, these are then organized depending on the x and y axes
- Group

  The plots are then grouped based upon what information is most useful to the designer. This is where the knowledge compiler makes intelligent decisions about the information collected. There may be some trendlines that are well-informing on their own but may not contribute to a knowledge plot when combined and compared with other trendlines.
- Combine

  Next is to combine the various grouped information plots into one singular plot. This will result in a knowledge plot that features multiple trendlines to compare between various categories based on what was decided on for comparison – whether it be configurations, cross-sections, speed regimes, etc.

- Annotate

  Perhaps the most important step in the process, a well-built knowledge graphic will have intelligent annotations to guide the designer on how to use the plot. Annotations that help would include commenting on the obvious conclusions that may be made about the tendencies of certain configurations, providing visual labeling as a means of better visualizing the configuration as shown in Figure 5.10, etc.

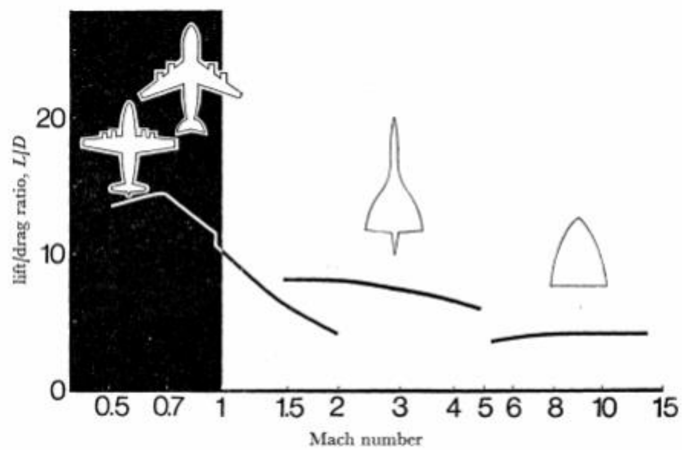

Figure 5.10. Lift-to-drag ratio against Mach number [16]

For the knowledgebase buildup, initially a list of design-critical knowledgebase plots is created as a guideline. Then the relevant data for each of those plots is sorted from the available data collected for the larger database. It is not guaranteed that every single vehicle will have the specific data required for every knowledgebase plot, of course. For example, although the lift-curve slope at supersonic speeds may be a desired knowledgebase plot for every single vehicle compiled, the reality may be that only 5 out of 7 vehicles have that dataset. In such cases, the knowledgebase plot will simply only show those 5 vehicles and the remaining two vehicles may be marked down as ‘seeking’, so future researchers may add the missing trends to the plot if found later.

A preliminary list of desired knowledge guidelines has been compiled and shown in Table 5.10:

Table 5.10. Initial List of KB Deliverables by Discipline

Synthesis/Sizing	Geometry	Aerodynamics	Aerothermodynamics
Solution Space	S_{wet}vs. V_{tot}	C_L vs. h/b	q vs. Mach
S_{pln} vs. ICI	S_{wet} vs. V_{prop}	C_L vs. α (low-speed)	Heat transfer vs. Mach
Tau vs. S_{pln}	S vs. tau	C_L vs. C_D	TPS thickness
$TOGW$ vs. S_{pln}	K_V vs. 1/tau	L/D vs. Mach	TPS materials selection
	$K_W$vs. tau	C_L vs. α	Heat flux vs Time/Mach
	K_{str} vs. tau	C_L vs. Mach	Surface temperature vs. Mach
		$C_D$vs. Mach	Temperature vs. Mach
		L/D vs. α	Temperature vs. Time
		L/D vs. C_L	
		Pressure distribution vs. Altitude	
		C_m vs C_L	

Propulsion	Performance/Trajectory	Stability and Control	Weights and Balances
SFC vs. Mach	Altitude vs. Mach	C_m vs. Mach	I_{str} vs. payload weight
I_{sp} vs. Mach	Altitude vs. Range	C_{l_β} vs. Mach	I_{str} vs. Temperature
I_{sp} vs. Altitude	Payload vs. Range	$C_{m_{\delta e}}$vs. Mach	$TOGW$ vs. S_{pln}
I_p vs. Mach	α vs. Mach	$C_{n_{\delta r}}$vs. Mach	OWE vs. S_{pln}
I_p vs. Range	SFCvs. Mach	$C_{n_{\delta a}}$ vs. Mach	Gross Weight vs. OWE
Propellant mass	V-N diagram	$C_{l_{\delta a}}$ vs. Mach	
Thrust for level flight vs. Speed	Separation characteristics for multi-stage systems	$C_{l_{\delta r}}$ vs. Mach	
T/D vs. Mach		C_m vs. Alpha	
Thrust vs. Mach		C_{n_β} vs. Alpha	
Nozzle performance characteristics		C_{l_β} vs. Alpha	
WR vs. Range		A.C. vs. Mach	
Thrust vs. Altitude		N.P. vs Mach	
		C.G. Shift vs. Mach	

Ideally the knowledgebase for the VCC knowledgebase would be programmed into the standalone user interface to where the software automatically plots relevant data using user input. Even further, the AVDS-VCC integrated system would then work to continually update this KB system to enhance the quality of knowledge-generation from the VCC side by the addition of more projects. However due to the tight deadlines for the development of the software, the current prototype VCC will house manually created knowledgebase plots hard coded into the interface, displayed according to the user selection of desired configurations.

5.4. Graphical User Interface Development

Once the foundation for the database and knowledgebase has been laid, next is the development of the actual software interface that the users of the compendium will directly interact with. Creating such an interface allows for a seamless experience for users to manipulate and study the data, information and knowledge contained within the compendium. The software development process detailed here is applied to the standalone VCC interface application. Best practices from this development activity may be adopted into the software upkeep of the integrated AVDS-VCC system which will be explained in the next subchapter.

The ideal cyclical nature of the proper development of a graphical user interface is demonstrated in Figure 5.11. The process consists of multiple iterations of the following four steps until the design is finalized: determining objectives and constraints, evaluating alternatives and identify risks, develop next product, and plan the next phase [17].

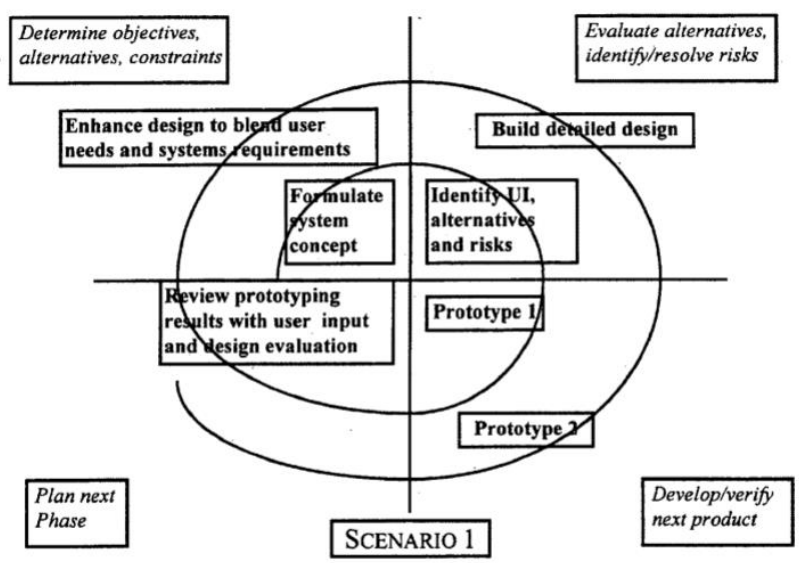

Figure 5.11. Cyclical GUI development process [17]

Microsoft has a published guide to the development of user interfaces, which states a similar approach but goes into more detail. Listed in Table 5.11 are the typical phases of GUI development, according to the Microsoft guide.

Table 5.11. Microsoft Guide for UI Development [18]

Designing	Functional Requirements	*Determine the initial requirements and goals for the application*
	User analysis	*Identify the user scenarios and understand the needs and expectations of users for each scenario*
	Conceptual design	*Model the underlying business that the application must support*
	Logical design	*Design the process and information flow of the application*
	Physical Design	*Decide how the logical design will be implemented on specific physical platforms*
Implementing	Prototype	*Develop paper or interactive screen mockups that focus on the interface and don't include distracting visual design elements*
	Construct	*Build the application and prepare for design change requests*
Testing	Usability testing	*Test the application with various users and scenarios*
	Accessibility testing	*Test the application with accessible technologies and automated test tools*

The functional requirements of the standalone compendium application have already been determined with the conceptualization of the VCC itself. The needs and expectations of the users are defined in that the users of this interface would be designers or design learners, seeking to revisit past project data and use this to aid in forecasting their own designs. The conceptual design models the business supported by the interface, which in this case would be vehicle design. The logical design stage is where the information flow is determined, and for the VCC, this has been modeled using a simple flowchart shown in Figure 5.12. For the final stage of the design of the GUI, which is physical design, has to do with the hardware used to implement the logical design.

The next step is implementation, where first a prototype is created, after which the actual application build happens. For the VCC, the prototype is implemented in the alpha version of the software. After implementation, the software is sent for user testing and accessibility testing. The VCC as it currently stands has an alpha software developed and sent for initial user testing. User testing is important for the standalone software especially, since the ease of accessing and viewing data, information and knowledge is the focus for the standalone software. Therefore, the graphical user interface does drive the software logic to some extent. For the integrated system with AVDS, which will be described later, the software logic is driven rather by the existing

AVDS architecture with the primary goal being smooth integration to allow for a seamless design experience overall.

The future iterations of VCC would need to undergo more thorough user testing and further accessibility testing to make sure that the application is truly usable by everyone. The need for testing is aptly stated by Microsoft: "… *Developers should recognize that they are not typical users. They have more intimate knowledge and understanding of the system that they are developing than the average user ever will.",* and *"... there is no substitute for the real interactions of actual users with the product"* [18]**.**

5.4.1. Standalone VCC User Interface Design

The standalone software is designed and iterated based on user input. Hence the design phase of the user interface is facilitated by the initial creation and iteration of a process flow diagram. Such a diagram details the functionality of the graphical user interface as experienced by a user. Figure 5.12 demonstrates the latest iteration of this flow diagram:

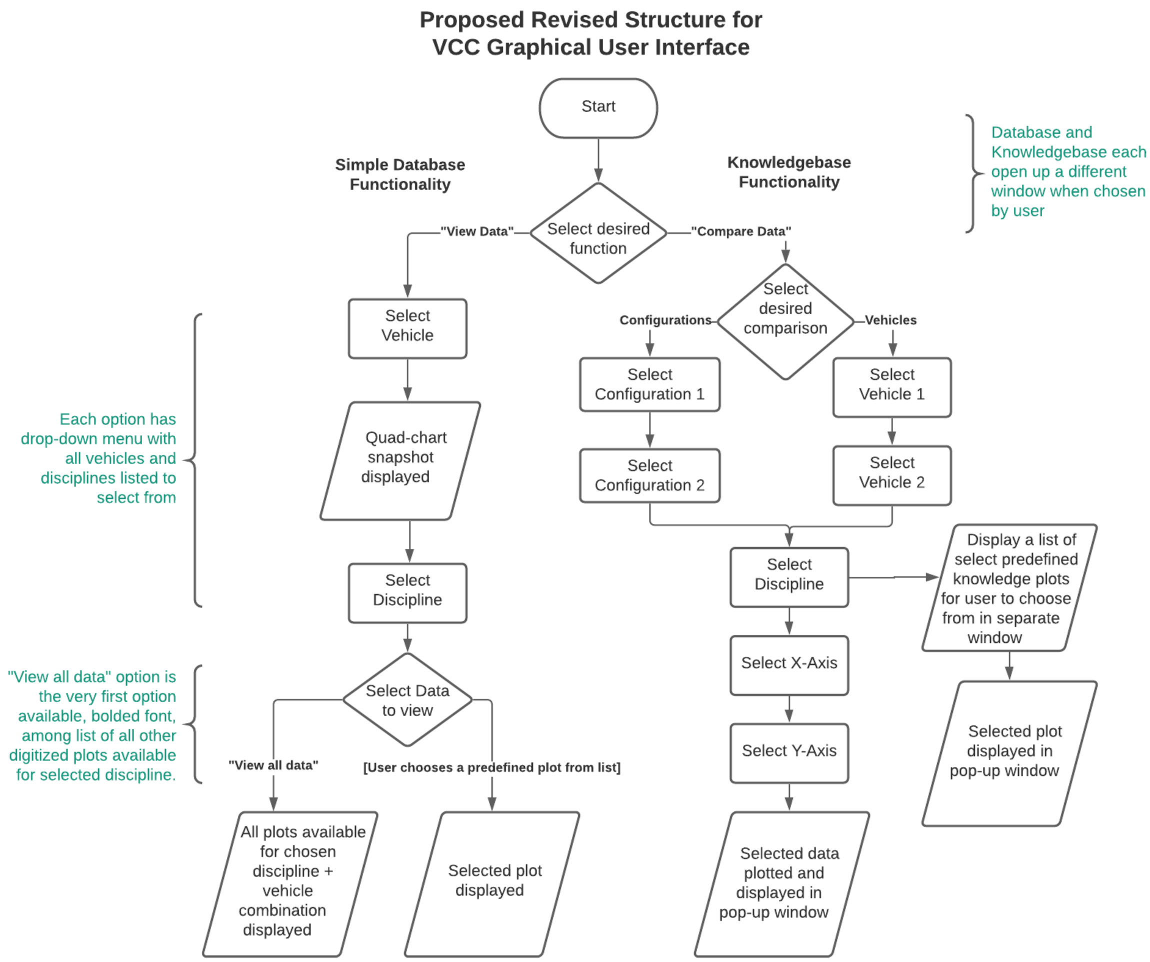

Figure 5.12. VCC graphical user interface logic flowchart

As per this flowchart, once the software is run, the first choice the user will be able to pick from is between '*View Data*' and '*Compare Data*', which will lead the user down either the data-information-base path or the knowledgebase path respectively.

If the user selects the database path, the user will then be given the option to select from the list of seven high-speed vehicles that have undergone the data compilation process (X-51, X-43A, XB-70, SR-71, Concorde, Sänger-II, NASP X-30). Upon the selection of this vehicle, a quad-chart snapshot of the vehicle will be displayed, which will be explained in more detail later. In short, this quad-chart is a quick overview of the most important characteristics of the vehicle chosen.

Once the vehicle is selected, another menu will appear that allows the user to select which of the 8 aerospace disciplines they would like to view data for. Once the discipline is selected, the user may then either choose to view all data or choose a specific predefined plot from a drop-down menu for viewing in a larger format. If the user chooses to 'view all data', then every single plot digitized and uploaded for that specific discipline and vehicle combination will appear in a 3x3 grid on the same window.

5.5. AVDS Integration Map

In addition to the VCC software being capable of running the database and knowledgebase system as a standalone software, the end goal for the fully developed system is to integrate this compendium with the AVDS (Aerospace Vehicle Design Synthesis) system in the future as mentioned in Chapter 1. The AVDS system is a synthesis software developed by the AVD Laboratory at UTA. The system steps through the conceptual design and preliminary design processes using a vast warehouse of methods, references, variables, processes, and data. The result is a sized, analyzed vehicle that meets performance requirements specified by the user initially.

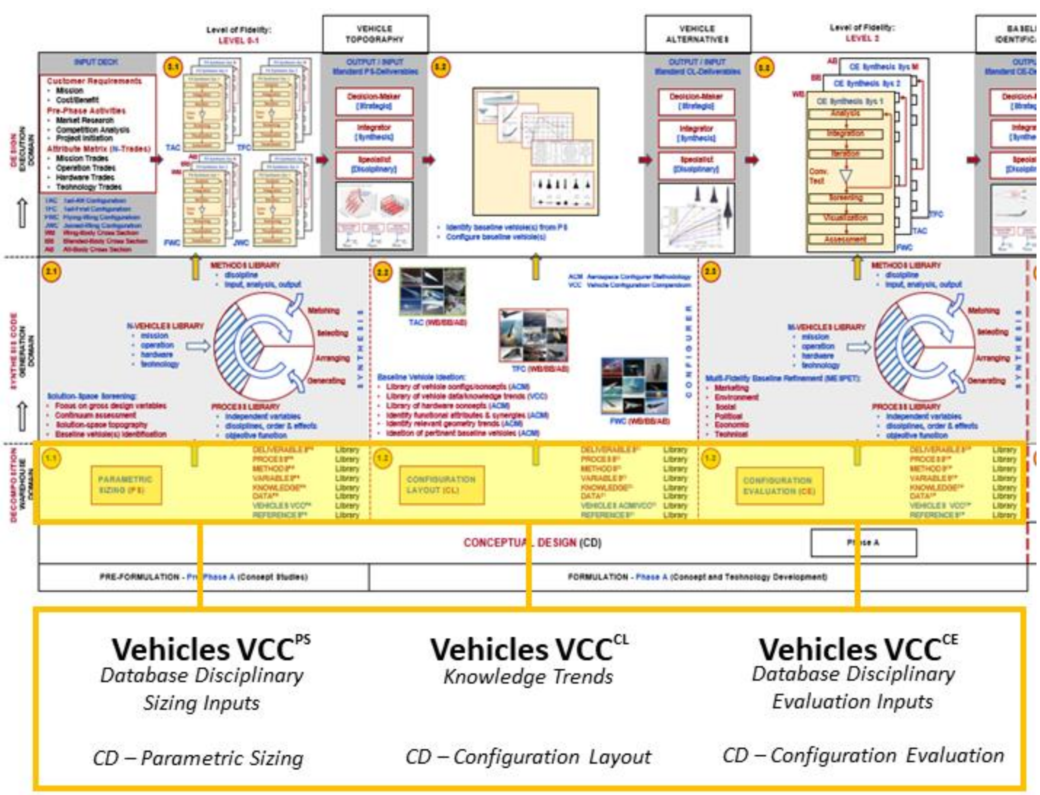

Figure 5.13. Integration of VCC in AVDS - CD phase

As seen in Figure 5.13, the VCC is to be accounted for in all phases of design conducted by the AVDS software, thereby creating an all-encompassing ideal design 'workspace' as envisioned in Figure 5.14. This 'cockpit' design system would be the designer's playground of sorts, increasing the quality of the design work done and enhancing the experience, streamlining the process of consulting past project data, and also streamlining the educational process.

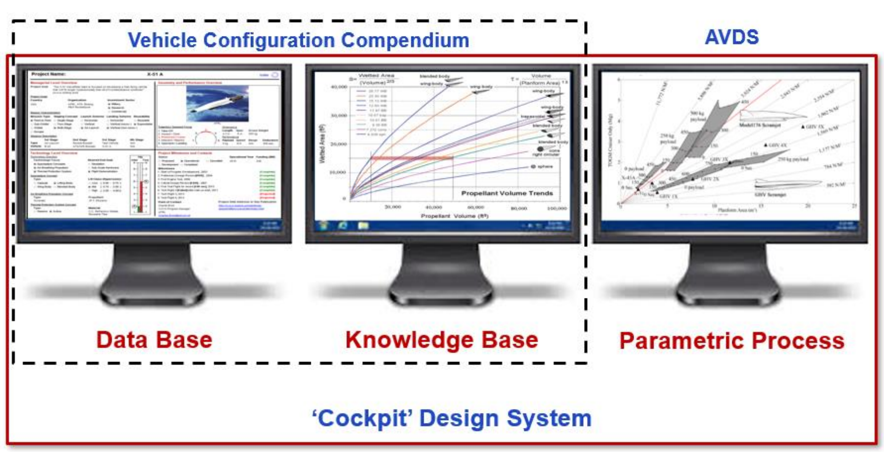

Figure 5.14. Designer's ideal workstation setup [19]

For each stage in design, AVDS pulls from the vast VCC library the pertinent information required. Since the scope of the current VCC prototype is the conceptual design (CD) phase, the later iterations will focus on incorporating preliminary design (PD) as well. For the current prototype version, the entry points for integration are identified, the pros and cons listed and documented, and the foundation laid for future research efforts to begin the full integration process between the VCC module and AVDS. Since the AVDS system is a Python-based software, VCC is also written using a Python script in order to facilitate future integration. The SQLite database is used by VCC for storage of data, which is also easily integrable into the AVDS for accessing raw data.

5.5.1. Integration Practices

For the integration of two pieces of software into a singular functioning unit, there are a few different approaches one may take, as listed in Table 5.12:

Table 5.12. Common Software Integration Formats [20]

Type of Integration	Description
Vertical Integration	*Subsystems are merged according to their functionalities*
Star Integration	*Subsystems connect with other subsystems through point-to-point connections*
Horizontal Integration	*A subsystem is used as an interface for other subsystems.*
Common data integration format	*Sets down an application-independent format with a goal of achieving a single format system.*

In the mapping out of the best future integration strategies for the AVDS and VCC systems, these types are studied in more depth and recommendations created and documented. Another aspect of software integration to consider for the future development of both systems is the concept of continuous integration (CI). Continuous integration is described as *"… a software development practice where members of a team integrate their work frequently, usually each person integrates at least daily – leading to multiple integrations per day. …"* [21]. This approach is said to increase opportunities for feedback and to decrease the risk of major issues in the integrated system due to the high frequency of integration and fixes of broken builds and utilizes a version control repository [22]**.**

5.6. Documentation Procedure

The final step in the process is creating proper documentation for the research conducted. This will ensure proper continuation of the project in the future and encourage consistency in the quality of work done by multiple researchers. An important aspect of this step is producing documentation that will enhance the experience of developers and users alike when dealing with either the backend or front end of the code. The user guide operates like a manual and helps the user of VCC understand how to gain the most out of the experience by helping them navigate the interface, while the developer's guide helps the programmer understand the architecture of the code and learn how to follow this to further develop the software later on.

One method to adapt for higher quality documentation is the *Docs like Code* method described by Anne Gentle, technical product manager for Cisco. According to Gentle, what often happens is *"… You want user-centered docs but instead you get project-centered docs. You want* *technically accurate docs but instead you get vague hand waving from your reviewers and a dearth of tests. …*" [23]**.** The proposed solution is to literally treat the documentation similar to how code is handled. The following steps are recommended for treating documents like code:

- *"Store the doc source files in a version control system"* [23]**.**
- *"Build the doc artifacts automatically"* [23]**.**
- *"Ensure that a trusted set of reviewers meticulously reviews the docs"* [23]**.**
- *"Publish the artifacts without much human intervention"* [23]**.**

There are two major documents developed as part of this research effort. The first one is the user manual for the front-end user of the VCC software. This includes basic instructions on how to operate the interface, suggestions for the learning process, and recommendations on how to draw conclusions from the knowledgebase shown.

The second document will be a more thorough data collection and digitization process document for future researchers to follow, along with a software developers guide. This will ensure that any future researchers are following the same process while maintaining quality of research. The software developers guide will be following the '*Docs like Code'* method for iterating through the documentation, with intermittent reviews and storing the source files in an easily accessible repository such as GitHub [24]**.**

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CHAPTER 6

SOURCE MATERIAL LIBRARY

6.1. Data Richness

6.1.1. Disciplinary Information Sought

Data richness is a gauge developed as part of this VCC data collection process. Developing an accurate data richness scheme would provide a good way to categorize each of the hypersonic vehicles being processed in terms of how rich they are in terms of conceptual design data published. There are two ways of approaching this: relative data richness, and absolute data richness. Absolute data richness depends on comparing the data collected to a standard list of deliverables. Based on the conceptual design process discussed earlier, a list of disciplinary parameters is generated, as was provided for each discipline in section 5.2.1, categorized by the different subphases in conceptual design: parametric sizing, configuration layout, and configuration evaluation. This gives an idea of what to filter for when surveying the sources.

6.1.2. Absolute Data-Information Richness

Absolute data-information richness (ADIR) is the determination of how rich the vehicle data is based upon a predetermined set of parameters sought for each discipline, which is based on the list of parameters mentioned in Chapter 5. This means that for each discipline involved in design, a set of variables or parameters is determined as crucial to the conceptual design process. This list is then considered 100% rich in ‘absolute data’ and serves as the scale against which the collected data is normalized. Absolute data richness is then output as a percentage value.

For example, let us consider the case where the propulsion discipline has seven parameters listed. If a vehicles data is looked through and it is determined that data was found for only three of the seven parameters listed, then that means that the absolute data richness is calculated as:

$$ADIR = \frac{\#\, parameters\ found}{\#\, parameters\ sought} x100$$

For this example case, this would result in an absolute data richness of:

$$ADIR = \frac{3}{7}x100 = 42.86\%$$

for the propulsion discipline. In addition to the disciplinary absolute data richness, overall data richness is also calculated, which is simply calculated from a summation of the different disciplinary parameters. It is worth noting that the absolute data richness does not represent the wealth of data that was found for each vehicle, which means a low ADIR percentage does not necessarily mean that data was scarce for that particular vehicle. ADIR only captures the amount of data found that was considered crucial to conceptual design. It is possible that other pieces of data that fall within the preliminary design or detail design phases were found but are not reflected within this data richness scheme.

The absolute data richness of the vehicles compiled for the VCC prototype are shown in Figure 6.1.

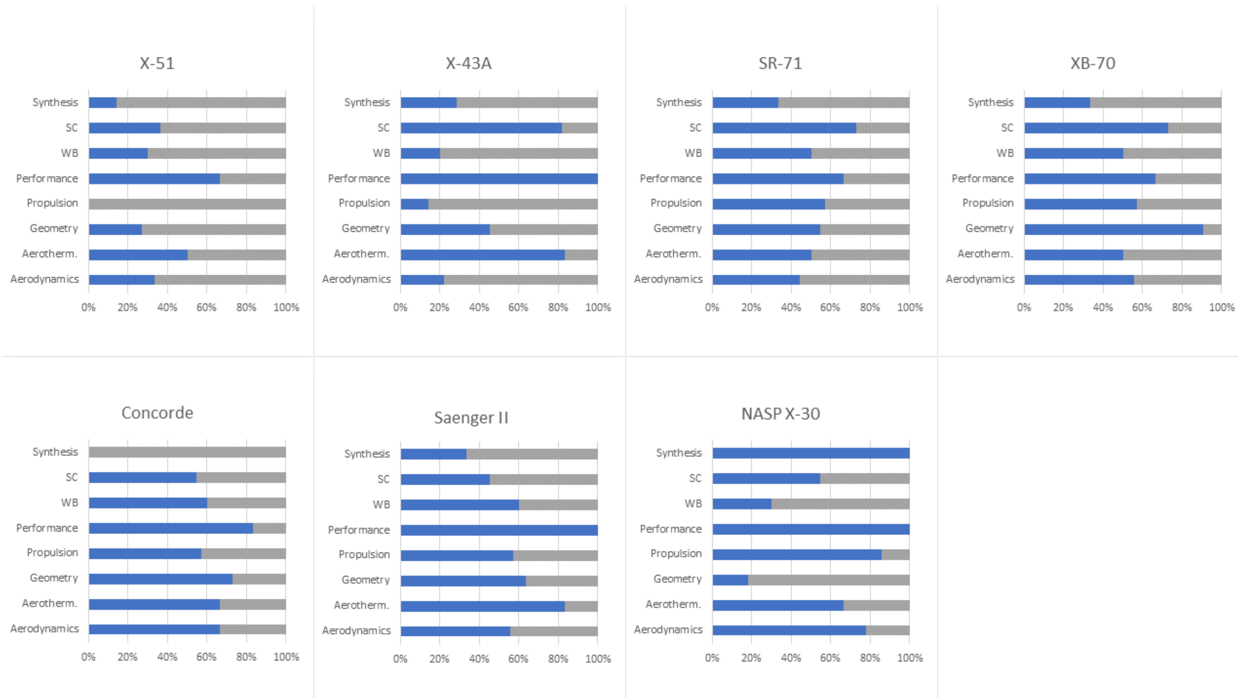

Figure 6.1. Absolute Data-Information Richness - VCC prototype vehicles

As seen in Figure 6.1, very few vehicles are 100% rich in 'absolute data' as determined by the parameter table. Sänger II yielded 100% of the performance data sought, as did the X-43A and NASP X-30.

7.1.3. Relative Data Richness

Next is the relative data richness, which is simply a measure of how many variables/parameters have been found broken down by discipline, regardless of whether the data found matched the earlier parameter list or not. Hence the data mentioned in the relative data richness section may not always be of use for conceptual design strictly. The results of the relative data richness for each of the vehicles compiled for VCC prototype is shown in Figure 6.2.

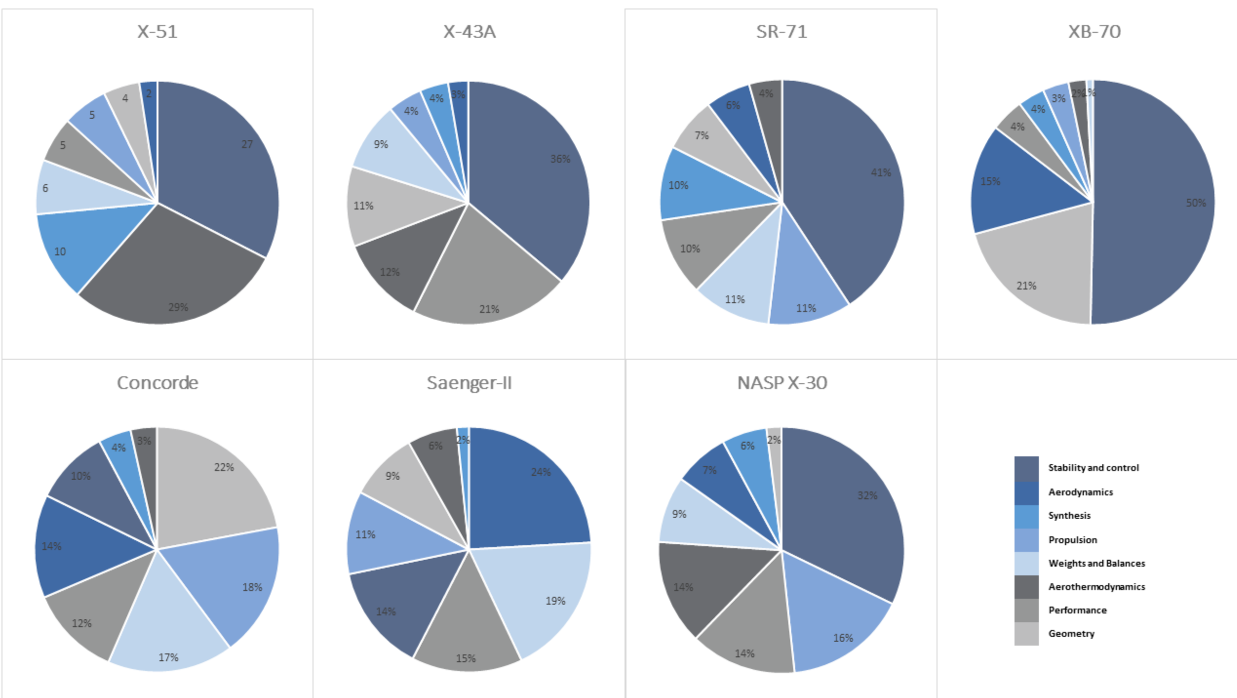

Figure 6.2. Relative Data Richness - VCC vehicles

The relative data richness aims more to give an idea of the relative weight of the amount of data found for each discipline. As seen above, about 50% of the data and information found for the XB-70 is stability & control data, while very little weights & balances information has been published. It is interesting to see how this varies for each of the vehicles. In the future, when many vehicles are populating the VCC, correlations may be developed between various factors surrounding the vehicle development or time period and the subsequent tendency to heavily feature a particular discipline in published literature regarding the project.

6.2. VCC Vehicle Selection

Seven high-speed aerospace vehicles have been processed and added to the VCC in its initial prototype phase. These vehicles are selected based on the archived data available within the AVD Laboratory, as well as due to the 2020 NASA study conducted by AVD Laboratory to utilize as verification and trade vehicles. This sample pool of vehicles represents a variety of configurations and mission characteristics. Full bibliographies have been compiled for each of these vehicles, as mentioned in Chapter 2, and the number of sources found for each vehicle is represented in Table 6.1.

Table 6.1. Summary of Vehicles - VCC Prototype

Vehicle	Developed by:	Year Developed	# of Sources Available
X-51	AFRL, DARPA	2010	34
X-43A	NASA	2004	162
XB-70	NAA	1964	123
SR-71	Lockheed Corporation	1964	94
Concorde	Aerospatiale, BAC	1965	257
Sänger II	MBB	1960’s	180
NASP	DARPA	1986	424

Some of these vehicles were developed to the point of a solid operational life as well as test flights, such as the Concorde, while others were unfortunately cancelled due to a lack of funding or other technical issues before a unit could be manufactured, such as Sänger-II or NASP X-30. Regardless of current status, documentation available on these vehicles are treasure troves of DIK to learn from, and therefore must be preserved accordingly. The following chapter sections will introduce the seven vehicles mentioned in Table 6.1, by first providing a general vehicle description with a discussion of any unique characteristics, a short discussion of the history and development cycle, as well as mentioning the types of data sources found for each vehicle.

6.2.1. X-51

The X-51 was the first vehicle to be subjected to the VCC documentation and compilation process, and thereby served as a test subject to understand the effectiveness of the methods used in this research effort. This allowed for the finalization of a system for all remaining vehicles moving forward. The X-51 is a hypersonic research vehicle that uses a scramjet engine, developed by the combined efforts of the US Air Force, DARPA, NASA, Boeing, and Pratt & Whitney companies. It was designed for an air-launch from the B-52 aircraft, and the primary objective of the program was to test the U.S. Air Force scramjet engine [1]. Due to the secretive nature of this project, very few sources of published data are available. It is said that over $250 million has been invested into this project for the sake of advancing hypersonic flight technology [2].

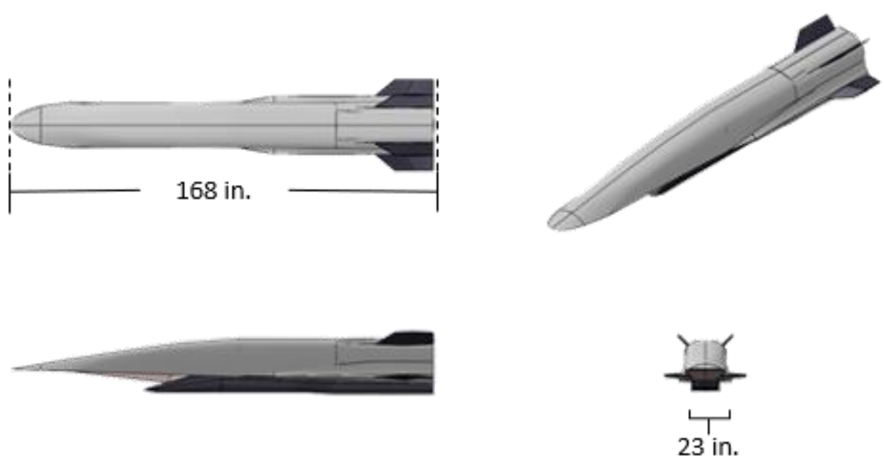

Figure 6.3. X-51 geometry [3]

The technologies featured on the vehicle includes a scramjet operating from Mach 4.5 to 7, an affordable high lift-to-drag airframe, and storable endothermic hydrocarbon JP-7 fuel [4]. The vehicle was about 14 ft long and almost 2 ft wide, as shown in Figure 6.3.

6.3.1.1. History and Development

The X-51 vehicle comes after the termination of the NASP program in the 1990's. The HyTECH program by the Air Force Research Laboratory (AFRL) was focused on development efforts for hypersonic propulsion. Pratt & Whitney developed the SJX61 engine, originally meant for the X-43C, which was then used for the X-51 after the cancellation of the X-43C program by NASA [1]. The development of the X-51 began in 2003, as shown in Figure 6.4.

The first flight test of the X-51A was conducted in 2010, with minimal issues. There was an inlet unstart about two minutes into the flight, from which the vehicle quickly recovered. The X-51A achieved a maximum speed of Mach 4.87 [1]. The flight was ended a little early due to a nozzle breach. The second flight in 2011 ended with an unstarted engine shortly after scramjet ignition and was hence unsuccessful. During the third flight test in 2013, the vehicle experienced loss of control before the engine could even be ignited due to a run-away control fin actuator. The fourth and final flight test was successful and resulted in a peak Mach of 5.1 and a 361-second-long controlled flight duration [5].

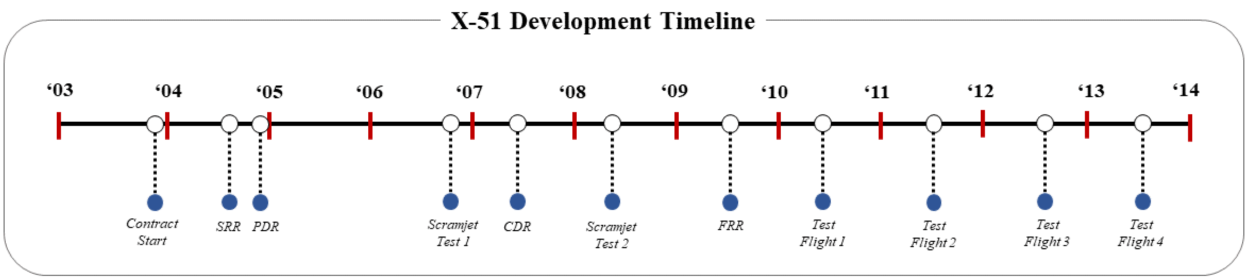

Figure 6.4. X-51 development timeline [6]

6.3.1.2. Sources Compiled

A total of 34 public domain sources have been collected for the bibliography of the X-51. This vehicle has the least number of published sources of data due to the secret classification of the technology as applied to the project, compared to the other vehicles added to the VCC prototype. The breakdown of the types of sources identified for this vehicle is shown in Figure 6.5.

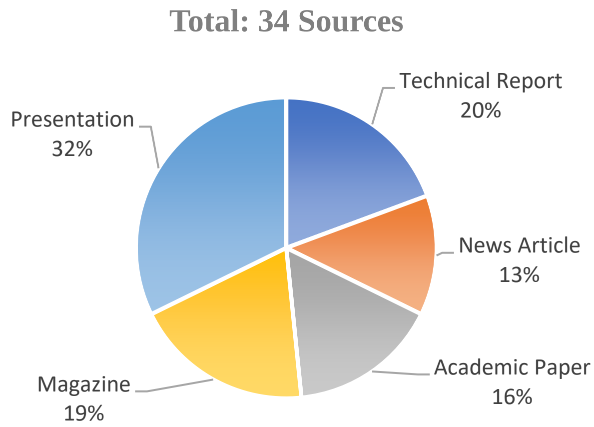

Figure 6.5. Source type breakdown - X-51A

As seen in this chart, most of the sources published for the X-51 are technical presentations, with the close second being technical reports and magazine articles regarding the new technology. The remaining sources are news articles regarding the project, and academic publications.

6.2.2. X-43A

The X-43 legacy series includes four variants: X-43A, B, C, and D. From this series, the X-43A, shown in Figure 6.6 has been the focus of the VCC effort. This vehicle has been part of NASA's Hyper-X program in the early 2000's to validate different experimental methods including design methods for scramjet powered hypersonic vehicles, and various tools and analysis techniques by conducting flight tests [7]. These experiments aimed to obtain data for scramjet propulsion feasibility, aerodynamic, aerothermal, structural, and guidance systems for the vehicle. This project involved an investment of $230 million [8]. Although the Hyper-X series set speed records of up to Mach 9.6, the project was eventually replaced by the X-51 project [9].

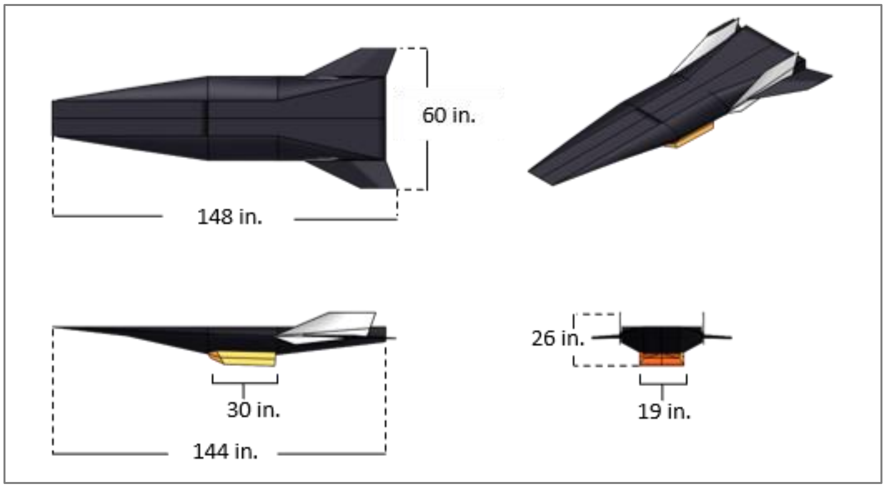

Figure 6.6. X-43A geometry [3]

This small-scale research vehicle was developed based on the NASP effort to provide data for a hydrogen-fueled, airframe-integrated scramjet engine [10]. In addition to the integrated scramjet engine, the vehicle featured two aft vertical control surfaces and two all moving wings and was about 12 feet long and 5 feet wide, seen Figure 6.6.

6.3.2.1. History and Development Cycle

A competition was held for contractors to develop the finalized design of the Hyper-X research vehicle, at the end of which a team including Micro Craft of Tullahoma and Boeing was awarded the contract in 1997. The development program concentrated on three main technology goals: risk reduction, flight validation of design predictions, and continued development of advanced tools [11].

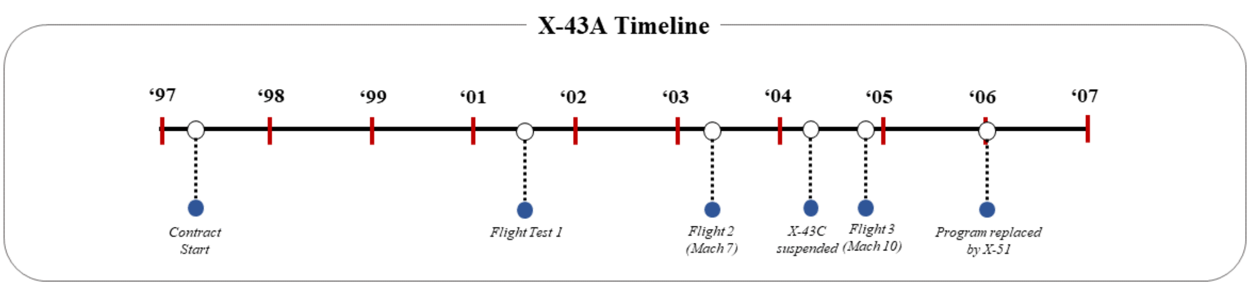

Figure 6.7. X-43A historical timeline [11]

As seen in the timeline in Figure 6.7, three flight tests have been conducted in total. The first flight was in 2001 and ended in a mishap soon after separation from the carrier aircraft, where the right and left fins and rudder broke off [8]. The cause of the failure was cited as the following: *"… The X-43A HXLV failed because the vehicle control system design was deficient for the trajectory flown due to inaccurate analytical models which overestimated the system margins. …"* [12]. After this incident, the model was refined for the next two flight tests. The second flight in 2003 achieved Mach 7 with all systems on both stages functioning well. The quality of data acquired from this flight was good and the engine performance was within 3% of the predictions. Finally, the third test flight in 2004 achieved a speed of Mach 10 and was another successful flight. This flight yielded the largest amount of test data for a Mach 10 scramjet. Later in 2006, the project ended up being replaced by the X-51 program [8].

6.3.2.2. Sources Compiled

For the X-43A, 162 sources have been compiled in total, a large majority of which are academic/conference publications, making up 56% of the total sources. The second largest group are technical reports, making up 24%. The rest of the sources are divided amongst presentations and magazine and news articles, see Figure 6.8.

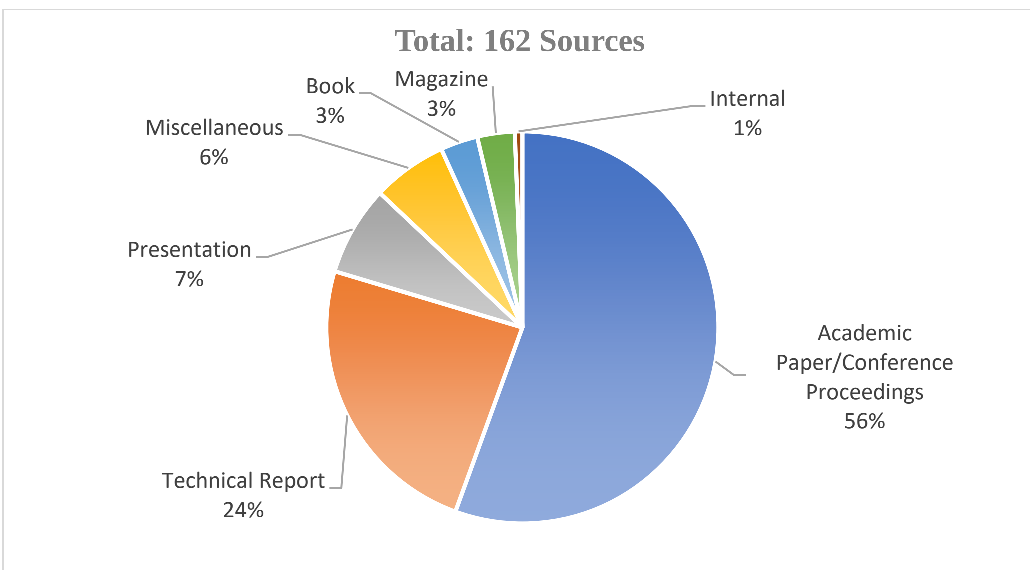

Figure 6.8. Source type breakdown - X-43A

The *'miscellaneous'* sources for the X-43A include a few graduate thesis documents and some standalone articles from NASA that are not technical reports or news articles.

6.2.3. XB-70

The XB-70, also known as the *Valkyrie*, was a supersonic Mach 3 vehicle developed by North American Aviation as a nuclear bomber prototype for the B-70 project. It was designed to cruise at Mach 3 and higher, and was designed with stealth considerations, as it was capable of moving out of radar range during bomber missions. The vehicle was built to carry out the same mission as the B-52 bomber but at the higher supersonic speed of Mach 3, according to the requirements of the US Air Force [13]. The XB-70 was expensive, with each vehicle costing $750 million, and the development cost was around $1.5 billion. The program was cancelled for several reasons, but it all came down to the fact that the technology for the vehicle was developed before its time which created many issues, unfortunately [14]. However, the fact remains that this vehicle pioneered many new technologies for supersonic aircraft and had the potential to become a Mach 3 passenger transport had it not been for the extreme costs associated with such repurposing [15].

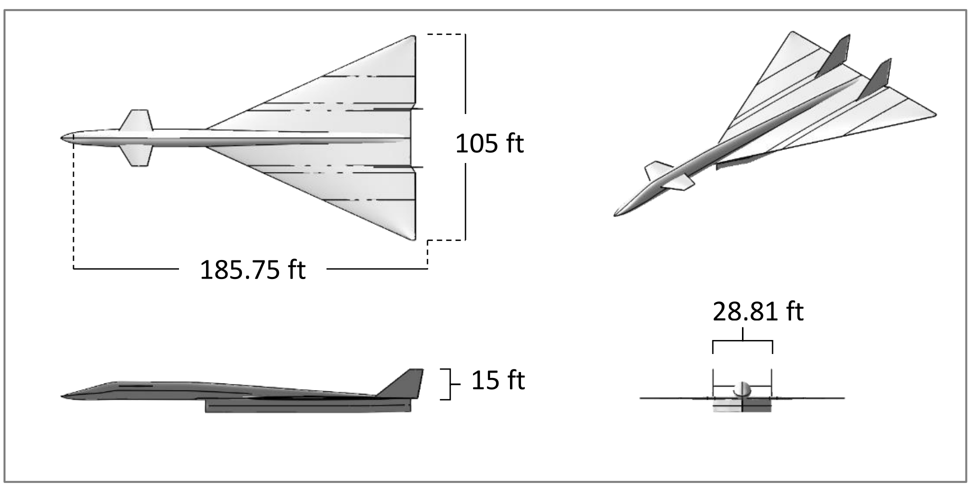

Figure 6.9. XB-70 geometry [3]

The XB-70 is 185 ft long, with a wingspan of 105 ft as seen in Figure 6.9. One of the unique characteristics of the vehicle is the wing droop. At subsonic speeds, the wings could make use of the large lifting surface to increase the lift to drag ratio, which helped with the takeoff and landing performance by utilizing compression lift, a concept that had been developed well before this project [16]. At supersonic speeds, this lifting surface could be decreased by folding down the wing tips, which reduced induced drag. These drooped wing tips also provided increased directional stability [16].

6.3.3.1. History and Development Cycle

North American Aviation was awarded a contract to build *Weapons System 110* in 1959. This vehicle was meant to achieve a cruise altitude of 70,000 ft, a range of 7,500 miles, and cruise at Mach 3. After searching through literature available on aerodynamic studies conducted prior, they came across a paper detailing the advantages of compression lift, a method of increasing lift by utilizing a conical body under the center of a wing. This was then used to conceptualize the XB-70, which applied compression lift using the wing droop mechanism detailed above.

The XB-70 bomber program was cancelled shortly after, in 1961, as shown in Figure 6.10. This was then replaced with a high-speed flight research program which called for three XB-70 prototype aircraft, each slightly different from each other. The initial prototype or AV/1 (Air Vehicle/1) broke the sound barrier, decelerated, and broke again through the sound barrier many times to check for transonic stability. Several subsequent flights of the first prototype experienced issues with things like drag chutes failing to deploy and several instances of hydraulic system failures and fuel leakage. Then in 1965 the second prototype, AV/2 made its first flight. This vehicle had more flexible hydraulic fittings, and an improved honeycomb skin, as well as carefully placed fuel tanks to avoid leakage. This vehicle had issues with dihedral effect, and pitch stability issues at Mach 3 [16].

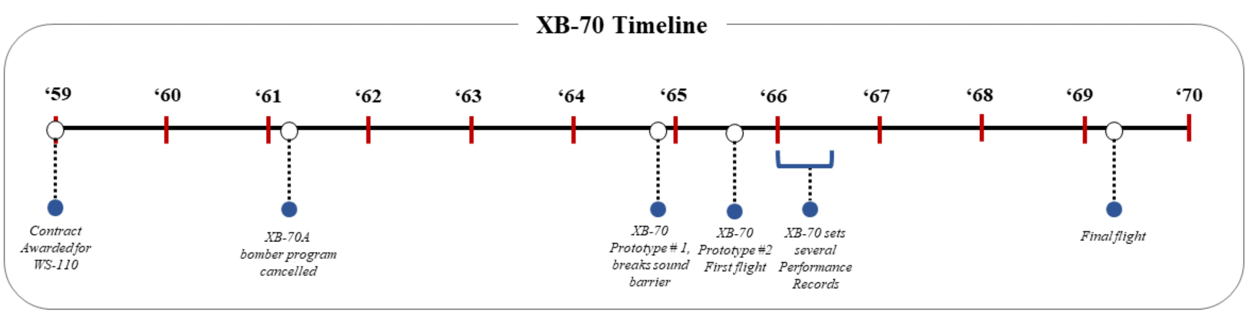

Figure 6.10. XB-70 historical timeline [17] [18]

Over the course of the next few years of flight tests through 1966, the vehicle established and broke its own records for longest sustained supersonic flights. The program was eventually abandoned as "… *the flight frequency went down and the costs went up.* …" [17].

6.3.3.2. Sources Compiled

A total of 138 sources have been located for the XB-70. Almost half of these resources are accounted for by various technical reports, most of which have been produced by NASA, as shown in Figure 6.11. The rest of the sources are mostly a mix of academic papers and conference proceedings, published books, and miscellaneous sources.

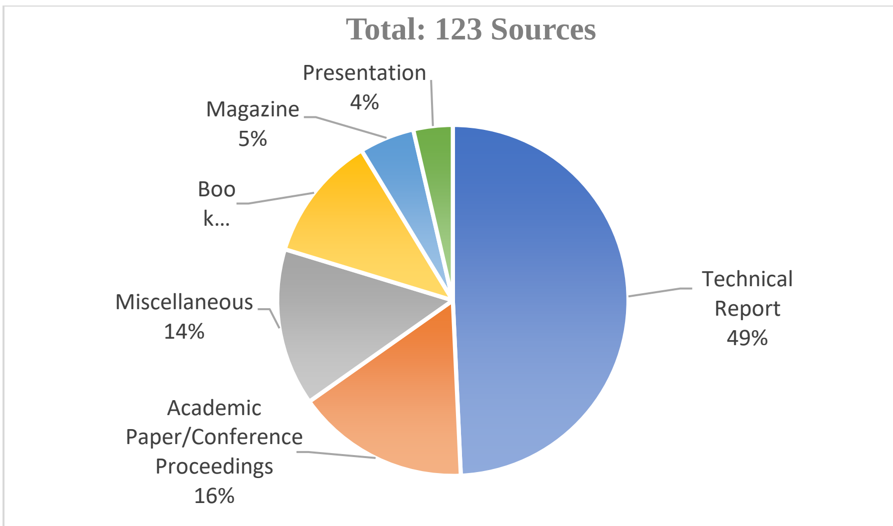

Figure 6.11. Source type breakdown - XB-70

In reference to the XB-70, *'miscellaneous sources'* consists of a mix of website articles and academic thesis documents.

6.2.4. SR-71

The SR-71, also known as the *Blackbird*, is a reconnaissance vehicle designed and produced by Lockheed for the U.S. Air Force in the 1960s. The vehicle has been designed to be capable of conducting both single-legged and multi-legged reconnaissance missions with aerial refueling factored in [19]. The vehicle is about 107 feet in length and has a wingspan of 55 feet, as shown in Figure 6.12. Several new technologies were developed that went into the SR-71, which made it a unique vehicle at the time. Kelly Johnson, design engineer who conceptualized the vehicle, said of the technologies developed: *"... everything on the aircraft, from rivets and fluids, including materials and power plants had to be invented from scratch. ..."* [20].

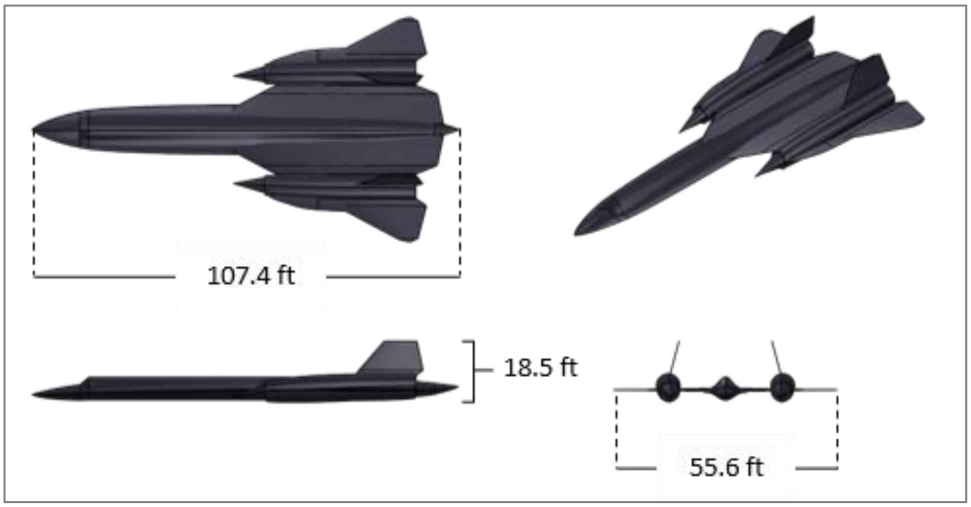

Figure 6.12. SR-71 geometry [3]

The Blackbird features a delta wing with two vertical tails that are canted inward to reduce the coupling of the vertical tails on the rolling moment. The vehicle utilizes two turbo-ramjet engines which allow for operation at both low speed and high speed as the airflow transitions between the turbojet and ramjet accordingly [19].

The forward fuselage is a blended body design, featuring fuselage chines. A chine is defined as a *"... long, narrow sideways extension to the fuselage, blending into the main wing. ..."* [21]. The chine has multiple functions, including the increase of the effective lifting surface with minimal increase in drag at supersonic speeds, and reducing the radar cross section of the vehicle for stealth [20].

6.3.4.1. History and Development Cycle

Although technically the official contract for the development of the SR-71 was awarded in 1962, the technologies that eventually have been applied with this reconnaissance vehicle were under development beforehand. The A-12, the predecessor of the SR-71, was developed by Skunk Works under project ARCHANGEL which was the replacement program of the previous U-2 vehicle [22].

The next iteration in this line was the YF-12, which was developed as an experimental fighter-interceptor version of the A-12 [23]. By the end of 1962, the US Air Force awarded a contract to Lockheed to build six SR-71s following interest in obtaining versions of the Blackbird meant for reconnaissance.

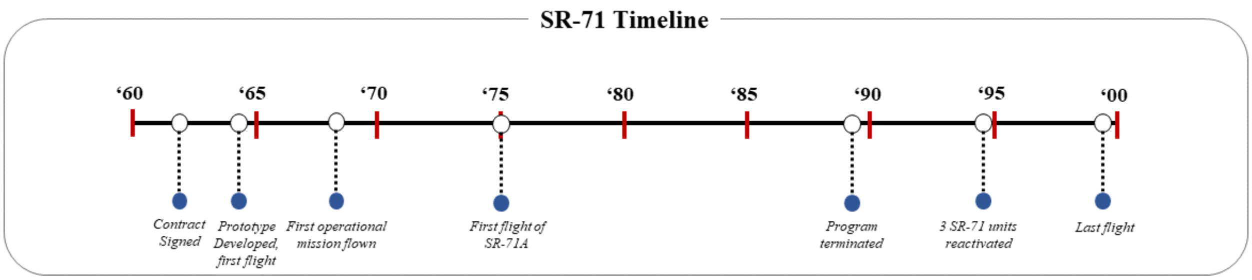

Figure 6.13. SR-71 historical timeline

As shown in Figure 6.13, the first flight of a developed prototype SR-71 was in 1964. The first operational SR-71 mission was flown in 1968, and within the four years leading up to that mission, many test flights of the YF-12, A-12, and SR-71 occurred, a few of which ended up in the loss of the aircraft [22].

In 1975, the big tail SR-71 took its first flight. Within the decade prior, several more SR-71 vehicles were lost during operational missions. Eventually the program was terminated by the Air Force and Intelligence Officials in 1989, although 3 units were shortly reactivated in 1995 [22].

6.3.4.2. Sources Compiled

A total of 95 sources have been compiled for the SR-71 vehicle, with an additional 26 collected for the YF-12. The breakdown of the sources type shown in Figure 6.14 only addresses the 95 sources specific to the SR-71. As seen in Figure 6.14, the majority of the sources collected are physical or digital books, with conference proceedings and technical reports making up the remaining majority.

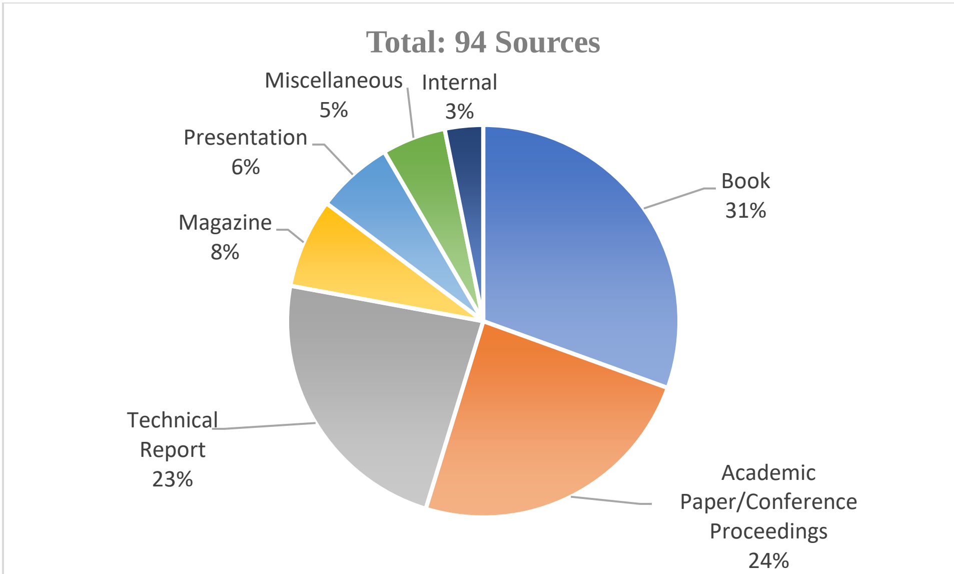

Figure 6.14. Source type breakdown - SR-71

The small number of miscellaneous sources found for this vehicle included AVD Laboratory internal documents, websites, and uncategorized documents such as the SR-71 historical timeline by Hildebrant [22].

6.2.5. Concorde

Concorde is a supersonic transport aircraft developed in the 1960's. The aircraft was originally envisioned to carry 128 passengers over 4,000 miles at Mach 2.2, but after further development activities, these ambitious mission criteria were reduced to a passenger capacity of 90 to 100 at Mach 2.05 [24]. The vehicle employs a unique design, featuring many revolutionary design concepts for the time, most notable of which is the ogival planform thin delta wing as shown in Figure 6.15.

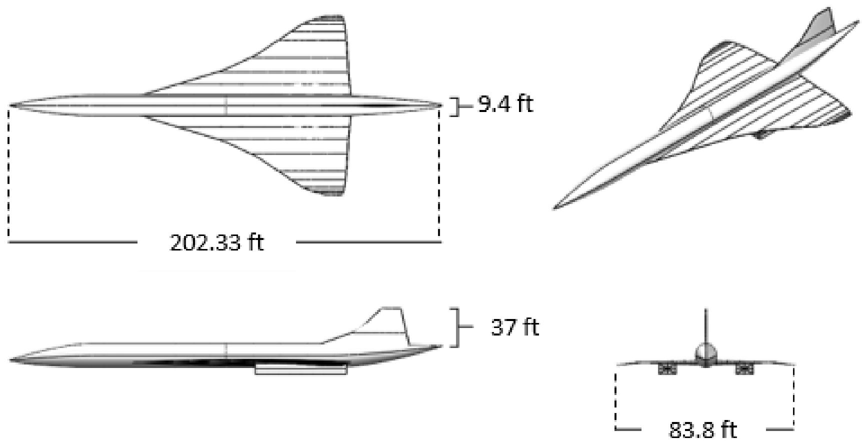

Figure 6.15. Concorde geometry [3]

As seen in Figure 6.15, Concorde is 202 ft long, with a wingspan of 84 ft and a vertical tail that raises 37 ft from the fuselage. The vehicle is an all-aluminum design and is powered by four Bristol/Siddeley Olympus turbojet engines, which also feature afterburners for use during takeoff and acceleration to cruise velocity [24].

6.3.5.1. History and Development Cycle

The Supersonic Transport Advisory Committee was formed in Britain in 1956 to investigate the possibility of supersonic air travel. As shown in Figure 6.16, development activities began in 1960, shortly after which France decided to join in. The four companies involved primarily were BAC (British Aircraft Corporation), Sud Aviation, Bristol Siddeley (now renamed Rolls-Royce) and SNECMA [25]. The construction of two prototypes began in 1965, and the first flight of a Concorde was in 1969 in Toulouse, France [26].

Concorde's commercial operations were kicked off with the first commercial flight in 1976, with flights from Paris to Rio de Janeiro by Air France and from London to Bahrain by British Airways. The Concorde had a long operating history commercially despite being described as a *supersonic bust* and as having *disastrous economics* [24].

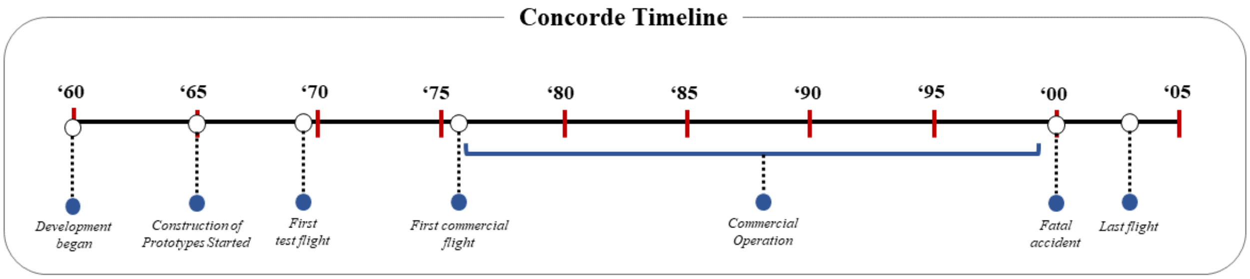

Figure 6.16. Concorde historical timeline

This long-standing legacy of the Concorde was damaged by the fatal accident that took place in the year 2000. The vehicle was taking off from Paris to New York with one hundred passengers and nine crew members, when the landing gear ran over a metal piece left behind by a previous aircraft, which punctured a tire at the left landing gear. Debris from this destroyed tire ruptured the underside of the left-wing fuel tanks, causing a severe fire to break out. This then resulted in both left-wing engines 1 and 2 suffering from a loss of thrust, after which the vehicle crashed into a nearby hotel. This accident resulted in the loss of the lives of all 100 passengers, all nine crew members, and four employees of the hotel [27].

6.3.5.2. Sources Compiled

For the Concorde, a total of 257 sources have been compiled. Most of the sources are internal documents from the AVD Laboratory, academic papers, and magazine articles as well as print books. The rest of the sources are divided between technical reports, news articles, and presentations, as shown in Figure 6.17.

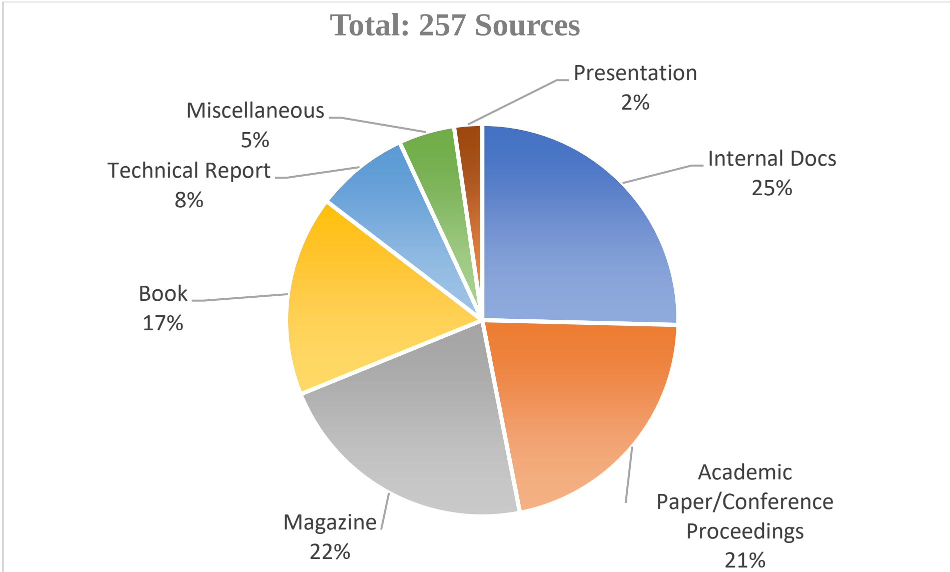

Figure 6.17. Source type breakdown - Concorde

The miscellaneous sources for Concorde contain course material, thesis documents, engineering notes, standalone case study documents that are not full reports, etc.

6.2.6. NASP X-30

The NASP (National AeroSpace Plane) program began in 1986 as a DARPA project to investigate the technologies to enable a single stage to orbit flight. The vehicle was meant to be a horizontal takeoff horizontal landing manned spaceplane with a rocket-based combined-cycle (RBCC) engine, capable of achieving Mach 25. The project was meant to receive a total of $3.33 billion in funding from the Department of Defense, for phase 2 of the development [28].

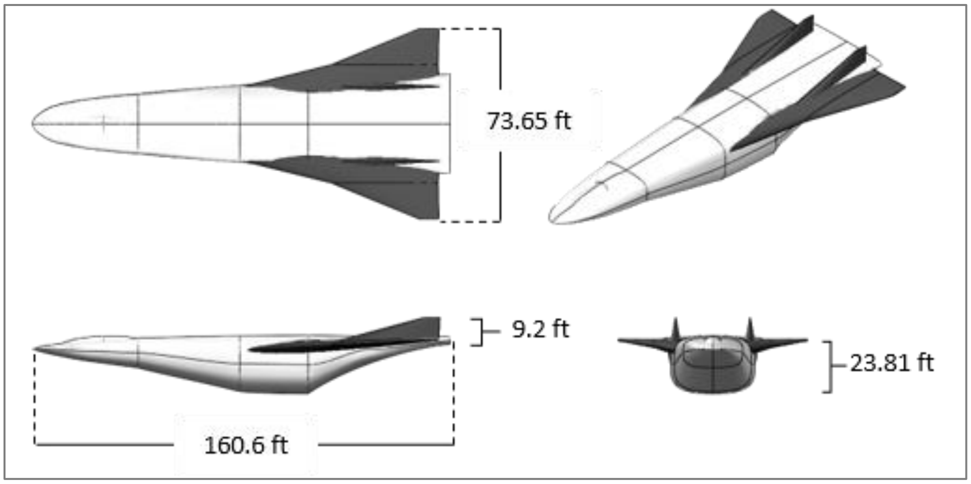

Figure 6.18. NASP X-30 geometry [29]

The vehicle, as shown in Figure 6.18, is about 314 ft high, with a span of 118 ft and a fuselage width of 52 ft. This project required technology advances in the following five areas: supersonic combustion jet propulsion, active cooing with hydrogen-based fuel, computational fluid dynamics (CFD), materials, and avionics [30]. NASP has been the first design that incorporated actively cooled surfaces to reduce the extreme heating from drag during hypersonic flight [31].

6.3.6.1. History and Development Cycle

In 1975, NASA began exploring an alternative to the Space Shuttle for routine space transportation. Of the two-stage-to-orbit (TSTO) and single-stage-to-orbit (SSTO) options explored, the SSTO benchmark concept for NASP was found more appealing due to resembling the operational concept of transport aircraft. Phase 1 of this effort began with the Copper Canyon project in the 1980's, as shown in Figure 6.19.

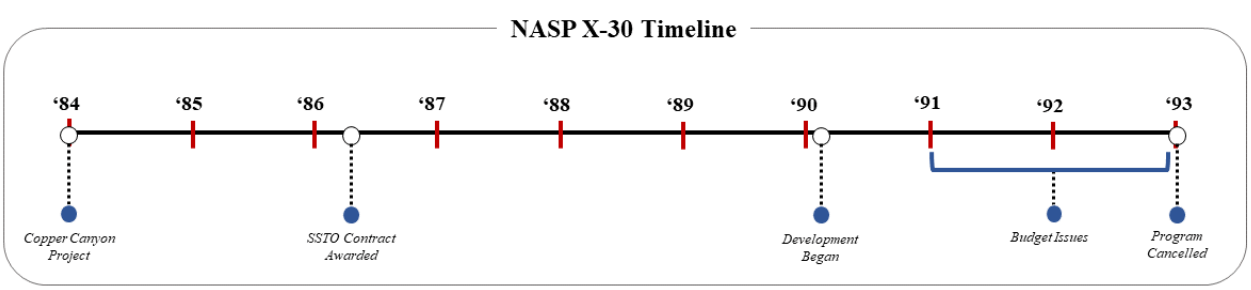

Figure 6.19. NASP X-30 historical timeline

The concept of a vehicle capable of transporting people from the Continental U.S. to East Asia in 2 hours or less was from Tony DuPont, with his idea for the *Orient Express* [32]. The companies involved in the NASP study decided that his initial concept was worth exploring, after which Marquardt and GASL worked on DuPont's engine study while Boeing, McDonnell Douglas, Lockheed, and General Dynamics focused on the airframe. Despite this fact, Du Pont's aerospace company was excluded from involvement in the development and production of the vehicle due to the massive engineering requirements that he may not have been able to provide at the time, but he remained a consultant [33].

Eventually in 1987, due to budget constraints, Boeing, Lockheed, and General Electric were eliminated from the contract, thereby downsizing the program. Phase 2 of the development was originally intended for as early as 1986 but ended up being extended to 1990 [34]. The following few years were met with more budget struggles, as the NASP mission objectives needed to be reassessed continually: *"... No amount of coordination, however, could counterbalance the continual funding turmoil that kept the JPO in a constant state of reviewing options…"* [33]. This led to the official cancellation of the program in 1993, before any units could be produced, or flight tests conducted.

6.3.6.2. Sources Compiled

The NASP X-30 has the largest bibliography of the seven vehicles considered for this compendium prototype, with 424 sources. The majority of these sources are academic papers and conference publications, as seen in Figure 6.20. The rest of the sources is comprised of printed books, technical reports, presentations, magazine articles, and AVD Lab internal documents.

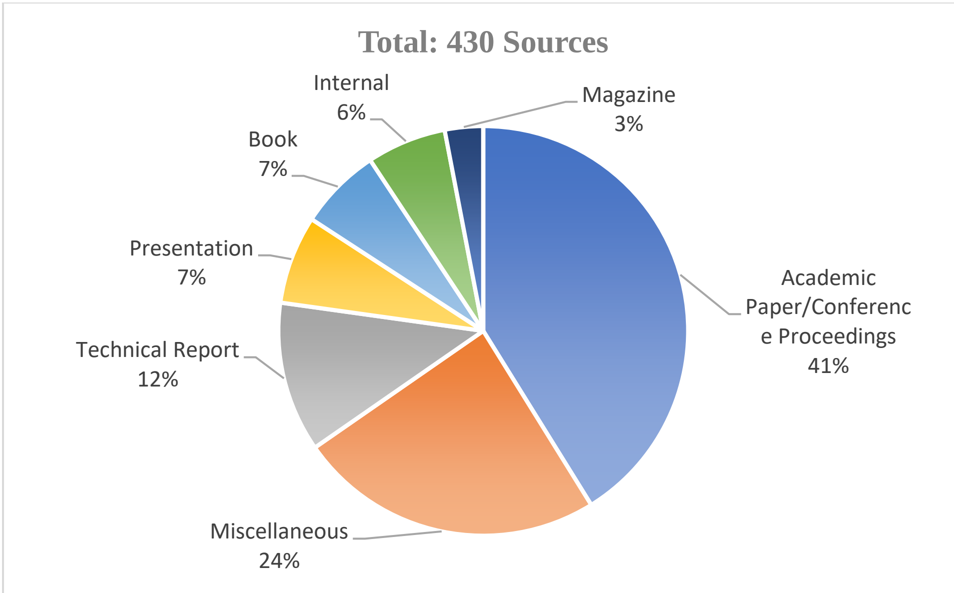

Figure 6.20. Source type breakdown - NASP X-30

The miscellaneous sources collected for the NASP X-30 include a wide variety of notes and informal memos produced during the development of the vehicle, communications back and forth with Tony DuPont, and other drawings and data collected during the project.

6.2.7. Sänger-II

The Sänger II was based on the German Sänger reference concept for a fully reusable two-stage-to-orbit system. Based on the design by German aerospace engineer Eugene Sänger, this vehicle featured an airbreathing, horizontal take off horizontal landing first stage and a rocket powered second stage. The vehicle was meant to be capable of delivering 8,500 kg of payload to low-earth orbit, and 3,000 kg if it was a manned mission [35]. The first stage was to be capable of reaching an altitude of 3100 km to separate, and the second stage would then take the payload of up to 6,000 kg to low-earth orbit [36].

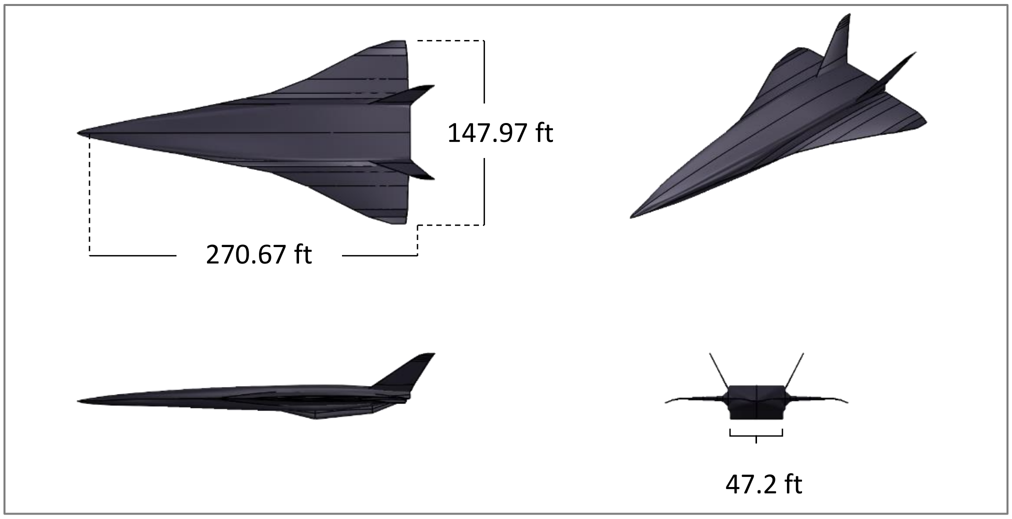

Figure 6.21. Sänger II geometry [3]

As seen in Figure 6.21, the vehicle is 270 ft long, with a span of 148 ft, and a fuselage width of 47 ft. One of the features of Sänger II is the airbreathing propulsion system that consisted of five turbojet engines, with a ramduct capable of transitioning between Mach 3.3 and 3.8 [35]. This vehicle was also meant to form the basis for a European hypersonic transport with an 11,000 km range capability.

6.3.7.1. History and Development Cycle

The Sänger concept was initiated by MBB (Messerschmitt-Bölkow-Blohm) in 1985. This led to a feasibility study contract by the German Ministry for Research and Technology in 1987. As shown in Figure 6.22, in 1988, the configurational characteristics of the Sänger-II vehicle were established, some of which were mentioned at the beginning of section 3.7 [37]. The time period from 1988 to 1993 saw further funding under Germany's Hypersonic Technology Program, which resulted in the ground run of Europe's first turboramjet engine in 1991. However, the Sänger program was cancelled due to the realization that further development would be incredibly costly with any design advantages being less than that offered by the Ariane 5 expendable vehicle at the time [36].

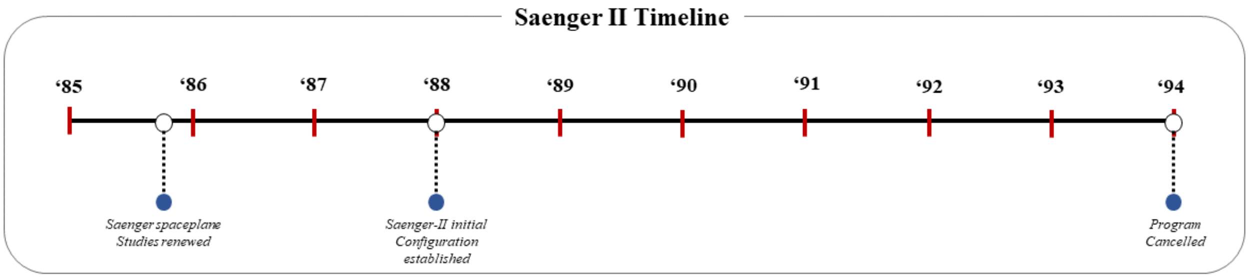

Figure 6.22. Sänger-II historical timeline

6.3.7.2. Sources Compiled

A total of 180 sources are compiled for the Sänger II vehicle. As shown in Figure 6.23, a large majority of the Sänger data has been located from academic publications and conference proceedings, making up 63% of the total bibliography. The rest of the sources are books, technical reports, magazines, and internal documents in the AVD Laboratory, as well as a very small percentage of presentations.

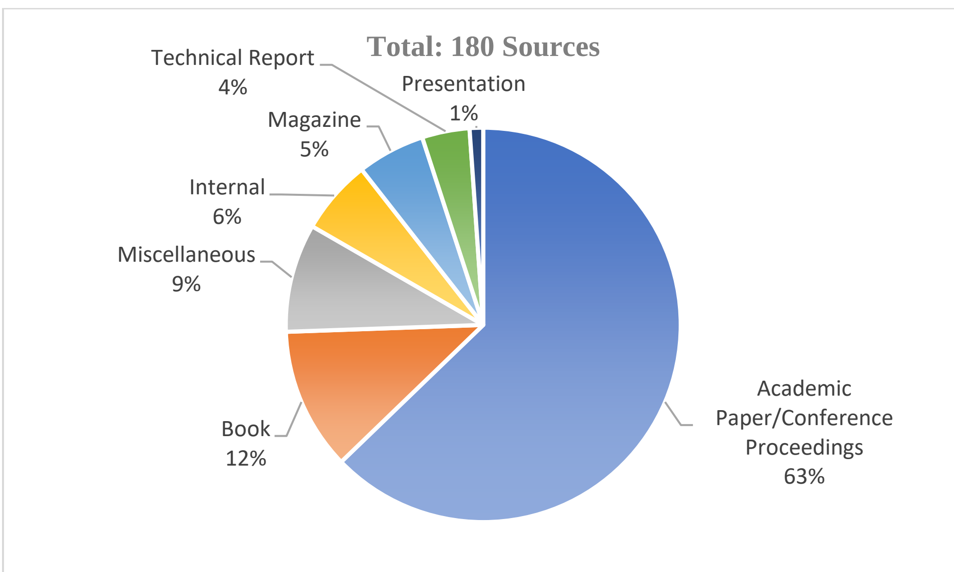

Figure 6.23. Source type breakdown - Sänger - II

For the Säenger-II bibliography, the miscellaneous sources are mostly dissertations, brochures, and various project specific drawings obtained.

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CHAPTER 7

COMPENDIUM IMPLEMENTATION

7.1. Data Collection

7.1.1. Defining Data

As Haney mentions in his dissertation, the data domain contains *"… facts, statistics, and media stored for future information requirements"* [1]. Data is purely numerical information about a system provided in raw format. Datasets by themselves do not provide further understanding regarding a topic but rather serve as lookup reference tables, although these do provide a more efficient way of storing data in tabulated format. Data is not as immediately useful as information or knowledge to the designer due to its nature. Dr. Chudoba explains: *"… Data represents raw material without implying any judgement or interpretation, thus it says nothing about its own importance or irrelevance. …"* [2]. Therefore, it takes intentional effort to define information from a dataset, or to organize it into digestible information.

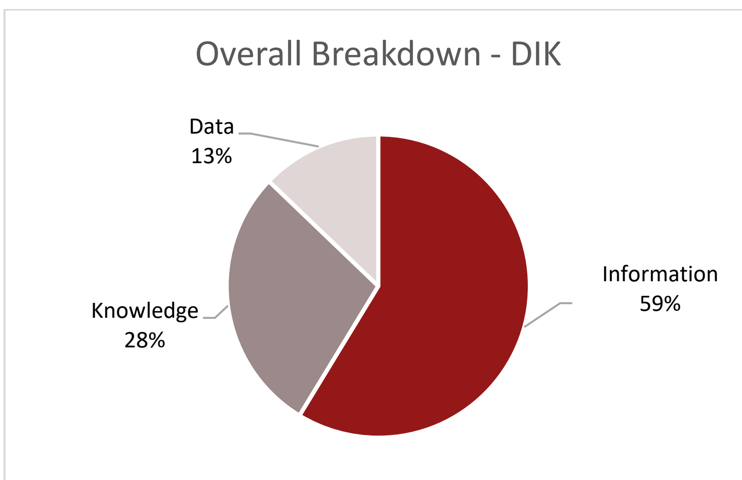


Figure 7.1. Overall percentage breakdown of DIK collected

As seen in Figure 7.1, about 13% of the design relevant parameters extracted are datasets in the form of tables and other numerical sets of data. This data has been categorized into the eight disciplines in a follow-on step. Table 7.1 lists some of the advantages and disadvantages of using raw data, especially for aerospace vehicle design.

Table 7.1. Advantages and Disadvantages of Data

Advantages	Disadvantages
Pure, raw numerical data presented directly; no extraction needed	*Does not provide any meaningful interpretations*
Easy to categorize and organize	*Inconvenient to search through hundreds of datapoints for necessary information*

Although tabulated data provides a structured and organized format for showcasing vehicle parameters and disciplinary design values, in larger numbers of entries, it becomes inconvenient to search for a particular value. Also, the lack of a visual element also makes this inconvenient. However, for storage purposes data is the simplest to handle; it is easier to recall data from a storage system since data is typically organized by header names.

7.1.2. Disciplinary Design Data

For the purpose of high-speed vehicle design, data includes any numerical parameter values that are either tabulated or mentioned within the text of technical reports and publications, etc. which would help a designer understand certain aspects of a particular vehicle. For example, the designer may be interested in knowing the maximum speed achieved by a certain vehicle, or the maximum lift to drag ratio achieved by a wing planform type. This type of inquiry can be quickly made using data stored as a lookup table, as long as the data is collected and organized accurately.

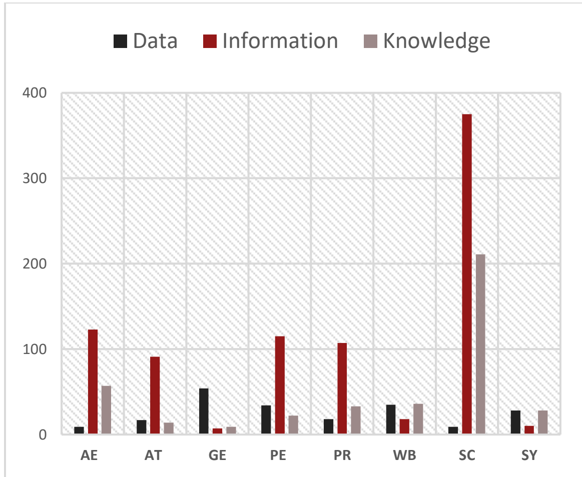
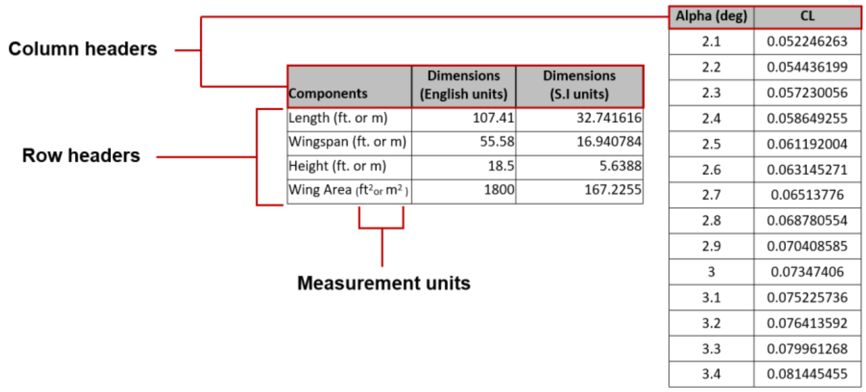


Figure 7.2. Amount of D-I-K found by discipline

As seen in Figure 7.2, from the survey of the sources collected as part of this research effort, the disciplines with the highest amount of data in comparison to information or knowledge are geometry, weights and balances, and synthesis. This is to be expected as most of the parameters found for each of these disciplines is typically presented in the form of tables. For example, the final weights and dimensions of a vehicle are not typically found to be changing with relation to any particular parameter to warrant plotting this as information, other than the change of fuel weight during a mission.

There are certain elements that may be considered crucial to the usefulness of a data table. This includes the following: appropriate column/row headers and identifiers, and units of measurement. If a data table is showcasing the relationship between two parameters and how one parameter is dependent on the other, then appropriate column headers do allow the user to easily identify the independent vs. dependent variables in this relation. If instead the data table is merely representing a series of numerical values accumulated for a particular vehicle, then appropriate row headers are to be expected as well. This is represented in Figure 7.3.



Components	Dimensions (English units)	Dimensions (S.I units)
Length (ft. or m)	107.41	32.741616
Wingspan (ft. or m)	55.58	16.940784
Height (ft. or m)	18.5	5.6388
Wing Area (ft^2 or m^2)	1800	167.2255

Alpha (deg)	CL
2.1	0.052246263
2.2	0.054436199
2.3	0.057230056
2.4	0.058649255
2.5	0.061192004
2.6	0.063145271
2.7	0.06513776
2.8	0.068780554
2.9	0.070408585
3	0.07347406
3.1	0.075225736
3.2	0.076413592
3.3	0.079961268
3.4	0.081445455

Figure 7.3. Elements of a data table

Column and row headers must be self-explanatory and may be abbreviated as necessary as long as it is clear to the user what the parameters are. In addition to clear and concise headers, the data tables must also include the units of measurement used for each row or column of data. This helps the user gain context for the physical meaning of the numbers and is important for the accurate use of the data contained in these data tables.

7.2. Information Conversion/Visualization

7.2.1. Defining Information

Most of the collected design parameters are presented in the form of information, specifically 59%, as seen in Figure 7.1. Even when looking at the number of data tables vs. information plots vs. knowledge visuals collected for an individual vehicle by discipline, information dominates in most of these categories, see Figure 7.4. This is to be expected due to the nature of information. Haney calls information the *central figure* to the decision-making process. He states that information may be singular in nature due to it influencing one decision at a time [1]. However, information is one step ahead of data in that there is a clear visual element to information. An information graphic provides a clear understanding of the relationship between two or more parameters of interest.

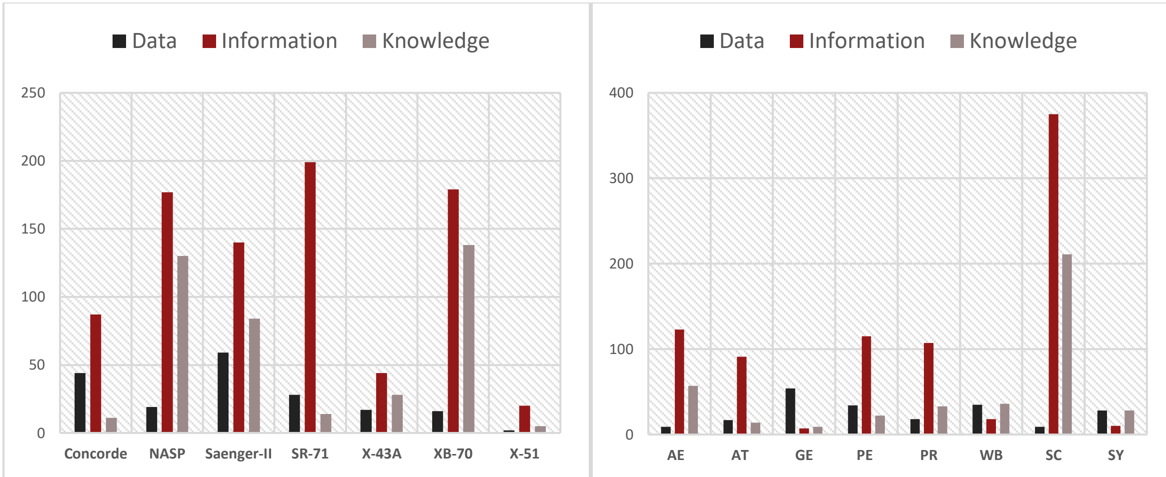


Figure 7.4. Amount of D-I-K found: (a) by vehicle, and (b) by discipline

A few plots that come to mind that are standard deliverables include the lift-curve slope (defines the relation between coefficient of lift and angle-of-attack of a vehicle), or a plot comparing the fuel consumption of an engine against the flight Mach number, etc. These plots may only influence a small number of design decisions at a time, and therefore may lessen their versatility with reference to the overall decision-making process when compared to a knowledge plot. Some of the main advantages and disadvantages of information plots are shown in Table 7.2.

Table 7.2. Advantages and Disadvantages of Information

Advantages	Disadvantages
Visual representation of relationship between two parameters; provides more context than numbers	*Numerical values not readily available; extraction from graph needed*
Singular nature of information allows for simpler understanding process	*Showcasing singular relationships at a time lessens the number of design decisions that could be supported from an information plot compared to a knowledge plot with multiple regressions*

The conversion process from data to information has been defined by Haney via the following step-by-step process, see Figure 7.5:

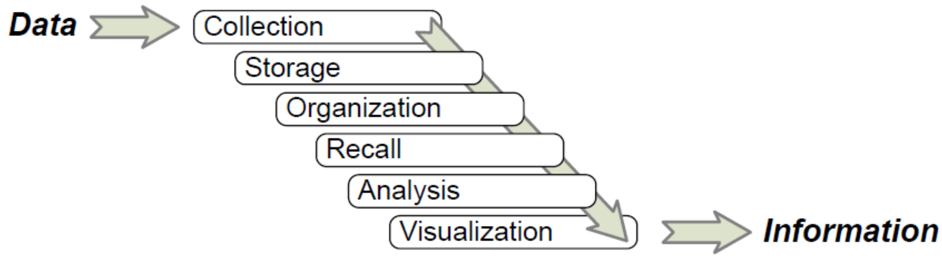


Figure 7.5. Data to information transformation process [1]

- Collection – this is the process of transferring data from its source to the working directory used by the researcher.
- Storage – this is simply the storage of the collected data in a database environment.
- Organization – the stored data must then be sorted base on the contents, dependent and independent variables, etc.
- Recall – Haney specifies this step separately to account for the querying process of existing data for use in a design context.
- Analysis – Analysis includes using mathematical operations and statistics to understand a dataset, which includes creating useful regression trends.
- Visualization – this is simply the process of representing the data in a visual format through the creation of figures or graphs.

There have not been many instances of utilizing such a conversion process during the VCC effort since a majority of the design parameters collected have already been in the form of information. The few data tables that have been collected did undergo this process as needed to produce information graphics.

7.2.2. Disciplinary Design Information

Aerodynamics, aerothermodynamics, stability & control, propulsion, and performance are the disciplines with a majority of the parameters represented in the form of information graphs. This is due to the fact that these disciplines typically showcase parameters with respect to other parameters (lift vs. drag, lift vs. angle of attack, temperature vs. Mach, etc.), as this information is important to the designer rather than standalone tabulated values of lift or temperature. Such parameter dependencies are important to understand the overall behavior of the vehicle with respect to each of these disciplines. These information plots have been extracted through the digitization process detailed in the Chapter 5, and the resulting extracted information is stored within an SQLite database alongside direct data found.

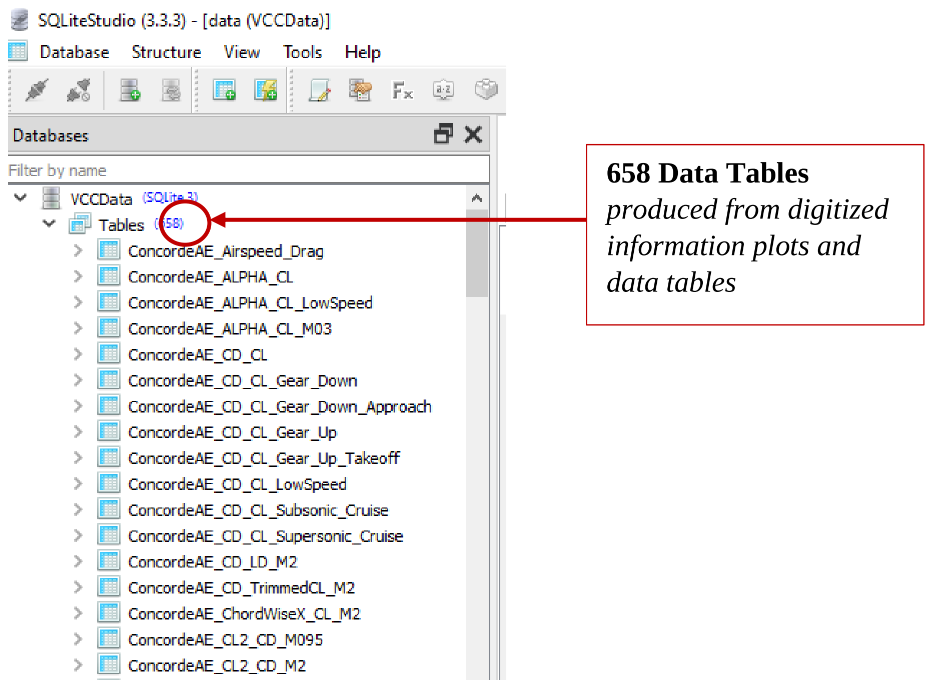


Figure 7.6. Screenshot from VCC database file showcasing amount of digital data stored

As seen in Figure 7.6, there are a total of 658 individual data tables added to the SQLite database for VCC. This includes the data tables manually typed and entered from sources, as well as the data extracted from information plots that are digitized. In order to express the effort invested in the current context, the effort required for the entire digitization and sorting process for the seven selected vehicles for the current VCC prototype spanned one year, with the labor divided amongst the author and two co-researchers: Samuel Atchison, and Ramlingam Pillai.

The key elements to a good information plot are as follows: well-defined visual axes with appropriate axis labels, units of measurement for each axis as necessary, and a descriptive plot/chart title, as seen in Figure 7.7. Information plots are typically found to be two-dimensional as these are easiest to represent in publications and for circulation. Three-dimensional plots are best visualized using a computer software or in a faux-3D environment such as a hologram.

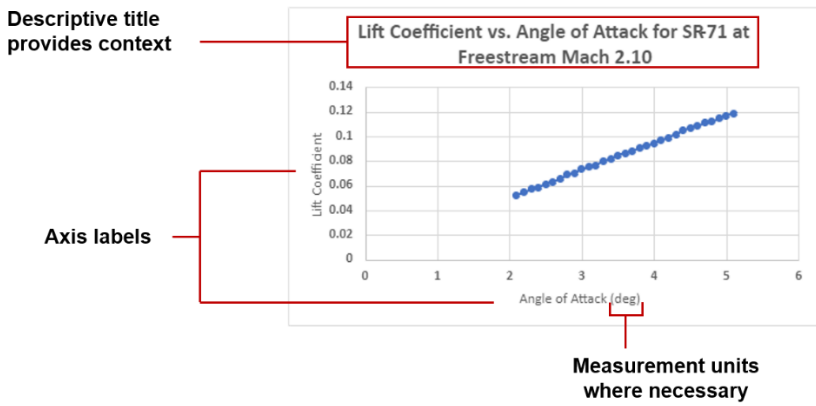


Figure 7.7. Elements of an information plot

Being two-dimensional in nature, information plots must have a clearly identified set of axes with a reasonable range of values that allow the capturing of the largest amount of information within the plot area. These axes must also include axis labels that include the parameters for each axis as well as the units of measurement for each parameter. Information plots should also include a descriptive plot title. This should provide context for the plot, and include such details as whether the information has been collected during flight test or simulation or wind tunnel test, etc., what the general conditions of this test have been – what is the speed or altitude of the flight, any major assumptions accompanying the test, etc. It is also useful to include what particular data collection methods have been utilized.

7.3. Knowledge Generation

7.3.1. Defining Knowledge

The Merriam-Webster dictionary defines knowledge as *"… the fact or condition of knowing something with familiarity gained through experience or association"* [3]. It becomes clear that knowledge comes primarily with experience in the topic of interest, which not all targeted users of the VCC may have. It is in fact impossible for every design engineer to gain direct experience with every single high-speed vehicle project, past to present, in order to gain knowledge from these projects. Hence the incentive to transition data and information generated by design teams with that profound experience into transferrable knowledge for the next generation.

Clearly, it is important to define and distinguish between all three terms - data, information, and knowledge – as accomplished for this research effort to contextualize. In addition to defining these terms as introduced in the previous chapters, a distinction must be made between each, to easily differentiate them from one another. With regards to the difference between information and knowledge, the Merriam-Webster dictionary provides a secondary definition for knowledge: *"… the range of one's information or understanding. …"* [3]. Then, knowledge is the result of a buildup of information, hence why it measures the range of information/understanding. Applying this same theory to the current research study, knowledge plots consisting of a range of information plots are deduced to deepen one's understanding of the subject matter. For example, a lift vs. drag plot informs a designer of the relationship between the two parameters but does not necessarily deepen their knowledge on the same subject matter. However, a plot with several lift vs. drag trends that vary depending on configurational characteristics, helps to understand the tendencies for this relationship to change, depending on the configuration. This visualization-style obtained becomes knowledge regarding the nature of this relationship. Table 7.3 describes a few of the advantages and possible disadvantages of a knowledge plot:

Table 7.3. Advantages and Disadvantages of Knowledge Graphics

Advantages	Disadvantages
Visual representation of relationship between two parameters and the effect of varying a third parameter.	*In large amounts of trends, could result in knowledge overload and overwhelm the user.*
Helps to gain deeper understanding regarding a subject area.	*Without proper annotation and labeling, a knowledge plot might become confusing.*
Aids in design decision-making by providing multiple design considerations.	

Although a basic understanding has been established about the nature of the relationship between information and knowledge, there must also be some clear parameters established that differentiate between a knowledge and information graphic. It is simple to distinguish between data and information due to the stark contrast between numerical data and visual plots. However, the distinction between information and knowledge may be less obvious since both are based on data to some extent. From the extent of the literature review conducted for this research activity, no sources have been identified that discusses specific metrics to distinguish between the two. Hence it is up to the author to establish the criteria for such a differentiation based on the observations from this research effort, having dealt with hundreds of data tables, information plots, and knowledge graphics. These criteria will be useful for categorizing plots or other such graphics that are debatable about whether they fall into information or knowledge primarily.

Before specifying such criteria, it must be noted that knowledge graphics in this context may be of two types: ones that allow for overall vehicle type comparison, and ones that allow for disciplinary parameter comparisons, as shown in Figure 7.8. Both types of graphics provide useful comparisons that aid in design decision-making to be considered ‘knowledge’.

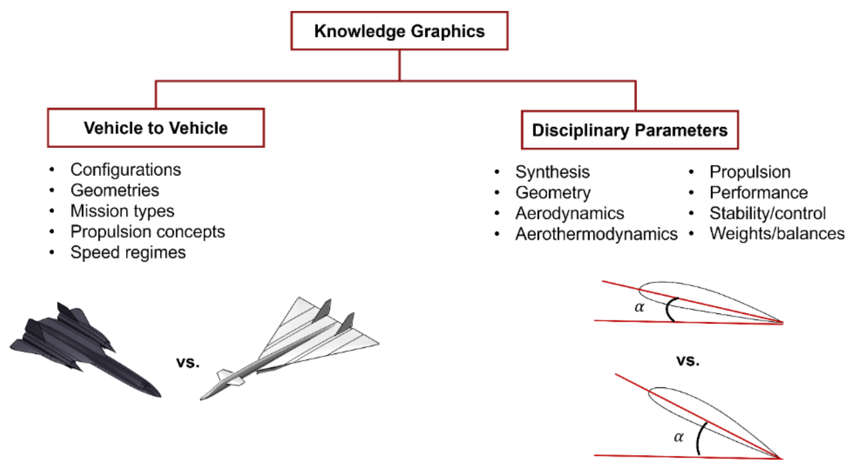


Figure 7.8. Two types of knowledge graphics illustrated

Each of the following are the minimum criteria for a plot to be considered ‘knowledge’ and not information. A knowledge plot must satisfy at the very least one of the following criteria:

- Compares at least 2 different configurations.
- Compares at least 2 different cross-sections.
- Compares Mach numbers from at least two different speed regimes (the range of Mach numbers crosses between subsonic and supersonic, or supersonic and hypersonic).
- Compares at least 2 different fuel types/propulsion concepts.
- Compares at least 2 different mission types.

- If the plot is comparing disciplinary parameters, it must compare at least three variations of that parameter.

It must be noted that plots comparing a vehicle wind tunnel test with flight test results, or comparing multiple methods of calculating the same parameter, are not considered knowledge plots in this study. The reason for this stems from the earlier definition of the basic function of a knowledge plot – to aid in making design decisions. If the multiple trendlines shown in one plot do not provide design options to the designer, then this is not considered a design knowledge plot. Method comparison plots may be considered as falling under ‘verification’ if the vehicle’s true flight-measured values are plotted for comparison. Such graphics rather provide knowledge regarding the accuracy of certain methods, and hence are not considered ‘design knowledge’.

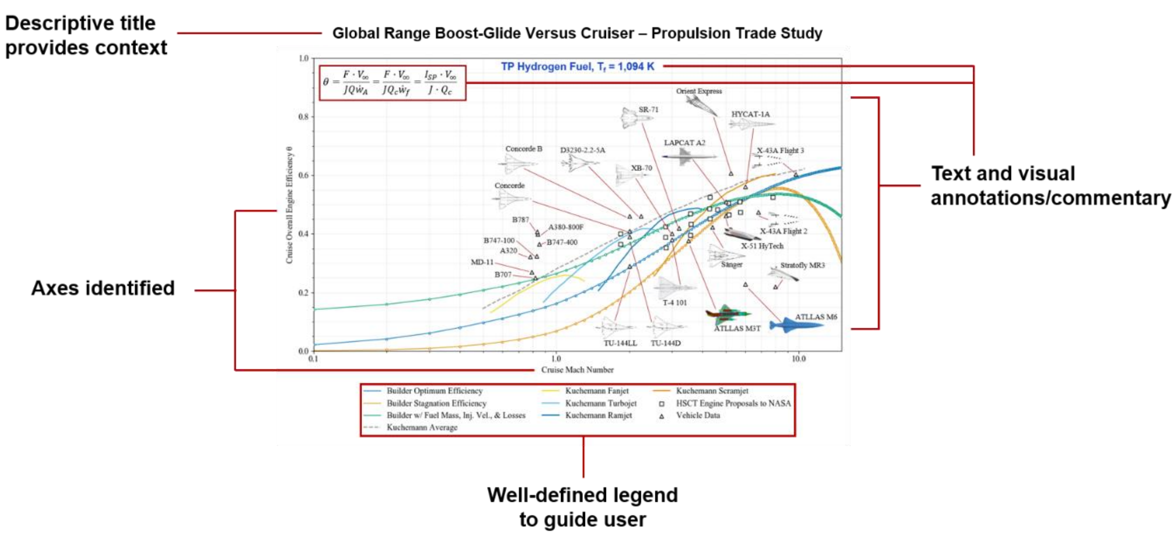


Figure 7.9. Elements of a knowledge graphic

The components of a knowledge plot that are necessary include the following: axis labels and units as necessary, descriptive figure title, well-defined legends, and verbal commentary and visual annotations to guide the user. This is demonstrated in Figure 7.9 with an example of a knowledge graphic produced as part of the AVD Laboratory NASA study [4] to which the VCC contributed to, the results of which will be discussed later in this chapter.

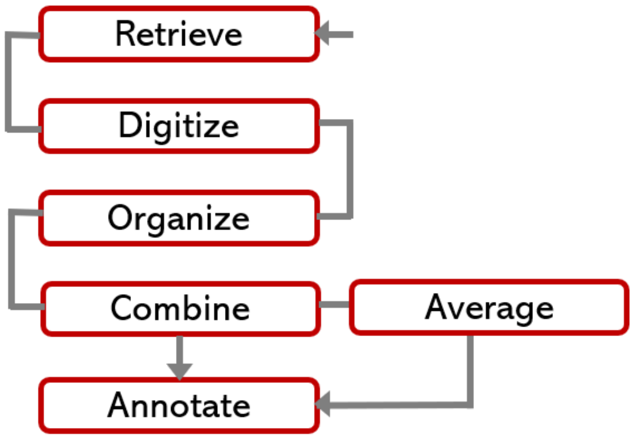


Figure 7.10. Process of converting information to knowledge

Similar to how Haney defined the process of data to information conversion in his study [1], this study adapts the steps to convert multiple pieces of information into knowledge. The conversion process is following the following six steps as outlined in Figure 7.10:

- Retrieve

  This is the process of digitally retrieving the information plots – by snipping them and storing them as .png files.

- Digitize

  These .png files are digitized to extract the numerical data that makes up the information plots.

- Organize

  This data is then organized based on the x and y axes presented, as well as based on what is most useful to the designer. For example, all the lift-curve slopes for a particular mission segment may be grouped for combining together, etc. This will then determine the contents of the plot legend.

- Combine

  Then the grouped datasets are combined by plotting them on one set of axes, to visualize multiple trendlines together.

- Average

  In addition to combining the different information plots, an average can be generated for each configuration or vehicle type if there is enough variation in information present in the same plot. For example, if there are multiple sets of information for each configuration, then those sets can be averaged to generate a general trendline that represents the tendencies of a particular configuration. This is added to the side as an additional step that may or may not be followed based on the quantity of information available for each configuration.

- Annotate

  Perhaps the most important step of producing a good knowledge plot, intelligent and helpful annotations must be provided that will guide the user. The legend discussed earlier is a part of such annotation. Knowledge graphics must be self-explanatory and leave no pressing questions to a designer who may already be overwhelmed with the intricacies of design. Annotations may include labeling trendlines with images of the vehicle or the vehicle name or both, adding legends that guide the user to the meaning behind particular plotting schemes, highlighting regions within the plot of particular significance, etc.

Provided is an example of this process carried out, shown in Figure 7.11. This is the process of compiling various C_l vs. *AOA* (angle-of-attack) plots into one knowledge plot.

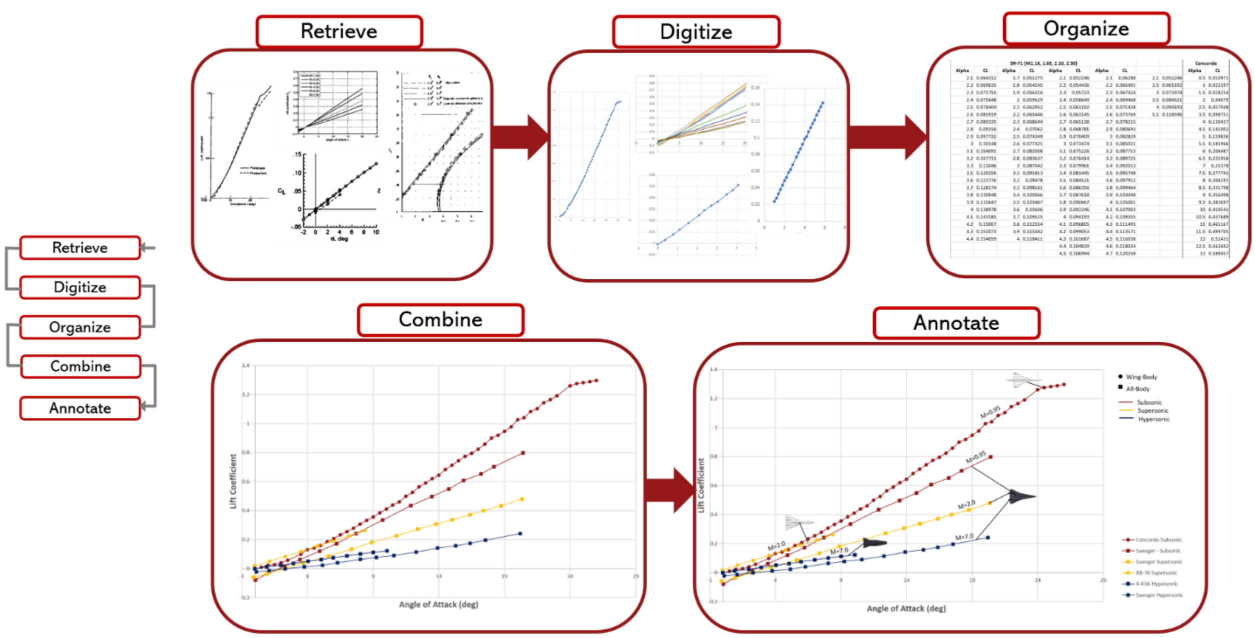


Figure 7.11. Example of information-to-knowledge process carried out

As shown, first the relevant information plots are retrieved by snipping them from the digital PDFs and storing as .png files for each vehicle. Next is the digitization process, where the numerical data that defines each plot is extracted. This data is plotted again using Microsoft Excel in order to visually verify the accuracy of the data extracted compared to the original images. After that comes the organization process, where the numerical data is sorted by vehicle name, vehicle category, and x and y axes, in an Excel spreadsheet. After this, the data is then combined into one singular plot on one single set of axes. Next comes the annotation process where the vehicle types compared are identified, as well as labeling of the trendlines for each vehicle with a visual of the vehicle and the Mach number of operation where this data has been collected.

It is clear to see that before annotation, the knowledge plot is of little use and would be rather confusing to someone trying to gain understanding from such a graphic. The annotations make up the key element that allows a knowledge graphic to be dissected and studied for the gaining of the knowledge contained within.

7.3.2. Categorizations for Comparison

For the building up of knowledge plots, there are many different comparison graphics that may be created depending on what a designer would find most useful to compare. Depending on the type of design activity conducted, the designer may be looking into comparisons based on configurations, specific cross-sections for the same configuration, specific wing sweep angles for the same cross-section, etc. Hence it becomes apparent that there are a multitude of possibilities for conducting comparisons. Some of the major categories for comparisons are described below for reference. It must be emphasized that the categorizations showcased in the following sub-sections are only for one of the two major knowledge types, which is vehicle-to-vehicle comparison. The identification of every single possible comparison on a disciplinary level is beyond the scope of this project. It must also be noted that the categories presented here are merely a suggested handful for illustration purposes, as there are multitudes of more vehicle categorizations of relevance.

7.3.2.1. Configurations

There are various flight vehicle configurations that may be considered for an aircraft, a list of which is shown in Figure 7.12 with the configurational characteristics demonstrated in the right column [5]. The configuration of an aircraft consists of the general layout of the vehicle with the placement of its major components. Different configurations may provide performance advantages for specific mission types or speed regimes.

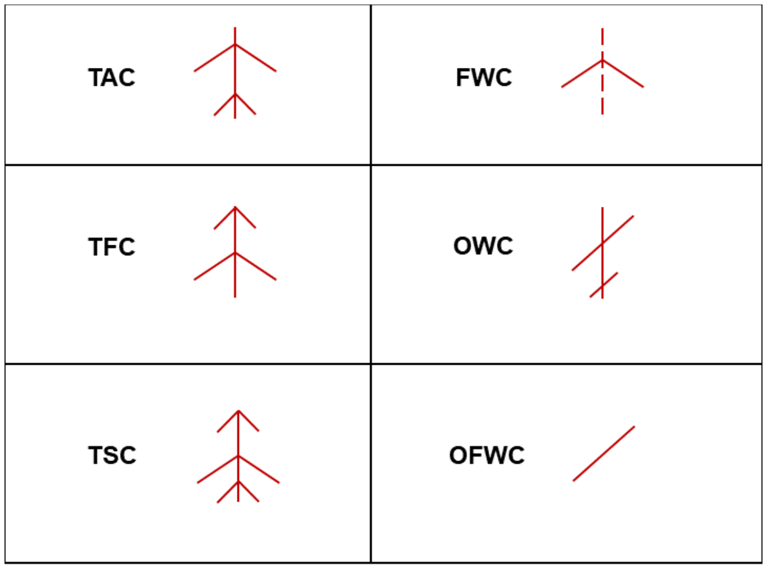


Figure 7.12. Various aircraft configurations – schematics reproduced from Dr. Chudoba [5]

The configurations shown in Figure 7.12 include the following:

- TAC (Tail-Aft Configuration) *[X-51, X-43A, NASP X-30]*
  This configuration features wings and an aft horizontal tailplane.
- TFC (Tail-Forward Configuration) *[XB-70]*
  In contrast to TAC, TFC features a horizontal lifting surface that sits in front of the wings (canard).
- TSC (Three-Surface Configuration)
  This configuration typically features a set of wings, an aft horizontal tailplane, and a forward canard surface to generate increased lift.
- FWC (Flying-Wing Configuration) *[Concorde, Sänger-II, SR-71]*
  Flying wing aircraft have no auxiliary horizontal tailplane but a prominent wing structure blended or intersecting with the fuselage.
- OWC (Oblique-Wing Configuration)
  This configuration features a wing that is designed to pivot on the center point so one of the wing tips is swept forward.
- OFWC (Oblique Flying-Wing Configuration)

An Oblique Flying Wing is an oblique wing-only aircraft with no fuselage like a typical flying wing concept.

7.3.2.2. Cross-Section Concepts

Another option is to allow the user to compare between various cross-sections of vehicles. There are three major types of cross-sections for aircraft that are considered, as shown in Figure 7.13.

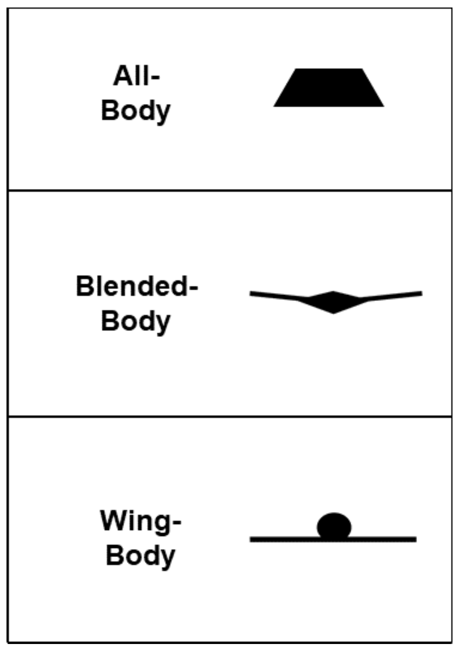


Figure 7.13. Various aircraft cross-sections

- All-Body *[X-51, X-43A, NASP X-30]*

  These aircraft do not have distinguishable wings. Many all-body (AB) aircraft are typically lifting body vehicles where the body itself produces the lift instead of wings.

- Blended-Body *[SR-71, Sänger-II]*

  Blended-body (BB) aircraft have wings that blend with the fuselage, and therefore it is difficult to find a distinguishing line where the wing stops and the fuselage begins, or vice versa.

- Wing-Body *[XB-70, Concorde]*

  This is the typically aircraft concept, common among passenger aircraft. There is a distinct fuselage and a set of wings that are clearly differentiated from one another.

7.3.2.3. Speed Regimes

Another useful comparison metric for a designer may be to compare the performance characteristics for various design speed regimes. Since a variation in speed does greatly affect the aerodynamics and stability & control of the vehicle overall, the designer may choose a specific Mach range for operation based on such comparison. There are three primary speed regimes:

- Subsonic (< Mach 1)
- Supersonic (Mach 1 >, <Mach 5) *[SR-71, XB-70, Concorde]*
- Hypersonic (> Mach 5) *[X-51, X-43A, Sänger II, NASP]*

7.3.2.5. Propulsion System Type

There is a large variety of propulsion systems that may be used in high-speed vehicles. A designer may want to compare the performance capabilities of vehicles that have been powered by different types of systems to understand the advantages and disadvantages of a specific type of engine. Given below are the primary engine types that may be considered as individual engines or combined-cycle implementations:

- Turbojet
- Afterburning turbojet
- Ramjet
- Scramjet
- Rocket

7.3.2.6. Mission Type

There are various missions for which high-speed vehicles are developed, and comparing certain parameters based on the mission definition might help a designer make technological decisions. The mission for which the vehicle is conceptualized affects the extent to which the vehicle is able to perform, which is why each high-speed vehicle is custom-tailored to its mission definition. The major types of mission types considered for this study include, but are not limited to the following:

- Technology demonstrator

  Some high-speed vehicles are developed as technology demonstrators. The sole purpose of such vehicles is to showcase the performance capabilities and allow an opportunity to collect data on a new piece of technology that has been developed. An example of this is the X-51A which was used by AFRL for demonstrating the new SJX61 scramjet engine [6].

- Aerospaceplane

    There are high-speed vehicles that may be developed as spaceplane concepts. There is currently a rise in interest in space due to the increasing popularity of space tourism, which means the concept of spaceplanes may be of interest in the future. An example of a previous project is the NASP X-30. Although the project was cancelled, the vehicle aimed at becoming a manned spaceplane in addition to vehicle derivatives capable of being a hypersonic cruiser, which leads to the next high-speed vehicle mission type.

- Reconnaissance

    High-speed vehicles may be used for reconnaissance purposes, such as the SR-71 or the F-15 which are considered long-range reconnaissance vehicles. Such vehicles may be used to collect intel from other countries, as well as for surveillance [7].

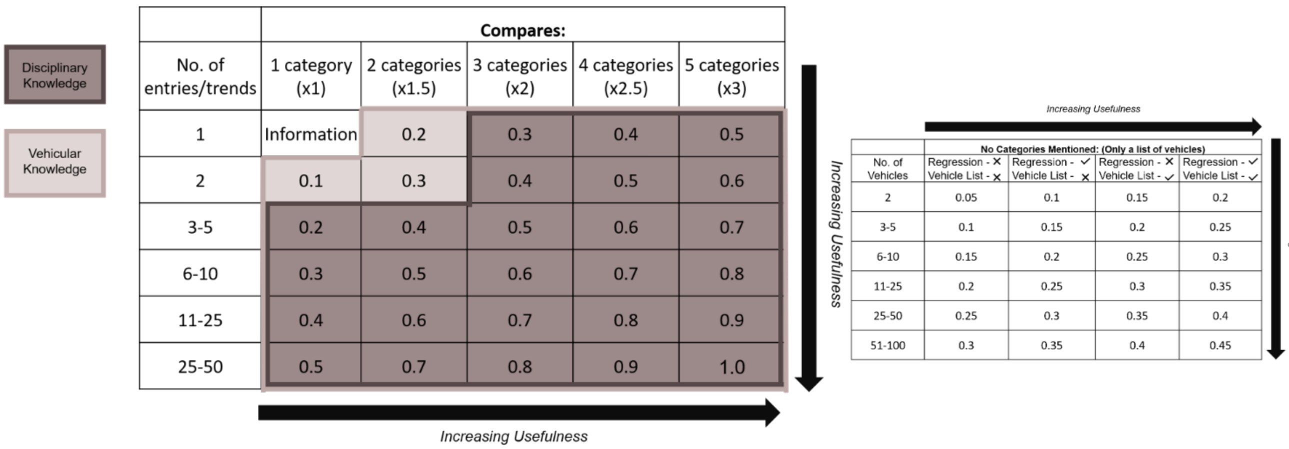
- Passenger Aircraft

    There are also high-speed passenger vehicles, such as supersonic business jets, which aim to cut down on travel time between major airports. The Concorde was one such vehicle that was cancelled after a few decades of successful operation in industry. Currently there are companies like Boom and Hermeus competing to be the next to bring such a passenger transport vehicle into industry.

7.3.3. Knowledge Usefulness Rubric

Some knowledge plots and graphics are more useful to the designer than others depending on the relevance of comparisons that may be made between different categories of vehicles. It is therefore of interest to develop a rubric by which to grade each of the knowledge plots identified or also generated in the next couple of subsections. This provides a scale to evaluate the relevance of individual knowledge plots.

As seen in the previous subsection, there are several ways to categorize vehicles to facilitate comparisons in one singular plot or graphic. The rubric shown in Figure 7.14 assumes that a single knowledge graphic is able to compare up to five different categories, and up to 50 individual trends/entries at once. It is the author's opinion that comparing any number of categories above 5 or any number of entries above 50 would lessen the usefulness of the visual and rather result in a 'knowledge overload' that could detract from the point of knowledge in the first place. This downward trend has not been accounted for in the rubric yet, as there are no existing examples from the VCC collection activity, and hence is outside the scope of this research activity.



	Compares:				
No. of entries/trends	1 category (x1)	2 categories (x1.5)	3 categories (x2)	4 categories (x2.5)	5 categories (x3)
1	Information	0.2	0.3	0.4	0.5
2	0.1	0.3	0.4	0.5	0.6
3-5	0.2	0.4	0.5	0.6	0.7
6-10	0.3	0.5	0.6	0.7	0.8
11-25	0.4	0.6	0.7	0.8	0.9
25-50	0.5	0.7	0.8	0.9	1.0

	No Categories Mentioned: (Only a list of vehicles)			
No. of Vehicles	Regression - ✕ Vehicle List - ✕	Regression - ✓ Vehicle List - ✕	Regression - ✕ Vehicle List - ✓	Regression - ✓ Vehicle List - ✓
2	0.05	0.1	0.15	0.2
3-5	0.1	0.15	0.2	0.25
6-10	0.15	0.2	0.25	0.3
11-25	0.2	0.25	0.3	0.35
25-50	0.25	0.3	0.35	0.4
51-100	0.3	0.35	0.4	0.45

Figure 7.14. Rubric developed for determining usefulness of a knowledge graphic

As shown in Figure 7.14, there is no score designated for a plot with only one category and one trend for that category, since this is simply defining the contents of a typical information plot. There are up to five different categories that may be compared in one singular plot. The score given by the rubric depends upon the number of trends showcased for each category involved in the plot. Recall that for example 'speed regimes' is a single category with three different entries possible (subsonic, supersonic and hypersonic). This is explained more efficiently with the aid of actual knowledge graphics, such as the ones shown in the following subsections.

7.3.3.1. Scoring Knowledge Graphic Type – Vehicle Comparison

Recall that earlier within this chapter two major types of knowledge graphics have been identified: vehicle-to-vehicle type comparisons, and disciplinary comparisons. The first example shown is that of a comparison of vehicle types.

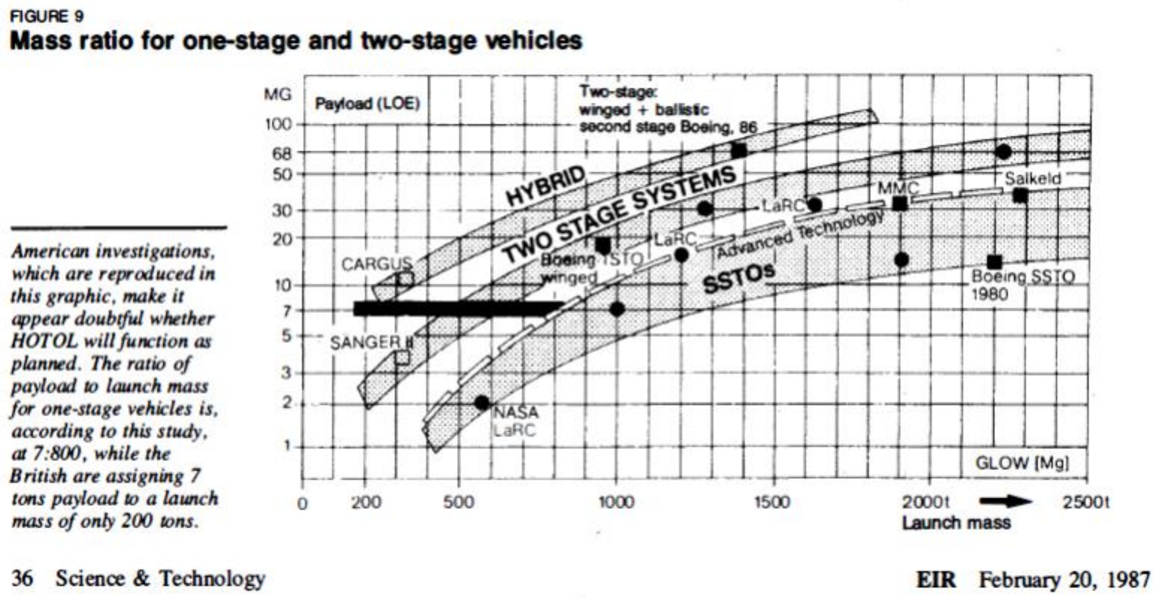


Figure 7.15. Mass ratio comparison [8]

Considering Figure 7.15, this plot provides the relationship between payload weight and gross lift-off weight for a variety of vehicles. At first, the number of categories compared is determined. Note that individual vehicles do not count as categories. From the graphic, it looks like the number of stages is being compared, which means there is only one category of comparison (category = 'number of stages'). For this category, there are three types within that category compared: single stage, two-stage, and hybrid. This means there are three 'entries' in that same category. According to the rubric developed, this means the overall usefulness score of this graphic is calculated to be 0.2 (3-5 entries) x 1 (corresponds to 1 category) = 0.2. The highest score a plot may receive on this scale is 1 (25-50 entries) x 3 (corresponds to 5 categories) = 3. Therefore, the usefulness of this knowledge graphic is 0.2 out of 3. Had the same plot compared multiple categories, as in comparing number of stages as well as propulsion concepts, then the score would have been higher.

7.3.3.2. Scoring Knowledge Graphic Type – Disciplinary Comparison

The other major type of knowledge graphic is identified as disciplinary in nature, in that the comparisons are not made across various vehicles or vehicle types but rather across a range of values for certain disciplinary parameters. Shown in Figure 7.16 is an example of this type of plot.

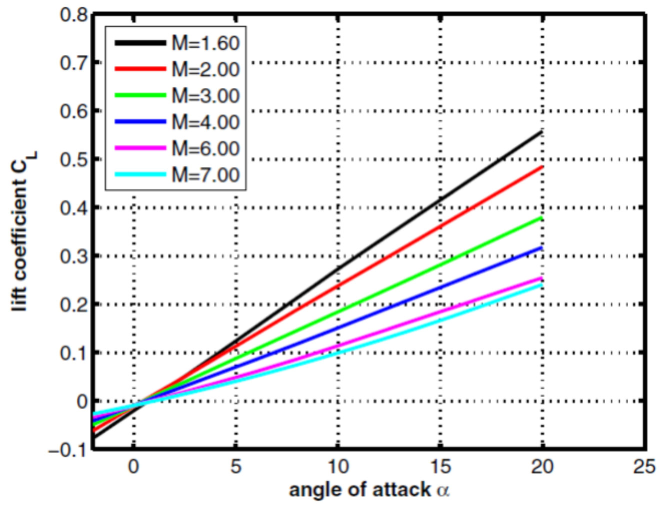


Figure 7.16. Lift coefficient vs. angle of attack - Sänger II [9]

Figure 7.16 shows how the lift coefficient of the Sänger II vehicle changes in relation to the angle of attack of the vehicle. Even though this plot is only based on one singular vehicle, this is still considered a knowledge plot since a range of different Mach numbers is compared (Mach 1.6 through Mach 7).

In terms of scoring this knowledge graphic based on the rubric mentioned before, there is only one category being compared, which is the Mach numbers, which means the score from the rubric is multiplied by 1. The number of trends within this category is 6 (six different Mach numbers), which means the final score for this would be: 0.3x1 = 0.3 out of 3.

7.3.3.3. No Categories Specified

In addition to the two major types of knowledge plots sampled in the previous sections, an additional example is given for the extended rubric section shown in Figure 7.14. This is for scoring a knowledge plot that has no categories defined but rather represents an amalgamation of data points, with each data point representing a singular vehicle. Such knowledge plots are not as useful as the plots which provide a focused categorization for the vehicles shown. The usefulness of these plots depends on whether one or both of the following are present: a list of individual vehicles, and a regression or trendline generated for the datapoints.

The example used here shows a number of vehicles plotted to show the relation between their net mass fraction and ascent propellant mass, as seen in Figure 7.17.

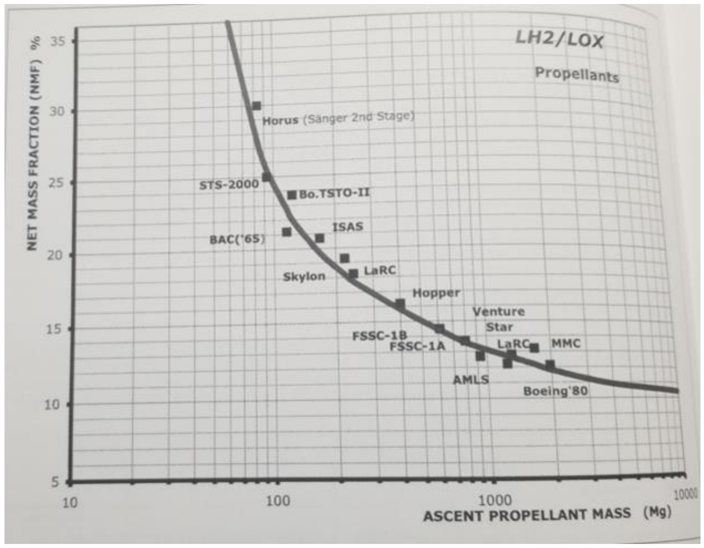


Figure 7.17. Net mass fraction vs. ascent propellant mass [10]

As seen with this example, there is both an identification of the vehicles listed, as well as a trendline/regression generated based on the general trend of the datapoints. According to the extended rubric, this results in a higher score since both elements that are seen as useful for such a plot are present. There are 15 individual data points/vehicles shown in this figure, meaning the overall score is 0.35 for this plot.

7.3.4. Design Knowledge Collected

Although there has been a lesser number of knowledge-graphics identified during the VCC search and digitization process compared to information, there are a few prominent ones that come to mind as potentially useful to the designer, which are shown below. Each of the knowledge plots are broken down to provide the following information:

- Figure title
- X-axis, units
- Y-axis, units
- Source of the figure
- Type of knowledge plot (disciplinary or vehicle to vehicle comparison)

- Number of comparisons made in the plot
- Highest number of trendlines/data entries found for any one category
- Type of annotation (Verbal annotation or visual annotation, or both)
- Knowledge usefulness score

The first knowledge plot shown is comparing various engines by their I_{sp} range, as seen in Figure 7.18. This plot has been selected from a source that is part of the NASP X-30 bibliography. As denoted in the image, there are clear axes and units identified and there are multiple engine types compared in one singular plot. Each engine type is indicated by text annotations.

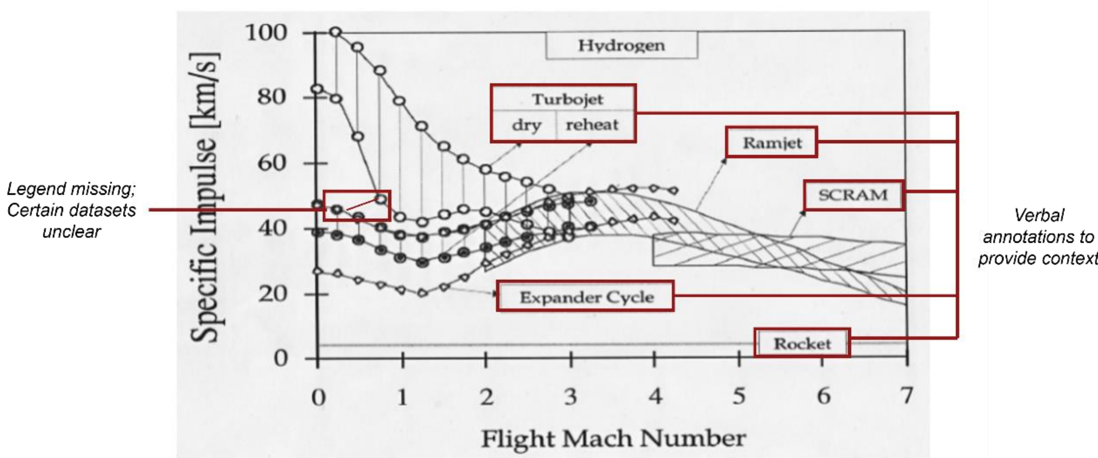


Figure 7.18. I_{sp} vs. Mach for various engines [11]

However, there is no legend for references, which means the reader is unable to decipher the difference between the datapoints and the shaded regions in the graph, if there is any. Not every data set is labeled either, which is not convenient. This is why legends are important additions to any knowledge graphic. This knowledge graphic is further broken down as shown in Figure 7.19.

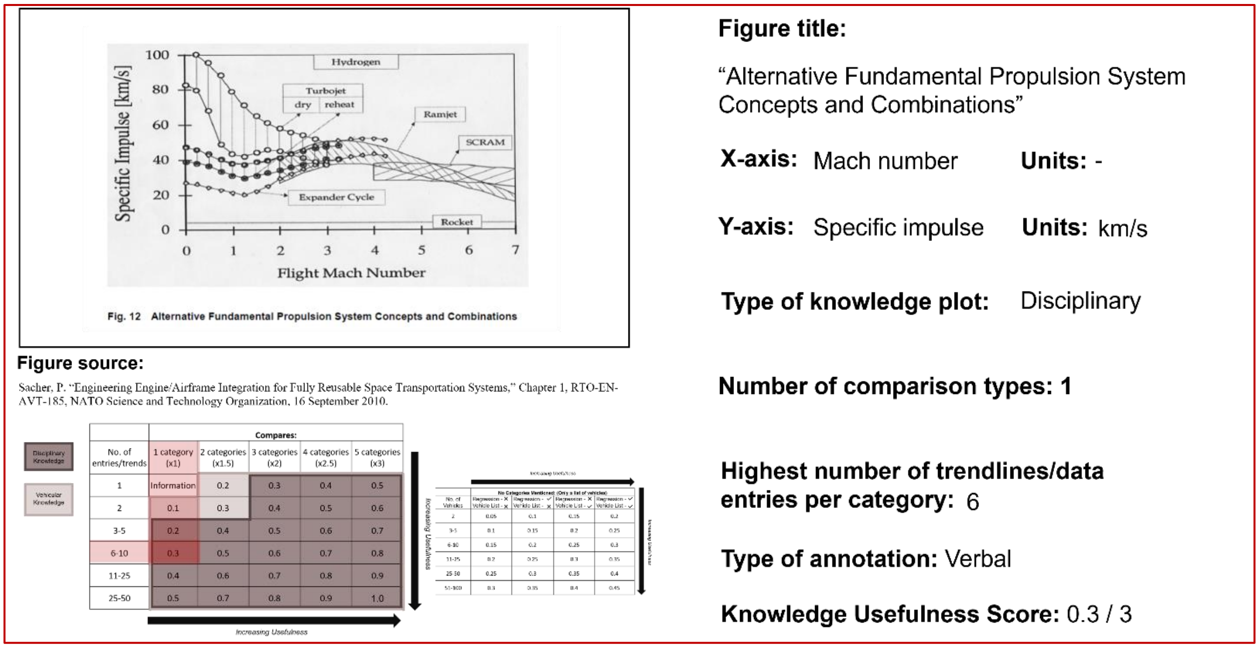


Figure 7.19. Breakdown of knowledge plot: I_{sp} vs. Mach comparison

The next knowledge plot shown also addresses the propulsion discipline, see Figure 7.20: This graphic is providing similar information as the first knowledge graphic, but in addition to comparing the different engines, this graphic also compares fuel types within the same plot. This knowledge plot is useful for a designer considering the effect of choosing hydrogen over a type of liquid hydrocarbon fuel, for a particular engine type.

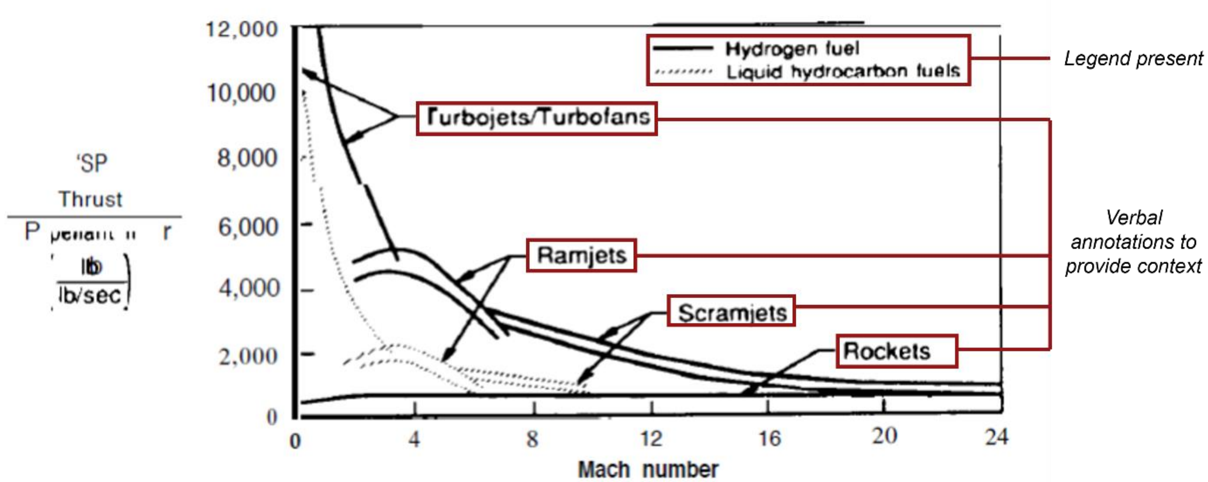


Figure 7.20. I_{sp} vs. Mach for different engine and fuel types [12]

As seen in Figure 7.20, this knowledge plot also provides verbal annotations, and a legend is also present which allows the reader to distinguish between the two types of lines shown in the plot. The further breakdown of this knowledge plot is shown in Figure 7.21.

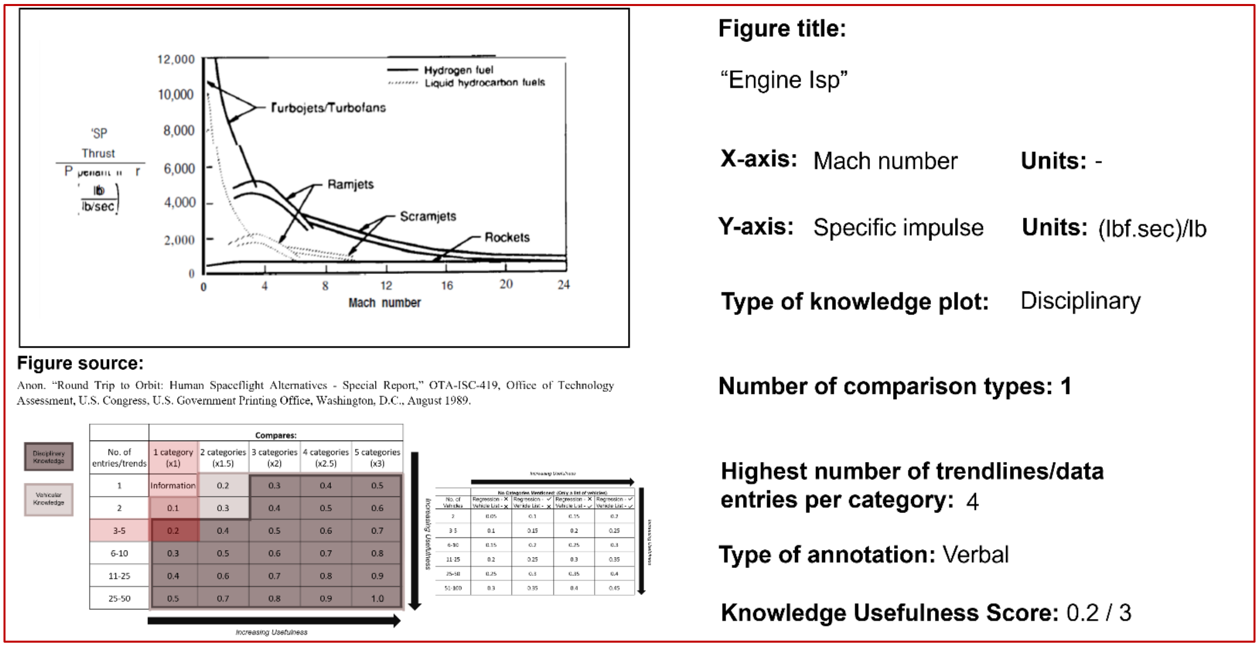


Figure 7.21. **Breakdown of knowledge plot: I_{sp} vs. Mach comparison (fuel types added)**

The third and last sample knowledge plot from the collection activity for the VCC is shown in Figure 7.22. This figure compares the lift-to-drag ratios of a variety of vehicle slenderness ratios.

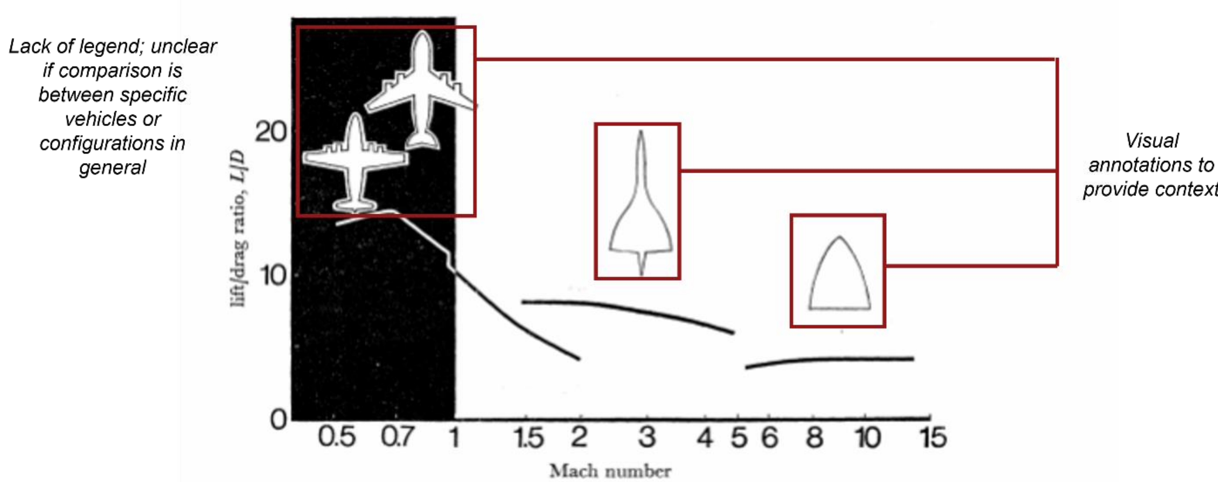


Figure 7.22. Lift-to-drag ratio against Mach number [13]

The visual annotations help to some extent to understand the comparison made in this plot, but there needs to be more detail added to this figure to make it useful for a designer. The subsonic speed regime is clearly defined in the graph but the same is not done to distinguish between the supersonic and hypersonic regimes. The full breakdown of this knowledge graphic is provided in the Figure 7.23:

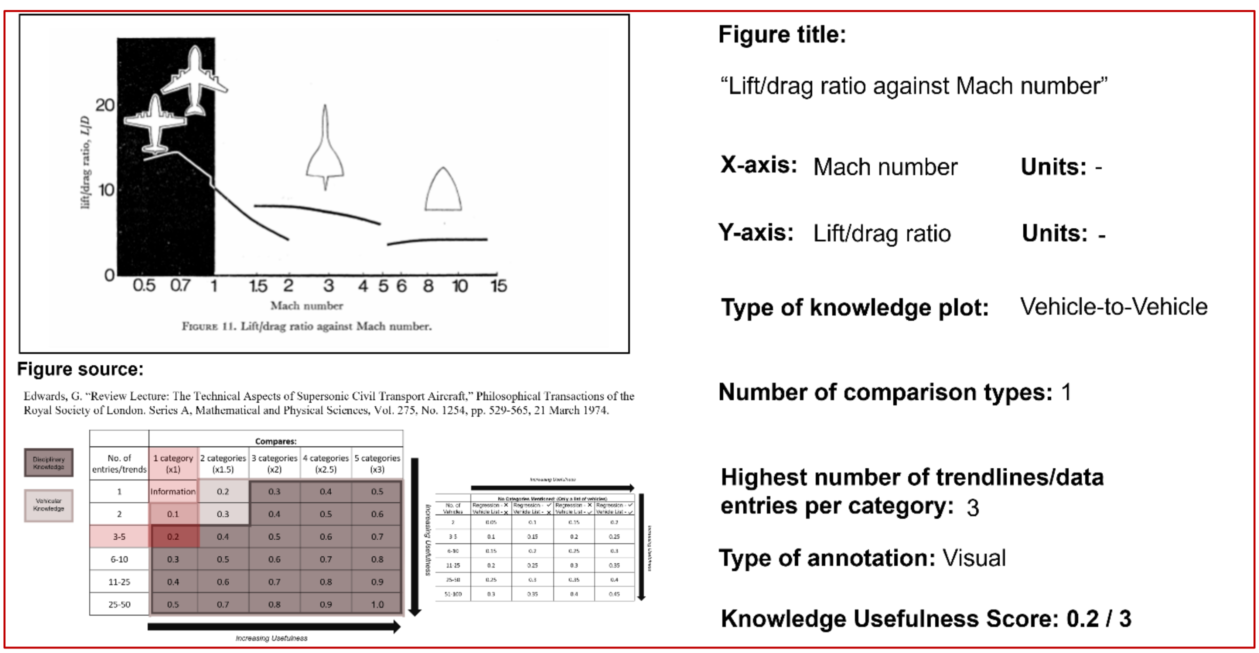


Figure 7.23. Breakdown of knowledge plot: lift to drag ratio vs. Mach number

7.3.5. Knowledge Trends Generated

In addition to the knowledge trends collected, a few knowledge trends have been generated using the information to knowledge conversion process mentioned in section 7.3.1. These knowledge trends serve as examples of what can be achieved even using such a small sample size of vehicles for the prototype VCC. The entirety of the data and information set collected for VCC has been surveyed including lists of relations generated for each vehicle and discipline. This then allows for the selection of disciplinary knowledge plots that address the highest number of vehicles for comparison, in order to produce the most useful knowledge plots possible.

7.3.5.1. Aerodynamics

For aerodynamics, the lift-curve slope has been isolated for four vehicles – the Concorde, Sänger-II, XB-70, and X-43A. In addition, the Sänger-II data contains lift vs. angle of attack values for all three speed regimes – subsonic, supersonic, and hypersonic. Combining this information with the other vehicle data sets allows the development of the knowledge plot shown in Figure 7.24 with two trends for each speed regime.

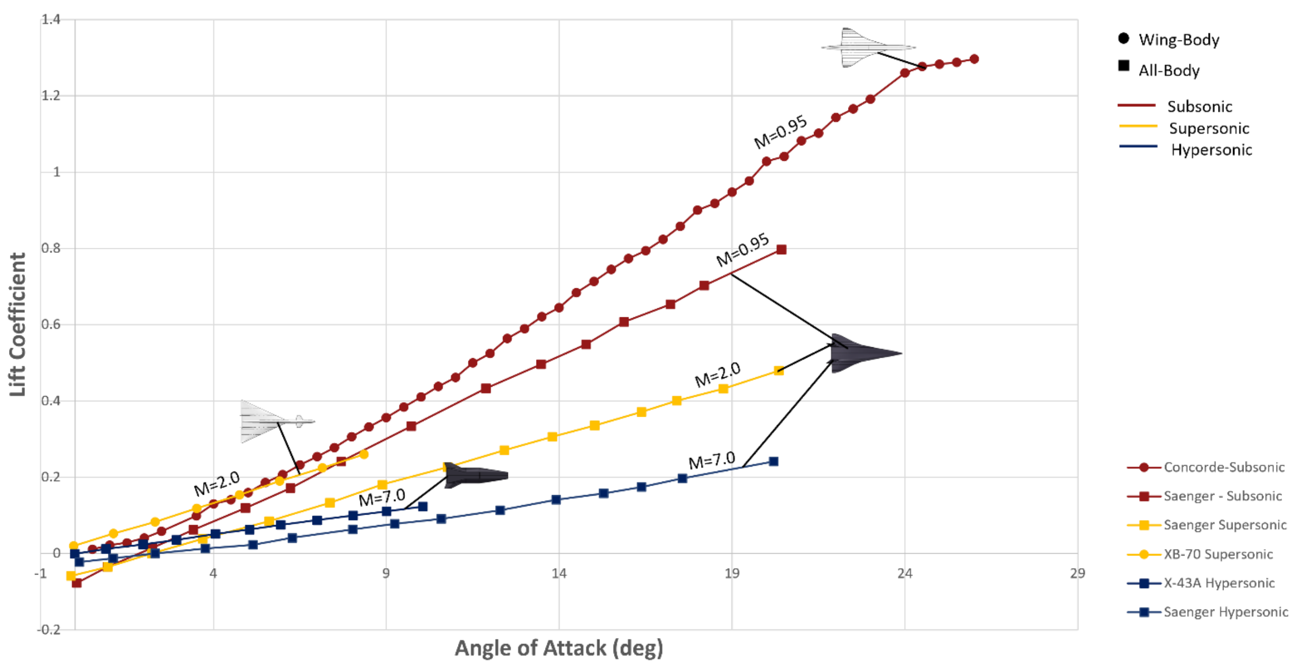


Figure 7.24. Knowledge plot – lift-curve slope for various vehicles comparing two configurations and three speed regimes

In Figure 7.24, each of the speed regimes is represented with a different color scheme, and the two different vehicle geometries (wing-body and all-body) are represented with distinct data markers. In addition to this, each of the trendlines are labeled with the specific Mach number for which this data applies to. This allows the designer to quickly compare vehicle geometries and speed regimes if needed, to view the tendency of the lift coefficient to angle of attack relation for these combinations. However, if the designer still likes to know the individual vehicles used in this comparison, that information is available as a secondary legend on the right side of the plot, and the trendlines are labeled using the vehicles as well. As such this knowledge plot makes every attempt at providing as much detail to the designer as possible while being as concise as practical.

Using the scoring rubric developed earlier, this plot receives the following score:
0.4 (3-5 entries per category – 4 entries for all-body) x 1.5 (corresponds to two categories compared – speed regimes and vehicle geometries) = 0.6 out of 3.

For aerodynamics, another knowledge graphic generated is the comparison of drag-polars, see Figure 7.25. A total of five vehicles has this information available in the VCC collection: NASP X-30, Sänger-II, X-51, Concorde, SR-71, and XB-70. For this knowledge graphic, the vehicles are compared based on their configuration. Three configurations are compared in Figure 7.25, namely the flying-wing configuration (FWC), the tail-aft configuration (TAC), and tail-first configuration (TFC). These configurations are identified using specific data point markers. In addition, the vehicle list is provided as an additional legend and so are the vehicle labeled on the trendlines.

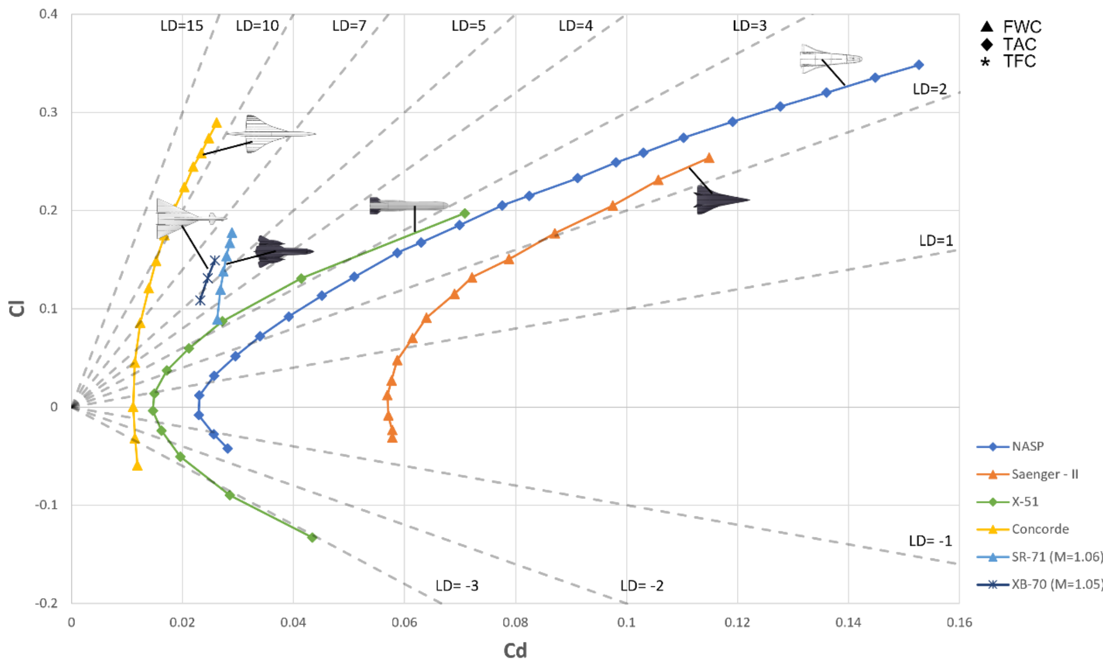


Figure 7.25. Knowledge plot - drag polar generated from VCC information plots

In addition to these characteristics, lift-to-drag ratios are plotted in the same graphic for a baseline comparison for the designer. L/D ratios ranging from -3 up to 15 are provided as dotted lines. This allows the designer to quickly relate the range of lift-to-drag ratios for a particular vehicle by visual inspection. For example, it is seen that the vehicle with the highest lift-to-drag ratio is Concorde, reaching approximately *L/D* = 11 according to the figure.

According to the knowledge usefulness rubric developed earlier, this plot scores as follows: 0.2 (3-5 entries per category: up to 3 FWC lines) x 1 (only one categorization of vehicles: configuration) = 0.2 out of 3.

7.3.5.2. Aerothermodynamics

Aerothermodynamic knowledge plots are more difficult to generate since most of the temperature information is typically provided in the form of labeled vehicle schematics, an example of which is shown in Figure 7.26.

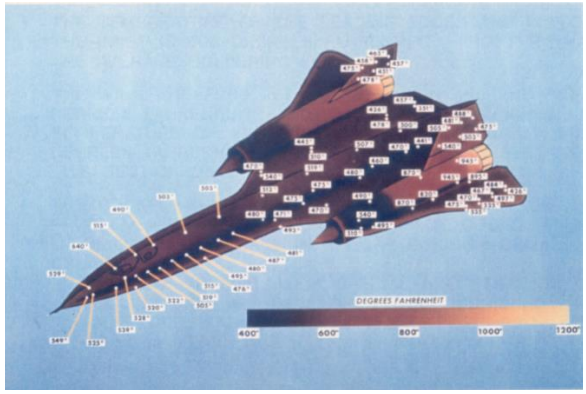


Figure 7.26. SR-71 temperature profile collected from VCC effort [14]

Hence components of the vehicle, that are common to most of the vehicles, are considered. As seen in Figure 7.27, these components included the nose, vertical and horizontal tail surfaces, and forward and mid fuselage. This temperature information has been collected for four vehicles (X-43A, Concorde, SR-71, and Sänger-II) plus a generic Mach-10 cruiser which describes the information collected in analogy to the X-43A.

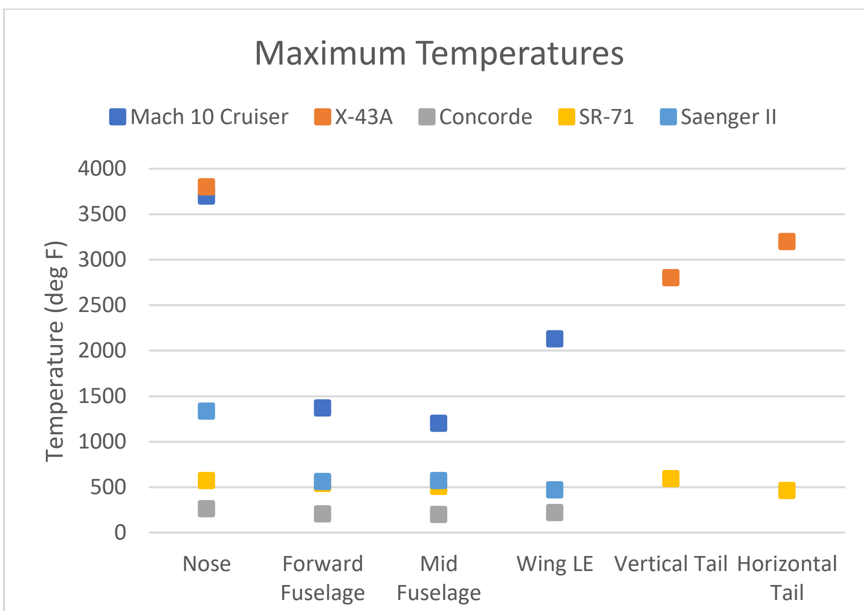


Figure 7.27. Knowledge plot - maximum temperatures experienced across vehicle body

As seen in Figure 7.27, the Mach-10 cruiser and X-43A have the highest temperatures compared to the other vehicles, while the Concorde experienced the lowest temperatures. This is to be expected since the Concore is a supersonic vehicle while the X-43A and cruiser are hypersonic vehicles. According to the knowledge scoring rubric, this plot needs to be scored using the extended rubric since there are no vehicle categorizations offered but simply a comparison of different vehicles. There is no regression or trendline produced; however, there is a vehicle list provided as a legend. There are five different vehicles plotted together, which means the score of this plot would be a 0.2 out of 3.

Another aerothermal knowledge plot generated is seen in Figure 7.28. This is a chart comparing different materials used for the vehicles covered in the VCC. This chart is divided into the hypersonic and supersonic regions, as the material needs for both speed regimes are significantly different. Hypersonic vehicle's structural material typically require thermal protection systems (TPS) for protection from the heat experienced at high speeds, while supersonic vehicle's specific airframe material are required to protect from heating at supersonic speeds.

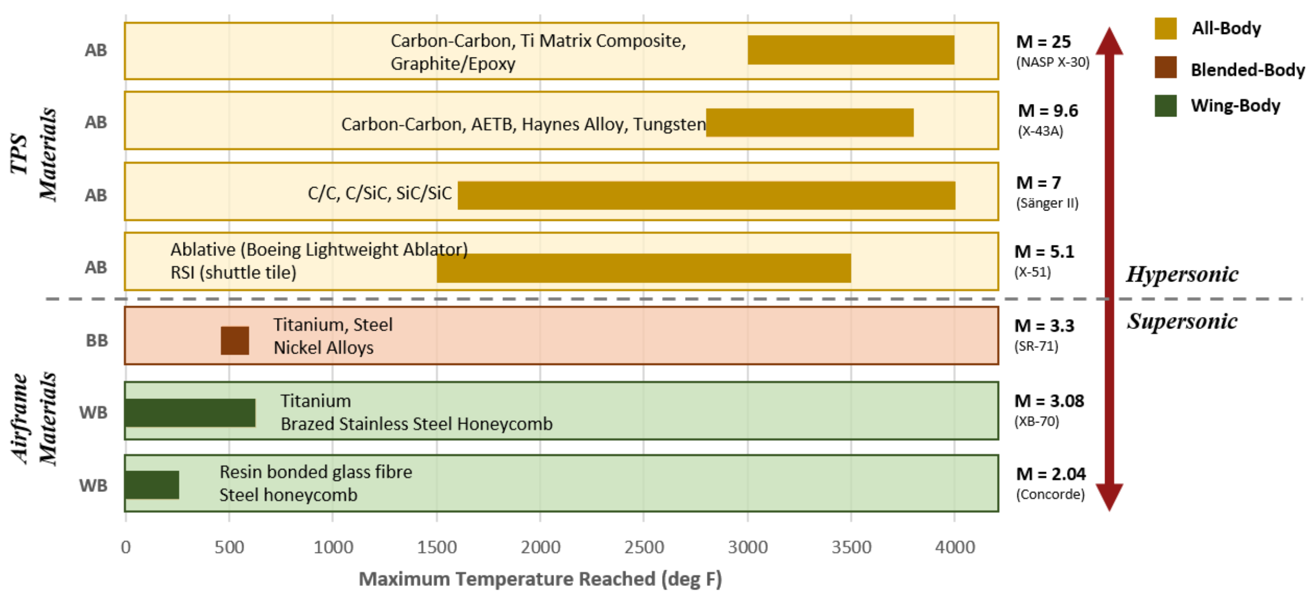


Figure 7.28. Knowledge chart - materials comparison for high-speed vehicles (TPS and airframe)

This separation is also clearly identified in the chart. Another classification shown is between the different vehicle geometries. The hypersonic vehicles considered are mostly all-body (AB) concepts while supersonic vehicles are mostly wing-body (WB) concepts with two examples incorporating the blended-body (BB) vehicle concept. A designer may gain understanding of what type of geometry is typically used for what speed regime, while simultaneously reading the maximum temperatures reached by each of the vehicles. The maximum speeds achieved by each vehicle are identified to the right side along with the actual vehicle names in case the designer needs to know the specific vehicle in addition to comparing general vehicle geometries.

7.3.5.3. Propulsion

For the propulsion discipline there are generally a smaller number of plots available that are consistent among multiple vehicles. The one relation that is frequently quantified is the specific fuel consumption (SFC) versus Mach number. The four vehicles showcased in this knowledge plot are the Concorde, Sänger-II, NASP X-30, and XB-70, see Figure 7.29.

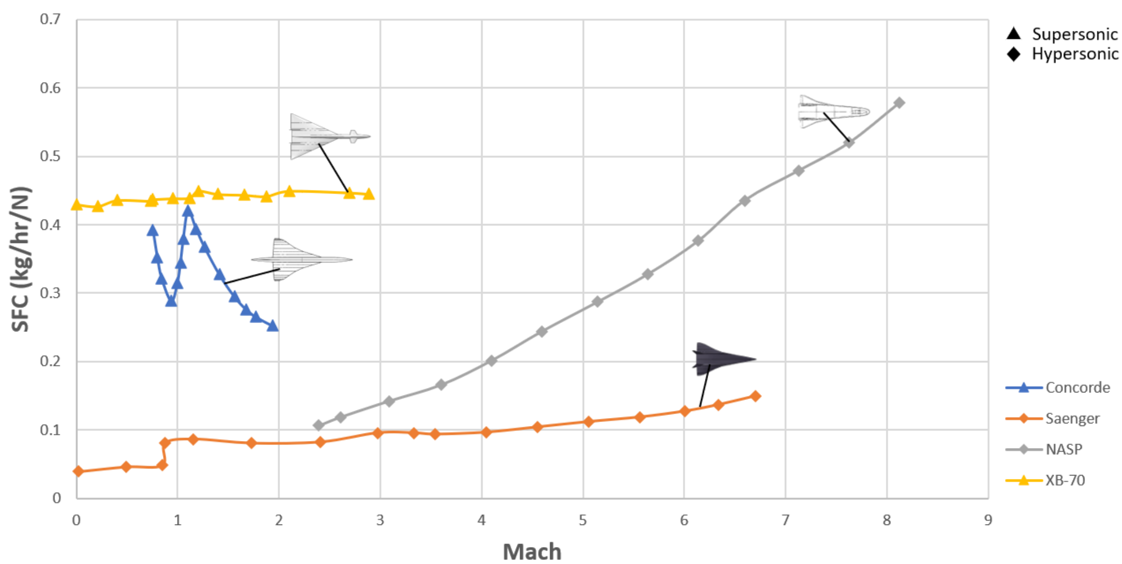


Figure 7.29. Knowledge plot - SFC vs. Mach number comparison for four vehicles

As shown with Figure 7.29, two vehicles each representing two different speed regimes are plotted together. The speed regimes are identified by distinct markers. This plot does only score 0.1 on the knowledge usefulness rubric developed since there is only one categorization (speed regime) and there are only two vehicles per speed regime.

7.3.5.4. Performance

For the performance and trajectory disciplinary knowledge category, the different flight trajectories for each of the vehicles are super-positioned as seen in Figure 7.30. Five different vehicles are plotted together: the Sänger-II, SR-71, XB-70, NASP X-30, and Concorde. For the NASP X-30 vehicle, there are two flight envelopes presented: the supersonic mission and the hypersonic cruiser mission. NASP X-30 and Sänger-II both have flight profiles in the hypersonic region which is designated on the plot and also identified on the mission profiles as dotted lines. The supersonic mission profiles of the other vehicles are presented using solid-colored lines, and the legends are once again shown on the right of the knowledge plot.

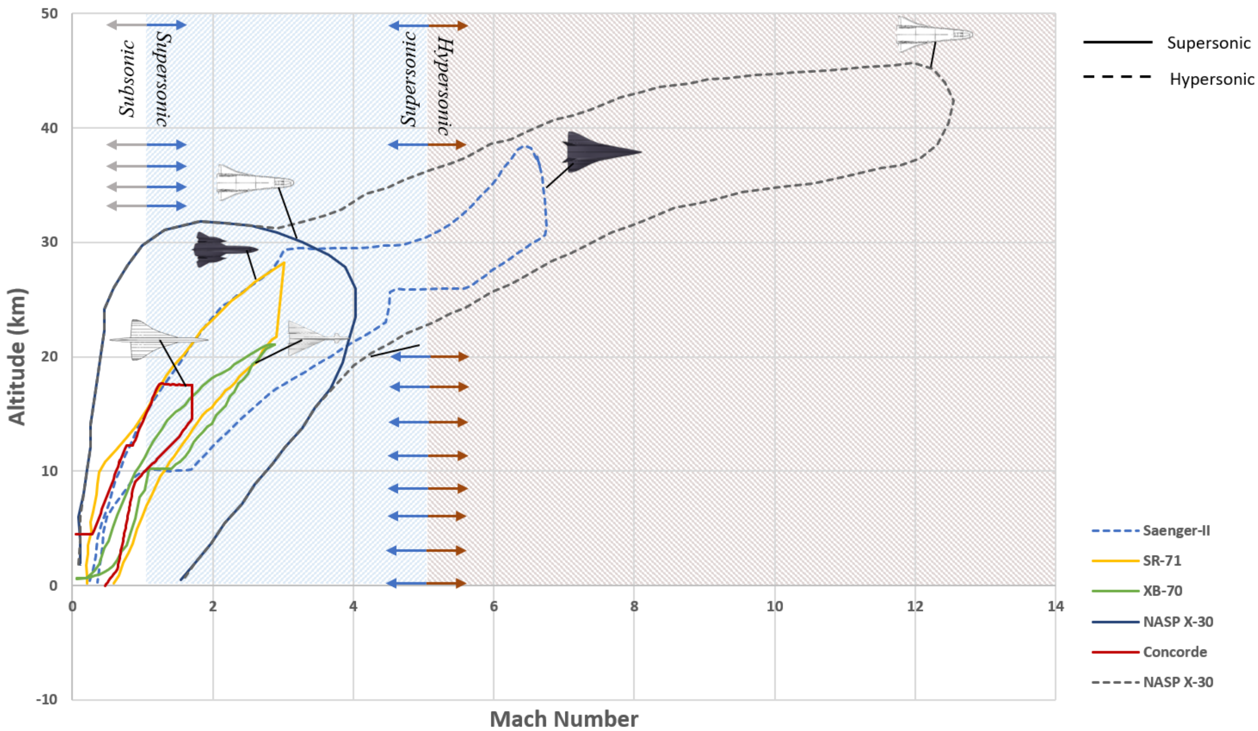


Figure 7.30. Knowledge plot - comparison of mission profiles

The designer may use such knowledge graphic to see the differences between the mission profiles of different speed regimes. Each of the vehicles are listed as well in case the designer compares different mission types and what the typical altitude or speed values might be for a particular mission type. For example, the designer may compare design attributes of the Concorde, which is a supersonic passenger aircraft, versus the SR-71 which is a supersonic reconnaissance vehicle.

7.3.5.5. Stability and Control

For stability & control, the coefficient of pitching moment (C_m) is plotted against angle of attack (α) for a variety of VCC vehicles. The only vehicle for which this relationship is not available is the Concorde. Once again, the knowledge conversion process is followed:

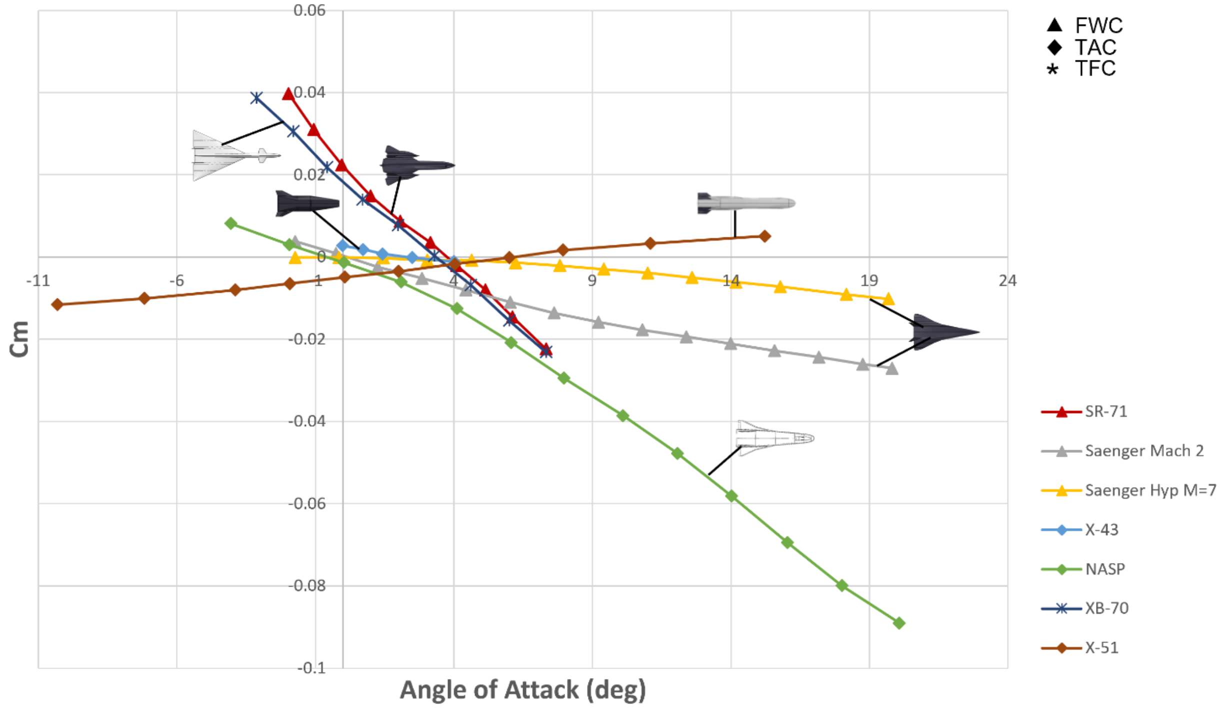


Figure 7.31. Knowledge plot - Cm vs. AOA - multiple configurations compared

As seen in Figure 7.31, three different configurations are compared: the FWC (flying wing configuration), TAC (tail-aft configuration) and TFC (tail-first configuration). These different configurations are denoted by the plot markers used, as shown in the legend. This graphic presents three trends for TAC and FWC each, while there is only one representative trendline for the TFC vehicle (XB-70). In addition to showcasing this collectively for comparison, another means of comparison are possible through adding averaging trendlines for each of the configurations, thereby representing each configuration with only one regression each. This is visualized in the following images:

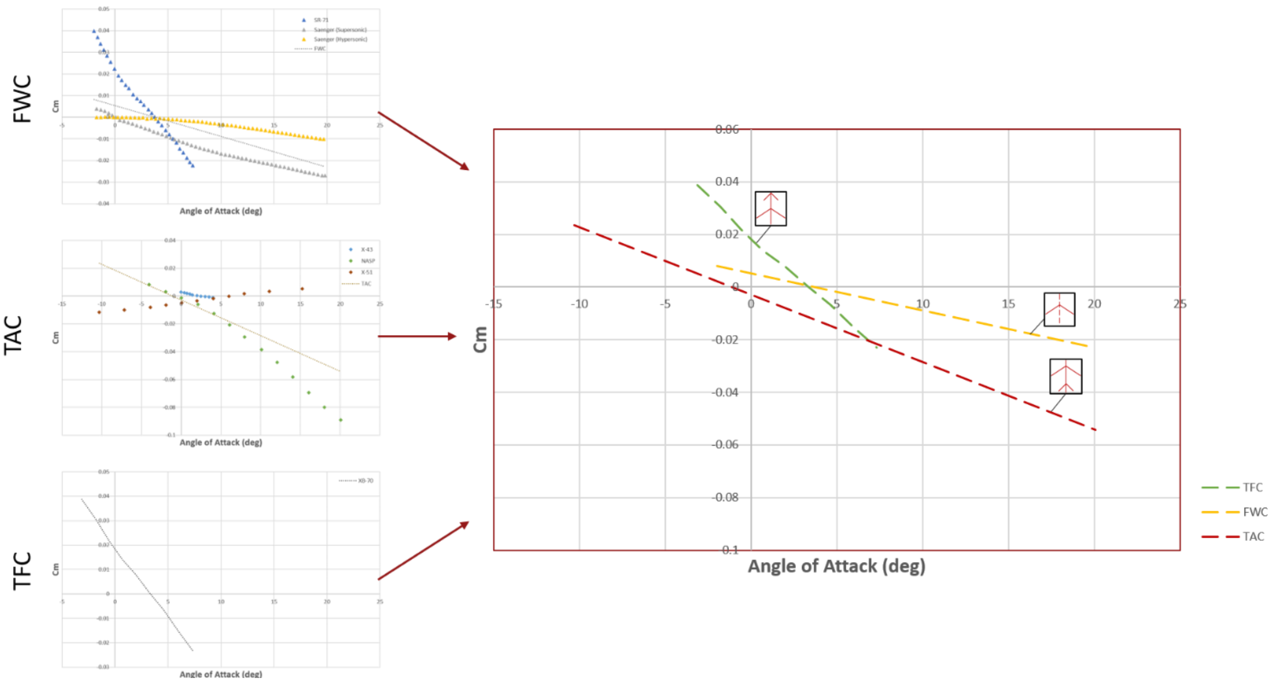


Figure 7.32. Using regressions to produce configurational comparison

As seen in Figure 7.32, each of the configurational information plots of C_m vs. AOA can be used to generate regressions that provide a general trend for the relation between these two variables. This is done for TFC, TAC, and FWC separately; these trendlines can be combined into one plot as shown in Figure 7.32. This provides a general sense of the tendencies of various configurations. Such a method of averaging would be even more useful and more accurate with a larger number of vehicles to retrieve average data from.

7.4. Compendium Usage – Case Studies and Examples

The Vehicle Configuration Compendium (VCC) is developed with the aim to evolve into its full potential as a valuable addition to any flight vehicle design setting, such as the AVDS synthesis methodology and software. However even in its prototype phase, the VCC has already proven its worth, albeit before the AVDS-VCC integration process.

In 2020-21, the AVD Laboratory has been involved in a research study funded by NASA Langley Research Center regarding the feasibility of hypersonic commercial transportation [4]. It has been a requirement to verify the AVDS system with a variety of high-speed vehicles to confirm the relevance of the methods chosen. For this purpose, the VCC has been utilized. This has been the first official use of the VCC data, information, and knowledge for verification before the implementation of the compendium in a graphical user interface. The NASA study verified the usefulness of this compendium design assistant early in the development process of the VCC. VCC proved to the research team the need to continue developing the compendium to its full potential. It must be noted that the usefulness of the VCC as an aid in this study resulted in full endorsement and highest compliments from the NASA support engineers. This also led to an explicit endorsement of the author, Samuel Atchison, and Ramlingam Pillai within the NASA report for the supporting work provided through the VCC collection process [4]. Provided in the following subsections are some verification examples from this study.

7.4.1. Disciplinary Verification

The VCC has been applied for the verification of the disciplinary methods selected within the AVDS system. Some examples are shown:

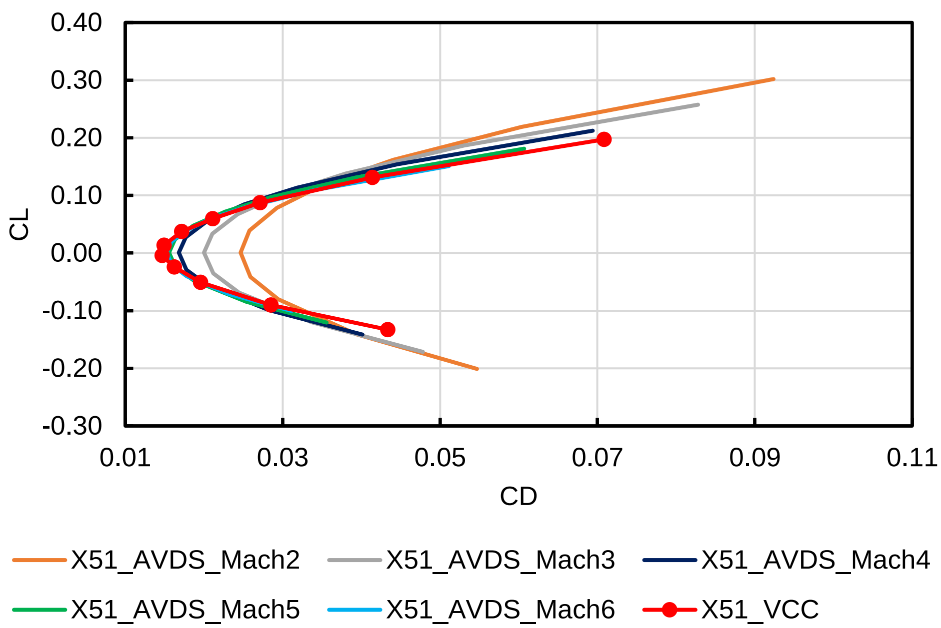


Figure 7.33. Drag polar for X-51 aerodynamics method verification using VSP model geometry[4]

Seen in Figure 7.33 is the verification of the X-51 drag polar by comparing the AVDS results with the plot collected as part of the VCC effort. One of the advantages of using the VCC compendium alongside the AVDS system is the ability for both systems to complement each other, as seen in this example. The drag polar constructed during the VCC effort has no specify

Mach number due to the secretive nature of the X-51 project. However, the method used in the AVDS system is addressing a range of Mach numbers for comparison, until the closest Mach number match is found in a reverse-engineering effort; the results are shown in Figure 7.34.

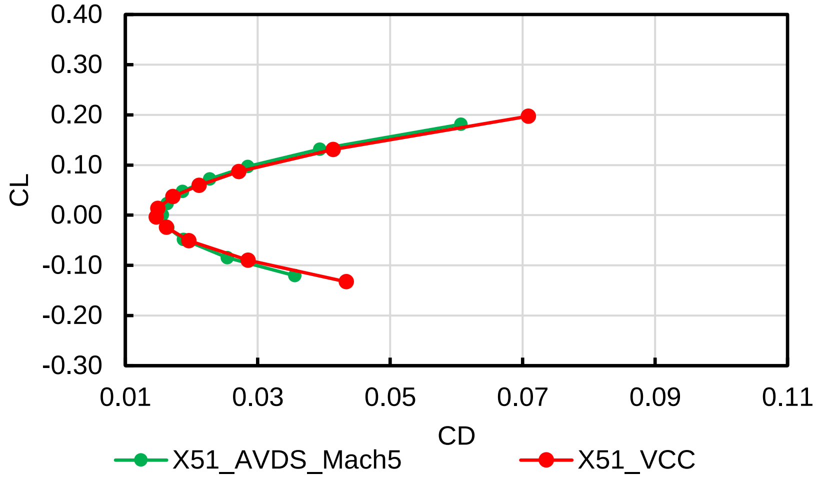


Figure 7.34. Drag polar for X-51 aero method verification using VSP model geometry - closest match at Mach 5 [4]

As seen in Figure 7.34, the X-51 drag polar documented is for Mach 5 since the Mach 5 curve generated by AVDS matched closely with the VCC data. The Mach number associated with the drag polar collected has been a piece of information missing from the X-51 VCC set. However, this could not have been verified by AVDS in case the original drag polar would not have been located in the first place. In this way, the VCC and AVDS can be integrated for mutual assistance. Similarly, the X-51 lift-curve slope has been also verified for Mach 5, see Figure 7.35.

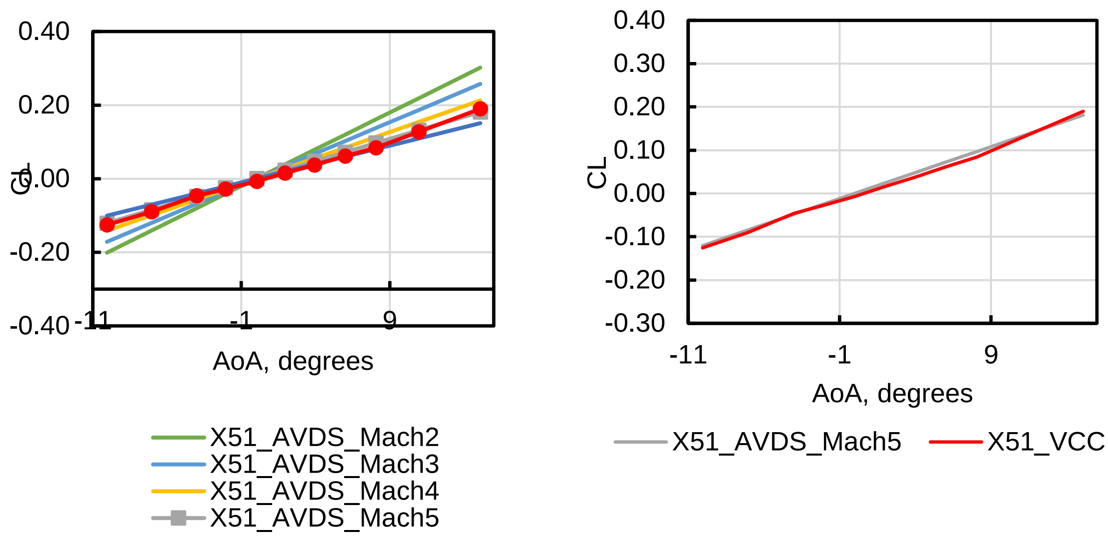


Figure 7.35. X-51 verification of lift-curve slope - survey of Mach numbers to find closest match[4]

Another vehicle verification example from the NASA study has been the XB-70, here in particular the propulsion system. During the engine sizing phase, the VCC data identified for thrust vs. altitude of the J-93 engine has been utilized for verification of the sized engine. Shown in Figure 7.36 is a side-by-side comparison of the original plot stemming from VCC, and a plot of the digitized data from that graph (labeled ‘Actual XB-70’) plotted against the thrust-altitude relation produced using the AVDS (labeled ‘XB-70 Verification’).

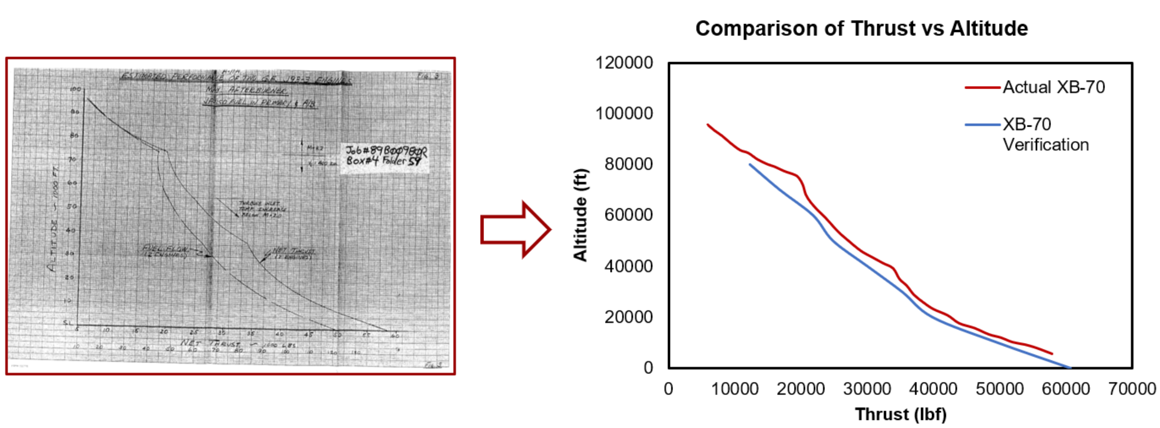


Figure 7.36. Thrust vs. altitude verification plot - XB-70 J-93 engine [4]

Mission profile trajectory decomposition for the X-51 has also been verified using a mission segment identified for the vehicle stemming from the VCC compilation process. Specifically, the 131-second cruise segment of the X-51 has been verified against the mission profile for X-51, see Figure 7.37. This verification is simultaneously proving the usefulness of a compendium like VCC for quick verification activities, as well as the accuracy of the AVDS synthesis system due to the low errors seen.

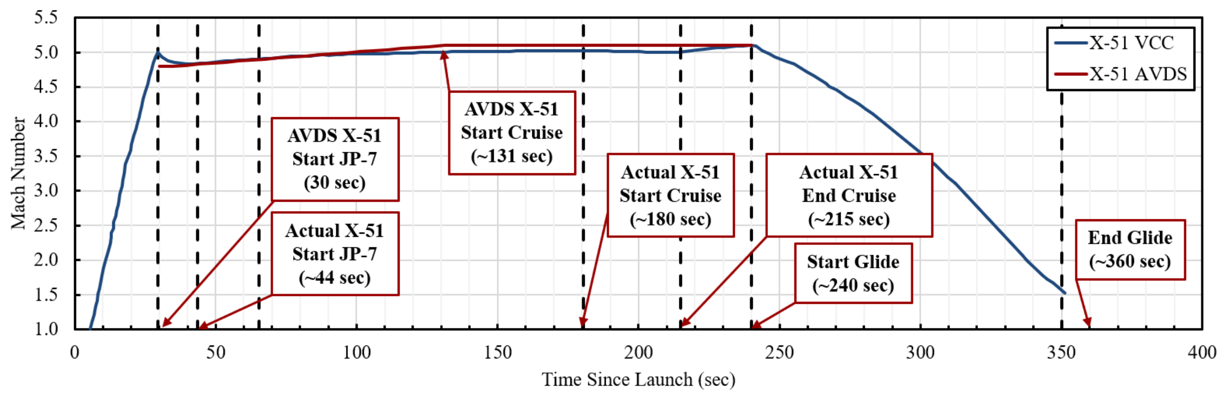


Figure 7.37. Verification of X-51 mission decomposition by AVDS against VCC [4]

Similarly, the Concorde mission profile retrieved via VCC has been used to verify the AVDS methodology for the entirety of the Concorde mission. Figure 7.38 shows both the mission profile of Concorde (altitude vs. Mach), and the altitude-range correlation. Note that the VCC provides three different altitude vs. range plots for the Concorde. This is most likely due to the original source material comparing this information between slightly differing flight conditions for the Concorde. However, the general trend for this can still be used for verifying that the AVDS method calculates similar altitude and range values.

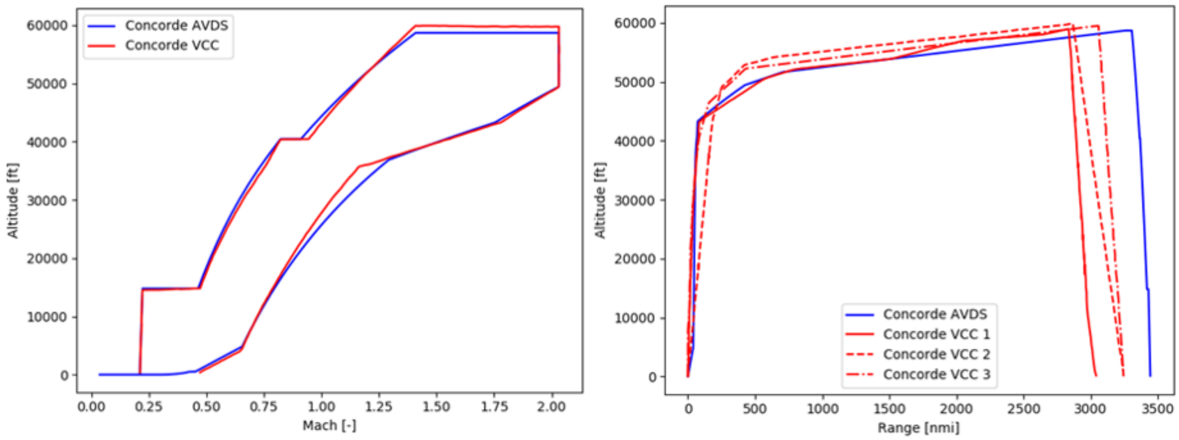


Figure 7.38. Verification of AVDS generated Concorde mission profile using VCC data [4]

Another example shown is how the lift to drag ratio for the Sänger vehicle is verified for a range of supersonic Mach numbers, see Figure 7.39. The dotted lines represent the results from the AVDS aerodynamics method, and the solid lines represent the actual Sänger values retrieved with VCC. Once again, VCC is providing data for comparison and to evaluate the accuracy of the methods chosen from the AVDS methods library.

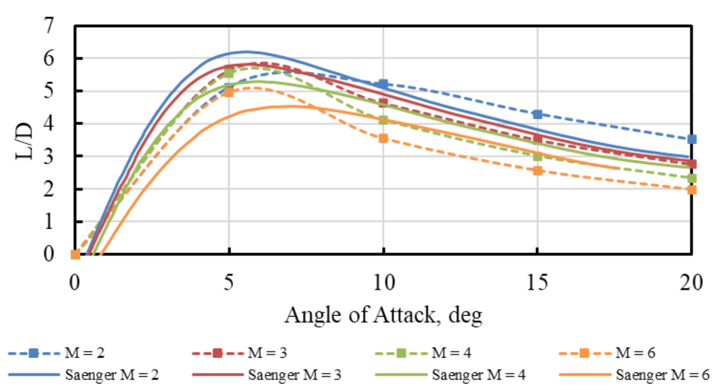


Figure 7.39. Sänger verification of supersonic lift-to-drag ratio [4]

7.4.2. Sizing Verification

In addition to verifying the disciplinary analysis methods selected within the AVDS system, the VCC material has also been used for verifying the sizing capability of AVDS. A few examples of vehicles sized included the X-51, the XB-70, and the SR-71. The results from the sizing verification of the X-51 are summarized in Table 7.4.

Table 7.4. Comparison of AVDS X-51 Sizing Results to Vehicle Data from VCC [4]

Sized Vehicle Attributes	X-51 [SI]	AVDS X-51 [SI]	% Error
Operating Weight Empty, lb or kg	555	548	-1.29
Operating Empty Weight, lb or kg	555	548	-1.29
Takeoff Gross Weight, lb or kg	682	673	-1.38
Structural Weight, lb or kg	-	133	-
Fuel Weight, lb or kg	127	124	-1.79
Payload Weight, lb or kg	0	0	-
Tau, Vtotal/Spln1.5	0.214*	0.214	-
Total Planform Area, ft2 or m2	2.27*	2.26	-0.50
Wing Planform Area, ft2 or m2	2.27*	2.26	-0.50
Wetted Surface Area, ft2 or m2	8.45*	7.95	-5.90
Total Volume, ft3 or m3	0.729*	0.725	-0.56
Ratio of Wetted to Total Planform Area	3.73*	3.52	-5.43
Structural Index, Istr = Wstr/Swet, lb/ft2 or N/m2	-	16.7	-
Propulsion Index, Ip = ρfuel/(WR-1), lb/ft3 or kg/m3	3,507	3,531	0.68
Industrial Capability Index, 10·Ip/Istr	-	2,116	-
Total Fuel Fraction, Wfuel/TOGW	0.186	0.185	-0.42
Total Weight Ratio, TOGW/OWE	1.23	1.23	-0.10
Total Planform Wing Loading, TOGW/Spln, lb/ft2 or N/m2	2,951*	2,925	-0.88
Wing Planform Wing Loading, TOGW/Swing, lb/ft2 or N/m2	2,951*	2,925	-0.88

As seen in the table, a variety of attributes of the sized vehicle design are compared to the actual vehicle data contained with VCC. This includes a variety of weight comparisons, planform and surface area comparisons, and important ratios to understand the vehicle such as fuel fraction or weight ratio, etc. The results for the X-51 include a very small margin of error, with the highest error being 5.9%. This shows the level of accuracy that the AVDS system can achieve in sizing a vehicle. This error margin is calculated due to the readily available data prepared via the VCC system, thereby making VCC a *PRIMER* or design companion that not only helps a designer while using AVDS, but also helps to build credibility for the synthesis system itself. If, however, the results would have shown much larger error percentages, then the VCC would still be helping the synthesis system by providing corroborating data, which allows for the refining of the AVDS system until the desired level of accuracy is achieved. The sizing verification results for the other vehicles mentioned are provided in Appendix B for reference.

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CHAPTER 8

SOFTWARE DEVELOPMENT

The ultimate goal with the Vehicle Configuration Compendium is two-fold, as mentioned before: the first is to produce a standalone software interface that will serve as the data-information-knowledge compendium design assistant, and the next is for this software to be fully integrated as a module of the AVDS system to directly aid in synthesis. This chapter therefore discusses the software development aspect of the VCC, for the standalone prototype. The first step is the full implementation of the VCC as a standalone software interface, without which future AVDS-integration will be impossible.

8.1. Mapping Out Release Schedule

In order to allow the effective planning of the VCC software, every future iteration must be well-defined. Obviously the very first version that is packaged and published will not be the best version of the software, but merely an ‘alpha’ version that will be the stepping stone for future iterations to build upon. Setting the performance boundaries and milestones for each iteration of the foreseeable future is important to allow the author working on the current iteration to understand the ultimate goal and to implement the prototype in a way that will support the future versions.

The software development life cycle (sdlc) model adopted for the VCC is called the “synchronize-and-stabilize” model, which is typically used by companies like Microsoft [1]. This is an iterative SDLC model involving multiple releases before finalizing the system. In this way the developers are able to gain customer feedback during the development process with each release and fix any issues before the final product design is locked.

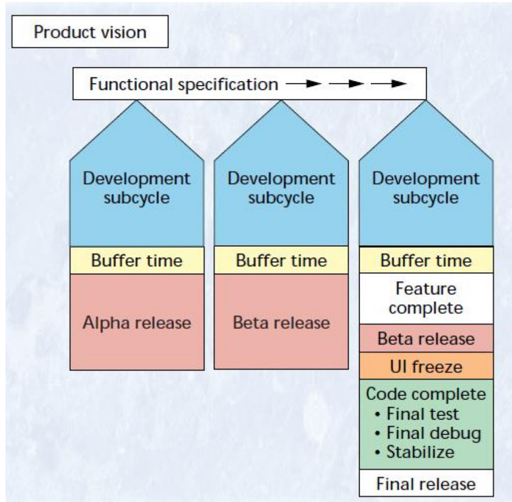

Figure 8.1. Synchronize-and-stabilize software development model used by Microsoft [1]

As seen in Figure 8.1, this model involves three or four different releases. First is the alpha release, followed by up to two beta releases before the final release. Each release is preceded by a period of development, termed the "*development subcycle*", as well as a buffer time to allow developers to respond to unexpected issues or delays. The advantage of using such a development cycle compared to other models is the ability to add new or previously unplanned features during development, and the flexibility to evolve the specification of the software with each release cycle. As such the VCC adopts such a development model with the current research effort ending on the alpha release of the software.

The planned release schedule of the VCC software along with the overall goals for each iteration are shown in Table 8.1, to be discussed in more detail in the following subsections.

Table 8.1. Planned Release Schedule of VCC Software

Alpha Version	Beta Version	Release Candidate
Fully functional database of eight hypersonic vehicles	Additional hypersonic vehicles added to database	All known hypersonic vehicles to date added to the database
Knowledgebase with predefined knowledgebase plots included	Knowledgebase made user-friendly with interactive options to choose data to plot	Knowledgebase made capable of conducting interpolations to fill in missing data to allow for forecasting trends of various configurations
First iteration of GUI packaged and made available as an executable standalone application	Second iteration of improved GUI with professional input	GUI made professional and fully user-friendly
Integration points with AVDS mapped out	Full integration with AVDS software achieved, VCC+AVDS packaged and made available together as single executable file	VCC software plus integrated AVDS software packaged together along with full user manual and downloadable bibliography plus database, made available for clients to download
Coding manual provided for future developers to build upon current work		

8.1.1. Alpha Prototype

The alpha prototype version of the VCC aims to prove the usefulness of a data-information-knowledge compendium and the enhancement of the user experience through an easy-to-use interface. The prototype houses a total of seven high-speed aerospace vehicles, which as discussed earlier, are the following: X-51, XB-70, SR-71, Concorde, Sänger-II, X-43A, and NASP X-30.

The development timeline for the alpha version of VCC is shown in Figure 8.2. As seen, the software development process began in December of 2020 with the initial specifications and user interface mapped out.

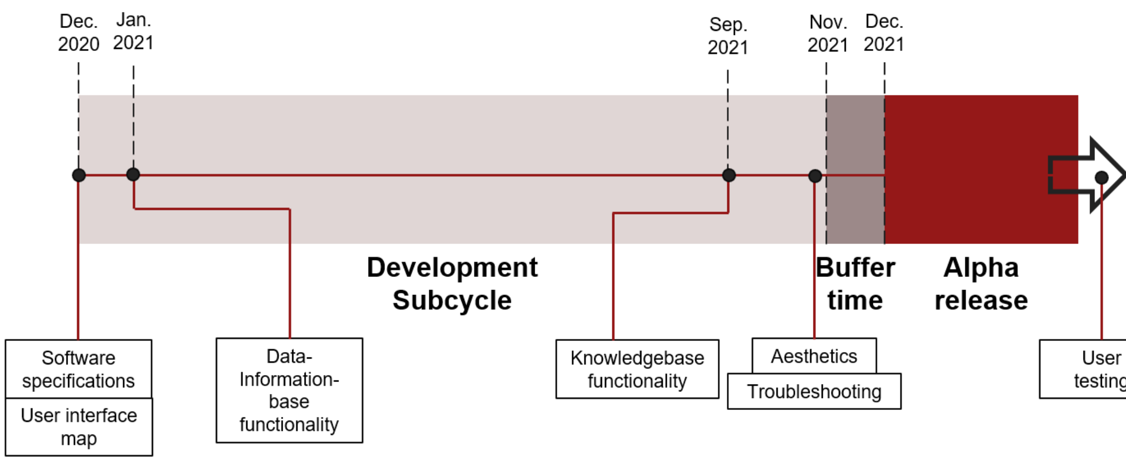

Figure 8.2. VCC alpha version development cycle

A majority of the development subcycle was allotted for the building up of the data and information base of the VCC, as there was a large volume of information to be showcased. The knowledge functionality was added in September of 2021, and as of December of 2021, the aesthetics and troubleshooting has begun, with concurrent user testing conducted during the conclusion of the alpha version in December.

The data and information base of the alpha iteration of the software displays the disciplinary data and information as plots based on the user selection. The user is also able to zoom in to each of the information plots as needed. The data-information base also displays a breakdown of the major configurational and performance details of the vehicles. The knowledgebase of the alpha iteration displays a handful of selected knowledge plots based on the user selection of comparison criteria. The user may select to compare between configurations or geometries.

8.1.2. Beta Version

For the beta release of the software, the vehicle library of the VCC will be expanded to include more high-speed vehicles. There may be multiple ‘beta’ level releases in the future due to the high volume of vehicles available from past to present projects. In general, the beta release will also have a more interactive user interface compared to the current version. The user will be able to select data points directly from the information plots and make live annotations on these graphs to have an engaging experience with the software.

Instead of the current knowledgebase model, the beta software will have a more interactive knowledgebase with a higher number of graphics. The limited number of knowledge graphics in the current version is due to the small sample size of vehicles housed in the compendium. With the addition of more vehicles in the beta phase, the VCC will house more knowledge overall, over a larger variety of vehicle configurations.

The beta phase will also feature the first attempt at direct integration of the VCC with the AVDS software interface. This process will likely result in an iterative process and therefore require multiple beta phase testing in order to fix issues that arise in the integration process.

8.1.3. Release Candidate

The release candidate will be the first full package of the AVDS+VCC system. The integration between the two software will be finalized and the dual software system will be packaged by this release. For this version of the VCC, the goal is to have all currently known high-speed vehicles added to the compendium ideally.

With such a large volume of data, information and knowledge housed in the compendium, the release candidate will require a data management system with higher storage capacity. Optimization activities will be required to address any lag in processing speeds associated with showcasing such a large volume of information. The GUI itself will be in its final version after having undergone multiple iterations to make it the most user-friendly and self-explanatory.

8.2. Graphical User Interface Development

8.2.1. Graphical Use Interface Logic Flow

Upon reviewing the initial design for the graphical user interface, modifications were made to the flow of the user input and output process from interactions with the software, and the following flowchart was created as a proposed restructuring of the interface:

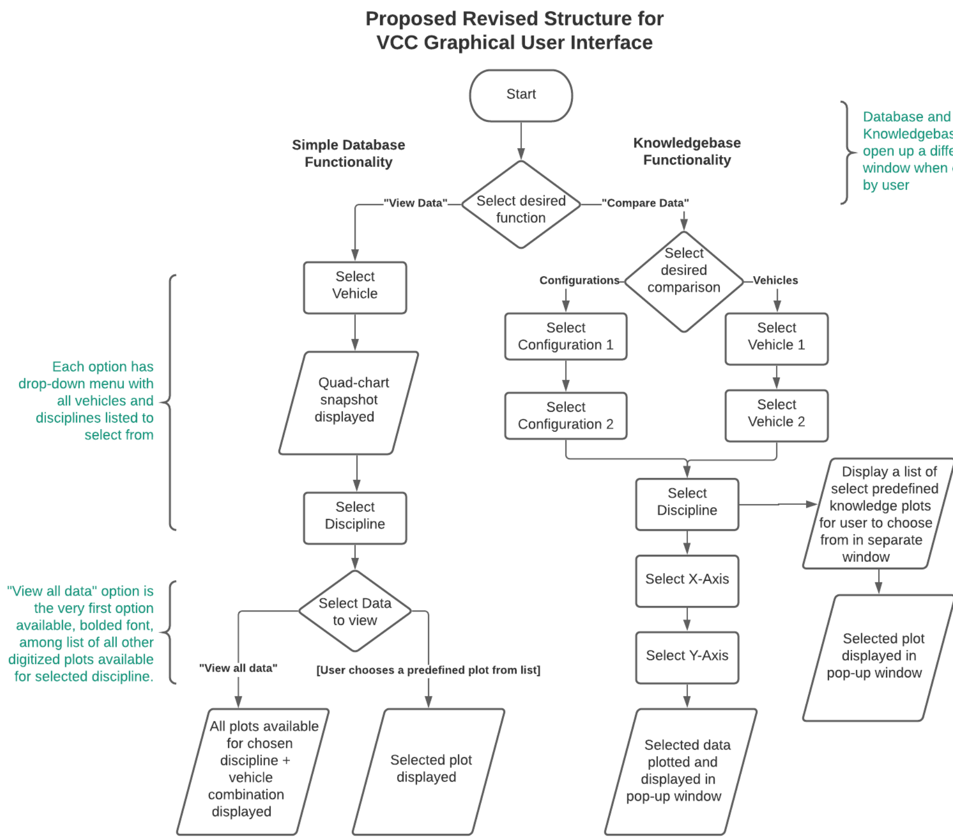

Figure 8.3. Graphical user interface logic flowchart

As per this flowchart, once the software is run, the first choice the user will be able to pick from is between “View Data” and “Compare Data”, which will lead the user down either the database path or the knowledgebase path respectively.

If the user selects the database path, the user will then be given the option to select from the list of eight hypersonic vehicles that we have compiled data for. Upon the selection of this vehicle, a quad-chart snapshot of the vehicle will be displayed, which will be explained in more detail later. In short, this quad-chart is a quick overview of the most important characteristics of the vehicle chosen.

Once the vehicle is selected, another menu will appear that allows the user to select which of the eight aerospace disciplines they would like to view data for. Once the discipline is selected, the user may then either choose to view all data or choose a specific predefined plot from a drop-down menu for viewing in a larger format. If the user chooses to "view all data", then every single plot digitized and uploaded for that specific discipline and vehicle combination will appear in a 3x3 grid on the same window.

8.2.2. Coding Using Python

In the coding process of this software, each of the Python modules shown in Table 8.2 are used. These modules are imported within the code in order to support different functions of the GUI.

Table 8.2. Imported Python Modules

Module Imported	Purpose
tkinter	Standard Python interface to Tk GUI toolkit
pandas	Data analysis toolkit
matplotlib	Data visualization/plotting toolkit for Python
sqlite3	Database connection
os	Manipulate paths for reading from files
PIL	Imaging library for including AVD logo as image file

Each of the packages mentioned above have a specific use within the code for the GUI. The coding on the alpha prototype results in the following GUI layout:

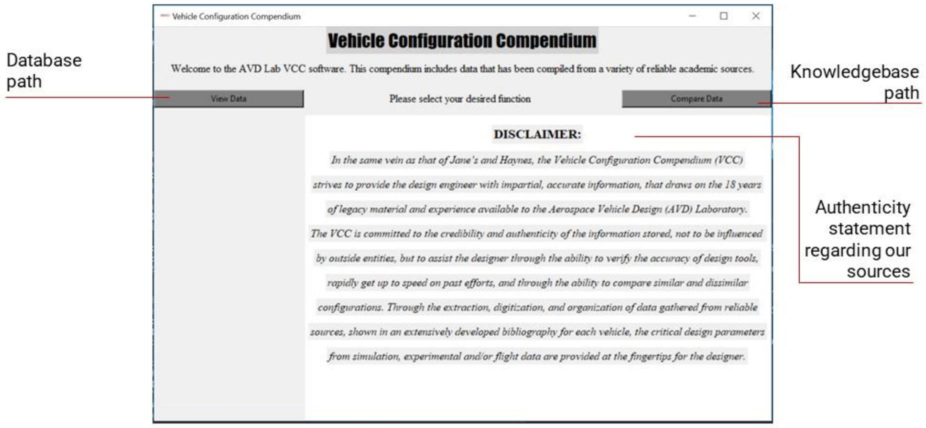

Figure 8.4. VCC interface - initial window

The software opens up with the disclaimer statement already displayed on the screen regarding the authenticity of the data compiled and provided through the VCC, as seen in Figure 8.4. The portion of the window where the disclaimer statement is situated will be the canvas where anything that the user has selected will be displayed.

The user is then given the option between viewing and comparing data which opens either the data-information-base or knowledgebase function. Selecting the DI-base functionality leads to:

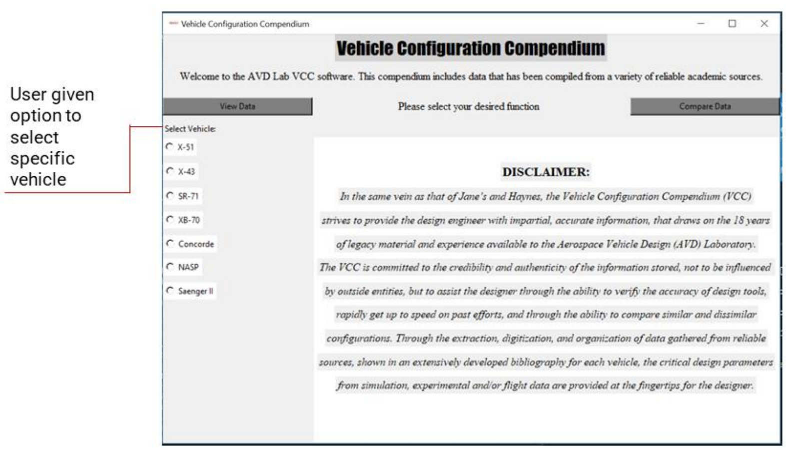

Figure 8.5. VCC interface - vehicle selection

Here the user is given a menu of vehicle options to choose from, on the left sidebar as shown in Figure 8.5.

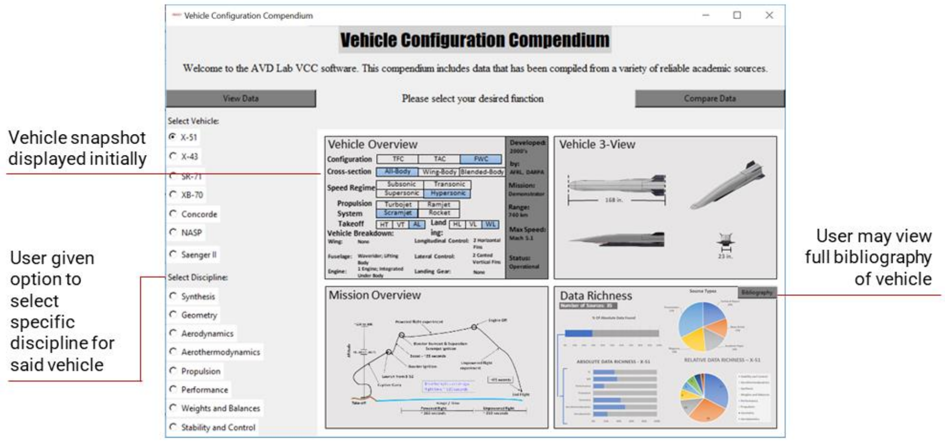

Figure 8.6. VCC interface - disciplinary selection

After the user selects a vehicle, two things happen. First of all, the user is shown a quad-chart in the same white box where the disclaimer statement was first displayed, where they can see a quick snapshot of the vehicle they have chosen. Inside this quad-chart, a button has been added for each vehicle that displays a pop-up window with a full bibliography list for that vehicle, as seen in Figure 8.6 and Figure 8.7. This bibliography shows every single source that we searched through while compiling data for the software.

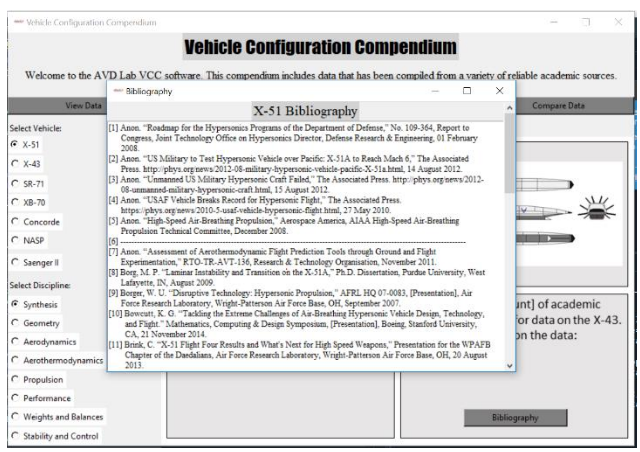

Figure 8.7. VCC interface - vehicle bibliography pop-up window

Second, the user is also given a list of aerospace disciplines for which they are able to view data, toward the bottom of the left sidebar.

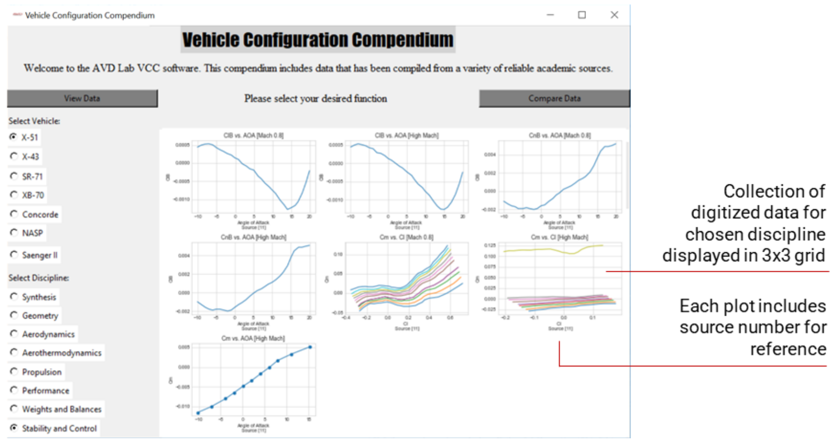

Figure 8.8. VCC interface - viewing data and information

After the user selects the discipline they would like to view data or information for, per the flowchart the user is able to view a 3x3 grid of disciplinary plots representing the data and information collected. Each plot has the source number at the bottom which allows the user to locate the origin of each piece of data/information displayed in the grid, as seen in Figure 8.8.

If, the user instead would like to access the knowledgebase, they must simply click on the "compare data" button, which will allow the user to compare between different configurations, or cross-sections. This is shown in Figure 8.9.

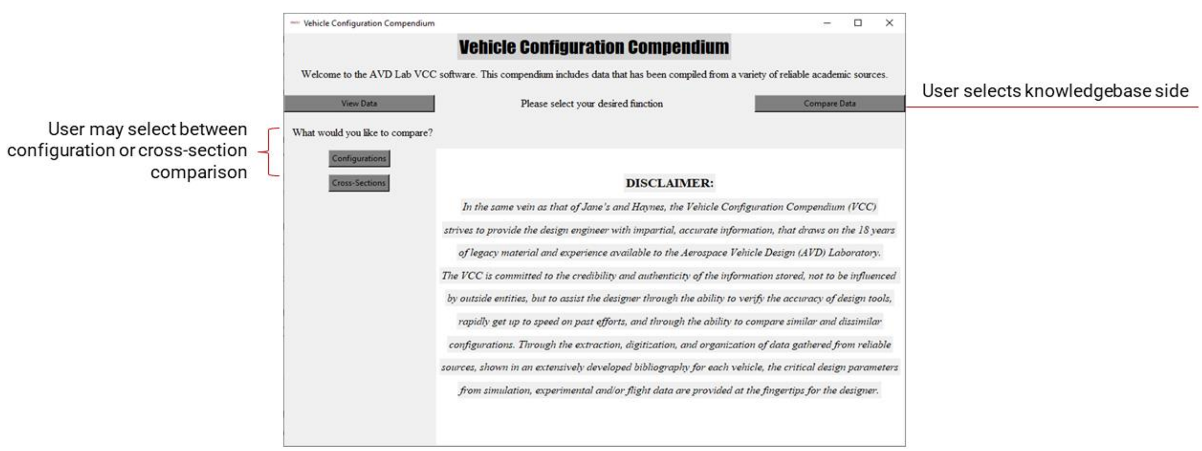

Figure 8.9. VCC interface - initiating knowledgebase

For example, if the user chooses to compare configurations, they are then given a list of currently available configurations in the VCC to select from, as seen in Figure 8.10. They are also shown a reference schematic with visuals of the different configurations, as well as the vehicles listed for these configurations in the VCC currently. The same happens if the user chooses to compare cross-sections instead.

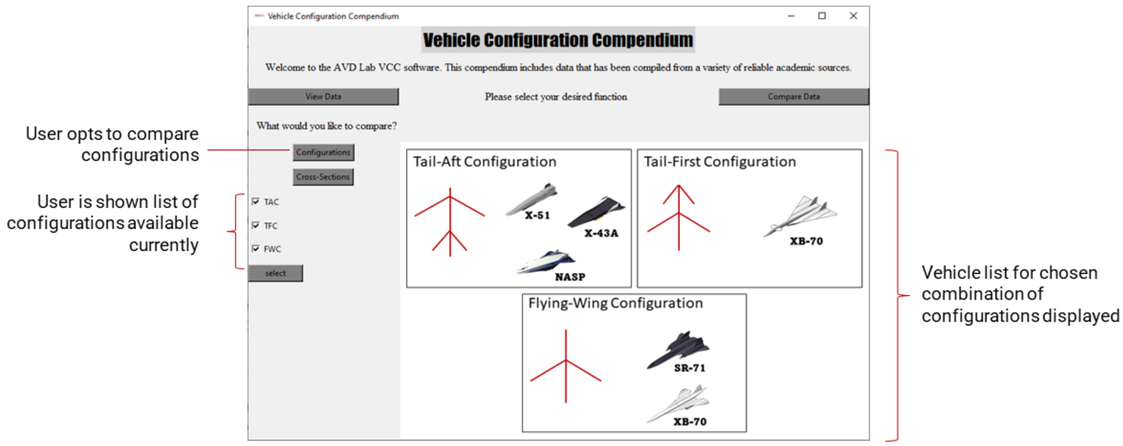

Figure 8.10. VCC interface - comparing configurations

Then the user is able to select from a list of disciplines to view knowledge plots for, which results in the displaying of the knowledge graphic as seen in Figure 8.11. These graphics contain legends with the configuration/cross-section information for the user to clearly identify the information they are looking for, and for easy comparison.

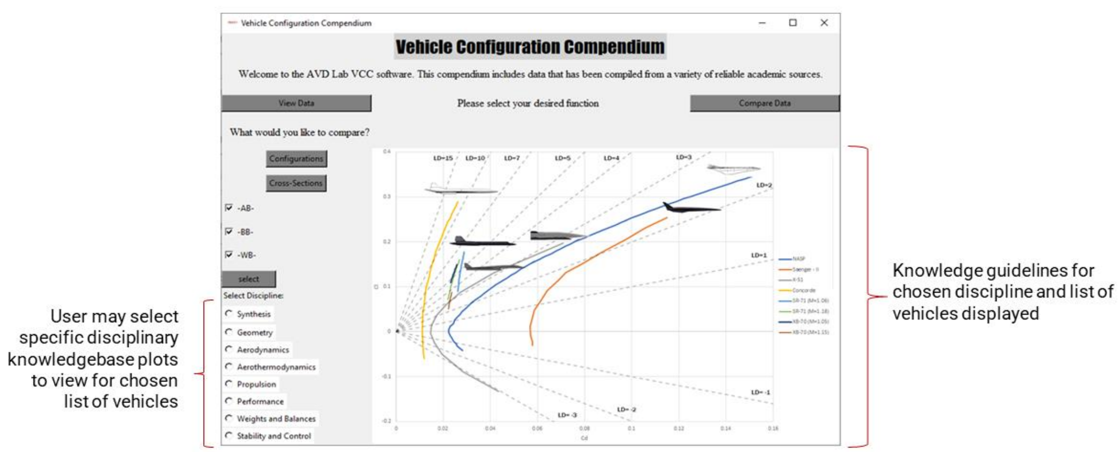

Figure 8.11. VCC interface - viewing knowledge graphic for a specific discipline

8.3. User Testing

As mentioned earlier, user testing is an important part of the development process of the interface, since the VCC must be user-friendly to professionals and students alike. The goal is to provide as much assistance for conceptual design as possible. The actual user interface should therefore not pose a hindrance in the design process with complicated functionality but must rather present a sensible and useful interface to the user. The best way to determine this is to conduct direct user testing, for which purpose a set of testing procedures is established. The usability test plan provided in Figure 8.12 is being followed:

VCC Usability Test Plan

Name of Product: Vehicle Configuration Compendium

Goals: Test the usability and accessibility of the software interface of the Vehicle Configuration Compendium. Ensure the application is easily navigable to professionals and non-professionals alike.

Time:

Date:

Location:

Format: In-person

Participant Name:

Tasks:

1) Open the bibliography of the X-43A.

2) Find out the year the XB-70 was developed.

3) View the propulsion plots for XB-70.

4) Expand one of the propulsion plots.

5) Find the source of the third aerodynamic plot for SR-71.

6) Compare the aerodynamic performance of two different configurations and produce the result of this comparison.

Task #	Completed? Y/N	Time to completion	Accuracy of completion	Assistance required
1				
2				
3				
4				
5				
6				

Figure 8.12. VCC usability test plan format

As seen, there is a series of six tasks ranging in complexity given to the user to complete using the graphical user interface of the VCC. The user testing is given in a setting where direct supervision is present, so as to make observations regarding user behavior during the activity. This provides insight into the level of difficulty experienced by the user during the use of VCC.

For each task, it is documented whether the user was able to successfully complete the task, and the amount of time it took to complete each task. Then the accuracy of completion is measured, by comparing the results of the user activity with the expected results. For example, did the user find the correct source for the SR-71 aerodynamic plot, did the user correctly identify the year of XB-70 development, etc. Finally, the level of assistance required to help the user complete the task is also assessed. This is an open-ended entry as the test facilitator may enter details like how many questions the user asked while navigating the interface, or what level of questions were asked.

These results will provide a first-order understanding of the ease with which the VCC may be used. In order to test both professional and non-professional usability of the software, test subjects are chosen from a variety of backgrounds, including aerospace engineering students, aerospace engineering researchers, professors, and students outside the field of aerospace engineering.

8.3.1. User Testing Results

A total of four user tests were conducted on the VCC software prototype. It must be especially noted that the software used for testing purposes did not include the entirety of the DIK of the alpha version. The entire alpha version houses multiple pages of data and information for each vehicle and discipline, and so the prototype version used for testing housed only a small percentage of that total data/information. The detailed results of the user testing are given in Appendix G.

From the user testing conducted with four aerospace researchers, it was shown that the biggest issue with the current alpha prototype is the lag time. This lag may be associated with the large volume of data that the compendium software must process in order to produce the information plots to display to the user. Further iterations will need to work on reducing this lag time. Users also felt that there needed to be more options to expand components of the GUI window to view data in a bigger font/format. Users overall expressed that the GUI is logical and the organization of the components make sense, with very little elements that are confusing except for the lag time.

Regarding the survey ratings, users rated the overall experience of using the software a 3.75 out of 5 and gave the VCC software an overall rating of 4 out of 5. This means that the user experience has been generally positive from the tests conducted. Detailed survey results are shown in the Appendix. Further user testing is needed to receive a larger sample of test results to gain more feedback.

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CHAPTER 9

FUTURE WORK

9.1. Expansion and Enhancement of the Compendium

As seen in the previous chapter, the VCC is already proving to be an incredible asset to designers, engineers, forecasters, and students alike. The plans for the compendium moving forward include continued development and passing down to future researchers who will inevitably improve upon the work and truly enhance the interface.

As mentioned in the previous chapter, the development of the Vehicle Configuration Compendium may be conducted based on the alpha, beta and release versions, with development between each. In addition to such a timeline applying to the software, the concurrent data-information-knowledge collection process may be conducted alongside the software with the same schedule. As such the following is the proposed timeline plan for the development of the VCC.

In this alpha prototype, the VCC needed the following team structure for development:

- 1 researcher to compile the bibliographies
- 2 researchers to collect and digitize data, information and knowledge from the sources
- 1 researcher of the collection team to develop the software interface

With this three-person team, the digitization itself took a total of 8 months of time for a total of seven vehicles. So, the future may be mapped out based on the following assumptions:

- 1 vehicle takes 5-6 weeks for the compilation process
- 1 researcher solely focused on bibliography generation
- 2 researchers solely focused on collection and digitization
- 1 researcher focused on software maintenance and further implementation
- 1 researcher focused on the continued integration between VCC and AVDS

With such a work team, 1 vehicle could be processed in about 5-6 weeks of time, resulting in an average of 9 vehicles added to the compendium per year. Of course, if the number of researchers added to the bibliography and collection teams increases, this development cycle could increase in pace. So in order to produce an accurate timeline for the full development of the VCC, there must be a survey conducted of all the currently known high-speed vehicles, including vehicles that have been flown, tested, or even only conceptualized. This will provide a comprehensive list to work from that will enrich the Vehicle Configuration Compendium, so that the knowledge generated using this compendium will be as inclusive as possible.

One of the further categorizations that was not conducted for the current VCC data was the type of collection conducted for the data or information. For example, the parameters retrieved from the sources may have been generated as a result of a flight test, a computer simulation, a wind tunnel test, a numerical prediction, or even collected during a normal operational flight of the vehicle. Showing this information with every single information plot or data table collected would be incredibly helpful to the designer using VCC, as it would provide context for the data viewed.

Another important aspect to be added to the data tables and information plots that would be of use is the context for technology capability at the time of the project. Technological capabilities change over time, as new advancements are made in industry. Therefore, a certain piece of information collected during a specific time period in the past may no longer make sense based on the current technological capabilities. For example, if a certain engine type had a particular thrust specific fuel consumption 30 years ago, it may very well be the case that there have been advancements in the technology concerning this engine type. Therefore, the same type of engine may currently be able to produce a lower fuel consumption and be more efficient in this regard. In such a situation, the old data might be misleading regarding the true nature of this engine type. However, providing some form of quantification or visualization of the technology capability at the time of the project alongside this plot would help the user understand the context, and make a judgement for themselves.

In addition, as the compendium expands, more vehicle projects will be added to the VCC, some of which may be very recent projects. If the compendium truly expands in the way that the author envisions and ends up housing almost all currently known supersonic and hypersonic vehicles, then it could very well be easy to generate a technological advancement history from the data available. For example, it may be that in the future the VCC is able to generate a comparison of the fuel consumption of the same engine over several years or even decades, and therefore show a chronological progression of the development of this technology. This would be incredibly useful to the designer, but at the same time can only be accomplished by continued development of the VCC and the continued adding of a large variety of vehicles to the compendium.

Another aspect of this situation of changing technological capabilities that must be mentioned is that the Vehicle Configuration Compendium is not always going to operate on its own. It will be soon packaged together with the AVDS system mentioned earlier in this document, and therefore the combined system will be a synthesis system with an incorporated parametric library that provides the designer with the highest level of design assistance. This could very well mean that if a plot generated from the VCC no longer holds true due to advancement in technology, the AVDS system will then be able to verify by implementing its own methods to check such values. This checking procedure together with VCC would provide the most context for a designer about the relevance of certain plots or parameters. This means that in addition to VCC verifying AVDS methods, AVDS methods could in turn verify the VCC data relevance. Once again, the AVDS-VCC system is showing the potential to become a truly integrated system with the highest usefulness to the designer.

9.2. Improving Upon Current Software Interface

The current software interface developed would be greatly enhanced by adding certain capabilities to the software that are not added due to the time constraint of the project. These additional capabilities would only serve to enhance the user experience.

For example, a capability useful to the designer would be to program the VCC to generate knowledge graphics on its own. The current prototype version houses knowledge plots generated using specific combinations of information sets; however, the retrieval of the information-datasets that make up the trendlines on these plots are currently hard-coded into the interface. Hence if new datasets were added to the SQLite database, they would not be automatically included in the knowledge plots but would require further coding to the original plot code. A way to avoid this issue is to program the software to be capable of checking through the entire data-informationbase and picking out datasets that could go into a knowledge plot based on its data table name.

In order to allow for this capability in the future, the data tables included in the SQLite database have already been named based on a simple format: each data table name includes the vehicle name, followed by a two-letter disciplinary code, followed by the x-axis variable and the y-axis variable. This would make it easier to simply program the software to be able to check through every dataset in the database and call datasets that contain a particular combination of x and y axes. In order to call specific configurations and geometries, etc., for a small number of vehicles it would be incredibly easy to just code the program to search for specific vehicles that belong to these categories. For example, if programming the software to automatically plot the lift vs. AOA trends of every single wing-body vehicle in the compendium, with the small handful of vehicles it would just be a matter of programming it to look for specific vehicle names in the database. However, if there is an incredibly large collection of vehicles in the compendium, then it would be more difficult to add these to the search list for the program. At this point the database tables would need to incorporate certain characteristics of the vehicle like the configuration or cross-section. Another approach to doing this would be to create a separate master file that contains a list of the entire set of vehicles included in the VCC, with the various categorizations.

From the user testing conducted, the results of which were shown in chapter 8, it was apparent that users would like to be able to interact with a live OpenVSP model instead of only viewing the 3-view of the vehicle as it currently is in the quad-chart performance overview slide. This can be accomplished by utilizing the API integration between OpenVSP and Python software interfaces. For Python Tkinter, the package "numpy-stl" could be utilized to display the STL file generated using OpenVSP, after exporting the VSP model as an STL file.

From user testing as well, the users would like to be able to expand the software window as needed. This capability has not been implemented as the GUI size is set to specific dimensions at the moment but can be implemented in the next iteration.

9.3. Map Out Automation of Processes

The VCC should be capable of conducting certain processes automatically in the future without the need for direct human input. Technology capabilities change over time and seeing as there is currently development in artificial intelligence, it would be beneficial to map out what features of the compendium may be automated in the future. By the time such a map is completed, it could be that the technology is available to begin implementation.

For example, the data and information digitization process could be automated. As described earlier, for this current project the entire digitization and collection process for data, information and knowledge was conducted by a three-person research team, including the author. If this tedious process was automated it would save valuable time for future research teams to then spend more energy and focus on further developing the insightful knowledge generation process or working on updating the standard deliverables list and producing more thorough standards and practices. This would be time well spent rather than on digitization which does not require much intelligent insight from a person, per se.

There are various aspects of the DIK collection process that an intelligent system may be able to take over, starting even with the bibliography collection. Of course, for a long time the research team working on the VCC will be dependent upon the vast library of sources collected within the AVD Laboratory. However as newer projects continue to be added to the growing vehicle list for the VCC, a computer algorithm may be developed that searches the entire internet and all of the libraries currently known for sources that are written specifically on certain vehicles, to build that thorough bibliography.

Another aspect that could be automated is the snipping of relevant DIK images from the PDF sources. Perhaps a program could be developed that knows what parameters to search for in any given document, that relate to design. The program could be trained to snip any plots or tables that showcase these parameters and store them with the source name as the filename.

The actual digitization of such plots and tables may also be digitized in the future. Perhaps even with some of the technology available today, this may be achieved. It is definitely a worthy endeavor to pursue as this would save valuable time that the human researchers with expertise and insight could be spending on more insightful developments relating to the research project.

9.4. Integration with AVDS

The other part of the future work for VCC would be to fully integrate the system with the AVDS software described in Chapter 3. The VCC data-information-base housed in SQLite must be integrated with the SQLite database of the AVDS software, in order to allow seamless retrieval between the two systems. The user interfaces of both software must be integrated which is a task heavily involved in software development, and this integration must be conducted regularly as each system is updated with new information throughout different project timelines. The integrated system must undergo user-testing to achieve very valuable feedback regarding the usability of the combined synthesis-DIK system for a designer.

9.5. Future Technology Integration

The VCC standalone software, as well as the VCC-AVDS integrated system – both have the potential to go far in the industry and be of much use to individuals of every level of expertise in the field of aerospace engineering. For example, an embedded AI program may be developed that automatically updates the stored data and checks for any new data regularly by scouring the internet for public domain academic papers and journals, adds these to the reference collection, and alerts the developers of new data found by searching through the new sources for keywords that described some of the previously stored data. The AI could be programmed to learn from the past hypersonic vehicle datasets to see what is missing and be on the lookout for data that would help us fill in those gaps, as well as be on the lookout for new hypersonic launch vehicles.

The AI program could be taught to digitize and store data to make the VCC software self-sustainable in the future.

In addition, from a pure user-experience perspective, it would be hard-pressing to think that the holograph technology will not be used in the future with the VCC. It may not be in the current generation that this is accomplished but it is very possible years into the future. The VCC could very well evolve into what is envisioned in sci-fi movies, where the user is able to interact with a holographic version of the software without even the need of a solid screen surface. The holograph could envelope the user and allow for a more immersive experience, with the user surrounded by the controls to allow them to interactively change the settings for viewing and manipulating data.

Overall, the Vehicle Configuration Compendium has already proven itself to be incredibly valuable in its current form, and in the future with further development this software combined with the AVDS system will change the way aerospace vehicle design has been conducted.

APPENDIX A
VEHICLE BIBLIOGRAPHIES

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APPENDIX B
VERIFICATION CONDUCTED USING AVDS-VCC DURING NASA STUDY

B.1. X-51 Sizing Verification

Sized Vehicle Attributes	X-51 [EN]	AVDS X-51 [EN]	X-51 [SI]	AVDS X-51 [SI]	% Error
Operating Weight Empty, lb or kg	1,225	1,209	555	548	-1.29
Operating Empty Weight, lb or kg	1,225	1,209	555	548	-1.29
Takeoff Gross Weight, lb or kg	1,504	1,483	682	673	-1.38
Structural Weight, lb or kg	-	292	-	133	-
Fuel Weight, lb or kg	279	274	127	124	-1.79
Payload Weight, lb or kg	0	0	0	0	-
Tau, $V_{total}/S_{pln}^{1.5}$	0.214*	0.214	0.214*	0.214	-
Total Planform Area, ft^2 or m^2	24.4*	24.3	2.27*	2.26	-0.50
Wing Planform Area, ft^2 or m^2	24.4*	24.3	2.27*	2.26	-0.50
Wetted Surface Area, ft^2 or m^2	90.9*	85.6	8.45*	7.95	-5.90
Total Volume, ft^3 or m^3	25.7*	25.6	0.729*	0.725	-0.56
Ratio of Wetted to Total Planform Area	3.73*	3.52	3.73*	3.52	-5.43
Structural Index, $I_{str} = W_{str}/S_{wet}$, lb/ft^2 or N/m^2	-	3.42	-	16.7	-
Propulsion Index, $I_p = \rho_{fuel}/(WR\text{-}1)$, lb/ft^3 or kg/m^3	219	220	3,507	3,531	0.68
Industrial Capability Index, $10 \cdot I_p/I_{str}$	-	645	-	2,116	-
Total Fuel Fraction, W_{fuel}/TOGW	0.186	0.185	0.186	0.185	-0.42
Total Weight Ratio, TOGW/OWE	1.23	1.23	1.23	1.23	-0.10
Total Planform Wing Loading, TOGW/S_{pln}, lb/ft^2 or N/m^2	61.6*	61.1	2,951*	2,925	-0.88
Wing Planform Wing Loading, TOGW/S_{wing}, lb/ft^2 or N/m^2	61.6*	61.1	2,951*	2,925	-0.88

*Values that have been obtained using the X-51 VSP geometry model

B.2. XB-70 Sizing Verification

Sized Vehicle Attributes	XB-70 [EN]	AVDS XB-70 [EN]	XB-70 [SI]	AVDS XB-70 [SI]	% Error
Operating Weight Empty, lb or kg	256,148	265,258	116,147	120,277	3.56
Operating Empty Weight, lb or kg	206,148	214,668	93,475	97,338	4.13
Takeoff Gross Weight, lb or kg	542,029	544,814	245,776	247,038	0.51
Structural Weight, lb or kg	124,203	105,837	56,318	47,990	-14.8
Fuel Weight, lb or kg	285,881	279,557	129,629	126,761	-2.21
Payload Weight, lb or kg	50,000	50,000	22,672	22,672	-
Tau, $V_{total}/S_{pln}^{1.5}$	0.0549*	0.0549	0.0549*	0.0549	-
Total Planform Area, ft^2 or m^2	7,099*	7,093	660*	659	-0.09
Wing Planform Area, ft^2 or m^2	6,297	6,291	585	584	-0.09
Wetted Surface Area, ft^2 or m^2	18,981*	18,964	1,763*	1,762	-0.09
Total Volume, ft^3 or m^3	27,442*	27,406	777*	776	-0.13
Ratio of Wetted to Total Planform Area	2.67*	2.67	2.67*	2.67	0.00
Structural Index, $I_{str} = W_{str}/S_{wet}$, lb/ft^2 or N/m^2	6.54*	5.58	313*	27.2	-14.7
Propulsion Index, $I_p = \rho_{fuel}/(WR\text{-}1)$, lb/ft^3 or kg/m^3	45.3	48.0	726	769	5.90
Industrial Capability Index, $10 \cdot I_p/I_{str}$	69.26*	86.0	227*	282	24.2
Total Fuel Fraction, W_{fuel}/TOGW	0.527	0.513	0.527	0.513	-2.71
Total Weight Ratio, TOGW/OWE	2.12	2.05	2.12	2.05	-2.94
Total Planform Wing Loading, TOGW/S_{pln}, lb/ft^2 or N/m^2	76.3*	76.8	3,656*	3,678	0.60
Wing Planform Wing Loading, TOGW/S_{wing}, lb/ft^2 or N/m^2	86.1	86.6	4,122	4,146	0.60

*Values that have been obtained using the XB-70 VSP geometry model

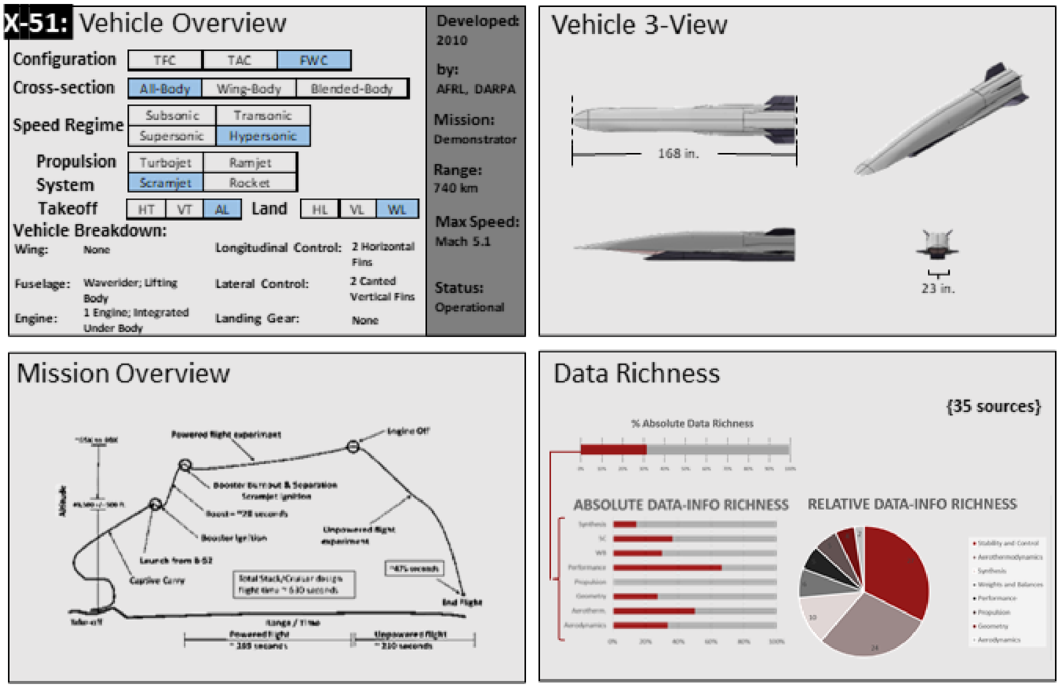
B.3. SR-71 Sizing Verification

Sized Vehicle Attributes	**SR-71 [EN]**	**AVDS SR-71 [EN]**	**SR-71 [SI]**	**AVDS SR-71 [SI]**	**% Error**
Operating Weight Empty, lb or kg	60,203	60,652	27,298	27,502	0.75
Operating Empty Weight, lb or kg	56,203	56,083	25,485	25,430	-0.21
Takeoff Gross Weight, lb or kg	140,853	143,024	63,868	64,852	1.54
Structural Weight, lb or kg	26,101	27,168	11,835	12,319	4.09
Fuel Weight, lb or kg	80,650	82,372	36,570	37,350	2.13
Payload Weight, lb or kg	4,000	4,000	1,814	1,814	-
Tau, $V_{total}/S_{pln}^{1.5}$	0.0442*	0.0442	0.0442*	0.0442	-
Total Planform Area, ft^2 or m^2	2,491*	2,518	231*	234	1.08
Wing Planform Area, ft^2 or m^2	1,795	1,815	167	169	1.09
Wetted Surface Area, ft^2 or m^2	6,469*	6,540	601*	608	1.09
Total Volume, ft^3 or m^3	5,493*	5,583	156*	158	1.63
Ratio of Wetted to Total Planform Area	2.60*	2.60	2.60*	2.60	0.01
Structural Index, $I_{str} = W_{str}/S_{wet}$, lb/ft^2 or N/m^2	4.03*	4.15	193*	20.3	2.97
Propulsion Index, $I_p = \rho_{fuel}/(WR\text{-}1)$, lb/ft^3 or kg/m^3	36.1	36	579	571	-1.36
Industrial Capability Index, $10 \cdot I_p/I_{str}$	89.54*	85.8	294*	281	-4.20
Total Fuel Fraction, W_{fuel}/TOGW	0.573	0.576	0.573	0.576	0.58
Total Weight Ratio, TOGW/OWE	2.34	2.36	2.34	2.36	0.79
Total Planform Wing Loading, TOGW/S_{pln}, lb/ft^2 or N/m^2	56.5*	56.8	2,707*	2,720	0.45
Wing Planform Wing Loading, TOGW/S_{wing}, lb/ft^2 or N/m^2	78.5	78.8	3,757	3,774	0.45

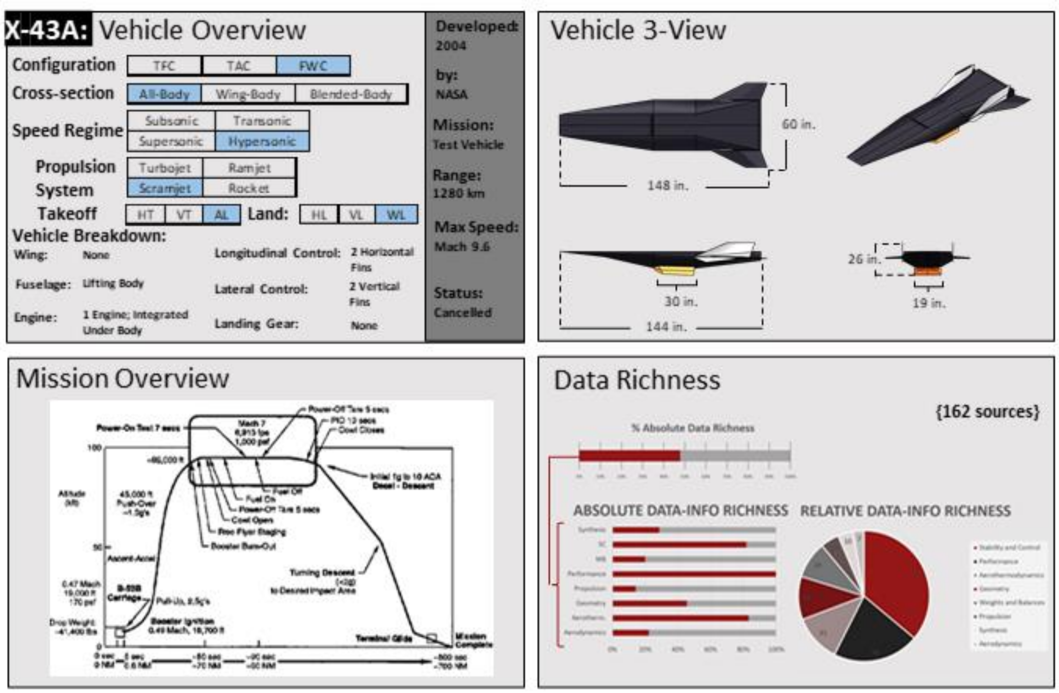
*Values that have been obtained using the SR-71 VSP geometry model

APPENDIX C
VEHICLE PERFORMANCE OVERVIEWS

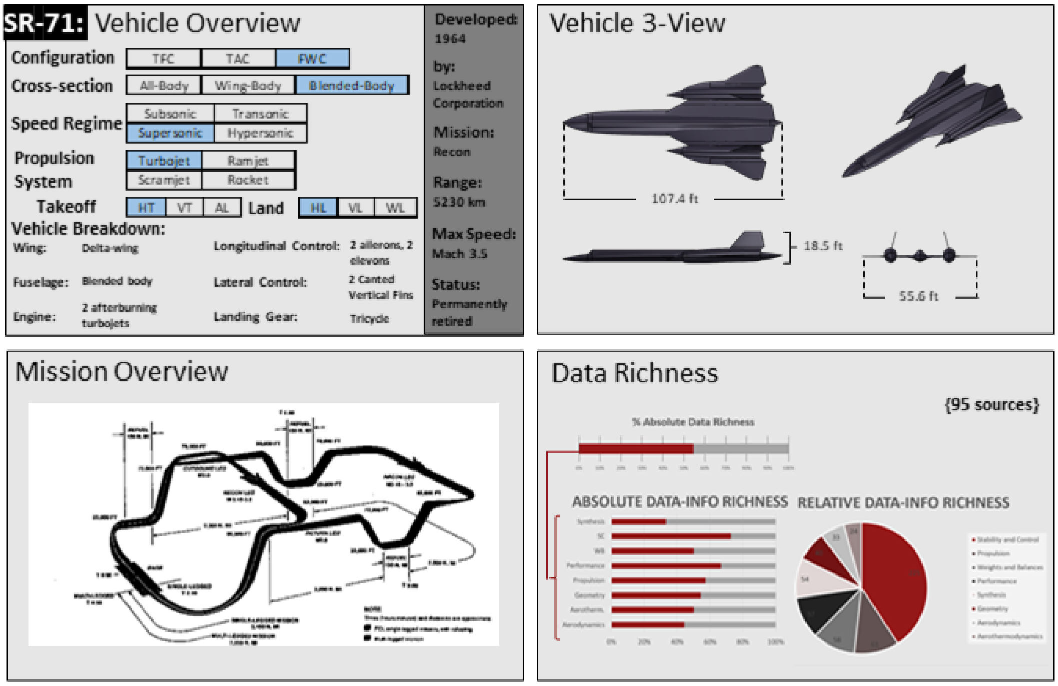
C.1. X-51 Performance Overview



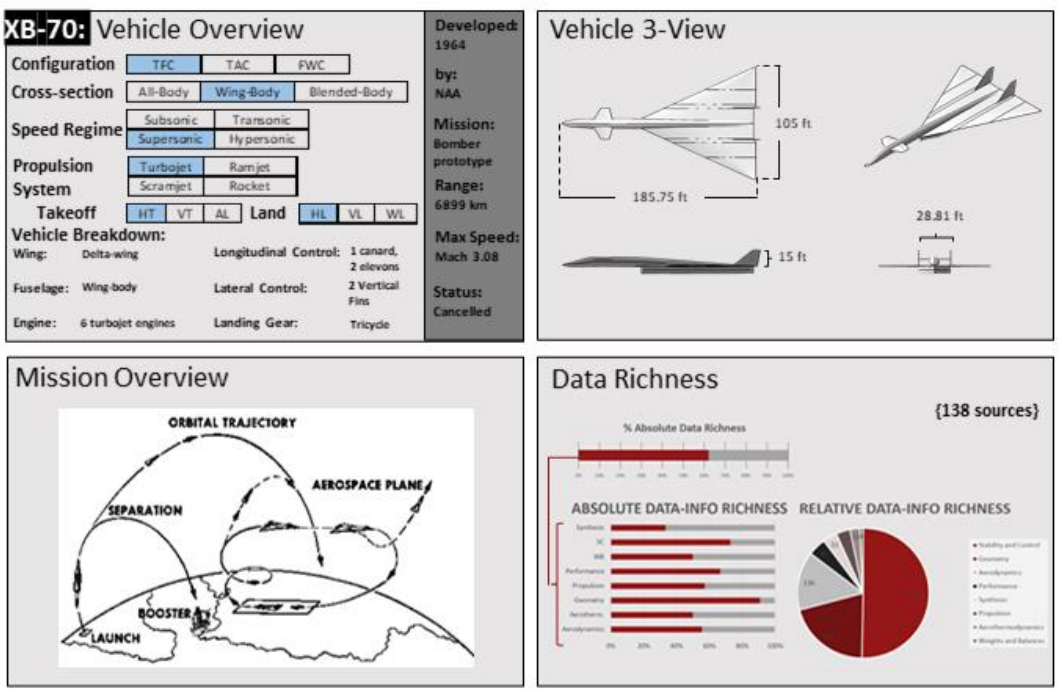
C.2. X-43A Performance Overview



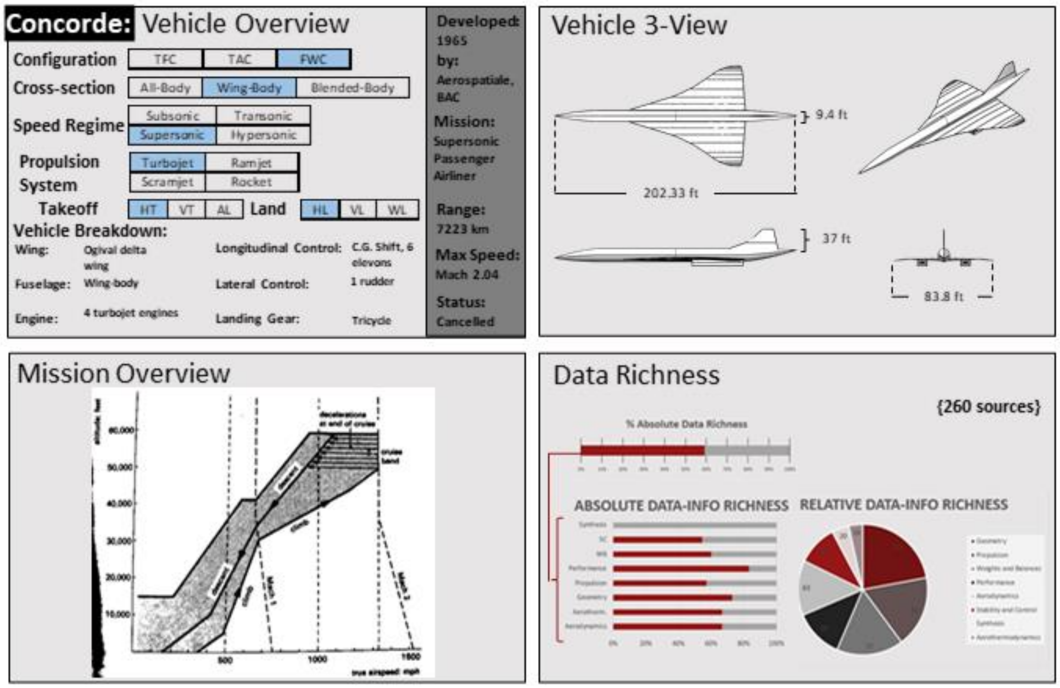
C.3. SR-71 Performance Overview



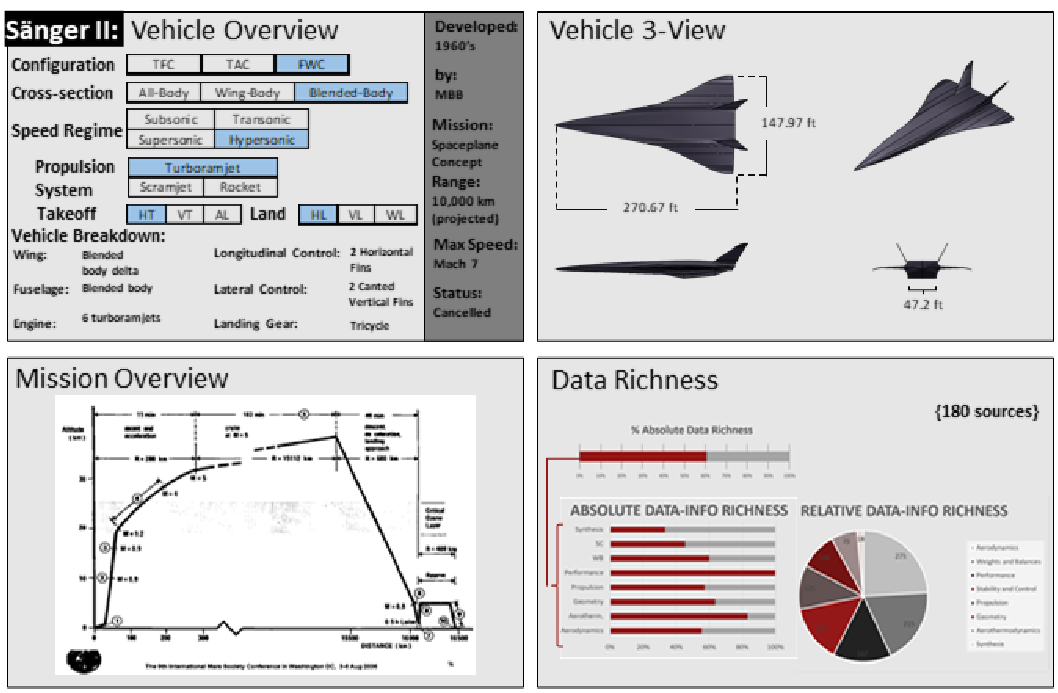
C.4. XB-70 Performance Overview



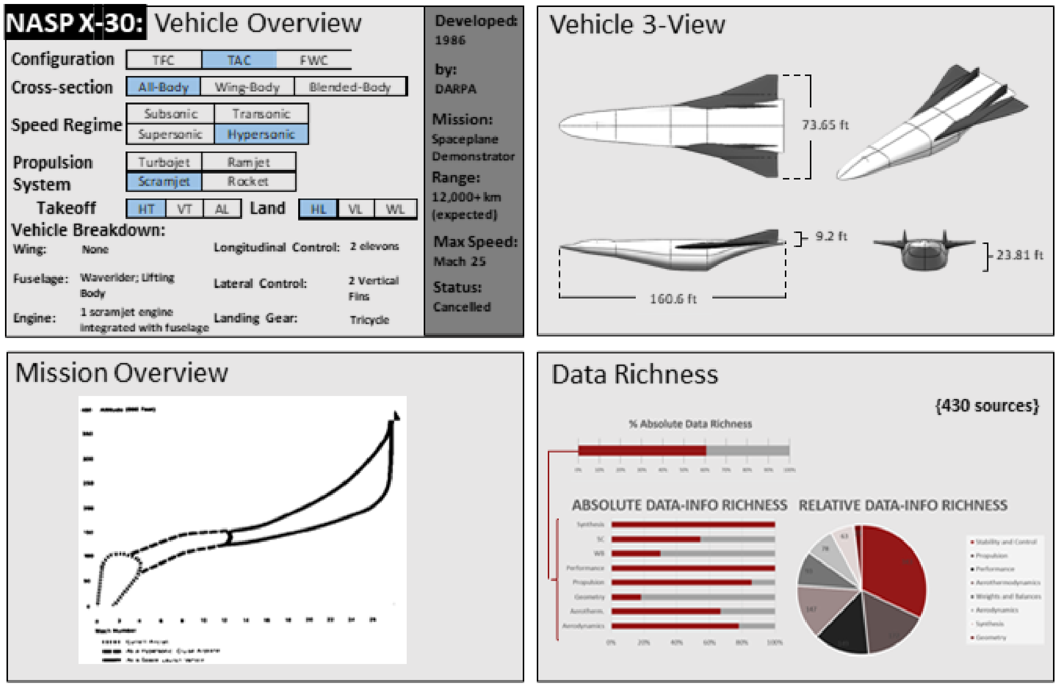
C.5. Concorde Performance Overview



C.6. Sänger-II Performance Overview



C.7. NASP X-30 Performance Overview



APPENDIX D
SOFTWARE USER MANUAL

VEHICLE CONFIGURATION COMPENDIUM

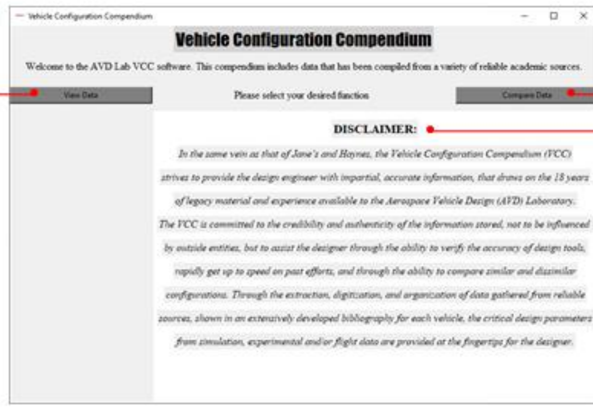
User Guide

TABLE OF CONTENTS

DATA-INFORMATION-BASE

Start screen:

"View Data" allows you to access the Data-Information-Base functionality

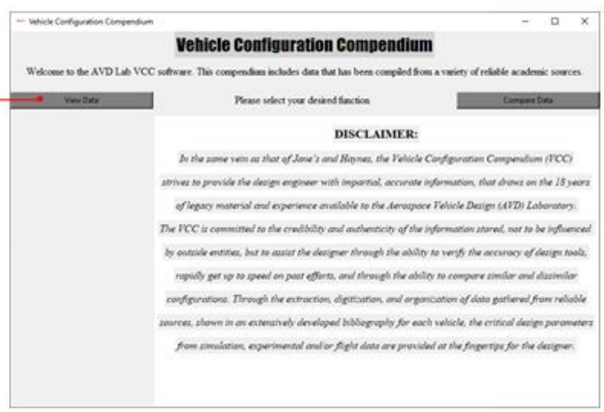


"Compare Data" allows you to access the Knowledgebase functionality

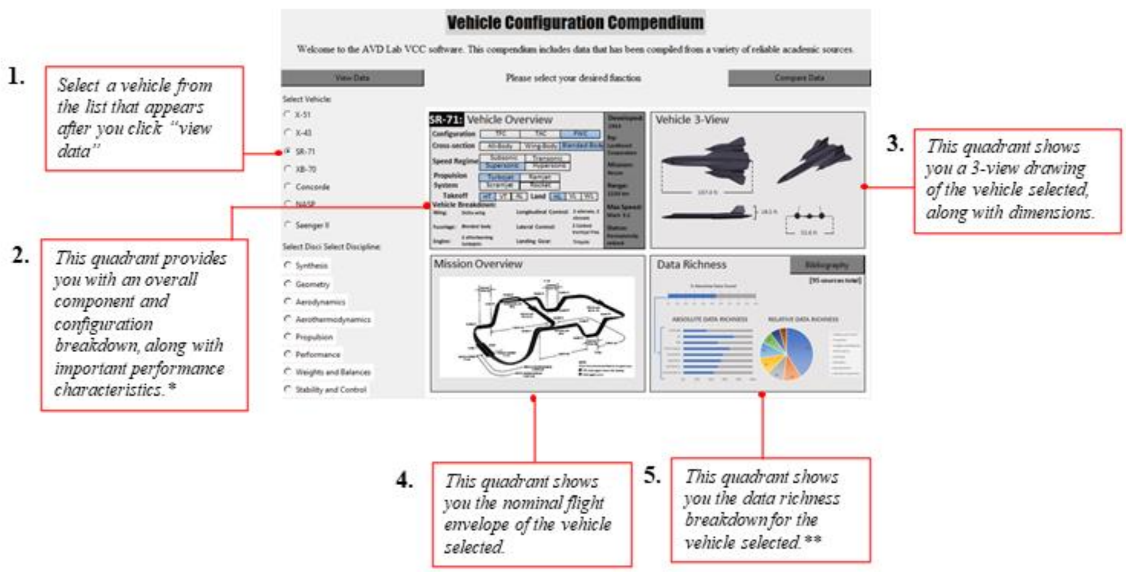
Our disclaimer statement provides context regarding the commitment of the VCC and its research team to providing authentic design data, information and knowledge.

Selecting the DI-BASE Function:

Click on "View Data"



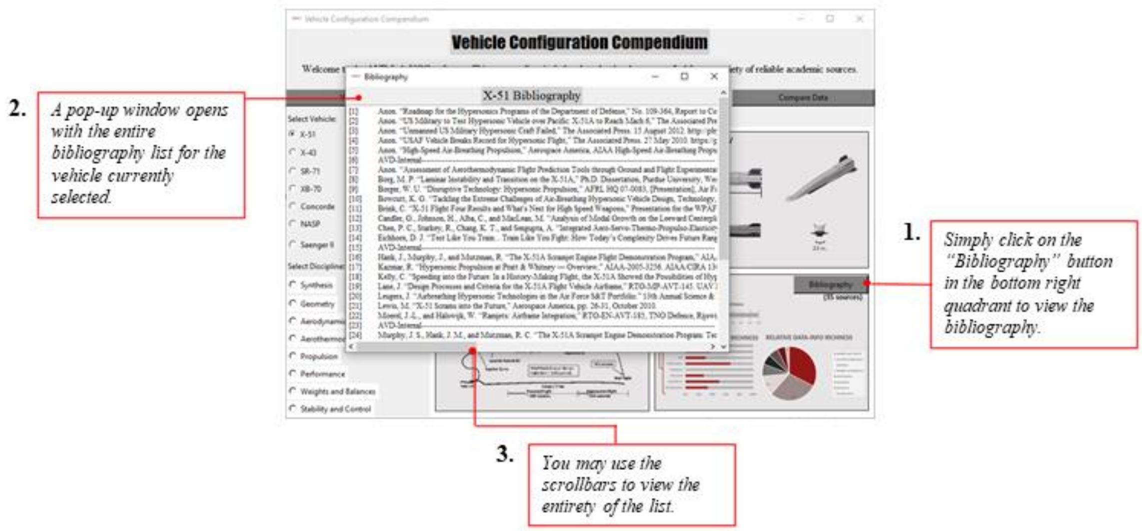
View an overview of each vehicle:



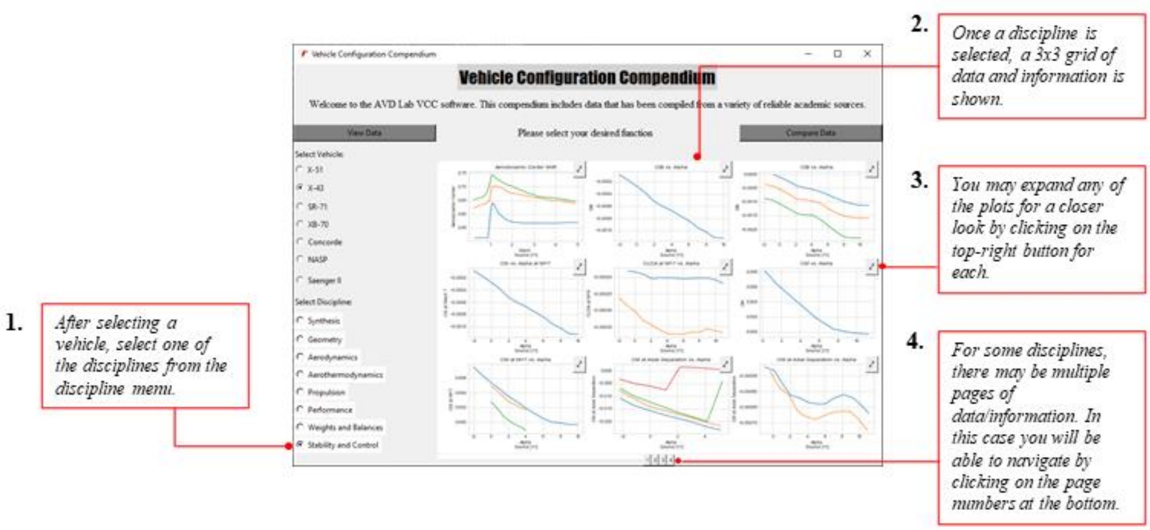
* The following items are provided in this quadrant: Configuration type, cross-section type, speed regime, propulsion system, takeoff and landing modes, wing type, fuselage type, number of engines, longitudinal and lateral control surfaces, landing gear type, year of development, primary company/entity involved in development, mission type, maximum range achieved/achievable, maximum speed achieved/achievable, and current status.

** Absolute data-information richness (ADIR) refers to the percentage of conceptual-design relevant data collected in comparison to a set list of parameters needed. To view this parameter list for each discipline, view ()
Relative data-information richness (RDIR) refers to the percentage breakdown of collected parameters by discipline.

View the bibliography for each vehicle:

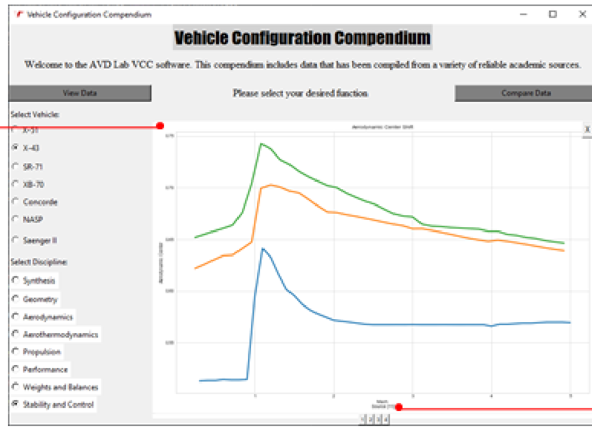


View disciplinary data/information for each vehicle:



View disciplinary data/information for each vehicle (contd.)

5. *Clicking on the "expand" icon will scale up that particular graph for better viewing, as seen here.*

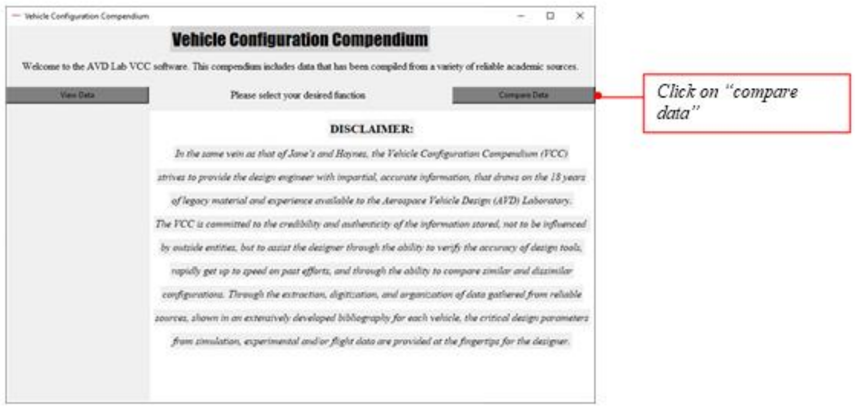


7. *After viewing the information, you may click on "X" to close the expanded view and return to the 3x3 grid of disciplinary data and information.*

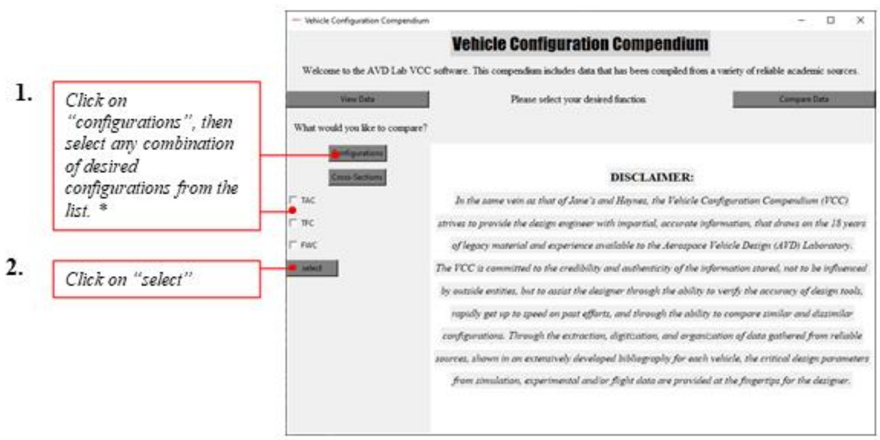
6. *The source number of the graphs are provided underneath the x-axis. These source numbers correspond to the source numbers listed in the vehicle bibliographies provided.*

KNOWLEDGE-BASE

Selecting the knowledgebase function:

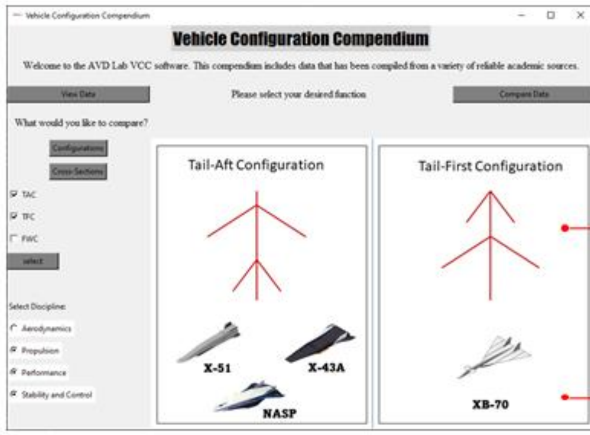


Compare different configurations:



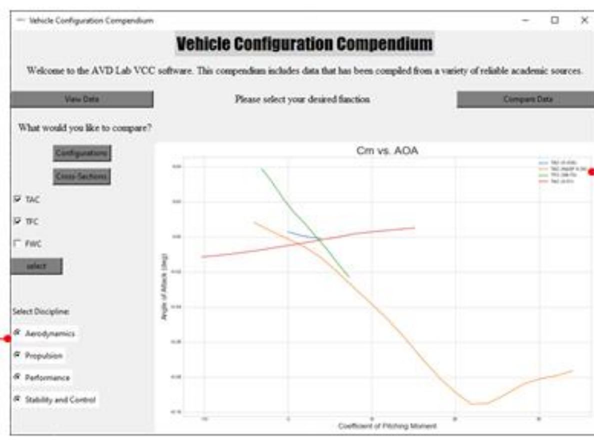
* TAC = Tail-Aft Configuration, TFC = Tail-First Configuration, and FWC = Flying Wing Configuration

Compare different configurations (contd.):



3. *A chart is displayed that provides a visual representation of the configurations chosen.*

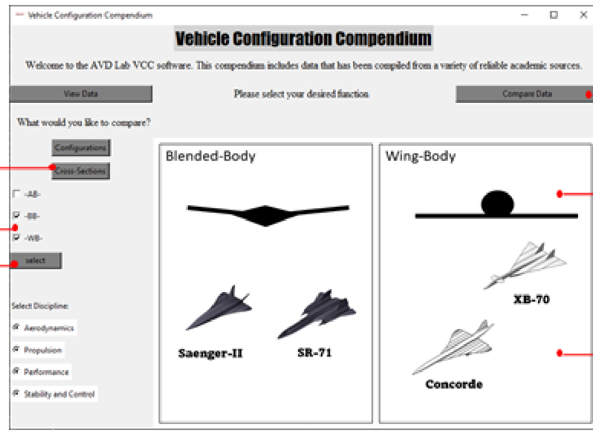
4. *The vehicles in the VCC are shown categorized by these configurations for your reference.*



5. *You may opt to view knowledge plots for any of the disciplines shown for your combination of configurations.*

6. *Legends are displayed for your reference – these include the configurations and vehicles displayed in the plot shown.*

Compare different cross-sections:



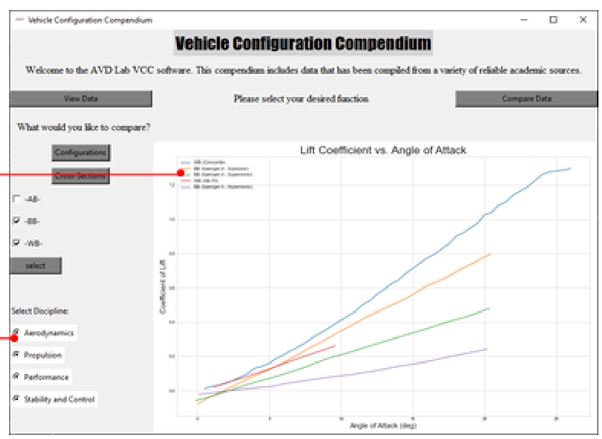
1. *Click on "compare data"*

2. *Click on "cross-sections", then select any combination of desired cross-sections from the list. **

3. *Click on "select"*

4. *A chart is displayed that provides a visual representation of the cross-sections chosen.*

5. *The vehicles in the VCC are shown categorized by these cross-sections for your reference.*

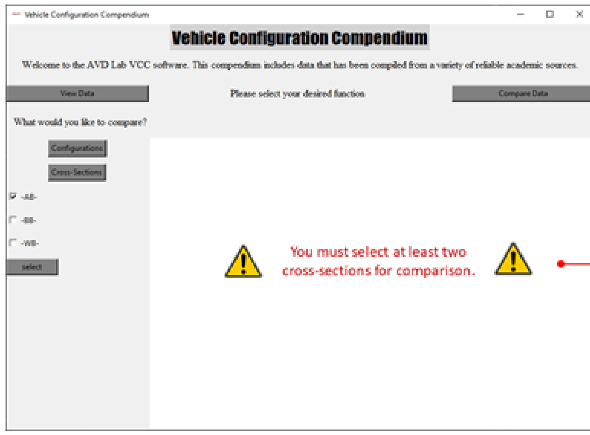


6. *You may opt to view knowledge plots for any of the disciplines shown for your combination of configurations.*

7. *Legends are displayed for your reference – these include the cross-sections and vehicles displayed in the plot shown.*

* AB = All-Body, BB = Blended-Body, and WB = Wing-Body

Knowledgebase error:



Please note: If you are shown this error message, this is due to selecting only one configuration or cross-section from the list. If this occurs, make an additional selection and click on "select".

APPENDIX F
SOFTWARE USER TESTING FORMAT

VCC Usability Test Plan

Name of Product: Vehicle Configuration Compendium

Goals: Test the usability and accessibility of the software interface of the Vehicle Configuration Compendium. Ensure the application is easily navigable to professionals and non-professionals alike.

Time:

Date:

Location:

Format: In-person

Participant Name:

Field of Study: Aerospace / Non-Aerospace

If Aerospace, # years of engagement:

Introduction:

This is the Vehicle Configuration Compendium, which is meant to be a compendium of aircraft design-related data, information and knowledge to help designers as well as design enthusiasts. The software we will be testing today is a prototype implementation of this compendium, so you will see a very low number of vehicles listed. We will begin with a series of tasks for you to complete. If at any point you need assistance, feel free to ask. Also feel free to vocalize what you are experiencing as you walk through each of the tasks.

Tasks:

1) Find out the year the XB-70 was developed.

2) Open up the XB-70 bibliography.

2) View the propulsion plots for XB-70.

3) Expand one of the XB-70 propulsion plots.

5) Find the source number of the third aerodynamic plot for SR-71.

6) Compare the aerodynamic performance of two different configurations.

Task #	Completed? Y/N	Time to completion	Assistance required?
1			
2			
3			
4			
5			
6			

Moderator notes:

Post-Test Survey:

Q1. How did you find using the VCC software to view disciplinary data for the XB-70?

Q2. What is a feature of the software that you found confusing to use? Why?

Q3. What is a feature of the software you found easy to use? Why?

Q4. Were there any features you expected to see in such a system that you did not?

Q4. How would you rate the GUI on the following: (on a scale of 1 to 5)

	Bad	Good
Overall experience:	1 2 3 4 5	
	Confusing	Clear
Layout of software:	1 2 3 4 5	
	Simplistic	Too Complex
Complexity of the system:	1 2 3 4 5	
	Low confidence	High confidence
Confidence level to use the system without help:	1 2 3 4 5	
	Not useful	Very useful
Level of usefulness of the information displayed for design:	1 2 3 4 5	
	Poorly organized	Well organized
Organization of the information on the screen:	1 2 3 4 5	
	Inadequate detail	Adequate detail
Level of detail of the information provided for each vehicle:	1 2 3 4 5	
	Bad	Good
Overall rating of the VCC:	1 2 3 4 5	

This page to be filled by test user

APPENDIX G
USER TESTING RESULTS

G.1. Task Completion

	User #	Completed?	Time to Completion	Assistance Required?
Task # 1	1	Yes	0:04:00	Yes
	2	Yes	0:02:00	Yes
	3	Yes	0:00:35	No
	4	Yes	0:01:27	Yes
Task # 2	1	Yes	0:00:03	No
	2	Yes	0:00:05	No
	3	Yes	0:00:13	No
	4	Yes	0:00:04	No
Task # 3	1	Yes	0:00:03	No
	2	Yes	0:00:30	Yes
	3	Yes	0:00:15	No
	4	Yes	0:00:01	No
Task # 4	1	Yes	0:00:02	No
	2	Yes	0:00:02	No
	3	Yes	0:00:08	No
	4	Yes	0:00:02	No
Task # 5	1	Yes	0:00:14	No
	2	Yes	0:00:15	No
	3	Yes	0:00:24	Yes
	4	Yes	0:00:43	Yes
Task # 6	1	Yes	0:00:26	No
	2	Yes	0:01:00	Yes
	3	Yes	0:00:57	Yes
	4	Yes	0:00:17	No

G.2. User Testing Survey Results

User #	1	2	3	4	Average:
Overall Experience	4	4	3	4	3.75
Layout of software	5	4	4	5	4.5
Complexity of the system	2	3	3	2	2.5
Confidence level to use the system without help	5	4	4	3	4
Level of usefulness of the information displayed for design	4	5	5	-	4.666667
Organization of the information on the screen	3	4	4	5	4
Level of detail of the information provided for each vehicle	4	5	3	4	4
Overall rating of the VCC	4	4	4	4	4

APPENDIX H
ABSTRACTS OF TOPIC-RELATED PUBLICATIONS FROM AVD LABORATORY

H.1. Chudoba, B., and Huang, X., "Development of a dedicated aerospace vehicle conceptual design knowledge-based system," *44th AIAA Aerospace Sciences Meeting and Exhibit*, 2006.

What has to be avoided most is that when knowledge stops evolving, it turns into opinion or dogma. This statement challenges rebuttal which immediately can be counter-acted by asking: How many truly capable aerospace vehicle design knowledge-based systems can be found to take advantage of design data, information, experience, and knowledge of past and present aerospace projects easily available at the fingertips? A major inconsistency can be observed in the ability to design advanced aerospace vehicles with respect to design knowledge required and design knowledge available. Advanced and especially 'novel' vehicle design is, as a fact, characterized by permanent lack of knowledge available at the conceptual design stage. As implied by novelty, design knowledge available naturally lags behind design knowledge required. The degree of this discrepancy is a measure for the design risks involved. As a consequence, the ability to perform efficient multi-disciplinary design is quickly becoming a lost skill without persistent knowledge-maintenance. A wide range of technical solutions for a multitude of problems have been assessed and demonstrated in aeronautical history. Unfortunately, much of that knowledge is either ignored for a variety of reasons or it has been simply forgotten. Some of today's conventional and unconventional flight vehicle design proposals would appear less risky or radical, if an up-to-date vehicle design knowledge-based system would be available to the practicing engineer and project lead. As a result, a striking discrepancy has to be accepted between 'what can be done' to 'what could be done'. This paper outlines the research strategy adopted at the AVD Laboratory towards the development of a dedicated aerospace vehicle conceptual design knowledge-based system (KBS). This apparent 'white space' is readily confirmed having provided a perspective on the original contribution the research makes to aerospace science and engineering. An approach towards the construction of a dedicated conceptual design KBS is presented, placing strong emphasis on a systematic and thorough knowledge utilization process. The researchers are confident that not only is the study distinctive and different from previous research, but that it is worth doing.

H.2. Roberts, K., and Chudoba, B., "Flight vehicle design heritage: Are we on the road to the same fate as Alexandria?," *45th AIAA Aerospace Sciences Meeting and Exhibit*, 2007.

Throughout the generations of aircraft design, much knowledge has been gained. Undoubtedly, much time, money, and energy have been expended towards this goal, both in the plans for commercial gain as well as in the scientific pursuit of knowledge. However, with any vast accumulation of knowledge comes the question: how do we organize it, remember it, and learn from it? Libraries, technical servers, and commercial collections have thus far strived towards serving this purpose. However, the requirement of an extensive literature survey from which historical insight can be extracted requires a large amount of time the design project engineer may not, and probably does not, have readily available. Additionally, what becomes of the knowledge and experience that the design engineers throughout the ages have learned personally? How is this information collected and learned from? Unfortunately, too much of this experiential knowledge has been lost. To help in solving these problems, a system that can incorporate engineering knowledge into aerospace conceptual design must be developed and implemented. In order to form a specification for such a system, an assessment of current knowledge management capabilities must be completed. This paper details this assessment, which involves significant research into the current state of knowledge management, as well as the level to which knowledge management is used in aerospace design today. In order to complete this assessment, a categorization system for KBS design has been established. Additionally, research into how an engineer works, thinks, processes, applies, and, overall, gains knowledge is included. This research helps to establish both the specification for the prototype of a KBS design system, as well as the 'ideal' KBS specification to be implemented in the future. Finally, a description of how the prototype specification is applied in the KBSDESIGN system in the conceptual design phase. It is the authors' view that with an adequate understanding of the knowledge generated in the past, design engineers will gain a clear perspective to apply to future vehicles.

H.3. Peng, X., and Chudoba, B., "Knowledge engineering - formalizing the engineering science discipline," *15th AIAA Aviation Technology, Integration, and Operations Conference*, 2015.

Knowledge is the most precious ingredient facilitating aerospace engineering research and product development. Inefficient knowledge retention methods have become a primary obstacle for knowledge transfer from the experienced to the next generation of engineers. Consequently, aerospace progress is impeded since few engineers pay attention as to how to efficiently manage past-to-present data, information and knowledge for future decisionmaking. The problem is: flawed input data, information, and knowledge yield flawed results, regardless of the quality of the analysis being conducted. Therefore, the task of how to efficiently manage data, information, and knowledge is vital to the future of aerospace growth. In order to provide development environments with a pragmatic knowledge management mindset and toolset, a best-practice knowledge management methodology – AVDKBS is proposed, resembling a dedicated aerospace design Knowledge-Based System (KBS). The research motivation, background and methodology of AVDKBS is explained in details. In addition, a quantitative evaluation criteria is proposed for the first time to measure the performances of the knowledge management methods, which works as an objective scale to determine their efficiencies. Lastly, a brief discussion is made on future developments.

H.4**.** Peng, X., and Chudoba, B., "Paving the way from the past to the future: AVDKBS, a software development in knowledge engineering," *15th AIAA Aviation Technology, Integration, and Operations Conference*, 2015.

Based on the unique knowledge engineering methodology, This paper does demonstrate the advantages of the new knowledge methodology via the functional software prototype AVDKBS.This dedicated aerospace knowledge-based system and software does introduce seven knowledge management functions: Knowledge Educating, Knowledge Updating, Knowledge Deleting, Trend Predicting, Data Updating, Data Deleting and Parametric Sizing Analysis. Both the function method logic and Graphical User Interface (GUI) developments are explained in detail. The advantages of AVDKBS is illustrated through a case study: Launch Vehicle Design. At the end of each application example throughout the case study, the AVDKBS efficiency advantages over traditional manual knowledge management methods are quantified summarized.

H.5. Simon, S., Atchison, S., and Chudoba, B., “Development of a hypersonic vehicle configuration compendium,” *AIAA AVIATION 2021 FORUM*, 2021.

Knowledge loss between projects or generations of designers and engineers is an issue that happens more often than it should, especially in the world of high-speed aerospace vehicle design. This results in future generations wasting valuable time and resources relearning information that has already been generated through experimentation in the past. This issue could be resolved with the creation of a parametric library that houses data and knowledge and is continually updated for generations to come, which is the undertaking of the research project detailed in this paper. The solution to this issue (as formulated by the collective effort of members of the University of Texas at Arlington AVD Laboratory) is the Vehicle Configuration Compendium, or the VCC. The VCC aims to keep vehicle designers better informed of past projects and able to easily access conceptual design-relevant project data and knowledge by housing them in an interactive software. Currently, seven high-speed vehicles have been processed into the compendium of gathered information, using a carefully formulated data and knowledge compilation and review process. This data is then incorporated into a user-friendly software interface that will in the future encourage designers and design enthusiasts of all experience or proficiency levels to consider various vehicle configurations and forecast any new vehicle design performances by consulting past projects.

H.6. Simon, S., Atchison, S., and Chudoba, B., “Conceptual design decision-making assisted by a comprehensive high-speed vehicle knowledgebase library,” *ASCEND 2021*, 2021.

In the recent years, the need for high-speed (supersonic to hypersonic) vehicle design has gained major significance in the aerospace industry. This is especially the case for within the commercial passenger transport area. A conceptual design tool has been initially developed called the Vehicle Configuration Compendium, or VCC, that can strategically collect and compare disciplinary data. This tool allows the storage of available design knowledge and can implement a multi-disciplinary approach to perform configuration studies through the analysis of comparing the unique configurations of the vehicles stored within. With seven representative high-speed vehicles compiled in the tool, the knowledgebase of the VCC can then be used to investigate a particular issue, or issues, in high-speed vehicle design to provide initial observations and recommendations on configuration choices given the issue(s) considered. This paper will conduct a case study of diving into one of these design issues and utilizing the knowledgebase functionality of the software for effective decision-making in the process.